Electrical installation handbook
Volume 2

3rd edition

Electrical devices

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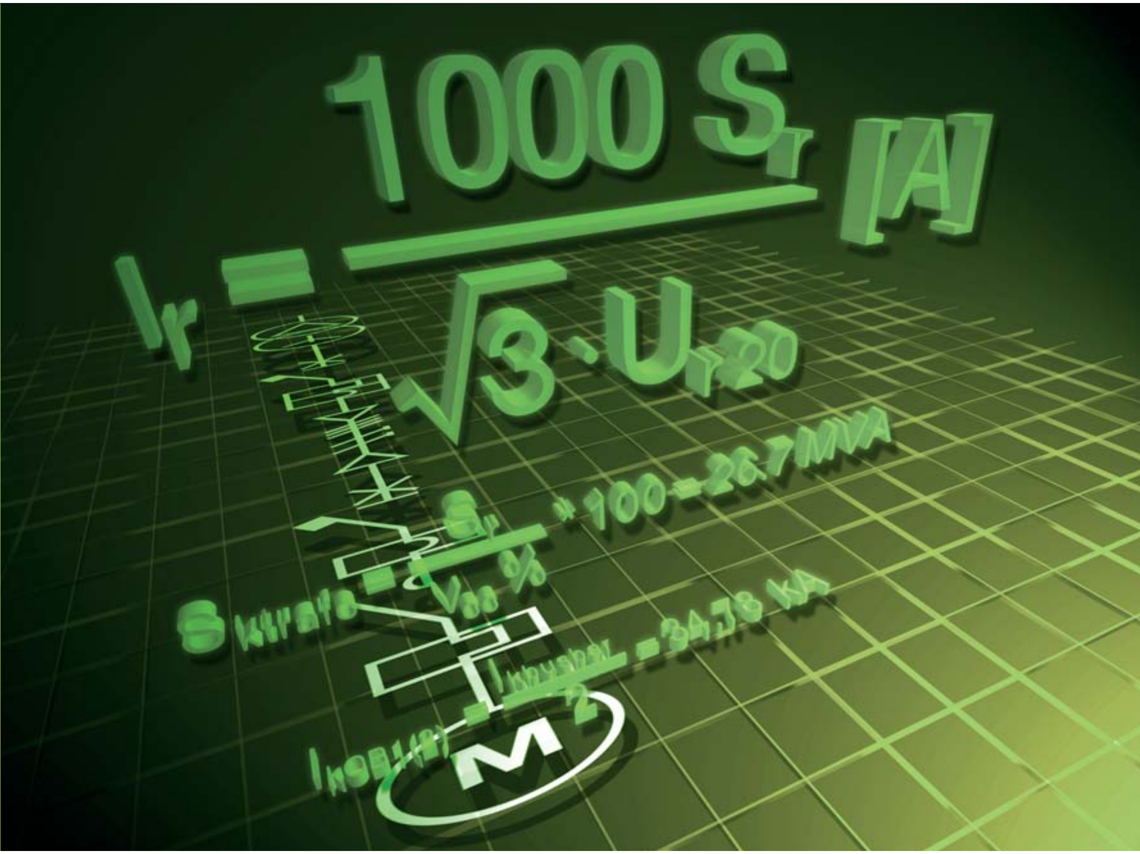

ABB SACE

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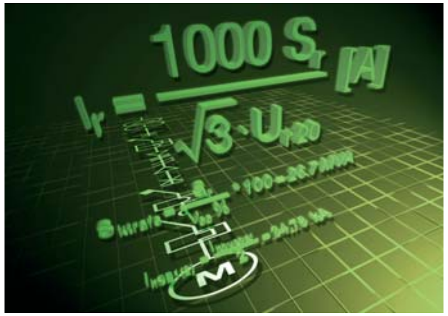

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Introduction

Scope and objectives

The scope of this electrical installation handbook is to provide the designer and user of electrical plants with a quick reference, immediate-use working tool. This is not intended to be a theoretical document, nor a technical catalogue, but, in addition to the latter, aims to be of help in the correct definition of equipment, in numerous practical installation situations.

The dimensioning of an electrical plant requires knowledge of different factors relating to, for example, installation utilities, the electrical conductors and other components; this knowledge leads the design engineer to consult numerous documents and technical catalogues. This electrical installation handbook, however, aims to supply, in a single document, tables for the quick definition of the main parameters of the components of an electrical plant and for the selection of the protection devices for a wide range of installations. Some application examples are included to aid comprehension of the selection tables.

Electrical installation handbook users

The electrical installation handbook is a tool which is suitable for all those who are interested in electrical plants: useful for installers and maintenance technicians through brief yet important electrotechnical references, and for sales engineers through quick reference selection tables.

Validity of the electrical installation handbook

Some tables show approximate values due to the generalization of the selection process, for example those regarding the constructional characteristics of electrical machinery. In every case, where possible, correction factors are given for actual conditions which may differ from the assumed ones. The tables are always drawn up conservatively, in favour of safety; for more accurate calculations, the use of DOCWin software is recommended for the dimensioning of electrical installations.

1 Standards

1.1 General aspects

In each technical field, and in particular in the electrical sector, a condition sufficient (even if not necessary) for the realization of plants according to the **“status of the art”** and a requirement essential to properly meet the demands of customers and of the community, is the respect of all the relevant laws and technical standards.
Therefore, a precise knowledge of the standards is the fundamental premise for a correct approach to the problems of the electrical plants which shall be designed in order to guarantee that **“acceptable safety level”** which is never absolute.

Juridical Standards
These are all the standards from which derive rules of behavior for the juridical persons who are under the sovereignty of that State.

Technical Standards
These standards are the whole of the prescriptions on the basis of which machines, apparatus, materials and the installations should be designed, manufactured and tested so that efficiency and function safety are ensured.
The technical standards, published by national and international bodies, are circumstantially drawn up and can have legal force when this is attributed by a legislative measure.

Application fields

	Electrotechnics and Electronics	Telecommunications	Mechanics, Ergonomics and Safety
International Body	IEC	ITU	ISO
European Body	CENELEC	ETSI	CEN

This technical collection takes into consideration only the bodies dealing with electrical and electronic technologies.

IEC International Electrotechnical Commission

The *International Electrotechnical Commission* (IEC) was officially founded in 1906, with the aim of securing the international co-operation as regards standardization and certification in electrical and electronic technologies. This association is formed by the International Committees of over 40 countries all over the world.
The IEC publishes international standards, technical guides and reports which are the bases or, in any case, a reference of utmost importance for any national and European standardization activity.
IEC Standards are generally issued in two languages: English and French.
In 1991 the IEC has ratified co-operation agreements with CENELEC (European standardization body), for a common planning of new standardization activities and for parallel voting on standard drafts.

1 Standards

CENELEC European Committee for Electrotechnical Standardization

The *European Committee for Electrotechnical Standardization* (CENELEC) was set up in 1973. Presently it comprises 28 countries (Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Portugal, Poland, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom) and cooperates with 7 affiliates (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Romania, Turkey, Ukraine) which have first maintained the national documents side by side with the CENELEC ones and then replaced them with the Harmonized Documents (HD).
There is a difference between EN Standards and Harmonization Documents (HD): while the first ones have to be accepted at any level and without additions or modifications in the different countries, the second ones can be amended to meet particular national requirements.
EN Standards are generally issued in three languages: English, French and German.
From 1991 CENELEC cooperates with the IEC to accelerate the standards preparation process of International Standards.
CENELEC deals with specific subjects, for which standardization is urgently required.
When the study of a specific subject has already been started by the IEC, the European standardization body (CENELEC) can decide to accept or, whenever necessary, to amend the works already approved by the International standardization body.

EC DIRECTIVES FOR ELECTRICAL EQUIPMENT

Among its institutional roles, the European Community has the task of promulgating directives which must be adopted by the different member states and then transposed into national law.
Once adopted, these directives come into juridical force and become a reference for manufacturers, installers, and dealers who must fulfill the duties prescribed by law.
Directives are based on the following principles:
- harmonization is limited to essential requirements;
- only the products which comply with the essential requirements specified by the directives can be marketed and put into service;
- the harmonized standards, whose reference numbers are published in the Official Journal of the European Communities and which are transposed into the national standards, are considered in compliance with the essential requirements;
- the applicability of the harmonized standards or of other technical specifications is facultative and manufacturers are free to choose other technical solutions which ensure compliance with the essential requirements;
- a manufacturer can choose among the different conformity evaluation procedure provided by the applicable directive.

The scope of each directive is to make manufacturers take all the necessary steps and measures so that the product does not affect the safety and health of persons, animals and property.

1 Standards

"Low Voltage" Directive 73/23/CEE – 93/68/CEE

The Low Voltage Directive refers to any electrical equipment designed for use at a rated voltage from 50 to 1000 V for alternating current and from 75 to 1500 V for direct current.
In particular, it is applicable to any apparatus used for production, conversion, transmission, distribution and use of electrical power, such as machines, transformers, devices, measuring instruments, protection devices and wiring materials.
The following categories are outside the scope of this Directive:
- electrical equipment for use in an explosive atmosphere;
- electrical equipment for radiology and medical purposes;
- electrical parts for goods and passenger lifts;
- electrical energy meters;
- plugs and socket outlets for domestic use;
- electric fence controllers;
- radio-electrical interference;
- specialized electrical equipment, for use on ships, aircraft or railways, which complies with the safety provisions drawn up by international bodies in which the Member States participate.

Directive EMC 89/336/EEC ("Electromagnetic Compatibility")

The Directive on electromagnetic compatibility regards all the electrical and electronic apparatus as well as systems and installations containing electrical and/or electronic components. In particular, the apparatus covered by this Directive are divided into the following categories according to their characteristics:
- domestic radio and TV receivers;
- industrial manufacturing equipment;
- mobile radio equipment;
- mobile radio and commercial radio telephone equipment;
- medical and scientific apparatus;
- information technology equipment (ITE);
- domestic appliances and household electronic equipment;
- aeronautical and marine radio apparatus;
- educational electronic equipment;
- telecommunications networks and apparatus;
- radio and television broadcast transmitters;
- lights and fluorescent lamps.

The apparatus shall be so constructed that:
a) the electromagnetic disturbance it generates does not exceed a level allowing radio and telecommunications equipment and other apparatus to operate as intended;
b) the apparatus has an adequate level of intrinsic immunity to electromagnetic disturbance to enable it to operate as intended.

An apparatus is declared in conformity to the provisions at points a) and b) when the apparatus complies with the harmonized standards relevant to its product family or, in case there aren't any, with the general standards.

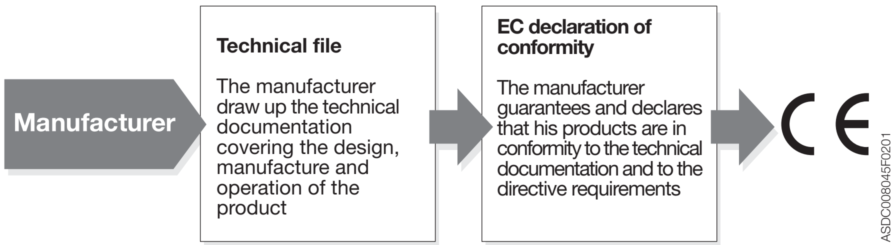
1 Standards

CE conformity marking

The CE conformity marking shall indicate conformity to all the obligations imposed on the manufacturer, as regards his products, by virtue of the European Community directives providing for the affixing of the CE marking.

When the CE marking is affixed on a product, it represents a declaration of the manufacturer or of his authorized representative that the product in question conforms to all the applicable provisions including the conformity assessment procedures. This prevents the Member States from limiting the marketing and putting into service of products bearing the CE marking, unless this measure is justified by the proved non-conformity of the product.

Flow diagram for the conformity assessment procedures established by the Directive 73/23/EEC on electrical equipment designed for use within particular voltage range:



Naval type approval

The environmental conditions which characterize the use of circuit breakers for on-board installations can be different from the service conditions in standard industrial environments; as a matter of fact, marine applications can require installation under particular conditions, such as:
- environments characterized by high temperature and humidity, including salt-mist atmosphere (damp-heat, salt-mist environment);
- on board environments (engine room) where the apparatus operate in the presence of vibrations characterized by considerable amplitude and duration.

In order to ensure the proper function in such environments, the shipping registers require that the apparatus has to be tested according to specific type approval tests, the most significant of which are vibration, dynamic inclination, humidity and dry-heat tests.

1 Standards

ABB SACE circuit-breakers (Isomax-Tmax-Emax) are approved by the following shipping registers:

• **RINA**	Registro Italiano Navale	Italian shipping register
• **DNV**	Det Norske Veritas	Norwegian shipping register
• **BV**	Bureau Veritas	French shipping register
• **GL**	Germanischer Lloyd	German shipping register
• **LRs**	Lloyd's Register of Shipping	British shipping register
• **ABS**	American Bureau of Shipping	American shipping register

It is always advisable to ask ABB SACE as regards the typologies and the performances of the certified circuit-breakers or to consult the section certificates in the website **http://bol.it.abb.com**.

Marks of conformity to the relevant national and international Standards

The international and national marks of conformity are reported in the following table, for information only:

COUNTRY	Symbol	Mark designation	Applicability/Organization
EUROPE		–	Mark of compliance with the harmonized European standards listed in the ENEC Agreement.
AUSTRALIA		AS Mark	Electrical and non-electrical products. It guarantees compliance with SAA (Standard Association of Australia).
AUSTRALIA		S.A.A. Mark	Standards Association of Australia (S.A.A.). The Electricity Authority of New South Wales Sydney Australia
AUSTRIA		Austrian Test Mark	Installation equipment and materials

1 Standards

COUNTRY	Symbol	Mark designation	Applicability/Organization
AUSTRIA		ÖVE Identification Thread	Cables
BELGIUM	CEBEC	CEBEC Mark	Installation materials and electrical appliances
BELGIUM	CEBEC	CEBEC Mark	Conduits and ducts, conductors and flexible cords
BELGIUM	CEBEC	Certification of Conformity	Installation material and electrical appliances (in case there are no equivalent national standards or criteria)
CANADA	SA®	CSA Mark	Electrical and non-electrical products. This mark guarantees compliance with CSA (Canadian Standard Association)
CHINA		CCEE Mark	Great Wall Mark Commission for Certification of Electrical Equipment
Czech Republic	EZC	EZU' Mark	Electrotechnical Testing Institute
Slovakia Republic	EVS	EVPU' Mark	Electrotechnical Research and Design Institute

1.1 General aspects

1 Standards

COUNTRY	Symbol	Mark designation	Applicability/Organization
CROATIA	KONČAR	KONKAR	Electrical Engineering Institute
DENMARK	D	DEMKO Approval Mark	Low voltage materials. This mark guarantees the compliance of the product with the requirements (safety) of the "Heavy Current Regulations"
FINLAND	SÄHKÖTARKASTUSLAITOKSEN HYVÄKSYMÄ GODKÄND AV ELEKTRISKA INSPEKTORATET *	Safety Mark of the Elektriska Inspektoratet	Low voltage material. This mark guarantees the compliance of the product with the requirements (safety) of the "Heavy Current Regulations"
FRANCE	CONTRÔLE NF LIMITÈ À LA SÈCURITÈ	ESC Mark	Household appliances
FRANCE	NF USE	NF Mark	Conductors and cables – Conduits and ducting – Installation materials
FRANCE		NF Identification Thread	Cables
FRANCE	OUTILLAGE NF ÉLECTRICITÉ	NF Mark	Portable motor-operated tools
FRANCE	NF ÉLECTRICITÉ	NF Mark	Household appliances

1 Standards

COUNTRY	Symbol	Mark designation	Applicability/Organization
GERMANY		VDE Mark	For appliances and technical equipment, installation accessories such as plugs, sockets, fuses, wires and cables, as well as other components (capacitors, earthing systems, lamp holders and electronic devices)
GERMANY		VDE Identification Thread	Cables and cords
GERMANY		VDE Cable Mark	For cables, insulated cords, installation conduits and ducts
GERMANY		VDE-GS Mark for technical equipment	Safety mark for technical equipment to be affixed after the product has been tested and certified by the VDE Test Laboratory in Offenbach; the conformity mark is the mark VDE, which is granted both to be used alone as well as in combination with the mark GS
HUNGARY		MEEI	Hungarian Institute for Testing and Certification of Electrical Equipment
JAPAN	JIS GIAPPONE	JIS Mark	Mark which guarantees compliance with the relevant Japanese Industrial Standard(s).
IRELAND	IIRS IRLANDA	IIRS Mark	Electrical equipment
IRELAND		IIRS Mark	Electrical equipment

1 Standards

COUNTRY	Symbol	Mark designation	Applicability/Organization
ITALY		IMQ Mark	Mark to be affixed on electrical material for non-skilled users; it certifies compliance with the European Standard(s).
NORWAY		Norwegian Approval Mark	Mandatory safety approval for low voltage material and equipment
NETHERLANDS	KEMA-KEUR	KEMA-KEUR	General for all equipment
POLAND		KWE	Electrical products
RUSSIA		Certification of Conformity	Electrical and non-electrical products. It guarantees compliance with national standard (Gosstandard of Russia)
SINGAPORE		SISIR	Electrical and non-electrical products
SLOVENIA	SIQ - Slovenia	SIQ	Slovenian Institute of Quality and Metrology
SPAIN		AEE	Electrical products. The mark is under the control of the Asociación Electrotécnica Española(Spanish Electrotechnical Association)

1 Standards

COUNTRY	Symbol	Mark designation	Applicability/Organization
SPAIN		AENOR	Asociación Española de Normalización y Certificación. (Spanish Standarization and Certification Association)
SWEDEN		SEMKO Mark	Mandatory safety approval for low voltage material and equipment.
SWITZERLAND		Safety Mark	Swiss low voltage material subject to mandatory approval (safety).
SWITZERLAND		–	Cables subject to mandatory approval
SWITZERLAND		SEV Safety Mark	Low voltage material subject to mandatory approval
UNITED KINGDOM		ASTA Mark	Mark which guarantees compliance with the relevant “British Standards”
UNITED KINGDOM		BASEC Mark	Mark which guarantees compliance with the “British Standards” for conductors, cables and ancillary products.
UNITED KINGDOM		BASEC Identification Thread	Cables

1 Standards

COUNTRY	Symbol	Mark designation	Applicability/Organization
UNITED KINGDOM		BEAB Safety Mark	Compliance with the “British Standards” for household appliances
UNITED KINGDOM		BSI Safety Mark	Compliance with the “British Standards”
UNITED KINGDOM		BEAB Kitemark	Compliance with the relevant “British Standards” regarding safety and performances
U.S.A.		UNDERWRITERS LABORATORIES Mark	Electrical and non-electrical products
U.S.A.		UNDERWRITERS LABORATORIES Mark	Electrical and non-electrical products
U.S.A.		UL Recognition	Electrical and non-electrical products
CEN		CEN Mark	Mark issued by the European Committee for Standardization (CEN): it guarantees compliance with the European Standards.
CENELEC		Mark	Cables

1 Standards

COUNTRY	Symbol	Mark designation	Applicability/Organization
CENELEC		Harmonization Mark	Certification mark providing assurance that the harmonized cable complies with the relevant harmonized CENELEC Standards – identification thread
EC		Ex EUROPEA Mark	Mark assuring the compliance with the relevant European Standards of the products to be used in environments with explosion hazards
CEEel		CEEel Mark	Mark which is applicable to some household appliances (shavers, electric clocks, etc).

EC - Declaration of Conformity

The EC Declaration of Conformity is the statement of the manufacturer, who declares under his own responsibility that all the equipment, procedures or services refer and comply with specific standards (directives) or other normative documents.
The EC Declaration of Conformity should contain the following information:
- name and address of the manufacturer or by its European representative;
- description of the product;
- reference to the harmonized standards and directives involved;
- any reference to the technical specifications of conformity;
- the two last digits of the year of affixing of the CE marking;
- identification of the signer.

A copy of the EC Declaration of Conformity shall be kept by the manufacturer or by his representative together with the technical documentation.

1 Standards

1.2 IEC Standards for electrical installation

STANDARD	YEAR	TITLE
IEC 60027-1	1992	Letter symbols to be used in electrical technology - Part 1: General
IEC 60034-1	2004	Rotating electrical machines - Part 1: Rating and performance
IEC 60617-DB-12M	2001	Graphical symbols for diagrams - 12-month subscription to online database comprising parts 2 to 11 of IEC 60617
IEC 61082-1	1991	Preparation of documents used in electrotechnology - Part 1: General requirements
IEC 61082-2	1993	Preparation of documents used in electrotechnology - Part 2: Function-oriented diagrams
IEC 61082-3	1993	Preparation of documents used in electrotechnology - Part 3: Connection diagrams, tables and lists
IEC 61082-4	1996	Preparation of documents used in electrotechnology - Part 4: Location and installation documents
IEC 60038	2002	IEC standard voltages
IEC 60664-1	2002	Insulation coordination for equipment within low-voltage systems - Part 1: Principles, requirements and tests
IEC 60909-0	2001	Short-circuit currents in three-phase a.c. systems - Part 0: Calculation of currents
IEC 60865-1	1993	Short-circuit currents - Calculation of effects - Part 1: Definitions and calculation methods
IEC 60781	1989	Application guide for calculation of short-circuit currents in low-voltage radial systems
IEC 60076-1	2000	Power transformers - Part 1: General
IEC 60076-2	1993	Power transformers - Part 2: Temperature rise
IEC 60076-3	2000	Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air
IEC 60076-5	2000	Power transformers - Part 5: Ability to withstand short circuit
IEC/TR 60616	1978	Terminal and tapping markings for power transformers
IEC 60076-11	2004	Power transformers - Part 11: Dry-type transformers
IEC 60445	1999	Basic and safety principles for man-machine interface, marking and identification - Identification of equipment terminals and of terminations of certain designated conductors, including general rules for an alphanumeric system

1 Standards

STANDARD	YEAR	TITLE
IEC 60073	2002	Basic and safety principles for man-machine interface, marking and identification – Coding for indicators and actuators
IEC 60446	1999	Basic and safety principles for man-machine interface, marking and identification - Identification of conductors by colours or numerals
IEC 60447	2004	Basic and safety principles for man-machine interface, marking and identification - Actuating principles
IEC 60947-1	2004	Low-voltage switchgear and controlgear - Part 1: General rules
IEC 60947-2	2003	Low-voltage switchgear and controlgear - Part 2: Circuit-breakers
IEC 60947-3	2001	Low-voltage switchgear and controlgear - Part 3: Switches, disconnectors, switch-disconnectors and fuse-combination units
IEC 60947-4-1	2002	Low-voltage switchgear and controlgear - Part 4-1: Contactors and motor-starters – Electromechanical contactors and motor-starters
IEC 60947-4-2	2002	Low-voltage switchgear and controlgear - Part 4-2: Contactors and motor-starters – AC semiconductor motor controllers and starters
IEC 60947-4-3	1999	Low-voltage switchgear and controlgear - Part 4-3: Contactors and motor-starters – AC semiconductor controllers and contactors for non-motor loads
IEC 60947-5-1	2003	Low-voltage switchgear and controlgear - Part 5-1: Control circuit devices and switching elements - Electromechanical control circuit devices
IEC 60947-5-2	2004	Low-voltage switchgear and controlgear - Part 5-2: Control circuit devices and switching elements – Proximity switches
IEC 60947-5-3	1999	Low-voltage switchgear and controlgear - Part 5-3: Control circuit devices and switching elements – Requirements for proximity devices with defined behaviour under fault conditions
IEC 60947-5-4	2002	Low-voltage switchgear and controlgear - Part 5: Control circuit devices and switching elements – Section 4: Method of assessing the performance of low energy contacts. Special tests
IEC 60947-5-5	1997	Low-voltage switchgear and controlgear - Part 5-5: Control circuit devices and switching elements - Electrical emergency stop device with mechanical latching function

1 Standards

STANDARD	YEAR	TITLE
IEC 60947-5-6	1999	Low-voltage switchgear and controlgear - Part 5-6: Control circuit devices and switching elements – DC interface for proximity sensors and switching amplifiers (NAMUR)
IEC 60947-6-1	1998	Low-voltage switchgear and controlgear - Part 6-1: Multiple function equipment – Automatic transfer switching equipment
IEC 60947-6-2	2002	Low-voltage switchgear and controlgear - Part 6-2: Multiple function equipment - Control and protective switching devices (or equipment) (CPS)
IEC 60947-7-1	2002	Low-voltage switchgear and controlgear - Part 7: Ancillary equipment - Section 1: Terminal blocks for copper conductors
IEC 60947-7-2	2002	Low-voltage switchgear and controlgear - Part 7: Ancillary equipment - Section 2: Protective conductor terminal blocks for copper conductors
IEC 60439-1	2004	Low-voltage switchgear and controlgear assemblies - Part 1: Type-tested and partially type-tested assemblies
IEC 60439-2	2000	Low-voltage switchgear and controlgear assemblies - Part 2: Particular requirements for busbar trunking systems (busways)
IEC 60439-3	2001	Low-voltage switchgear and controlgear assemblies - Part 3: Particular requirements for low-voltage switchgear and controlgear assemblies intended to be installed in places where unskilled persons have access for their use - Distribution boards
IEC 60439-4	2004	Low-voltage switchgear and controlgear assemblies - Part 4: Particular requirements for assemblies for construction sites (ACS)
IEC 60439-5	1998	Low-voltage switchgear and controlgear assemblies - Part 5: Particular requirements for assemblies intended to be installed outdoors in public places - Cable distribution cabinets (CDCs) for power distribution in networks
IEC 61095	2000	Electromechanical contactors for household and similar purposes

1 Standards

STANDARD	YEAR	TITLE
IEC 60890	1987	A method of temperature-rise assessment by extrapolation for partially type-tested assemblies (PTTA) of low-voltage switchgear and controlgear
IEC/TR 61117	1992	A method for assessing the short-circuit withstand strength of partially type-tested assemblies (PTTA)
IEC 60092-303	1980	Electrical installations in ships. Part 303: Equipment - Transformers for power and lighting
IEC 60092-301	1980	Electrical installations in ships. Part 301: Equipment - Generators and motors
IEC 60092-101	2002	Electrical installations in ships - Part 101: Definitions and general requirements
IEC 60092-401	1980	Electrical installations in ships. Part 401: Installation and test of completed installation
IEC 60092-201	1994	Electrical installations in ships - Part 201: System design - General
IEC 60092-202	1994	Electrical installations in ships - Part 202: System design - Protection
IEC 60092-302	1997	Electrical installations in ships - Part 302: Low-voltage switchgear and controlgear assemblies
IEC 60092-350	2001	Electrical installations in ships - Part 350: Shipboard power cables - General construction and test requirements
IEC 60092-352	1997	Electrical installations in ships - Part 352: Choice and installation of cables for low-voltage power systems
IEC 60364-5-52	2001	Electrical installations of buildings - Part 5-52: Selection and erection of electrical equipment – Wiring systems
IEC 60227		Polyvinyl chloride insulated cables of rated voltages up to and including 450/ 750 V
	1998	Part 1: General requirements
	2003	Part 2: Test methods
	1997	Part 3: Non-sheathed cables for fixed wiring
	1997	Part 4: Sheathed cables for fixed wiring
	2003	Part 5: Flexible cables (cords)
	2001	Part 6: Lift cables and cables for flexible connections
	2003	Part 7: Flexible cables screened and unscreened with two or more conductors
IEC 60228	2004	Conductors of insulated cables
IEC 60245		Rubber insulated cables - Rated voltages up to and including 450/750 V
	2003	Part 1: General requirements
	1998	Part 2: Test methods
	1994	Part 3: Heat resistant silicone insulated cables

1 Standards

STANDARD	YEAR	TITLE
	1994	Part 5: Lift cables
	1994	Part 6: Arc welding electrode cables
	1994	Part 7: Heat resistant ethylene-vinyl acetate rubber insulated cables
	2004	Part 8: Cords for applications requiring high flexibility
IEC 60309-2	1999	Plugs, socket-outlets and couplers for industrial purposes - Part 2: Dimensional interchangeability requirements for pin and contact-tube accessories
IEC 61008-1	2002	Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs) - Part 1: General rules
IEC 61008-2-1	1990	Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCB's). Part 2-1: Applicability of the general rules to RCCB's functionally independent of line voltage
IEC 61008-2-2	1990	Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCB's). Part 2-2: Applicability of the general rules to RCCB's functionally dependent on line voltage
IEC 61009-1	2003	Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBOs) - Part 1: General rules
IEC 61009-2-1	1991	Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBO's) Part 2-1: Applicability of the general rules to RCBO's functionally independent of line voltage
IEC 61009-2-2	1991	Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBO's) - Part 2-2: Applicability of the general rules to RCBO's functionally dependent on line voltage
IEC 60670-1	2002	Boxes and enclosures for electrical accessories for household and similar fixed electrical installations - Part 1: General requirements
IEC 60669-2-1	2002	Switches for household and similar fixed electrical installations - Part 2-1: Particular requirements – Electronic switches
IEC 60669-2-2	2002	Switches for household and similar fixed electrical installations - Part 2: Particular requirements – Section 2: Remote-control switches (RCS)
IEC 60669-2-3	1997	Switches for household and similar fixed electrical installations - Part 2-3: Particular requirements – Time-delay switches (TDS)

1 Standards

STANDARD	YEAR	TITLE
IEC 60079-10	2002	Electrical apparatus for explosive gas atmospheres - Part 10: Classification of hazardous areas
IEC 60079-14	2002	Electrical apparatus for explosive gas atmospheres - Part 14: Electrical installations in hazardous areas (other than mines)
IEC 60079-17	2002	Electrical apparatus for explosive gas atmospheres - Part 17: Inspection and maintenance of electrical installations in hazardous areas (other than mines)
IEC 60269-1	1998	Low-voltage fuses - Part 1: General requirements
IEC 60269-2	1986	Low-voltage fuses. Part 2: Supplementary requirements for fuses for use by authorized persons (fuses mainly for industrial application)
IEC 60269-3-1	2004	Low-voltage fuses - Part 3-1: Supplementary requirements for fuses for use by unskilled persons (fuses mainly for household and similar applications) - Sections I to IV: Examples of types of standardized fuses
IEC 60127-1/10		Miniature fuses -
	2003	Part 1: Definitions for miniature fuses and general requirements for miniature fuse-links
	2003	Part 2: Cartridge fuse-links
	1988	Part 3: Sub-miniature fuse-links
	1996	Part 4: Universal Modular Fuse-Links (UMF)
	1988	Part 5: Guidelines for quality assessment of miniature fuse-links
	1994	Part 6: Fuse-holders for miniature cartridge fuse-links
	2001	Part 10: User guide for miniature fuses
IEC 60730-2-7	1990	Automatic electrical controls for household and similar use. Part 2: Particular requirements for timers and time switches
IEC 60364-1	2001	Electrical installations of buildings - Part 1: Fundamental principles, assessment of general characteristics, definitions
IEC 60364-4	2001	Electrical installations of buildings - Part 4: Protection for safety
IEC 60364-5	2001…2002	Electrical installations of buildings - Part 5: Selection and erection of electrical equipment
IEC 60364-6	2001	Electrical installations of buildings - Part 6: Verification
IEC 60364-7	1983…2002	Electrical installations of buildings. Part 7: Requirements for special installations or locations

1 Standards

STANDARD	YEAR	TITLE
IEC 60529	2001	Degrees of protection provided by enclosures (IP Code)
IEC 61032	1997	Protection of persons and equipment by enclosures - Probes for verification
IEC/TR 61000-1-1	1992	Electromagnetic compatibility (EMC) - Part 1: General - Section 1: Application and interpretation of fundamental definitions and terms
IEC/TS 61000-1-2	2001	Electromagnetic compatibility (EMC) - Part 1-2: General - Methodology for the achievement of the functional safety of electrical and electronic equipment with regard to electromagnetic phenomena
IEC/TR 61000-1-3	2002	Electromagnetic compatibility (EMC) - Part 1-3: General - The effects of high-altitude EMP (HEMP) on civil equipment and systems

2 Protection of feeders

2.1 Introduction

The following definitions regarding electrical installations are derived from the Standard IEC 60050.

Characteristics of installations

Electrical installation (of a building) An assembly of associated electrical equipment to fulfil a specific purpose and having coordinated characteristics.

Origin of an electrical installation The point at which electrical energy is delivered to an installation.

Neutral conductor (symbol N) A conductor connected to the neutral point of a system and capable of contributing to the transmission of electrical energy.

Protective conductor PE A conductor required by some measures for protection against electric shock for electrically connecting any of the following parts:
- exposed conductive parts;
- extraneous conductive parts;
- main earthing terminal;
- earth electrode;
- earthed point of the source or artificial neutral.

PEN conductor An earthed conductor combining the functions of both protective conductor and neutral conductor

Ambient temperature The temperature of the air or other medium where the equipment is to be used.

Voltages

Nominal voltage (of an installation) Voltage by which an installation or part of an installation is designated.
Note: the actual voltage may differ from the nominal voltage by a quantity within permitted tolerances.

Currents

Design current (of a circuit) The current intended to be carried by a circuit in normal service.

Current-carrying capacity (of a conductor) The maximum current which can be carried continuously by a conductor under specified conditions without its steady-state temperature exceeding a specified value.

Overcurrent Any current exceeding the rated value. For conductors, the rated value is the current-carrying capacity.

Overload current (of a circuit) An overcurrent occurring in a circuit in the absence of an electrical fault.

Short-circuit current An overcurrent resulting from a fault of negligible impedance between live conductors having a difference in potential under normal operating conditions.

2 Protection of feeders

Conventional operating current (of a protective device) A specified value of the current which cause the protective device to operate within a specified time, designated conventional time.

Overcurrent detection A function establishing that the value of current in a circuit exceeds a predetermined value for a specified length of time.

Leakage current Electrical current in an unwanted conductive path other than a short circuit.

Fault current The current flowing at a given point of a network resulting from a fault at another point of this network.

Wiring systems

Wiring system An assembly made up of a cable or cables or busbars and the parts which secure and, if necessary, enclose the cable(s) or busbars.

Electrical circuits

Electrical circuit (of an installation) An assembly of electrical equipment of the installation supplied from the same origin and protected against overcurrents by the same protective device(s).

Distribution circuit (of buildings) A circuit supplying a distribution board.

Final circuit (of building) A circuit connected directly to current using equipment or to socket-outlets.

Other equipment

Electrical equipment Any item used for such purposes as generation, conversion, transmission, distribution or utilization of electrical energy, such as machines, transformers, apparatus, measuring instruments, protective devices, equipment for wiring systems, appliances.

Current-using equipment Equipment intended to convert electrical energy into another form of energy, for example light, heat, and motive power

Switchgear and controlgear Equipment provided to be connected to an electrical circuit for the purpose of carrying out one or more of the following functions: protection, control, isolation, switching.

Portable equipment Equipment which is moved while in operation or which can easily be moved from one place to another while connected to the supply.

Hand-held equipment Portable equipment intended to be held in the hand during normal use, in which the motor, if any, forms an integral part of the equipment.

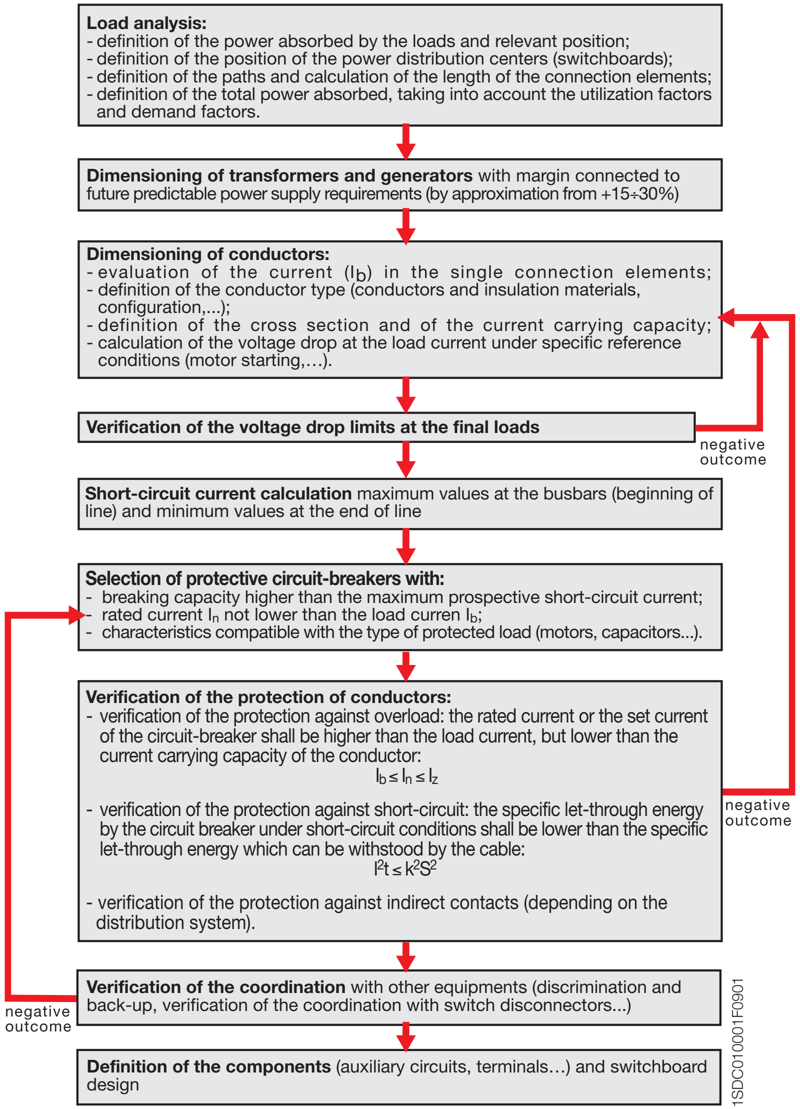
Stationary equipment Either fixed equipment or equipment not provided with a carrying handle and having such a mass that it cannot easily be moved.

Fixed equipment Equipment fastened to a support or otherwise secured in a specific location.

2 Protection of feeders

Installation dimensioning

The flow chart below suggests the procedure to follow for the correct dimensioning of a plant.



2 Protection of feeders

2.2 Installation and dimensioning of cables

For a correct dimensioning of a cable, it is necessary to:
- choose the type of cable and installation according to the environment;
- choose the cross section according to the load current;
- verify the voltage drop.

2.2.1 Current carrying capacity and methods of installation

Selection of the cable

The international reference Standard ruling the installation and calculation of the current carrying capacity of cables in residential and industrial buildings is IEC 60364-5-52 *"Electrical installations of buildings – Part 5-52 Selection and Erection of Electrical Equipment- Wiring systems".*
The following parameters are used to select the cable type:
- conductive material (copper or aluminium): the choice depends on cost, dimension and weight requirements, resistance to corrosive environments (chemical reagents or oxidizing elements). In general, the carrying capacity of a copper conductor is about 30% greater than the carrying capacity of an aluminium conductor of the same cross section. An aluminium conductor of the same cross section has an electrical resistance about 60% higher and a weight half to one third lower than a copper conductor.

- insulation material (none, PVC, XLPE-EPR): the insulation material affects the maximum temperature under normal and short-circuit conditions and therefore the exploitation of the conductor cross section [see Chapter 2.4 "Protection against short-circuit"].

- the type of conductor (bare conductor, single-core cable without sheath, single-core cable with sheath, multi-core cable) is selected according to mechanical resistance, degree of insulation and difficulty of installation (bends, joints along the route, barriers...) required by the method of installation.

Table 1 shows the types of conductors permitted by the different methods of installation.

Table 1: Selection of wiring systems

Conductors and cables		Method of installation: Without fixings	Clipped direct	Conduit	Cable trunking (including skirting trunking, flush floor trunking)	Cable ducting	Cable ladder Cable tray Cable brackets	On insulators	Support wire
Bare conductors		-	-	-	-	-	-	+	-
Insulated conductors		-	-	+	+	+	-	+	-
Sheathed cables (including armoured and mineral insulated)	Multi-core	+	+	+	+	+	+	0	+
	Single-core	0	+	+	+	+	+	0	+

\+ Permitted.
– Not permitted.
0 Not applicable, or not normally used in practice.

2 Protection of feeders

For industrial installations, multi-core cables are rarely used with cross section greater than 95 mm^2.

Methods of installation

To define the current carrying capacity of the conductor and therefore to identify the correct cross section for the load current, the standardized method of installation that better suits the actual installation situation must be identified among those described in the mentioned reference Standard.
From Tables 2 and 3 it is possible to identify the installation identification number, the method of installation (A1, A2, B1, B2, C, D, E, F, G) and the tables to define the theoretical current carrying capacity of the conductor and any correction factors required to allow for particular environmental and installation situations.

Table 2: Method of installation

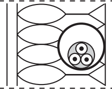
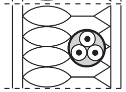
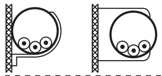
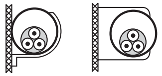
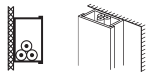
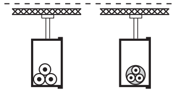
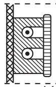
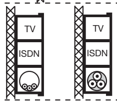
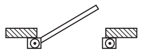
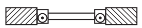
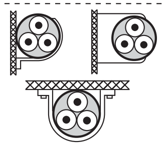
	Method of installation							
Situations	**Without fixings**	**With fixings**	**Conduit**	**Cable trunking (including skirting trunking, flush floor trunking)**	**Cable ducting**	**Cable ladder Cable tray Cable brackets**	**On insulators**	**Support wire**
Building voids	40, 46, 15, 16	0	15, 16	-	0	30, 31, 32, 33, 34	-	-
Cable channel	56	56	54, 55	0	44	30, 31, 32, 33, 34	-	-
Buried in Ground	72, 73	0	70, 71	-	70, 71	0	-	-
Embedded in Structure	57, 58	3	1, 2 59, 60	50, 51, 52, 53	44, 45	0	-	-
Surface Mounted	-	20, 21	4, 5	6, 7, 8, 9, 12, 13, 14	6, 7, 8, 9	30, 31, 32, 33, 34	36	-
Overhead	-	-	0	10, 11	-	30, 31, 32, 33, 34	36	35

The number in each box indicates the item number in Table 3.
- Not permitted.
0 Not applicable or not normally used in practice.

2.2 Installation and dimensioning of cables

2 Protection of feeders

Table 3: Examples of methods of installation

Methods of installation	Item n.	Description	Reference method of installation to be used to obtain current-carrying capacity
 Room	1	Insulated conductors or single-core cables in conduit in a thermally insulated wall	A1
 Room	2	Multi-core cables in conduit in a thermally insulated wall	A2
 Room	3	Multi-core cable direct in a thermally insulated wall	A1
	4	Insulated conductors or single-core cables in conduit on a wooden, or masonry wall or spaced less than 0.3 times conduit diameter from it	B1
	5	Multi-core cable in conduit on a wooden, or masonry wall or spaced less than 0.3 times conduit diameter from it	B2
	6 7	Insulated conductors or single-core cables in cable trunking on a wooden wall – run horizontally (6) – run vertically (7)	B1
	8 9	Insulated conductors or single-core cable in suspended cable trunking (8) Multi-core cable in suspended cable trunking (9)	B1 (8) or B2 (9)
	12	Insulated conductors or single-core cable run in mouldings	A1
	13 14	Insulated conductors or single-core cables in skirting trunking (13) Multi-core cable in skirting trunking (14)	B1 (13) or B2 (14)
	15	Insulated conductors in conduit or single-core or multi-core cable in architrave	A1
	16	Insulated conductors in conduit or single-core or multi-core cable in window frames	A1
	20 21	Single-core or multi-core cables: – fixed on, or spaced less than 0.3 times (20) cable diameter from a wooden wall – fixed directly under a wooden ceiling (21)	C

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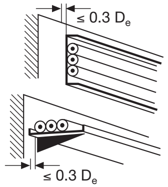
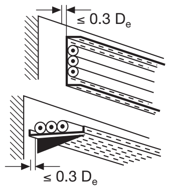
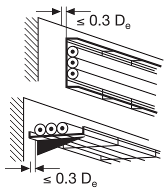
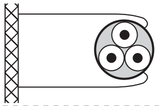
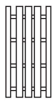
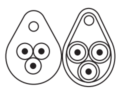
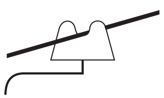
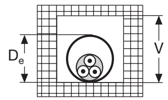
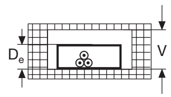
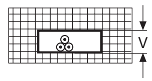
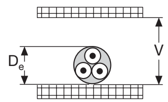
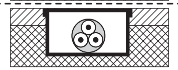
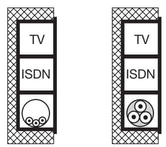
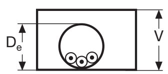
2 Protection of feeders

Methods of installation	Item n.	Description	Reference method of installation to be used to obtain current-carrying capacity
	30	On unperforated tray [1]	C
	31	On perforated tray [1]	E or F
	32	On brackets or on a wire mesh [1]	E or F
	33	Spaced more than 0.3 times cable diameter from a wall	E or F or G
	34	On ladder	E or F
	35	Single-core or multi-core cable suspended from or incorporating a support wire	E or F
	36	Bare or insulated conductors on insulators	G

2 Protection of feeders

Methods of installation	Item n.	Description	Reference method of installation to be used to obtain current-carrying capacity
	40	Single-core or multi-core cable in a building void [2]	$1.5\ D_e \leq V < 20\ D_e$ B2 $V \geq 20\ D_e$ B1
	24	Insulated conductors in cable ducting in a building void [2]	$1.5\ D_e \leq V < 20\ D_e$ B2 $V \geq 20\ D_e$ B1
	44	Insulated conductors in cable ducting in masonry having a thermal resistivity not greater than 2 Km/W	$1.5\ D_e \leq V < 5\ D_e$ B2 $5\ D_e \leq V < 50\ D_e$ B1
	46	Single-core or multi-core cable: – in a ceiling void – in a suspended floor [1]	$1.5\ D_e \leq V < 5\ D_e$ B2 $5\ D_e \leq V < 50\ D_e$ B1
	50	Insulated conductors or single-core cable in flush cable trunking in the floor	B1
	51	Multi-core cable in flush cable trunking in the floor	B2
	52 53	Insulated conductors or single-core cables in embedded trunking (52) Multi-core cable in embedded trunking (53)	B1 (52) or B2 (53)
	54	Insulated conductors or single-core cables in conduit in an unventilated cable channel run horizontally or vertically [2]	$1.5\ D_e \leq V < 20\ D_e$ B2 $V \geq 20\ D_e$ B1

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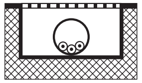
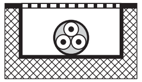
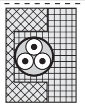
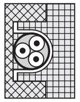
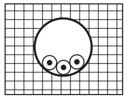
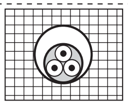
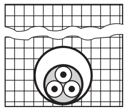
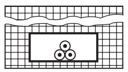
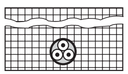
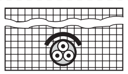
2 Protection of feeders

Methods of installation	Item n.	Description	Reference method of installation to be used to obtain current-carrying capacity
	55	Insulated conductors in conduit in an open or ventilated cable channel in the floor	B1
	56	Sheathed single-core or multi-core cable in an open or ventilated cable channel run horizontally or vertically	B1
	57	Single-core or multi-core cable direct in masonry having a thermal resistivity not greater than 2 Km/W Without added mechanical protection	C
	58	Single-core or multi-core cable direct in masonry having a thermal resistivity not greater than 2 Km/W With added mechanical protection	C
	59	Insulated conductors or single-core cables in conduit in masonry	B1
	60	Multi-core cables in conduit in masonry	B2
	70	Multi-core cable in conduit or in cable ducting in the ground	D
	71	Single-core cable in conduit or in cable ducting in the ground	D
	72	Sheathed single-core or multi-core cables direct in the ground – without added mechanical protection	D
	73	Sheathed single-core or multi-core cables direct in the ground – with added mechanical protection	D

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[1] D_e is the external diameter of a multi-core cable:
– 2.2 x the cable diameter when three single core cables are bound in trefoil, or
– 3 x the cable diameter when three single core cables are laid in flat formation.
[2] D_e is the external diameter of conduit or vertical depth of cable ducting.
V is the smaller dimension or diameter of a masonry duct or void, or the vertical depth of a rectangular duct, floor or ceiling void.
The depth of the channel is more important than the width.

2 Protection of feeders

Installation not buried in the ground: choice of the cross section according to cable carrying capacity and type of installation

The cable carrying capacity of a cable that is not buried in the ground is obtained by using this formula:

$$I_z = I_0 k_1 k_2 = I_0 k_{tot}$$

where:
- I_0 is the current carrying capacity of the single conductor at 30 °C reference ambient temperature;
- k_1 is the correction factor if the ambient temperature is other than 30 °C;
- k_2 is the correction factor for cables installed bunched or in layers or for cables installed in a layer on several supports.

Correction factor k_1

The current carrying capacity of the cables that are not buried in the ground refers to 30 °C ambient temperature. If the ambient temperature of the place of installation is different from this reference temperature, the correction factor k_1 on Table 4 shall be used, according to the insulation material.

Table 4: Correction factor for ambient air temperature other than 30 °C

	Insulation			
			Mineral [a]	
Ambient temperature [a] °C	PVC	XLPE and EPR	PVC covered or bare and exposed to touch 70 °C	Bare not exposed to touch 105 °C
10	1.22	1.15	1.26	1.14
15	1.17	1.12	1.20	1.11
20	1.12	1.08	1.14	1.07
25	1.06	1.04	1.07	1.04
35	0.94	0.96	0.93	0.96
40	0.87	0.91	0.85	0.92
45	0.79	0.87	0.87	0.88
50	0.71	0.82	0.67	0.84
55	0.61	0.76	0.57	0.80
60	0.50	0.71	0.45	0.75
65	–	0.65	–	0.70
70	–	0.58	–	0.65
75	–	0.50	–	0.60
80	–	0.41	–	0.54
85	–	–	–	0.47
90	–	–	–	0.40
95	–	–	–	0.32

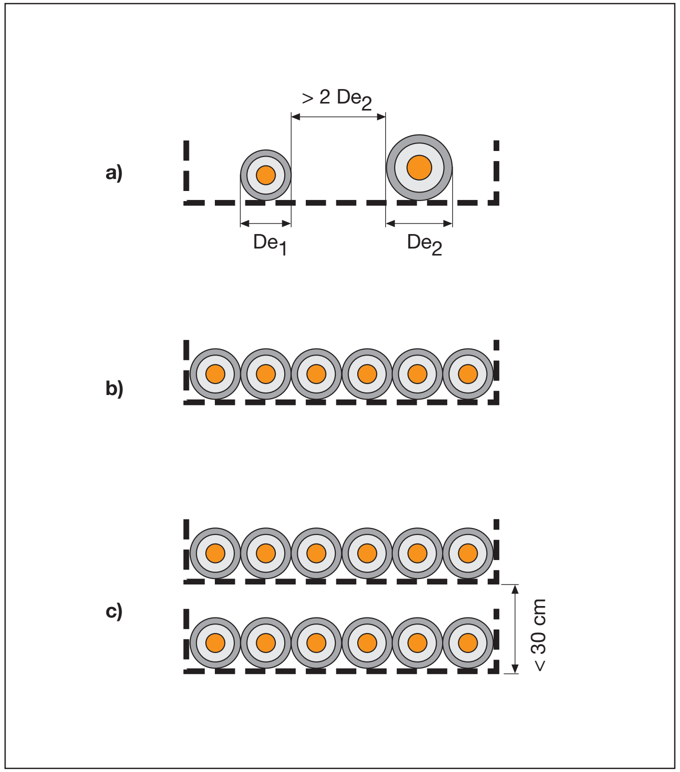
[a] For higher ambient temperatures, consult manufacturer.

2 Protection of feeders

Correction factor k_2

The cable current carrying capacity is influenced by the presence of other cables installed nearby. The heat dissipation of a single cable is different from that of the same cable when installed next to the other ones. The factor k_2 is tabled according to the installation of cables laid close together in layers or bunches.

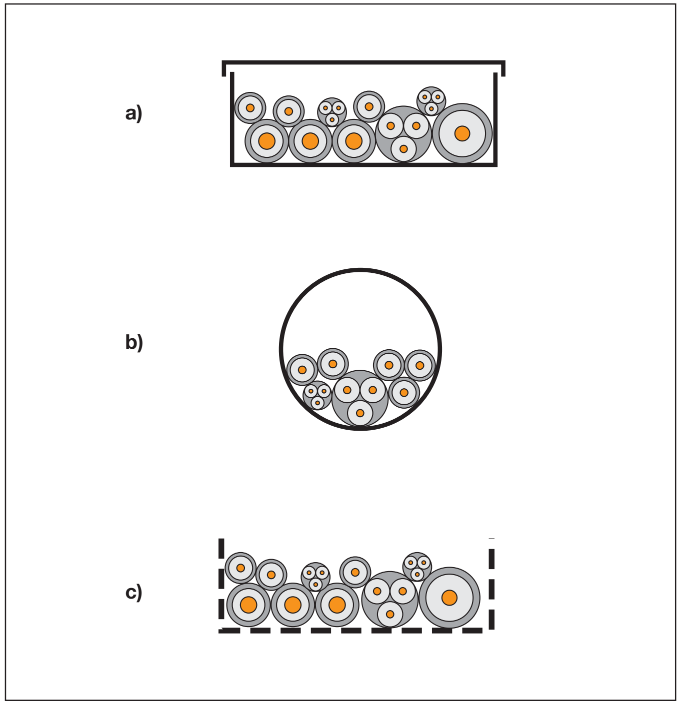
Definition of layer or bunch
layer: several circuits constituted by cables installed one next to another, spaced or not, arranged horizontally or vertically. The cables on a layer are installed on a wall, tray, ceiling, floor or on a cable ladder;



Cables in layers: a) spaced; b) not spaced; c) double layer

bunch: several circuits constituted by cables that are not spaced and are not installed in a layer; several layers superimposed on a single support (e.g. tray) are considered to be a bunch.

2 Protection of feeders



Bunched cables: a) in trunking; b) in conduit; c) on perforated tray

The value of correction factor k_2 is 1 when:
- the cables are spaced:
  - two single-core cables belonging to different circuits are spaced when the distance between them is more than twice the external diameter of the cable with the larger cross section;
  - two multi-core cables are spaced when the distance between them is at least the same as the external diameter of the larger cable;
- the adjacent cables are loaded less than 30 % of their current carrying capacity.

The correction factors for bunched cables or cables in layers are calculated by assuming that the bunches consist of similar cables that are equally loaded. A group of cables is considered to consist of similar cables when the calculation of the current carrying capacity is based on the same maximum allowed operating temperature and when the cross sections of the conductors is in the range of three adjacent standard cross sections (e.g. from 10 to 25 mm^2).
The calculation of the reduction factors for bunched cables with different cross sections depends on the number of cables and on their cross sections. These factors have not been tabled, but must be calculated for each bunch or layer.

2 Protection of feeders

The reduction factor for a group containing different cross sections of insulated conductors or cables in conduits, cable trunking or cable ducting is:

$$k_2 = \frac{1}{\sqrt{n}}$$

where:
- k_2 is the group reduction factor;
- n is the number of circuits of the bunch.

The reduction factor obtained by this equation reduces the danger of overloading of cables with a smaller cross section, but may lead to under utilization of cables with a larger cross section. Such under utilization can be avoided if large and small cables are not mixed in the same group.

The following tables show the reduction factor (k_2).

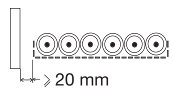
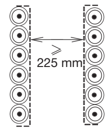
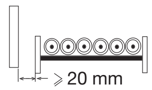
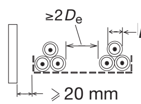
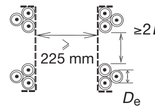
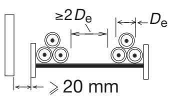
Table 5: Reduction factor for grouped cables

Item	Arrangement (cables touching)	1	2	3	4	5	6	7	8	9	12	16	20	To be used with current-carrying capacities, reference
		Number of circuits or multi-core cables												
1	Bunched in air, on a surface, embedded or enclosed	1.00	0.80	0.70	0.65	0.60	0.57	0.54	0.52	0.50	0.45	0.41	0.38	Methods A to F
2	Single layer on wall, floor or unperforated tray	1.00	0.85	0.79	0.75	0.73	0.72	0.72	0.71	0.70	No further reduction factor for more than nine circuits or multicore cables			Method C
3	Single layer fixed directly under a wooden ceiling	0.95	0.81	0.72	0.68	0.66	0.64	0.63	0.62	0.61				
4	Single layer on a perforated horizontal or vertical tray	1.00	0.88	0.82	0.77	0.75	0.73	0.73	0.72	0.72				Methods E and F
5	Single layer on ladder support or cleats etc.	1.00	0.87	0.82	0.80	0.80	0.79	0.79	0.78	0.78				

NOTE 1 These factors are applicable to uniform groups of cables, equally loaded.
NOTE 2 Where horizontal clearances between adjacent cables exceeds twice their overall diameter, no reduction factor need be applied.
NOTE 3 The same factors are applied to:
– groups of two or three single-core cables;
– multi-core cables.
NOTE 4 If a system consists of both two- and three-core cables, the total number of cables is taken as the number of circuits, and the corresponding factor is applied to the tables for two loaded conductors for the two-core cables, and to the tables for three loaded conductors for the three-core cables.
NOTE 5 If a group consists of n single-core cables it may either be considered as n/2 circuits of two loaded conductors or n/3 circuits of three loaded conductors.

2 Protection of feeders

Table 6: Reduction factor for single-core cables with method of installation F

Method of installation in Table 3			Number of trays	Number of three-phase circuits (note 4) 1	2	3	Use as a multiplier to rating for
Perforated trays (note 2)	31	Touching 	1 2 3	0.98 0.96 0.95	0.91 0.87 0.85	0.87 0.81 0.78	Three cables in horizontal formation
Vertical perforated trays (note 3)	31	Touching 	1 2	0.96 0.95	0.86 0.84	– –	Three cables in vertical formation
Ladder supports, cleats, etc. (note 2)	32 33 34	Touching 	1 2 3	1.00 0.98 0.97	0.97 0.93 0.90	0.96 0.89 0.86	Three cables in horizontal formation
Perforated trays (note 2)	31		1 2 3	1.00 0.97 0.96	0.98 0.93 0.92	0.96 0.89 0.86	
Vertical perforated trays (note 3)	31	Spaced 	1 2	1.00 1.00	0.91 0.90	0.89 0.86	Three cables in trefoil formation
Ladder supports, cleats, etc. (note 2)	32 33 34		1 2 3	1.00 0.97 0.96	1.00 0.95 0.94	1.00 0.93 0.90	

NOTE 1 Factors are given for single layers of cables (or trefoil groups) as shown in the table and do not apply when cables are installed in more than one layer touching each other. Values for such installations may be significantly lower and must be determined by an appropriate method.

NOTE 2 Values are given for vertical spacings between trays of 300 mm. For closer spacing the factors should be reduced.

NOTE 3 Values are given for horizontal spacing between trays of 225 mm with trays mounted back to back and at least 20 mm between the tray and any wall. For closer spacing the factors should be reduced.

NOTE 4 For circuits having more than one cable in parallel per phase, each three phase set of conductors should be considered as a circuit for the purpose of this table.

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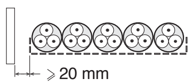
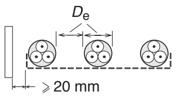
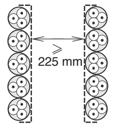
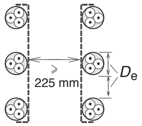
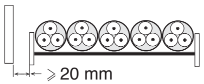
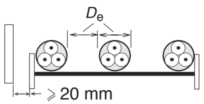
2 Protection of feeders

Table 7: Reduction factor for multi-core cables with method of installation E

Method of installation in Table 3			Number of trays	Number of cables: 1	2	3	4	6	9
Perforated trays (note 2)	31	Touching 	1	1.00	0.88	0.82	0.79	0.76	0.73
			2	1.00	0.87	0.80	0.77	0.73	0.68
			3	1.00	0.86	0.79	0.76	0.71	0.66
		Spaced 	1	1.00	1.00	0.98	0.95	0.91	–
			2	1.00	0.99	0.96	0.92	0.87	–
			3	1.00	0.98	0.95	0.91	0.85	–
Vertical perforated trays (note 3)	31	Touching 	1	1.00	0.88	0.82	0.78	0.73	0.72
			2	1.00	0.88	0.81	0.76	0.71	0.70
		Spaced 	1	1.00	0.91	0.89	0.88	0.87	–
			2	1.00	0.91	0.88	0.87	0.85	–
Ladder supports, cleats, etc. (note 2)	32 33 34	Touching 	1	1.00	0.87	0.82	0.80	0.79	0.78
			2	1.00	0,86	0.80	0.78	0.76	0.73
			3	1.00	0.85	0.79	0.76	0.73	0.70
		Spaced 	1	1.00	1.00	1.00	1.00	1.00	–
			2	1.00	0.99	0.98	0.97	0.96	–
			3	1.00	0.98	0.97	0.96	0.93	–

NOTE 1 Factors apply to single layer groups of cables as shown above and do not apply when cables are installed in more than one layer touching each other. Values for such installations may be significantly lower and must be determined by an appropriate method.

NOTE 2 Values are given for vertical spacings between trays of 300 mm and at least 20 mm between trays and wall. For closer spacing the factors should be reduced.

NOTE 3 Values are given for horizontal spacing between trays of 225 mm with trays mounted back to back. For closer spacing the factors should be reduced.

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2 Protection of feeders

To summarize:

The following procedure shall be used to determine the cross section of the cable:

1. from Table 3 identify the method of installation;
2. from Table 4 determine the correction factor k_1 according to insulation material and ambient temperature;
3. use Table 5 for cables installed in layer or bunch, Table 6 for single-core cables in a layer on several supports, Table 7 for multi-core cables in a layer on several supports or the formula shown in the case of groups of cables with different sections to determine the correction factor k_2 appropriate for the numbers of circuits or multi-core cables;
4. calculate the value of current I'_b by dividing the load current I_b (or the rated current of the protective device) by the product of the correction factors calculated:

$$I'_b = \frac{I_b}{k_1 k_2} = \frac{I_b}{k_{tot}}$$

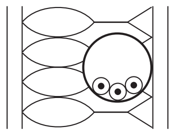
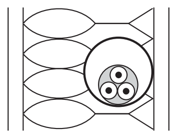
5. from Table 8 or from Table 9, depending on the method of installation, on insulation and conductive material and on the number of live conductors, determine the cross section of the cable with capacity $I_0 \geq I'_b$;
6. the actual cable current carrying capacity is calculated by $I_Z = I_0 k_1 k_2$.

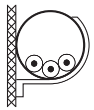
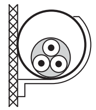
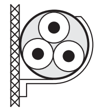
2 Protection of feeders

2.2 Installation and dimensioning of cables

2 Protection of feeders

Table 8: Current carrying capacity of cables with PVC or EPR/XLPE insulation (method A-B-C)

Installation method	A1								A2							
																
Conductor	Cu				Al				Cu				Al			
Insulation	XLPE EPR		PVC		XLPE EPR		PVC		XLPE EPR		PVC		XLPE EPR		PVC	
S[mm^2] / Loaded conductors	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3
1.5	19	17	14.5	13.5					18.5	16.5	14	13				
2.5	26	23	19.5	18	20	19	15	14	25	22	18.5	17.5	19.5	18	14.5	13.5
4	35	31	26	24	27	25	20	18.5	33	30	25	23	26	24	19.5	17.5
6	45	40	34	31	35	32	26	24	42	38	32	29	33	31	25	23
10	61	54	46	42	48	44	36	32	57	51	43	39	45	41	33	31
16	81	73	61	56	64	58	48	43	76	68	57	52	60	55	44	41
25	106	95	80	73	84	76	63	57	99	89	75	68	78	71	58	53
35	131	117	99	89	103	94	77	70	121	109	92	83	96	87	71	65
50	158	141	119	108	125	113	93	84	145	130	110	99	115	104	86	78
70	200	179	151	136	158	142	118	107	183	164	139	125	145	131	108	98
95	241	216	182	164	191	171	142	129	220	197	167	150	175	157	130	118
120	278	249	210	188	220	197	164	149	253	227	192	172	201	180	150	135
150	318	285	240	216	253	226	189	170	290	259	219	196	230	206	172	155
185	362	324	273	245	288	256	215	194	329	295	248	223	262	233	195	176
240	424	380	321	286	338	300	252	227	386	346	291	261	307	273	229	207
300	486	435	367	328	387	344	289	261	442	396	334	298	352	313	263	237
400																
500																
630																

Installation method	B1								B2								C							
																								
Conductor	Cu				Al				Cu				Al				Cu				Al			
Insulation	XLPE EPR		PVC		XLPE EPR		PVC		XLPE EPR		PVC		XLPE EPR		PVC		XLPE EPR		PVC		XLPE/EPR		PVC	
S[mm^2] / Loaded conductors	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3
1.5	23	20	17.5	15.5					22	19.5	16.5	15					24	22	19.5	17.5				
2.5	31	28	24	21	25	22	18.5	16.5	30	26	23	20	23	21	17.5	15.5	33	30	27	24	26	24	21	18.5
4	42	37	32	28	33	29	25	22.0	40	35	30	27	31	28	24	21	45	40	36	32	35	32	28	25
6	54	48	41	36	43	38	32	28	51	44	38	34	40	35	30	27.0	58	52	46	41	45	41	36	32
10	75	66	57	50	59	52	44	39	69	60	52	46	54	48	41	36	80	71	63	57	62	57	49	44
16	100	88	76	68	79	71	60	53	91	80	69	62	72	64	54	48	107	96	85	76	84	76	66	59
25	133	117	101	89	105	93	79	70	119	105	90	80	94	84	71	62	138	119	112	96	101	90	83	73
35	164	144	125	110	130	116	97	86	146	128	111	99	115	103	86	77	171	147	138	119	126	112	103	90
50	198	175	151	134	157	140	118	104	175	154	133	118	138	124	104	92	209	179	168	144	154	136	125	110
70	253	222	192	171	200	179	150	133	221	194	168	149	175	156	131	116	269	229	213	184	198	174	160	140
95	306	269	232	207	242	217	181	161	265	233	201	179	210	188	157	139	328	278	258	223	241	211	195	170
120	354	312	269	239	281	251	210	186	305	268	232	206	242	216	181	160	382	322	299	259	280	245	226	197
150																	441	371	344	299	324	283	261	227
185																	506	424	392	341	371	323	298	259
240																	599	500	461	403	439	382	352	305
300																	693	576	530	464	508	440	406	351
400																								
500																								
630																								

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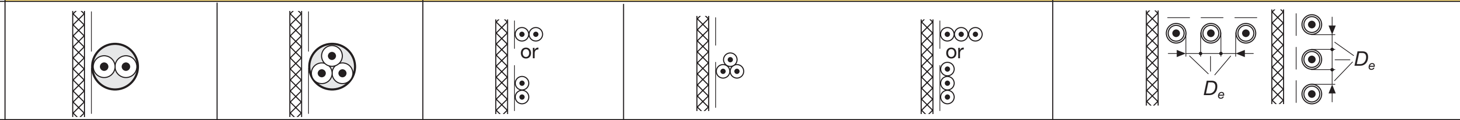
2 Protection of feeders

2.2 Installation and dimensioning of cables

2 Protection of feeders

Table 8: Current carrying capacity of cables with PVC or EPR/XLPE insulation (method E-F-G)



Installation method	E								F												G							
	Cu		Al		Cu		Al		Cu		Al		Cu		Al		Cu		Al		Cu				Al			
Insulation	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR	PVC	XLPE EPR		PVC		XLPE EPR		PVC	
S[mm²] / Loaded conductors	2				3				2				3				3				3H	3V	3H	3V	3H	3V	3H	3V
1.5	26	22			23	18.5																						
2.5	36	30	28	23	32	25	24	19.5																				
4	49	40	38	31	42	34	32	26																				
6	63	51	49	39	54	43	42	33																				
10	86	70	67	54	75	60	58	46																				
16	115	94	91	73	100	80	77	61																				
25	149	119	108	89	127	101	97	78	161	131	121	98	135	110	103	84	141	114	107	87	182	161	146	130	138	122	112	99
35	185	148	135	111	158	126	120	96	200	162	150	122	169	137	129	105	176	143	135	109	226	201	181	162	172	153	139	124
50	225	180	164	135	192	153	146	117	242	196	184	149	207	167	159	128	216	174	165	133	275	246	219	197	210	188	169	152
70	289	232	211	173	246	196	187	150	310	251	237	192	268	216	206	166	279	225	215	173	353	318	281	254	271	244	217	196
95	352	282	257	210	298	238	227	183	377	304	289	235	328	264	253	203	342	275	264	212	430	389	341	311	332	300	265	241
120	410	328	300	244	346	276	263	212	437	352	337	273	383	308	296	237	400	321	308	247	500	454	396	362	387	351	308	282
150	473	379	346	282	399	319	304	245	504	406	389	316	444	356	343	274	464	372	358	287	577	527	456	419	448	408	356	327
185	542	434	397	322	456	364	347	280	575	463	447	363	510	409	395	315	533	427	413	330	661	605	521	480	515	470	407	376
240	641	514	470	380	538	430	409	330	679	546	530	430	607	485	471	375	634	507	492	392	781	719	615	569	611	561	482	447
300	741	593	543	439	621	497	471	381	783	629	613	497	703	561	547	434	736	587	571	455	902	833	709	659	708	652	557	519
400									940	754	740	600	823	656	663	526	868	689	694	552	1085	1008	852	795	856	792	671	629
500									1083	868	856	694	946	749	770	610	998	789	806	640	1253	1169	982	920	991	921	775	730
630									1254	1005	996	808	1088	855	899	711	1151	905	942	746	1454	1362	1138	1070	1154	1077	900	852

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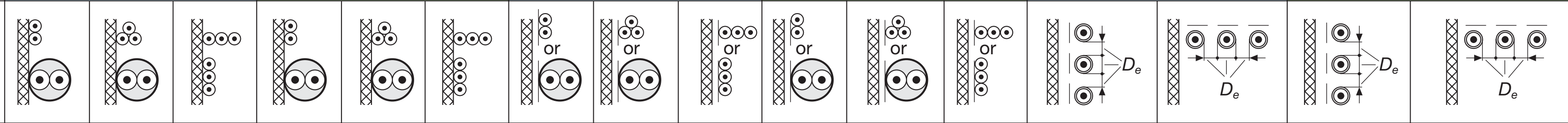
2 Protection of feeders

2.2 Installation and dimensioning of cables

2 Protection of feeders

Table 9: Current carrying capacity of cables with mineral insulation

	Installation method	C						E or F						G			
	Sheath	Metallic sheath temperature 70 °C			Metallic sheath temperature 105 °C			Metallic sheath temperature 70 °C			Metallic sheath temperature 105 °C			Metallic sheath temperature 70 °C		Metallic sheath temperature 105 °C	
		PVC covered or bare exposed to touch			Bare cable not exposed to touch			PVC covered or bare exposed to touch			Bare cable not exposed to touch			PVC covered or bare exposed to touch		Bare cable not exposed to touch	
	Loaded conductors																
	S[mm²]	2	3	3	2	3	3	2	3	3	2	3	3	3	3	3	3
500 V	1.5	23	19	21	28	24	27	25	21	23	31	26	29	26	29	33	37
	2.5	31	26	29	38	33	36	33	28	31	41	35	39	34	39	43	49
	4	40	35	38	51	44	47	44	37	41	54	46	51	45	51	56	64
750 V	1.5	25	21	23	31	26	30	26	22	26	33	28	32	28	32	35	40
	2.5	34	28	31	42	35	41	36	30	34	45	38	43	37	43	47	54
	4	45	37	41	55	47	53	47	40	45	60	50	56	49	56	61	70
	6	57	48	52	70	59	67	60	51	57	76	64	71	62	71	78	89
	10	77	65	70	96	81	91	82	69	77	104	87	96	84	95	105	120
	16	102	86	92	127	107	119	109	92	102	137	115	127	110	125	137	157
	25	133	112	120	166	140	154	142	120	132	179	150	164	142	162	178	204
	35	163	137	147	203	171	187	174	147	161	220	184	200	173	197	216	248
	50	202	169	181	251	212	230	215	182	198	272	228	247	213	242	266	304
	70	247	207	221	307	260	280	264	223	241	333	279	300	259	294	323	370
	95	296	249	264	369	312	334	317	267	289	400	335	359	309	351	385	441
	120	340	286	303	424	359	383	364	308	331	460	385	411	353	402	441	505
	150	388	327	346	485	410	435	416	352	377	526	441	469	400	454	498	565
	185	440	371	392	550	465	492	472	399	426	596	500	530	446	507	557	629
	240	514	434	457	643	544	572	552	466	496	697	584	617	497	565	624	704

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Note 1 For single-core cables the sheaths of the cables of the circuit are connected together at both ends.
Note 2 For bare cables exposed to touch, values should be multiplied by 0.9.
Note 3 D_e is the external diameter of the cable.
Note 4 For metallic sheath temperature 105 °C no correction for grouping need to be applied.

2 Protection of feeders

Installation in ground: choice of the cross section according to cable carrying capacity and type of installation

The current carrying capacity of a cable buried in the ground is calculated by using this formula:

$$I_z = I_0 k_1 k_2 k_3 = I_0 k_{tot}$$

where:
- I_0 is the current carrying capacity of the single conductor for installation in the ground at 20°C reference temperature;
- k_1 is the correction factor if the temperature of the ground is other than 20°C;
- k_2 is the correction factor for adjacent cables;
- k_3 is the correction factor if the soil thermal resistivity is different from the reference value, 2.5 Km/W.

Correction factor k_1

The current carrying capacity of buried cables refers to a ground temperature of 20 °C. If the ground temperature is different, use the correction factor k_1 shown in Table 10 according to the insulation material.

Table 10: Correction factors for ambient ground temperatures other than 20 °C

Ground temperature °C	Insulation: PVC	Insulation: XLPE and EPR
10	1.10	1.07
15	1.05	1.04
25	0.95	0.96
30	0.89	0.93
35	0.84	0.89
40	0.77	0.85
45	0.71	0.80
50	0.63	0.76
55	0.55	0.71
60	0.45	0.65
65	–	0.60
70	–	0.53
75	–	0.46
80	–	0.38

2 Protection of feeders

Correction factor k_2

The cable current carrying capacity is influenced by the presence of other cables installed nearby. The heat dissipation of a single cable is different from that of the same cable installed next to the other ones.
The correction factor k_2 is obtained by the formula:

$$k_2 = k_2' \cdot k_2''$$

Tables 11, 12, and 13 show the factor k_2' values for single-core and multi-core cables that are laid directly in the ground or which are installed in buried ducts, according to their distance from other cables or the distance between the ducts.

Table 11: Reduction factors for cables laid directly in the ground

Number of circuits	Cable to cable clearance (a): Nil (cables touching)	One cable diameter	0.125 m	0.25 m	0.5 m
2	0.75	0.80	0.85	0.90	0.90
3	0.65	0.70	0.75	0.80	0.85
4	0.60	0.60	0.70	0.75	0.80
5	0.55	0.55	0.65	0.70	0.80
6	0.50	0.55	0.60	0.70	0.80

Multi-core cables

Single-core cables

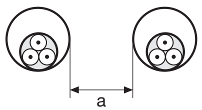
NOTE The given values apply to an installation depth of 0.7 m and a soil thermal resistivity of 2.5 Km/W.

2 Protection of feeders

Table 12: Reduction factors for multi-core cables laid in single way ducts in the ground

Number of circuits	Cable to cable clearance (a) Nil (cables touching)	0.25 m	0.5 m	1.0 m
2	0.85	0.90	0.95	0.95
3	0.75	0.85	0.90	0.95
4	0.70	0.80	0.85	0.90
5	0.65	0.80	0.85	0.90
6	0.60	0.80	0.80	0.90

Multi-core cables

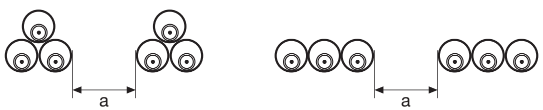


NOTE The given values apply to an installation depth of 0.7 m and a soil thermal resistivity of 2.5 Km/W.

Table 13: Reduction factors for single-core cables laid in single way ducts in the ground

Number of single-core circuits of two or three cables	Duct to duct clearance (a) Nil (ducts touching)	0.25 m	0.5 m	1.0 m
2	0.80	0.90	0.90	0.95
3	0.70	0.80	0.85	0.90
4	0.65	0.75	0.80	0.90
5	0.60	0.70	0.80	0.90
6	0.60	0.70	0.80	0.90

Single-core cables



NOTE The given values apply to an installation depth of 0.7 m and a soil thermal resistivity of 2.5 Km/W.

2 Protection of feeders

For correction factor k_2”:
- for cables laid directly in the ground or if there are not other conductors within the same duct, the value of k_2” is 1;
- if several conductors of similar sizes are present in the same duct (for the meaning of “group of similar conductors”, see the paragraphs above), k_2” is obtained from the first row of Table 5;
- if the conductors are not of similar size, the correction factor is calculated by using this formula:

$$k_2'' = \frac{1}{\sqrt{n}}$$

where:
n is the number of circuits in the duct.

Correction factor k_3

Soil thermal resistivity influences the heat dissipation of the cable. Soil with low thermal resistivity facilitates heat dissipation, whereas soil with high thermal resistivity limits heat dissipation. IEC 60364-5-52 states as reference value for the soil thermal resistivity 2.5 Km/W.

Table 14: Correction factors for soil thermal resistivities other than 2.5 Km/W

Thermal resistivities Km/W	1	1.5	2	2.5	3
Correction factor	1.18	1.1	1.05	1	0.96

Note 1: the overall accuracy of correction factors is within ±5%.
Note 2: the correction factors are applicable to cables drawn into buried ducts; for cables laid direct in the ground the correction factors for thermal resistivities less than 2.5 Km/W will be higher. Where more precise values are required they may be calculated by methods given in IEC 60287.
Note 3: the correction factors are applicable to ducts buried at depths of up to 0.8 m.

2 Protection of feeders

To summarize:

Use this procedure to determine the cross section of the cable:

1. from Table 10, determine the correction factor k_1 according to the insulation material and the ground temperature;

2. use Table 11, Table 12, Table 13 or the formula for groups of non-similar cables to determine the correction factor k_2 according to the distance between cables or ducts;

3. from Table 14 determine factor k_3 corresponding to the soil thermal resistivity;

4. calculate the value of the current I'_b by dividing the load current I_b (or the rated current of the protective device) by the product of the correction factors calculated:

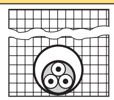
$$I'_b = \frac{I_b}{k_1 k_2 k_3} = \frac{I_b}{k_{tot}}$$

5. from Table 15, determine the cross section of the cable with $I_0 \geq I'_b$, according to the method of installation, the insulation and conductive material and the number of live conductors;

6. the actual cable current carrying capacity is calculated by.

$$I_z = I_0 k_1 k_2 k_3$$

Table 15: Current carrying capacity of cables buried in the ground

	Installation method	D							
									
	Conductor	Cu				Al			
	Insulation	XLPE EPR		PVC		XLPE EPR		PVC	
S[mm²]	Loaded conductors	2	3	2	3	2	3	2	3
1.5		26	22	22	18				
2.5		34	29	29	24	26	22	22	18.5
4		44	37	38	31	34	29	29	24
6		56	46	47	39	42	36	36	30
10		73	61	63	52	56	47	48	40
16		95	79	81	67	73	61	62	52
25		121	101	104	86	93	78	80	66
35		146	122	125	103	112	94	96	80
50		173	144	148	122	132	112	113	94
70		213	178	183	151	163	138	140	117
95		252	211	216	179	193	164	166	138
120		287	240	246	203	220	186	189	157
150		324	271	278	230	249	210	213	178
185		363	304	312	258	279	236	240	200
240		419	351	361	297	322	272	277	230
300		474	396	408	336	364	308	313	260

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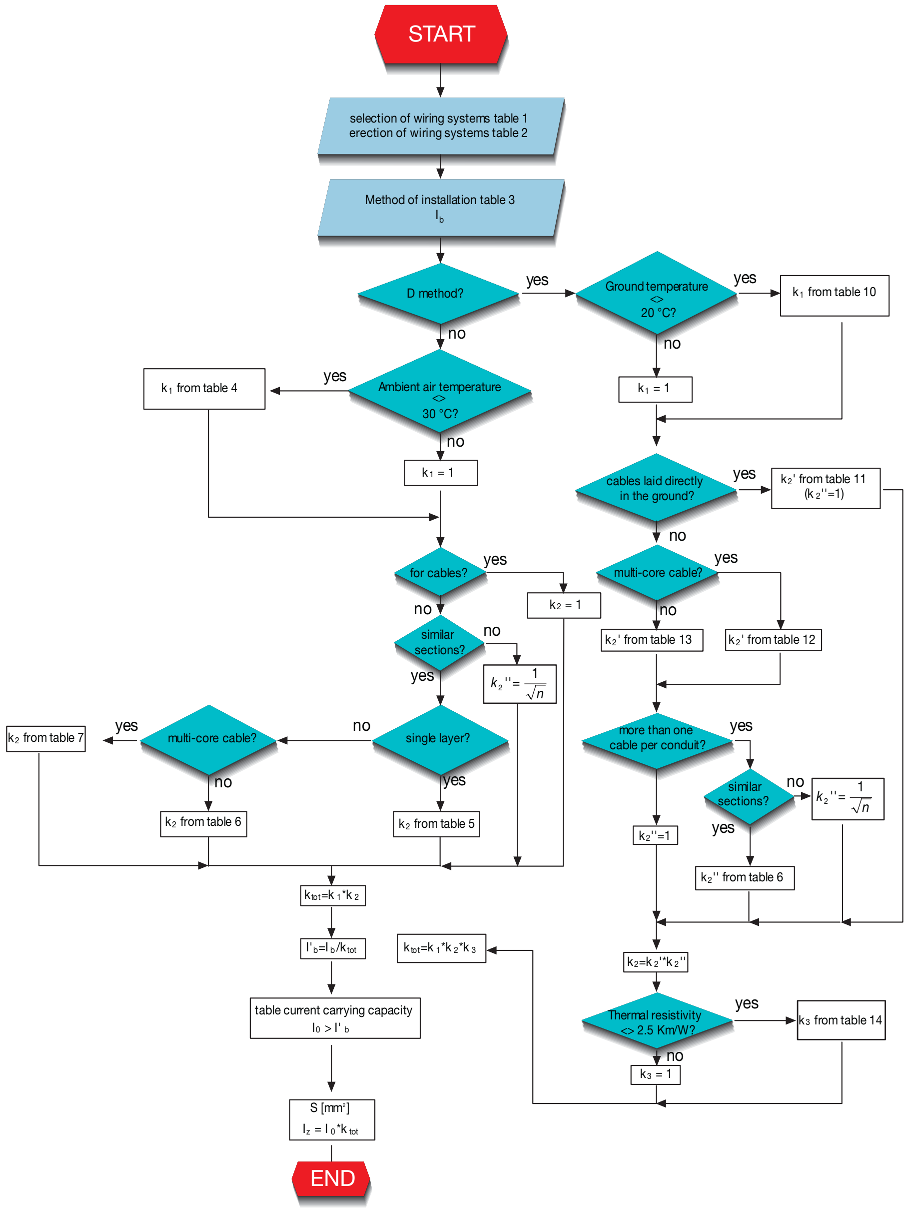
2 Protection of feeders



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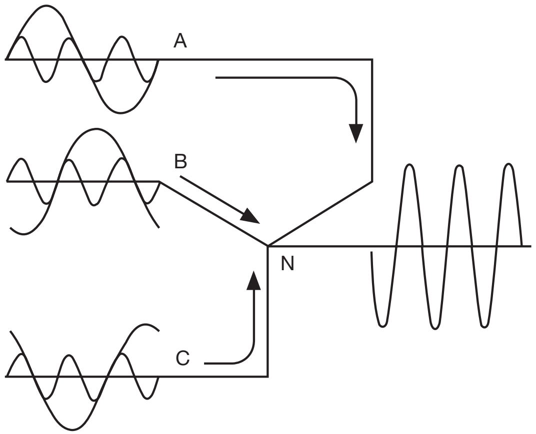
2 Protection of feeders

Note on current carrying capacity tables and loaded conductors

Tables 8, 9 and 15 provide the current carrying capacity of loaded conductors (current carrying conductors) under normal service conditions.
In single-phase circuits, the number of loaded conductors is two.
In balanced or slightly unbalanced three-phase circuits the number of loaded conductors is three, since the current in the neutral conductor is negligible.
In three-phase systems with high unbalance, where the neutral conductor in a multi-core cable carries current as a result of an unbalance in the phase currents the temperature rise due to the neutral current is offset by the reduction in the heat generated by one or more of the phase conductors. In this case the conductor size shall be chosen on the basis of the highest phase current. In all cases the neutral conductor shall have an adequate cross section.

Effect of harmonic currents on balanced three-phase systems: reduction factors for harmonic currents in four-core and five-core cables with four cores carrying current

Where the neutral conductor carries current without a corresponding reduction in load of the phase conductors, the current flowing in the neutral conductor shall be taken into account in ascertaining the current-carrying capacity of the circuit.
This neutral current is due to the phase currents having a harmonic content which does not cancel in the neutral. The most significant harmonic which does not cancel in the neutral is usually the third harmonic. The magnitude of the neutral current due to the third harmonic may exceed the magnitude of the power frequency phase current. In such a case the neutral current will have a significant effect on the current-carrying capacity of the cables in the circuit.



2 Protection of feeders

Equipment likely to cause significant harmonic currents are, for example, fluorescent lighting banks and dc power supplies such as those found in computers (for further information on harmonic disturbances see the IEC 61000).
The reduction factors given in Table 16 only apply in the balanced three-phase circuits (the current in the fourth conductor is due to harmonics only) to cables where the neutral conductor is within a four-core or five-core cable and is of the same material and cross-sectional area as the phase conductors. These reduction factors have been calculated based on third harmonic currents. If significant, i.e. more than 10 %, higher harmonics (e.g. 9th, 12th, etc.) are expected or there is an unbalance between phases of more than 50 %, then lower reduction factors may be applicable: these factors can be calculated only by taking into account the real shape of the current in the loaded phases.
Where the neutral current is expected to be higher than the phase current then the cable size should be selected on the basis of the neutral current.
Where the cable size selection is based on a neutral current which is not significantly higher than the phase current, it is necessary to reduce the tabulated current carrying capacity for three loaded conductors.
If the neutral current is more than 135 % of the phase current and the cable size is selected on the basis of the neutral current, then the three phase conductors will not be fully loaded. The reduction in heat generated by the phase conductors offsets the heat generated by the neutral conductor to the extent that it is not necessary to apply any reduction factor to the current carrying capacity for three loaded conductors.

Table 16: Reduction factors for harmonic currents in four-core and five-core cables

Third harmonic content of phase current	**Reduction factor**			
%	**Size selection is based on phase current**	**Current to take in account for the cable selection I_b'**	**Size selection is based on neutral current**	**Current to take in account for the cable selection I_b'**
0 ÷ 15	1	$I'_b = \frac{I_b}{k_{tot}}$	-	-
15 ÷ 33	0.86	$I'_b = \frac{I_b}{k_{tot} \cdot 0.86}$	-	-
33 ÷ 45	-	-	0.86	$I'_b = \frac{I_N}{0.86}$
> 45	-	-	1	$I'_b = I_N$

Where I_N is the current flowing in the neutral calculated as follows: $I_N = \frac{I_b}{k_{tot}} \cdot 3 \cdot k_{III}$

I_b is the load current;
k_{tot} is the total correction factor;
k_{III} is the third harmonic content of phase current;

2 Protection of feeders

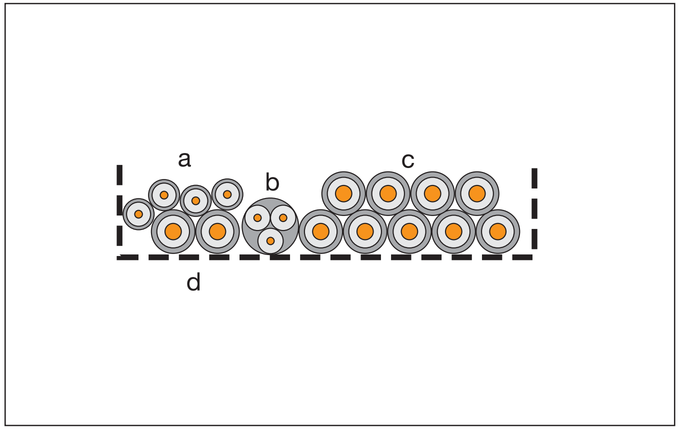
Example of cable dimensioning in a balanced three-phase circuit without harmonics

Dimensioning of a cable with the following characteristics:

- conductor material: : copper
- insulation material: : PVC
- type of cable: : multi-core
- installation: : cables bunched on horizontal perforated tray
- load current: : 100 A

Installation conditions:

- ambient temperature: : 40 °C
- adjacent circuits with
  a) three-phase circuit consisting of 4 single-core cables, 4x50 mm^2;
  b) three-phase circuit consisting of one multi-core cable, 1x(3x50) mm^2;
  c) three-phase circuit consisting of 9 single-core (3 per phase) cables, 9x95 mm^2;
  d) single-phase circuit consisting of 2 single-core cables, 2x70 mm^2.



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2 Protection of feeders

Procedure:

Type of installation

In Table 3, it is possible to find the reference number of the installation and the method of installation to be used for the calculations. In this example, the reference number is 31, which corresponds to method E (multi-core cable on tray).

Correction factor of temperature k_1

From Table 4, for a temperature of 40 °C and PVC insulation material, k_1 = 0.87.

$$k_1 = 0.87$$

Correction factor for adjacent cables k_2

For the multi-core cables grouped on the perforated tray see Table 5.
As a first step, the number of circuits or multi-core cables present shall be determined; given that:

- each circuit a), b) and d) constitute a separate circuit;
- circuit c) consists of three circuits, since it is composed by three cables in parallel per phase;
- the cable to be dimensioned is a multi-core cable and therefore constitutes a single circuit;
  the total number of circuits is 7.
  Referring to the row for the arrangement (cables bunched) and to the column for the number of circuits (7)

$$k_2 = 0.54$$

After k_1 and k_2 have been determined, I'_b is calculated by:

$$I'_b = \frac{I_b}{k_1 k_2} = \frac{100}{0.87 \cdot 0.54} = 212.85\text{A}$$

From Table 8, for a multi-core copper cable with PVC insulation, method of installation E, with three loaded conductors, a cross section with current carrying capacity of $I_0 \geq I'_b$ = 212.85 A, is obtained. A 95 mm^2 cross section cable can carry, under Standard reference conditions, 238 A.
The current carrying capacity, according to the actual conditions of installation, is I_z = 238 · 0.87· 0.54 = 111.81 A

2 Protection of feeders

Example of dimensioning a cable in a balanced three-phase circuit with a significant third-harmonic content

Dimensioning of a cable with the following characteristics:

- conductor material: : copper
- insulation material: : PVC
- type of cable: : multi-core
- installation: : layer on horizontal perforated tray
- load current: : 115 A

Installation conditions:

- ambient temperature: : 30 °C
- no adjacent circuits.

Procedure:

Type of installation

On Table 3, it is possible to find the reference number of the installation and the method of installation to be used for the calculations. In this example, the reference number is 31, which corresponds to method E (multi-core cable on tray).

Temperature correction factor k_1

From Table 4, for a temperature of 30 °C and PVC insulation material

$$k_1 = 1$$

Correction factor for adjacent cables k_2

As there are no adjacent cables, so

$$k_2 = 1$$

After k_1 and k_2 have been determined, I'_b is calculated by:

$$I'_b = \frac{I_b}{k_1 k_2} = 115A$$

2.2 Installation and dimensioning of cables

2 Protection of feeders

If no harmonics are present, from Table 8, for a multi-core copper cable with PVC insulation, method of installation E, with three loaded conductors, a cross section with current carrying capacity of $I_0 \geq I'_b = 115$ A, is obtained. A 35 mm² cross section cable can carry, under Standard reference conditions, 126 A. The current carrying capacity, according to the actual conditions of installation, is still 126 A, since the value of factors k_1 and k_2 is 1.

The third harmonic content is assumed to be 28%.
Table 16 shows that for a third harmonic content of 28% the cable must be dimensioned for the current that flows through the phase conductors, but a reduction factor of 0.86 must be applied. The current I'_b becomes:

$$I'_b = \frac{I_b}{k_1 \cdot k_2 \cdot 0.86} = \frac{115}{0.86} = 133.7A$$

From Table 8, a 50 mm² cable with carrying capacity of 153 A shall be selected.

If the third harmonic content is 40 %, Table 16 shows that the cable shall be dimensioned according to the current of the neutral conductor and a reduction factor of 0.86 must be applied.
The current in the neutral conductor is:

$$I_N = \frac{I_b}{k_{tot}} \cdot 3 \cdot k_{III} = 115 \cdot 3 \cdot 0.4 = 138A$$

and the value of current I'_b is:

$$I'_b = \frac{I_N}{0.86} = \frac{138}{0.86} = 160.5A$$

From Table 8, a 70 mm² cable with 196 A current carrying capacity shall be selected.
If the third harmonic content is 60 %, Table 16 shows that the cable shall be dimensioned according to the current of the neutral conductor, but a reduction factor of 1 must be applied.
The current in the neutral conductor is:

$$I_N = \frac{I_b}{k_{tot}} \cdot 3 \cdot k_{III} = 115 \cdot 3 \cdot 0.6 = 207A$$

and current I'_b is:

$$I'_b = I_N = 207A$$

From Table 8, a 95 mm² cable with current carrying capacity of 238 A must be selected.

2 Protection of feeders

2.2.2 Voltage drop

In an electrical installation it is important to evaluate voltage drops from the point of supply to the load.
The performance of a device may be impaired if supplied with a voltage different from its rated voltage. For example:

- *motors*: the torque is proportional to the square of the supply voltage; therefore, if the voltage drops, the starting torque shall also decrease, making it more difficult to start up motors; the maximum torque shall also decrease;
- *incandescent lamps:* the more the voltage drops the weaker the beam becomes and the light takes on a reddish tone;
- *discharge lamps*: in general, they are not very sensitive to small variations in voltage, but in certain cases, great variation may cause them to switch off;
- *electronic appliances*: they are very sensitive to variations in voltage and that is why they are fitted with stabilizers;
- *electromechanical devices:* the reference Standard states that devices such as contactors and auxiliary releases have a minimum voltage below which their performances cannot be guaranteed. For a contactor, for example, the holding of the contacts becomes unreliable below 85% of the rated voltage.

To limit these problems the Standards set the following limits:

- IEC 60364-5-52 *"Electrical installations of buildings. Selection and erection of electrical equipment - Wiring systems"* Clause 525 states that *"in the absence of other considerations it is recommended that in practice the voltage drop between the origin of consumer's installation and the equipment should not be greater than 4% of the rated voltage of the installation. Other considerations include start-up time for motors and equipment with high inrush current. Temporary conditions such as voltage transients and voltage variation due to abnormal operation may be disregarded".*
- IEC 60204-1*"Safety of machinery – Electrical equipment of machines – General requirements"* Clause 13.5 recommends that: *"the voltage drop from the point of supply to the load shall not exceed 5% of the rated voltage under normal operating conditions".*
- IEC 60364-7-714 *"Electrical installations of buildings - Requirements for special installations or locations - External lighting installations"* Clause 714.512 requires that *"the voltage drop in normal service shall be compatible with the conditions arising from the starting current of the lamps".*

2 Protection of feeders

Voltage drop calculation

For an electrical conductor with impedance Z, the voltage drop is calculated by the following formula:

$$\Delta U = kZI_b = kI_b \frac{L}{n}(r\cos\varphi + x\sin\varphi) \text{ [V]} \qquad (1)$$

where

- k is a coefficient equal to:
  - 2 for single-phase and two-phase systems;
  - $\sqrt{3}$ for three-phase systems;
- I_b [A] is the load current; if no information are available, the cable carrying capacity I_z shall be considered;
- L [km] is the length of the conductor;
- n is the number of conductors in parallel per phase;
- r [Ω/km] is the resistance of the single cable per kilometre;
- x [Ω/km] is the reactance of the single cable per kilometre;
- cosφ is the power factor of the load: $\sin\varphi = \sqrt{1-\cos^2\varphi}$.

Normally, the percentage value in relation to the rated value U_r is calculated by:

$$\Delta u\% = \frac{\Delta U}{U_r}100 \qquad (2)$$

Resistance and reactance values per unit of length are set out on the following table by cross-sectional area and cable formation, for 50 Hz; in case of 60 Hz, the reactance value shall be multiplied by 1.2.

2 Protection of feeders

Table 1: Resistance and reactance per unit of length of copper cables

S [mm²]	single-core cable r[Ω/km] @ 80 [°C]	single-core cable x[Ω/km]	two-core/three-core cable r[Ω/km] @ 80 [°C]	two-core/three-core cable x[Ω/km]
1.5	14.8	0.168	15.1	0.118
2.5	8.91	0.156	9.08	0.109
4	5.57	0.143	5.68	0.101
6	3.71	0.135	3.78	0.0955
10	2.24	0.119	2.27	0.0861
16	1.41	0.112	1.43	0.0817
25	0.889	0.106	0.907	0.0813
35	0.641	0.101	0.654	0.0783
50	0.473	0.101	0.483	0.0779
70	0.328	0.0965	0.334	0.0751
95	0.236	0.0975	0.241	0.0762
120	0.188	0.0939	0.191	0.074
150	0.153	0.0928	0.157	0.0745
185	0.123	0.0908	0.125	0.0742
240	0.0943	0.0902	0.0966	0.0752
300	0.0761	0.0895	0.078	0.075

Table 2: Resistance and reactance per unit of length of aluminium cables

S [mm²]	single-core cable r[Ω/km] @ 80 [°C]	single-core cable x[Ω/km]	two-core/three-core cable r[Ω/km] @ 80 [°C]	two-core/three-core cable x[Ω/km]
1.5	24.384	0.168	24.878	0.118
2.5	14.680	0.156	14.960	0.109
4	9.177	0.143	9.358	0.101
6	6.112	0.135	6.228	0.0955
10	3.691	0.119	3.740	0.0861
16	2.323	0.112	2.356	0.0817
25	1.465	0.106	1.494	0.0813
35	1.056	0.101	1.077	0.0783
50	0.779	0.101	0.796	0.0779
70	0.540	0.0965	0.550	0.0751
95	0.389	0.0975	0.397	0.0762
120	0,310	0.0939	0.315	0.074
150	0.252	0.0928	0.259	0.0745
185	0.203	0.0908	0.206	0.0742
240	0.155	0.0902	0.159	0.0752
300	0.125	0.0895	0.129	0.075

2 Protection of feeders

The following tables show the ΔU_x [V/(A·km)] values by cross section and formation of the cable according to the most common cosφ values.

Table 3: Specific voltage drop at cosφ = 1 for copper cables

S[mm²]	cosφ = 1 single-core cable single-phase	single-core cable three-phase	two-core cable single-phase	three-core cable three-phase
1.5	29.60	25.63	30.20	26.15
2.5	17.82	15.43	18.16	15.73
4	11.14	9.65	11.36	9.84
6	7.42	6.43	7.56	6.55
10	4.48	3.88	4.54	3.93
16	2.82	2.44	2.86	2.48
25	1.78	1.54	1.81	1.57
35	1.28	1.11	1.31	1.13
50	0.95	0.82	0.97	0.84
70	0.66	0.57	0.67	0.58
95	0.47	0.41	0.48	0.42
120	0.38	0.33	0.38	0.33
150	0.31	0.27	0.31	0.27
185	0.25	0.21	0.25	0.22
240	0.19	0.16	0.19	0.17
300	0.15	0.13	0.16	0.14

Table 4: Specific voltage drop at cosφ = 0.9 for copper cables

S[mm²]	cosφ = 0.9 single-core cable single-phase	single-core cable three-phase	two-core cable single-phase	three-core cable three-phase
1.5	26.79	23.20	27.28	23.63
2.5	16.17	14.01	16.44	14.24
4	10.15	8.79	10.31	8.93
6	6.80	5.89	6.89	5.96
10	4.14	3.58	4.16	3.60
16	2.64	2.28	2.65	2.29
25	1.69	1.47	1.70	1.48
35	1.24	1.08	1.25	1.08
50	0.94	0.81	0.94	0.81
70	0.67	0.58	0.67	0.58
95	0.51	0.44	0.50	0.43
120	0.42	0.36	0.41	0.35
150	0.36	0.31	0.35	0.30
185	0.30	0.26	0.29	0.25
240	0.25	0.22	0.24	0.21
300	0.22	0.19	0.21	0.18

2 Protection of feeders

Table 5: Specific voltage drop at cosφ = 0.85 for copper cables

	cosφ = 0.85			
	single-core cable		two-core cable	three-core cable
S[mm²]	single-phase	three-phase	single-phase	three-phase
1.5	25.34	21.94	25.79	22.34
2.5	15.31	13.26	15.55	13.47
4	9.62	8.33	9.76	8.45
6	6.45	5.59	6.53	5.65
10	3.93	3.41	3.95	3.42
16	2.51	2.18	2.52	2.18
25	1.62	1.41	1.63	1.41
35	1.20	1.04	1.19	1.03
50	0.91	0.79	0.90	0.78
70	0.66	0.57	0.65	0.56
95	0.50	0.44	0.49	0.42
120	0.42	0.36	0.40	0.35
150	0.36	0.31	0.35	0.30
185	0.30	0.26	0.29	0.25
240	0.26	0.22	0.24	0.21
300	0.22	0.19	0.21	0.18

Table 6: Specific voltage drop at cosφ = 0.8 for copper cables

	cosφ = 0.8			
	single-core cable		two-core cable	three-core cable
S[mm²]	single-phase	three-phase	single-phase	three-phase
1.5	23.88	20.68	24.30	21.05
2.5	14.44	12.51	14.66	12.69
4	9.08	7.87	9.21	7.98
6	6.10	5.28	6.16	5.34
10	3.73	3.23	3.74	3.23
16	2.39	2.07	2.39	2.07
25	1.55	1.34	1.55	1.34
35	1.15	0.99	1.14	0.99
50	0.88	0.76	0.87	0.75
70	0.64	0.55	0.62	0.54
95	0.49	0.43	0.48	0.41
120	0.41	0.36	0.39	0.34
150	0.36	0.31	0.34	0.29
185	0.31	0.26	0.29	0.25
240	0.26	0.22	0.24	0.21
300	0.23	0.20	0.21	0.19

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Table 7: Specific voltage drop at cosφ=0.75 for copper cables

	cosφ = 0.75			
	single-core cable		two-core cable	three-core cable
S[mm²]	single-phase	three-phase	single-phase	three-phase
1.5	22.42	19.42	22.81	19.75
2.5	13.57	11.75	13.76	11.92
4	8.54	7.40	8.65	7.49
6	5.74	4.97	5.80	5.02
10	3.52	3.05	3.52	3.05
16	2.26	1.96	2.25	1.95
25	1.47	1.28	1.47	1.27
35	1.10	0.95	1.08	0.94
50	0.84	0.73	0.83	0.72
70	0.62	0.54	0.60	0.52
95	0.48	0.42	0.46	0.40
120	0.41	0.35	0.38	0.33
150	0.35	0.31	0.33	0.29
185	0.30	0.26	0.29	0.25
240	0.26	0.23	0.24	0.21
300	0.23	0.20	0.22	0.19

Table 8: Specific voltage drop at cosφ = 1 for aluminium cables

	cosφ = 1			
	single-core cable		two-core cable	three-core cable
S[mm²]	single-phase	three-phase	single-phase	three-phase
1.5	48.77	42.23	49.76	43.09
2.5	29.36	25.43	29.92	25.91
4	18.35	15.89	18.72	16.21
6	12.22	10.59	12.46	10.79
10	7.38	6.39	7.48	6.48
16	4.65	4.02	4.71	4.08
25	2.93	2.54	2.99	2.59
35	2.11	1.83	2.15	1.87
50	1.56	1.35	1.59	1.38
70	1.08	0.94	1.10	0.95
95	0.78	0.67	0.79	0.69
120	0.62	0.54	0.63	0.55
150	0.50	0.44	0.52	0.45
185	0.41	0.35	0.41	0.36
240	0.31	0.27	0.32	0.28
300	0.25	0.22	0.26	0.22

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Table 9: Specific voltage drop at cosφ = 0.9 for aluminium cables

	cosφ = 0.9			
	single-core cable		two-core cable	three-core cable
S[mm²]	single-phase	three-phase	single-phase	three-phase
1.5	44.04	38.14	44.88	38.87
2.5	26.56	23.00	27.02	23.40
4	16.64	14.41	16.93	14.66
6	11.12	9.63	11.29	9.78
10	6.75	5.84	6.81	5.89
16	4.28	3.71	4.31	3.73
25	2.73	2.36	2.76	2.39
35	1.99	1.72	2.01	1.74
50	1.49	1.29	1.50	1.30
70	1.06	0.92	1.06	0.91
95	0.78	0.68	0.78	0.68
120	0.64	0.55	0.63	0.55
150	0.53	0.46	0.53	0.46
185	0.44	0.38	0.44	0.38
240	0.36	0.31	0.35	0.30
300	0.30	0.26	0.30	0.26

Table 10: Specific voltage drop at cosφ = 0.85 for aluminium cables

	cosφ = 0.85			
	single-core cable		two-core cable	three-core cable
S[mm²]	single-phase	three-phase	single-phase	three-phase
1.5	41.63	36.05	42.42	36.73
2.5	25.12	21.75	25.55	22.12
4	15.75	13.64	16.02	13.87
6	10.53	9.12	10.69	9.26
10	6.40	5.54	6.45	5.58
16	4.07	3.52	4.09	3.54
25	2.60	2.25	2.63	2.27
35	1.90	1.65	1.91	1.66
50	1.43	1.24	1.43	1.24
70	1.02	0.88	1.01	0.88
95	0.76	0.66	0.76	0.65
120	0.63	0.54	0.61	0.53
150	0.53	0.46	0.52	0.45
185	0.44	0.38	0,43	0.37
240	0.36	0.31	0.35	0.30
300	0.31	0.27	0.30	0.26

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Table 11: Specific voltage drop at cosφ = 0.8 for aluminium cables

	cosφ = 0.8			
	single-core cable		two-core cable	three-core cable
S[mm²]	single-phase	three-phase	single-phase	three-phase
1.5	39.22	33.96	39.95	34.59
2.5	23.67	20.50	24.07	20.84
4	14.85	12.86	15.09	13.07
6	9.94	8.61	10.08	8.73
10	6.05	5.24	6.09	5.27
16	3.85	3.34	3.87	3.35
25	2.47	2.14	2.49	2.16
35	1.81	1.57	1.82	1.57
50	1.37	1.18	1.37	1.18
70	0.98	0.85	0.97	0.84
95	0.74	0.64	0.73	0.63
120	0.61	0.53	0.59	0.51
150	0.51	0.45	0.50	0.44
185	0.43	0.38	0.42	0.36
240	0.36	0.31	0.34	0.30
300	0.31	0.27	0.30	0.26

Table 12: Specific voltage drop at cosφ = 0.75 for aluminium cables

	cosφ = 0.75			
	single-core cable		two-core cable	three-core cable
S[mm²]	single-phase	three-phase	single-phase	three-phase
1.5	36.80	31.87	37.47	32.45
2.5	22.23	19.25	22.58	19.56
4	13.95	12.08	14.17	12.27
6	9.35	8.09	9.47	8.20
10	5.69	4.93	5.72	4.96
16	3.63	3.15	3.64	3.15
25	2.34	2.02	2.35	2.03
35	1.72	1.49	1.72	1.49
50	1.30	1.13	1.30	1.12
70	0.94	0.81	0.92	0.80
95	0.71	0.62	0.70	0.60
120	0.59	0.51	0.57	0.49
150	0.50	0.43	0.49	0.42
185	0.42	0.37	0.41	0.35
240	0.35	0.31	0.34	0.29
300	0.31	0.27	0.29	0.25

2 Protection of feeders

Example 1

To calculate a voltage drop on a three-phase cable with the following specifications:
- rated voltage: 400 V;
- cable length: 25 m;
- cable formation: single-core copper cable, 3x50 mm^2;
- load current I_b: 100 A;
- power factor cosφ: 0.9.

From Table 4, for a 50 mm^2 single-core cable it is possible to read that a ΔU_x voltage drop corresponds to 0.81 V/(A·km). By multiplying this value by the length in km and by the current in A, it results:

$$\Delta U = \Delta U_x \cdot I_b \cdot L = 0.81 \cdot 100 \cdot 0.025 = 2.03 \text{ V}$$

which corresponds to this percentage value:

$$\Delta u\% = \frac{\Delta U}{U_r} \cdot 100 = \frac{2.03}{400} \cdot 100 = 0.51\%$$

Example 2

To calculate a voltage drop on a three-phase cable with the following specifications:
- rated voltage: 690 V;
- cable length: 50 m;
- cable formation: multi-core copper cable, 2x(3x10) mm^2;
- load current I_b: 50 A;
- power factor cosφ: 0.85.

From Table 5, for a multi-core 10 mm^2 cable it is possible to read that ΔU_x voltage drop corresponds to 3.42 V/(A·km). By multiplying this value by the length in km and by the current in A, and by dividing it by the number of cables in parallel, it results:

$$\Delta U = \Delta U_x \cdot I_b \cdot \frac{L}{2} = 3.42 . 50 \cdot \frac{0.05}{2} = 4.28 \text{ V}$$

which corresponds to this percentage value:

$$\Delta u\% = \frac{\Delta U}{U_r} \cdot 100 = \frac{4.28}{690} \cdot 100 = 0.62\%$$

2 Protection of feeders

Method for defining the cross section of the conductor according to voltage drop in the case of long cables

In the case of long cables, or if particular design specifications impose low limits for maximum voltage drops, the verification using as reference the cross section calculated on the basis of thermal considerations (calculation according to chapter 2.2.1 “Current carrying capacity and methods of installation”) may have a negative result.
To define the correct cross section, the maximum ΔU_{xmax} value calculated by using the formula:

$$\Delta U_{xmax} = \frac{\Delta u\% \cdot U_r}{100 \cdot I_b \cdot L} \quad (3)$$

is compared with the corresponding values on Tables 4÷12 by choosing the smallest cross section with a ΔU_x value lower than ΔU_{xmax}.

Example:
Supply of a three-phase load with P_u = 35 kW (U_r=400 V, f_r= 50 Hz, cosφ=0.9) with a 140 m cable installed on a perforated tray, consisting of a multi-core copper cable with EPR insulation.
Maximum permitted voltage drop 2%.

Load current I_b is:

$$I_b = \frac{P_u}{\sqrt{3} \cdot U_r \cdot \cos\varphi} = \frac{35000}{\sqrt{3} \cdot 400 \cdot 0.9} = 56 \text{ A}$$

The Table 8 of Chapter 2.2.1 shows S = 10 mm^2.
From Table 4, for the multi-core 10 mm^2 cable it is possible to read that the voltage drop per A and per km is 3.60 V/(A·km). By multiplying this value by the length in km and by the current in A, it results:

$$\Delta U = 3.60 \cdot I_b \cdot L = 3.6 \cdot 56 \cdot 0.14 = 28.2 \text{ V}$$

which corresponds to this percentage value:

$$\Delta u\% = \frac{\Delta U}{U_r} \cdot 100 = \frac{28.2}{400} \cdot 100 = 7.05\%$$

This value is too high.
Formula (3) shows:

$$\Delta U_{xmax} = \frac{\Delta u\% \cdot U_r}{100 \cdot I_b \cdot L} = \frac{2\% \cdot 400}{100 \cdot 56 \cdot 0.14} = 1.02 \text{ V/(A} \cdot \text{km)}$$

2 Protection of feeders

From Table 4 a cross section of 50 mm² can be chosen.
For this cross section ΔU_x = 0.81< 1.02 V/(A·km).
By using this value it results:

$$\Delta U = \Delta U_x \cdot I_b \cdot L = 0.81 \cdot 56 \cdot 0.14 = 6.35 \text{ V}$$

This corresponds to a percentage value of:

$$\Delta u\% = \frac{\Delta U}{U_r} \cdot 100 = \frac{6.35}{400} \cdot 100 = 1.6\%$$

2.2.3 Joule-effect losses

Joule-effect losses are due to the electrical resistance of the cable.
The lost energy is dissipated in heat and contributes to the heating of the conductor and of the environment.
A first estimate of three-phase losses is:

$$P_j = \frac{3 \cdot r \cdot I_b^2 \cdot L}{1000} \text{ [W]}$$

whereas single-phase losses are:

$$P_j = \frac{2 \cdot r \cdot I_b^2 \cdot L}{1000} \text{ [W]}$$

where:
- I_b is the load current [A];
- r is the phase resistance per unit of length of the cable at 80 °C [Ω/km] (see Table 1);
- L is the cable length [m].

Table 1: Resistance values [Ω/km] of single-core and multi-core cables in copper and aluminium at 80 °C

S [mm²]	Single-core cable Cu	Single-core cable Al	Two-core/three-core cable Cu	Two-core/three-core cable Al
1.5	14.8	24.384	15.1	24.878
2.5	8.91	14.680	9.08	14.960
4	5.57	9.177	5.68	9.358
6	3.71	6.112	3.78	6.228
10	2.24	3.691	2.27	3.740
16	1.41	2.323	1.43	2.356
25	0.889	1.465	0.907	1.494
35	0.641	1.056	0.654	1.077
50	0.473	0.779	0.483	0.796
70	0.328	0.540	0.334	0.550
95	0.236	0.389	0.241	0.397
120	0.188	0.310	0.191	0.315
150	0.153	0.252	0.157	0.259
185	0.123	0.203	0.125	0.206
240	0.0943	0.155	0.0966	0.159
300	0.0761	0.125	0.078	0.129

2 Protection of feeders

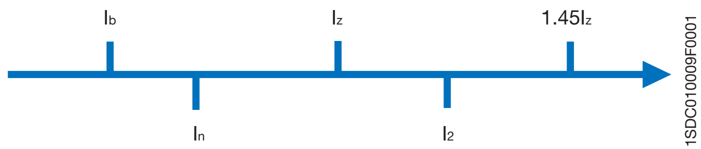
2.3 Protection against overload

The Standard IEC 60364-4-43 *"Electrical installation of buildings - Protection against overcurrent"* specifies coordination between conductors and overload protective devices (normally placed at the beginning of the conductor to be protected) so that it shall satisfy the two following conditions:

$$I_b \le I_n \le I_z \qquad (1)$$

$$I_2 \le 1.45 \cdot I_z \qquad (2)$$

Where:
- I_b is the current for which the circuit is dimensioned;
- I_z is the continuous current carrying capacity of the cable;
- I_n is the rated current of the protective device; for adjustable protective releases, the rated current I_n is the set current;
- I_2 is the current ensuring effective operation in the conventional time of the protective device.



According to condition (1) to correctly choose the protective device, it is necessary to check that the circuit-breaker has a rated (or set) current that is:
- higher than the load current, to prevent unwanted tripping;
- lower than the current carrying capacity of the cable, to prevent cable overload.

The Standard allows an overload current that may be up to 45% greater than the current carrying capacity of the cable but only for a limited period (conventional trip time of the protective device).
The verification of condition (2) is not necessary in the case of circuit-breakers because the protective device is automatically tripped if:
- $I_2 = 1.3 \cdot I_n$ for circuit-breakers complying with IEC 60947-2 (circuit-breakers for industrial use);
- $I_2 = 1.45 \cdot I_n$ for circuit-breakers complying with IEC 60898 (circuit-breakers for household and similar installations).

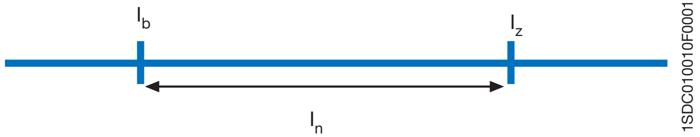
Therefore, for circuit-breakers, if $I_n \le I_z$, the formula $I_2 \le 1.45 \cdot I_z$ will also be verified.
When the protective device is a fuse, it is also essential to check formula (2) because IEC 60269-2-1 on *"Low-voltage fuses"* states that a $1.6 \cdot I_n$ current must automatically melt the fuse. In this case, formula (2) becomes $1.6 \cdot I_n \le 1.45 \cdot I_z$ or $I_n \le 0.9 \cdot I_z$.

2 Protection of feeders

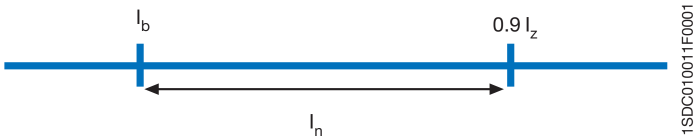
To summarize: to carry out by a fuse protection against overload, the following must be achieved:

$$I_b \leq I_n \leq 0.9 \cdot I_z$$

and this means that the cable is not fully exploited.



Circuit-breaker: choice of rated current



Fuse: choice of rated current

Where the use of a single conductor per phase is not feasible, and the currents in the parallel conductors are unequal, the design current and requirements for overload protection for each conductor shall be considered individually.

Examples

Example 1

Load specifications

P_r = 70 kW; U_r = 400 V; cosφ = 0.9; three-phase load so I_b = 112 A

Cable specifications

I_z = 134 A

Protective device specifications

T1B160 TMD I_n125; set current I1 = 125 A

2 Protection of feeders

Example 2

Load specifications

P_r = 80 kW; cosφ = 0.9; U_r = 400 V; three-phase load so I_b = 128 A

Cable specifications

I_z = 171 A

Protective device specifications

T2N160 PR221DS-LS I_n160; set current I1 = 0.88 x I_n = 140.8 A

Example 3

Load specifications

P_r = 100 kW; cosφ = 0.9; U_r = 400 V ; three-phase load so I_b = 160 A

Cable specifications

I_z = 190 A

Protective device specifications

T3N250 TMD I_n200; set current I1 = 0.9 x I_n = 180 A

Example 4

Load specifications

P_r = 25 kW; cosφ = 0.9; U_r = 230 V ; single-phase load so I_b = 121 A

Cable specifications

I_z = 134 A

Protective device specifications

T1B160 1P TMF I_n125

2 Protection of feeders

2.4 Protection against short-circuit

A cable is protected against short-circuit if the specific let-through energy of the protective device (I^2t) is lower or equal to the withstood energy of the cable (k^2S^2):

$$I^2t \le k^2S^2 \quad (1)$$

where
- I^2t is the specific let-through energy of the protective device which can be read on the curves supplied by the manufacturer (see *Electrical installation handbook*, Vol. 1, Chapter 3.4 "Specific let-through energy curves") or from a direct calculation in the case of devices that are not limiting and delaying;
- S is the cable cross section [mm^2]; in the case of conductors in parallel it is the cross section of the single conductor;
- k is a factor that depends on the cable insulating and conducting material. The values of the most common installations are shown in Table 1; for a more detailed calculation, see Annex D.

Table 1: Values of k for phase conductor

	Conductor insulation					
	PVC ≤300 mm^2	PVC >300 mm^2	EPR XLPE	Rubber 60 °C	Mineral	
					PVC	Bare
Initial temperature °C	70	70	90	60	70	105
Final temperature °C	160	140	250	200	160	250
Material of conductor:						
Copper	115	103	143	141	115	135/115 [a]
Aluminium	76	68	94	93	-	-
tin-soldered joints in copper conductors	115	-	-	-	-	-

[a] This value shall be used for bare cables exposed to touch.

NOTE 1 Other values of k are under consideration for.
- small conductors (particularly for cross section less than 10 mm^2);
- duration of short-circuit exceeding 5 s;
- other types of joints in conductors;
- bare conductors.

NOTE 2 The nominal current of the short-circuit protective device may be greater than the current carrying capacity of the cable.

NOTE 3 The above factors are based on IEC 60724.

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2 Protection of feeders

Table 2 shows the maximum withstood energy for cables according to the cross section, the conductor material and the type of insulation, which are calculated by using the parameters of Table 1.

Table 2: Maximum withstood energy for cables $k^2 S^2$ [(kA)^2 s]

			Cross section [mm^2]							
Cable		**k**	1.5	2.5	4	6	10	16	25	35
PVC	Cu	115	$2.98\cdot10^{-2}$	$8.27\cdot10^{-2}$	$2.12\cdot10^{-1}$	$4.76\cdot10^{-1}$	1.32	3.39	8.27	$1.62\cdot10^{1}$
	Al	76	$1.30\cdot10^{-2}$	$3.61\cdot10^{-2}$	$9.24\cdot10^{-2}$	$2.08\cdot10^{-1}$	$5.78\cdot10^{-1}$	1.48	3.61	7.08
EPR/XLPE	Cu	143	$4.60\cdot10^{-2}$	$1.28\cdot10^{-1}$	$3.27\cdot10^{-1}$	$7.36\cdot10^{-1}$	2.04	5.23	$1.28\cdot10^{1}$	$2.51\cdot10^{1}$
	Al	94	$1.99\cdot10^{-2}$	$5.52\cdot10^{-2}$	$1.41\cdot10^{-1}$	$3.18\cdot10^{-1}$	$8.84\cdot10^{-1}$	2.26	5.52	$1.08\cdot10^{1}$
Rubber	Cu	141	$4.47\cdot10^{-2}$	$1.24\cdot10^{-1}$	$3.18\cdot10^{-1}$	$7.16\cdot10^{-1}$	1.99	5.09	$1.24\cdot10^{1}$	$2.44\cdot10^{1}$
	Al	93	$1.95\cdot10^{-2}$	$5.41\cdot10^{-2}$	$1.38\cdot10^{-1}$	$3.11\cdot10^{-1}$	$8.65\cdot10^{-1}$	2.21	5.41	$1.06\cdot10^{1}$

			Cross section [mm^2]							
Cable		**k**	50	70	95	120	150	185	240	300
PVC	Cu	115	$3.31\cdot10^{1}$	$6.48\cdot10^{1}$	$1.19\cdot10^{2}$	$1.90\cdot10^{2}$	$2.98\cdot10^{2}$	$4.53\cdot10^{2}$	$7.62\cdot10^{2}$	$1.19\cdot10^{3}$
	Al	76	$1.44\cdot10^{1}$	$2.83\cdot10^{1}$	$5.21\cdot10^{1}$	$8.32\cdot10^{1}$	$1.30\cdot10^{2}$	$1.98\cdot10^{2}$	$3.33\cdot10^{2}$	$5.20\cdot10^{2}$
EPR/XLPE	Cu	143	$5.11\cdot10^{1}$	$1.00\cdot10^{1}$	$1.85\cdot10^{1}$	$2.94\cdot10^{2}$	$4.60\cdot10^{2}$	$7.00\cdot10^{2}$	$1.18\cdot10^{3}$	$1.84\cdot10^{3}$
	Al	94	$2.21\cdot10^{1}$	$4.33\cdot10^{1}$	$7.97\cdot10^{1}$	$1.27\cdot10^{2}$	$1.99\cdot10^{2}$	$3.02\cdot10^{2}$	$5.09\cdot10^{2}$	$7.95\cdot10^{2}$
G2	Cu	141	$4.97\cdot10^{1}$	$9.74\cdot10^{1}$	$1.79\cdot10^{1}$	$2.86\cdot10^{2}$	$4.47\cdot10^{2}$	$6.80\cdot10^{2}$	$1.15\cdot10^{3}$	$1.79\cdot10^{3}$
	Al	93	$2.16\cdot10^{1}$	$4.24\cdot10^{1}$	$7.81\cdot10^{1}$	$1.25\cdot10^{2}$	$1.95\cdot10^{2}$	$2.96\cdot10^{2}$	$4.98\cdot10^{2}$	$7.78\cdot10^{2}$

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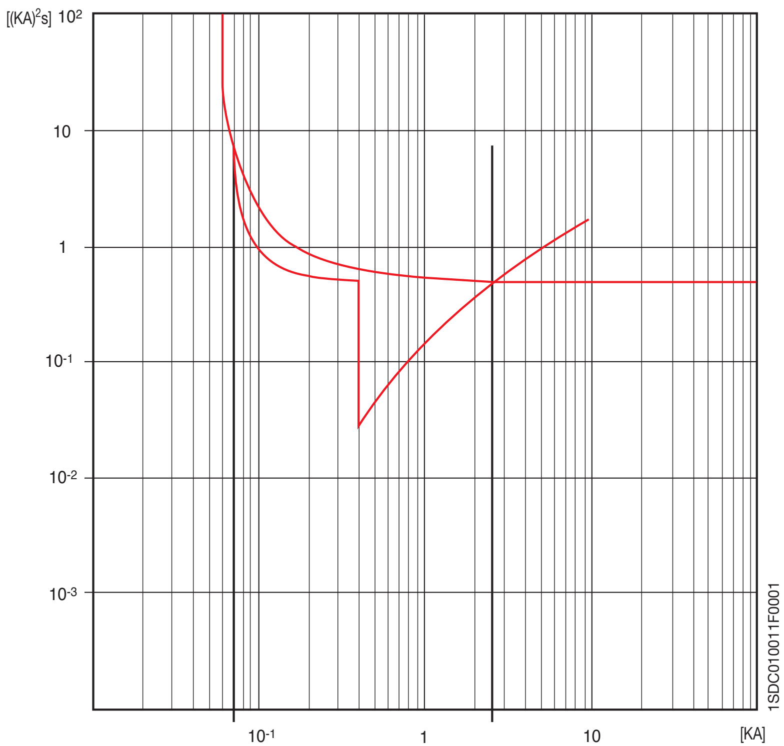
The formula (1) must be verified along the whole length of the cable. Due to the shape of the specific let-through energy curve of a circuit breaker, it is generally sufficient to verify formula (1) only for the maximum and minimum short-circuit current that may affect the cable. The maximum value is normally the value of the three-phase short-circuit current at the beginning of the line, while the minimum value is the value of the phase to neutral short-circuit current (phase to phase if the neutral conductor is not distributed) or phase to earth at the end of the cable.

2 Protection of feeders



This verification can be simplified by comparing only the let-through energy value of the circuit-breaker at the maximum short-circuit current with the withstood energy of the cable and by ensuring that the circuit breaker trips instantaneously at the minimum short-circuit current: the threshold of the short-circuit protection (taking into consideration also the tolerances) shall therefore be lower than the minimum short-circuit current at the end of the conductor.

2 Protection of feeders

Calculation of short-circuit current at end of the conductor

Minimum short-circuit current can be calculated by the following approximate formulas:

$$I_{kmin} = \frac{0.8 \cdot U_r \cdot k_{sec} \cdot k_{par}}{1.5 \cdot \rho \cdot \frac{2L}{S}}$$ with non-distributed neutral conductor (2.1)

$$I_{kmin} = \frac{0.8 \cdot U_0 \cdot k_{sec} \cdot k_{par}}{1.5 \cdot \rho \cdot (1+m) \cdot \frac{L}{S}}$$ with distributed neutral conductor (2.2)

where:

- I_{kmin} is the minimum value of the prospective short-circuit current [kA];
- U_r is the supply voltage [V];
- U_0 is the phase to earth supply voltage [V];
- ρ is the resistivity at 20 °C of the material of the conductors in $\Omega mm^2/m$ and is:
  - 0.018 for copper;
  - 0.027 for aluminium;
- L is the length of the protected conductor [m];
- S is the cross section of the conductor [mm^2];
- k_{sec} is the correction factor which takes into account the reactance of the cables with cross section larger than 95 mm^2:

S[mm^2]	120	150	185	240	300
k_{sec}	0.9	0.85	0.80	0.75	0.72

- k_{par} is the correcting coefficient for conductors in parallel:

number of parallel conductors	2	3	4	5
k_{par}*	2	2.7	3	3.2

*k_{par} = 4 (n-1)/n where: n = number of conductors in parallel per phase

- m is the ratio between the resistances of the neutral conductor and the phase conductor (if they are made of the same material m is the ratio between the cross section of the phase conductor and the cross section of the neutral conductor).

After calculating the minimum short-circuit current, verify that

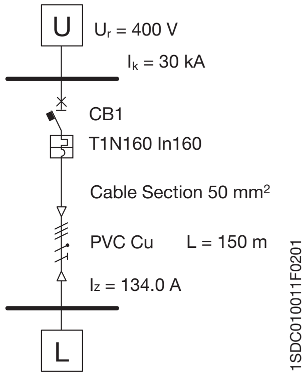
$$I_{kmin} > 1.2 \cdot I_3 \quad (3)$$

where:

- I_3 is the current that trips the magnetic protection of the circuit-breaker;
- 1.2 is the tolerance at the trip threshold.

2 Protection of feeders

Example



Choice of CB1

System data:
Rated voltage 400 V
I_k = 30 kA

Cable data:
Insulated copper conductor in PVC
Length = 150 m
S = 50 mm²
I_z = 134 A

Protection against short-circuit at the beginning of the conductor

T1N160 In160 (breaking capacity 36 kA@400 V)
I^2t (@30 kA) = $7.5\ 10^{-1}$ $(kA)^2s$ (for the curves of specific let-through energy, see Volume 1, Chapter 3.4)
$k^2S^2 = 115^2 \cdot 50^2 = 3.31 \cdot 10^1$ $(kA)^2s$
The cable is therefore protected against short-circuit at the beginning of the conductor.

Protection against short-circuit at end of the conductor

The minimum short-circuit current at end of the conductor (k_{sec}=1 and k_{par}=1) is:

$$I_{kmin} = \frac{0.8 \cdot U \cdot k_{sec} \cdot k_{par}}{1.5 \cdot \rho \cdot \dfrac{2L}{S}} = 1.98\ \text{kA}$$

The magnetic threshold of the circuit breaker T1N160 In160 is set at 1600 A. If tolerance is 20%, the circuit breaker shall definitely trip if the values exceed 1920 A; the cable is therefore fully protected against short-circuit.

Maximum protected length

The formula (3), when solved for the length, enables the maximum length protected by the protective device to be obtained for a precise instantaneous trip threshold. In Table 3, the maximum protected length can be identified for a given cross section of the cable and for the setting threshold of the instantaneous protection of the circuit breaker against short-circuit:
- three-phase system, 400 V rated voltage;
- non-distributed neutral;
- copper conductor with resistivity equal to 0.018 Ωmm²/m.

The values on the table below take into account the 20% tolerance coefficient for the magnetic trip value, the increase in cable resistivity due to heating caused by the short-circuit current and the reduction of voltage due to the fault.
The correction factors shown after the table must be applied if the system conditions are different from the reference conditions.

2 Protection of feeders

Table 3: Maximum protected length

	section [mm²]															
I_3[A]	1.5	2.5	4	6	10	16	25	35	50	70	95	120	150	185	240	300
20	370	617														
30	246	412	658													
40	185	309	494	741												
50	148	247	395	593												
60	123	206	329	494												
70	105	176	282	423	705											
80	92	154	246	370	617											
90	82	137	219	329	549											
100	74	123	197	296	494	790										
120	61	102	164	246	412	658										
140	52	88	141	211	353	564										
150	49	82	131	197	329	527										
160	46	77	123	185	309	494	772									
180	41	68	109	164	274	439	686									
200	37	61	98	148	247	395	617									
220	33	56	89	134	224	359	561	786								
250	29	49	79	118	198	316	494	691								
280	26	44	70	105	176	282	441	617								
300	24	41	65	98	165	263	412	576								
320	23	38	61	92	154	247	386	540	772							
350	21	35	56	84	141	226	353	494	705							
380	19	32	52	78	130	208	325	455	650							
400	18	30	49	74	123	198	309	432	617							
420	17	29	47	70	118	188	294	412	588							
450	16	27	43	65	110	176	274	384	549	768						
480	15	25	41	61	103	165	257	360	514	720						
500	14	24	39	59	99	158	247	346	494	691						
520	14	23	38	57	95	152	237	332	475	665						
550	13	22	35	53.	90	144	224	314	449	629						
580	12	21	34	51	85	136	213	298	426	596	809					
600	12	20	32	49	82	132	206	288	412	576	782					
620	11	19	31	47	80	127	199	279	398	558	757					
650	11	19	30	45	76	122	190	266	380	532	722					
680	10	18	29	43	73	116	182	254	363	508	690					
700	10	17	28	42	71	113	176	247	353	494	670	847				
750		16	26	39	66	105	165	230	329	461	626	790	840			
800		15	24	37	62	99	154	216	309	432	586	667	787			
850		14	23	34	58	93	145	203	290	407	552	627	741			
900		13	21	32	55	88	137	192	274	384	521	593	700			
950		13	20	31	52	83	130	182	260	364	494	561	663			
1000		12	19	29	49	79	123	173	247	346	469	533	630	731		
1250			15	23	40	63	99	138	198	277	375	427	504	585	711	
1500			13	19	33	53	82	115	165	230	313	356	420	487	593	
1600			12	18	31	49	77	108	154	216	293	333	394	457	556	667
2000				14	25	40	62	86	123	173	235	267	315	365	444	533
2500				11	20	32	49	69	99	138	188	213	252	292	356	427
3000					16	26	41	58	82	115	156	178	210	244	296	356
3200					15	25	39	54	77	108	147	167	197	228	278	333
4000					12	20	31	43	62	86	117	133	157	183	222	267
5000					10	16	25	35	49	69	94	107	126	146	178	213
6300						13	20	27	39	55	74	85	100	116	141	169
8000						10	15	22	31	43	59	67	79	91	111	133
9600							13	18	26	36	49	56	66	76	93	111
10000							12	17	25	35	47	53	63	73	89	107
12000							10	14	21	29	39	44	52	61	74	89
15000								12	16	23	31	36	42	49	59	71
20000									12	17	23	27	31	37	44	53
24000									10	14	20	22	26	30	37	44
30000										12	16	20	25	30	40	49

2 Protection of feeders

Correction factor for voltage other than 400 V: k_v

Multiply the length value obtained from the table by the correction factor k_V:

U_r [V] (three-phase value)	k_V
230(*)	0.58
400	1
440	1.1
500	1.25
690	1.73

(*) 230 V single-phase is the equivalent of a three-phase 400 V system with distributed neutral and with the cross section of the phase conductor the same as the cross section area of the neutral conductor, so that k_v is 0.58.

Correction factor for distributed neutral: k_d

Multiply the length value obtained from the table by the correction factor k_d:

$$k_d = \frac{2}{\sqrt{3}} \cdot \frac{1}{1+\frac{S}{S_N}}$$

where
- *S* is the phase cross section [mm^2];
- S_N is the neutral cross section [mm^2].

In particular:

$$\text{if } S = S_N \longrightarrow k_d \text{ is } 0.58;$$
$$\text{if } S = 2 \cdot S_N \longrightarrow k_d \text{ is } 0.39.$$

Correction factor for aluminium conductors: k_r

If the cable is in aluminium, multiply the length value obtained from the table above by the correction factor k_r = 0.67.

2.4 Protection against short-circuit

2 Protection of feeders

To summarize:

On the table, for the cross section and magnetic trip threshold it is possible to read a maximum protected value L_0. This length shall then be multiplied, if necessary, by the correction factors in order to obtain a value that is compatible with the installation operating conditions:

$$L = L_0 k_v k_d k_r$$

Example 1

Neutral not distributed
Rated voltage = 400 V
Protective device: T2N160 TMD In100
Magnetic threshold: I_3 = 1000 A
Phase cross section = Neutral cross section = 70 mm^2
The table shows that at I_3 = 1000 A, the 70 mm^2 cable is protected up to 346 m.

Example 2

Neutral distributed
Rated voltage = 400 V
Protective device: T3S250 TMD In200
Magnetic threshold: I_3 = 2000 A
Phase cross section = 300 mm^2
Neutral cross section = 150 mm^2
For I_3 = 2000 A and S = 300 mm^2, a protected length equivalent of L_0= 533 m is obtained.

By applying the correction factor k_d required when the neutral is distributed:

$$k_d = \frac{2}{\sqrt{3}} \cdot \frac{1}{1+\frac{S}{S_N}} = \frac{2}{\sqrt{3}} \cdot \frac{1}{1+\frac{300}{150}} = 0.39$$

L= $L_0 \cdot 0.39 = 533 \cdot 0.39 = 207.9$ m
This is the maximum protected length with neutral distributed.

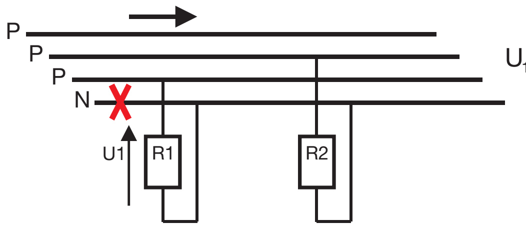
2.5 Neutral and protective conductors

Neutral conductor

The neutral conductor is a conductor that is connected to the system neutral point (which generally but not necessarily coincides with the star centre of the secondary windings of the transformer or the windings of the generator); it is able to contribute to the transmission of electric power, thereby making available a voltage that is different from the phase to phase voltage. In certain cases and under specific conditions, the functions of neutral conductor and protective conductor can be combined in a single conductor (PEN).

Protection and disconnection of the neutral conductor

If fault conditions arise, a voltage to earth may occur on the neutral conductor. This may be caused by a phase to neutral short-circuit and by the disconnection of the neutral conductor due to accidental breaking or to tripping of single-pole devices (fuses or single-pole circuit breakers).
If the neutral conductor only is disconnected in a four-conductor circuit, the supply voltage to the single-phase loads may be altered so that they are supplied by a voltage different from the U_0 phase to neutral voltage (as shown in Fig. 1). Therefore, all the necessary measures to prevent this type of fault shall be taken, e.g. by not protecting the neutral conductor with single-pole devices.



$$U_1 = \frac{\sqrt{3} \cdot U_0 \cdot R_1}{R_1 + R_2}$$

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Figure 1: Disconnection of the neutral conductor

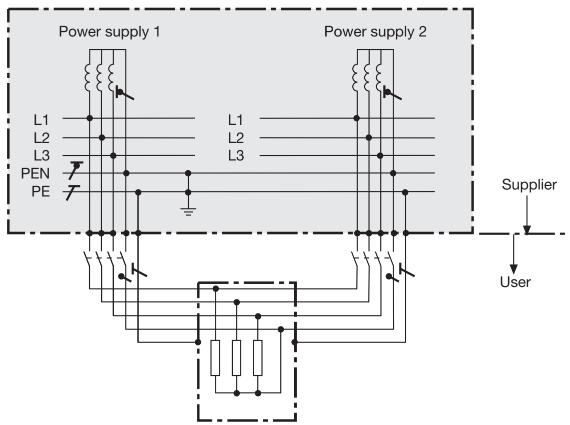
Moreover, in TN-C systems, voltage to earth arising on the neutral conductor constitutes a hazard for people; in fact, since this conductor is also a protective conductor, this voltage reaches the connected exposed conductive parts. For TN-C systems, the Standards specify minimum cross sections (see next clause) for the neutral conductor in order to prevent accidental breaking and they forbid the use of any device (single-pole or multi-pole) that could disconnect the PEN.
The need for protection on the neutral conductor and the possibility of disconnecting the circuit depend on the distribution system:

TT or TN systems:
- if the cross section of the neutral conductor is the same or larger than the cross section of the phase conductor, there is neither the need to detect overcurrents on the neutral conductor nor to use a breaking device (neutral conductor is not protected or disconnected); this requirement applies only if there are no harmonics that may, at any instant, cause r.m.s. current values on the neutral conductor higher than the maximum current detected on the phase conductors;
- if the cross section of the neutral conductor is less than the cross section of the phase conductor, overcurrents on the neutral conductor must be detected so as to have the phase conductors, but not necessarily the neutral conductor, disconnected (neutral conductor protected but not disconnected): in this case the overcurrents on the neutral conductor do not need to be detected if the following conditions are simultaneously fulfilled:
  1. the neutral conductor is protected against short-circuit by the protective device of the phase conductors;
  2. the maximum current that can flow through the neutral conductor during normal service is lower than the neutral current carrying capacity.

In TN-S systems, the neutral need not be disconnected if the supply conditions are such that the neutral conductor can be considered to be reliable at earth potential.
As already mentioned, in TN-C systems, the neutral conductor is also a protective conductor and cannot therefore be disconnected. Furthermore, if the neutral conductor is disconnected, the exposed conductive parts of the single-phase equipment could take the system rated voltage to earth.
In certain specific cases, the neutral conductor has to be disconnected to prevent currents circulating between parallel supply sources (see Figures 2 and 3).

Figure 2: Three-phase alternative power supply with a 4-pole switch

NOTE - This method prevents electromagnetic fields due to stray currents in the main supply system of an installation. The sum of the currents within one cable must be zero. This ensures that the neutral current will flow only in the neutral conductor of the respective switched on circuit. The 3rd harmonic (150 Hz) current of the line conductors will be added with the same phase angle to the neutral conductor current.



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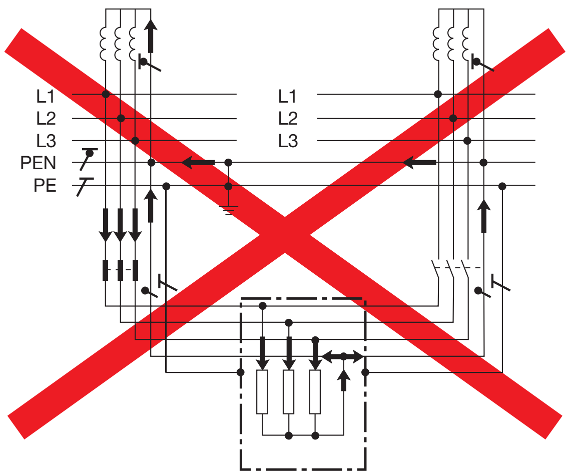
2 Protection of feeders

Figure 3: Three-phase alternative power supply with non-suitable 3-pole switch



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NOTE – A three-phase alternative power supply with a non-suitable 3-pole switch, due to unintentional circular stray currents generating electromagnetic fields.

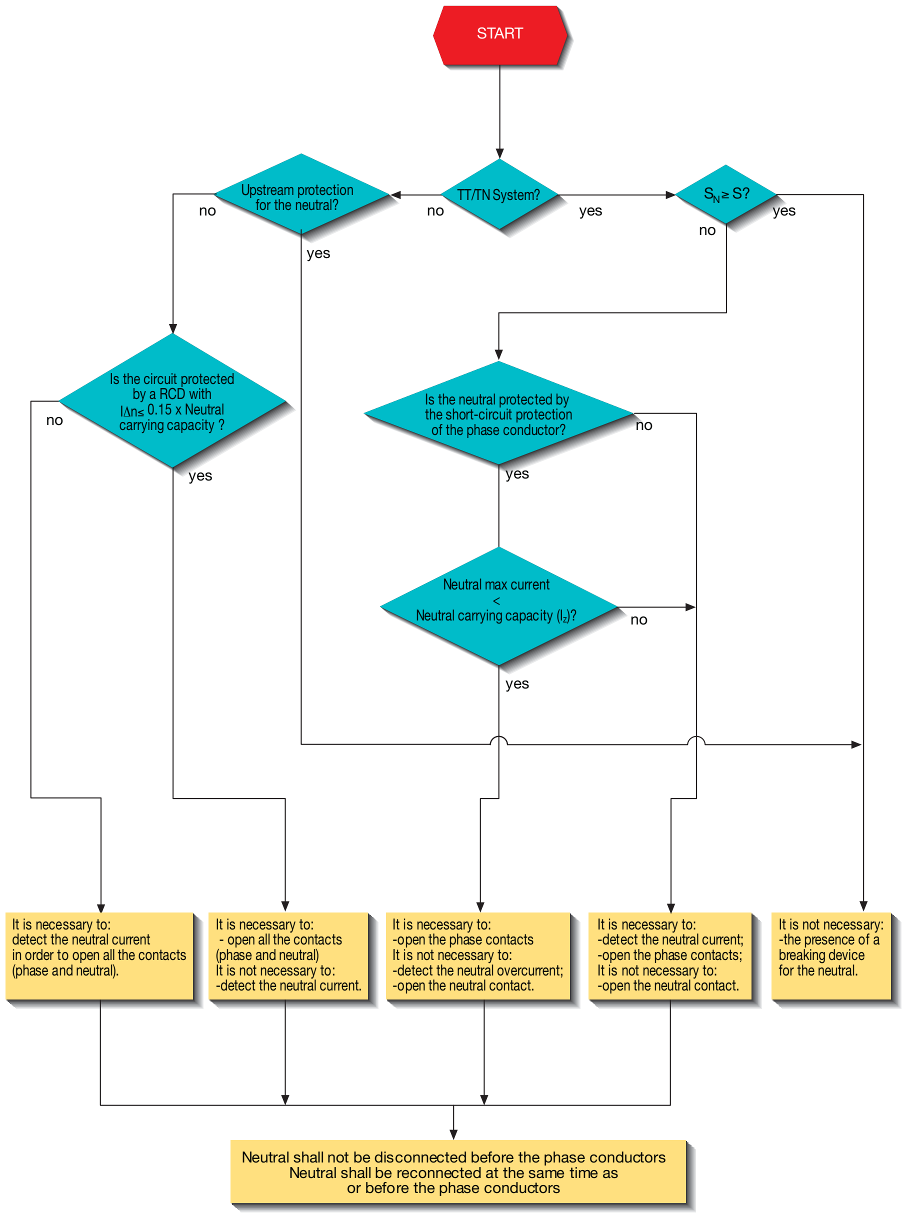
IT system:
The Standard advises against distributing the neutral conductor in IT systems. If the neutral conductor is distributed, the overcurrents must be detected on the neutral conductor of each circuit in order to disconnect all the live conductors on the corresponding circuit, including the neutral one (neutral conductor protected and disconnected).
Overcurrents do not need to be detected on the neutral conductor in any of the following cases:

- the neutral conductor is protected against short-circuit by a protective device fitted upstream;
- the circuit is protected by a residual current device with rated residual current lower than 0.15 times the current carrying capacity of the corresponding neutral conductor. This device must disconnect all the live conductors, the neutral conductor included.

For all distribution systems, whenever necessary, connection and disconnection of the neutral conductor, shall ensure that:

- the neutral conductor is not disconnected before the phase conductor;
- the neutral conductor is connected at the same moment or before the phase conductor.

2 Protection of feeders



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2 Protection of feeders

Determination of the minimum cross section of the neutral conductor

The neutral conductor, if any, shall have the same cross section as the line conductor:
- in single-phase, two-wire circuits whatever the section;
- in polyphase and single-phase three-wire circuits, when the size of the line conductors is less than or equal to 16 mm^2 in copper, or 25 mm^2 in aluminium.[1]

The cross section of the neutral conductor can be less than the cross section of the phase conductor when the cross section of the phase conductor is greater than 16 mm^2 with a copper cable, or 25 mm^2 with an aluminium cable, if both the following conditions are met:
- the cross section of the neutral conductor is at least 16 mm^2 for copper conductors and 25 mm^2 for aluminium conductors;
- there is no high harmonic distortion of the load current. If there is high harmonic distortion (the harmonic content is greater than 10%), as for example in equipment with discharge lamps, the cross section of the neutral conductor cannot be less than the cross section of the phase conductors.

Table 1: Minimum cross sections of the neutral conductor

	Phase cross section S [mm^2]	Min. neutral cross section S_N [mm^2]
Single-phase/two-phase circuits		
Cu/Al	Any	S*
Three-phase circuits	S ≤ 16	S*
Cu	S > 16	16
Three-phase circuits	S ≤ 25	S*
Al	S > 25	25

*for TN-C systems, the Standards specify a minimum cross section of 10 mm^2 for copper and 16 mm^2 for aluminium conductors

[1] The cross section of phase conductors shall be dimensioned in compliance with the instructions of the Chapter 2.2.1 "Current carrying capacity and methods of installation"

2 Protection of feeders

Protective conductor

Determination of the minimum cross sections

The minimum cross section of the protective conductor can be determined by using the following table:

Table 2: Cross section of the protective conductor

Cross section of line conductor S [mm^2]	Minimum cross section of the corresponding protective conductor [mm^2]	
	If the protective conductor is of the same material as the line conductor	If the protective conductor is not of the same material as the line conductor
S ≤ 16	S	$\frac{k_1}{k_2} \cdot S$
16 < S ≤ 35	16*	$\frac{k_1}{k_2} \cdot 16$
S > 35	$\frac{S}{2}$*	$\frac{k_1}{k_2} \cdot \frac{S}{2}$

Where

k_1 is the value of k for the line conductor, selected from Table 1 Chapter 2.4 according to the materials of the conductor and insulation;

k_2 is the value of k for the protective conductor.

* For a PEN conductor, the reduction of the cross section is permitted only in accordance with the rules for sizing of the neutral conductor.

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For a more accurate calculation and if the protective conductor is subjected to adiabatic heating from an initial known temperature to a final specified temperature (applicable for fault extinction time no longer than 5s), the minimum cross section of the protective conductor S_{PE} can be obtained by using the following formula:

$$S_{PE} = \frac{\sqrt{I^2 t}}{k} \quad (1)$$

where:
- S_{PE} is the cross section of the protective conductor [mm^2];
- I is the r.m.s. current flowing through the protective conductor in the event of a fault with low impedance [A];
- t is the trip time of the protective device [s];

2 Protection of feeders

• k is a constant which depends on the material of the protective conductor, on the type of insulation and on initial and final temperature. The most common values can be taken from Tables 3 and 4.

Table 3: Values of *k* for insulated protective conductors not incorporated in cables and not bunched with other cables

Conductor insulation	Temperature °C [b]		Material of conductor		
			Copper	Aluminium	Steel
	Initial	Final	Values for k		
70 °C PVC	30	160/140 [a]	143/133 [a]	95/88 [a]	52/49 [a]
90 °C PVC	30	143/133 [a]	143/133 [a]	95/88 [a]	52/49 [a]
90 °C thermosetting	30	250	176	116	64
60 °C rubber	30	200	159	105	58
85 °C rubber	30	220	168	110	60
Silicon rubber	30	350	201	133	73

[a] The lower value applies to PVC insulated conductors of cross section greater than 300 mm^2.
[b] Temperature limits for various types of insulation are given in IEC 60724.

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Table 4: Values of *k* for protective conductors as a core incorporated in a cable or bunched with other cables or insulated conductors

Conductor insulation	Temperature °C [b]		Material of conductor		
			Copper	Aluminium	Steel
	Initial	Final	Values for k		
70 °C PVC	70	160/140 [a]	115/103 [a]	76/68 [a]	42/37 [a]
90 °C PVC	90	160/140 [a]	100/86 [a]	66/57 [a]	36/31 [a]
90 °C thermosetting	90	250	143	94	52
60 °C rubber	60	200	141	93	51
85 °C rubber	85	220	134	89	48
Silicon rubber	180	350	132	87	47

[a] The lower value applies to PVC insulated conductors of cross section greater than 300 mm^2.
[b] Temperature limits for various types of insulation are given in IEC 60724.

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2 Protection of feeders

Further values of k can be taken from the Tables in Annex D, which provides the formula for accurate calculation of the value of k.

If Table 2 or formula (1) do not provide a standardized cross section, a larger standardized cross section shall be chosen.

Regardless of whether Table 2 or formula (1) are used, the cross section of the protective conductor, which is not part of the supply cable, shall be at least:

- 2.5 mm^2 Cu/16 mm^2 Al, if a mechanical protection is provided;
- 4 mm^2 Cu/16 mm^2 Al, if no mechanical protection is provided.

For current using equipment intended for permanent connection and with a protective conductor current exceeding 10 mA, reinforced protective conductors shall be designed as follows:
• either the protective conductor shall have a cross-sectional area of at least 10 mm^2 Cu or 16 mm^2 Al, through its total run;
• or a second protective conductor of at least the same cross-sectional area as required for protection against indirect contact shall be laid up to a point where the protective conductor has a cross-sectional area not less than 10 mm^2 Cu or 16 mm^2 Al. This requires that the appliance has a separate terminal for a second protective conductor.

When overcurrent protective devices are used for protection against electric shock, the protective conductor shall be incorporated in the same wiring system as the live conductors or be located in their immediate proximity.

2 Protection of feeders

2.6 Busbar trunking systems (BTSs)

In electrical installations for industrial environments, busbar trunking systems (BTSs) optimize the power distribution despite the inevitable modifications that are carried out (additions, displacements, replacement of loads) and to facilitate maintenance work and safety verifications.
They are mainly used for:
- supplying sources of light, safety and low power distribution;
- lighting lines (medium power);
- power supply and distribution (medium and large power);
- supplying moving equipment (bridge cranes).

Busbar trunking systems are subject to the following Standards:
- IEC 60439 – 1 *"Low-voltage switchgear and controlgear assemblies – Part 1: Type-tested and partially type-tested assemblies"*
- IEC 60439 – 2 *"Low-voltage switchgear and controlgear assemblies – Part 2: Particular requirements for busbar trunking systems (busways)"*.

BTSs consist of:

- *conductors/busbars;*
- *coupling:* electrical and mechanical connecting elements for different elements;
- *straight elements:* base elements of the line for carrying energy from the source to the loads;
- *routing elements:* flexible joints for the creation of curves or overcoming obstacles, horizontal and vertical angles, tee joints and cross elements to create any type of route;
- *pull boxes:* elements that enable lamps or operating machines to be supplied directly with integrated protection (fuses or circuit breakers);
- *suspensions/accessories*: hanging and fixing elements for BTS and for any support required for special loads (lighting components, etc).

Dimensioning of a BTS

To dimension a BTS, the load current must be determined using the following data:

Power supply

- General type of load supply:
  - single-phase
  - three-phase.
- Type of BTS supply:
  - from one end;
  - from both ends;
  - central power supply.
- Rated voltage
- Short-circuit current at the supply point
- Ambient temperature.

Loads

- Number, distribution, power and cosφ and type of loads supplied by the same BTS

2 Protection of feeders

BTS geometry

- Type of installation:
  - flat;
  - edge-on;
  - vertical.
- Length.

NOTE: BTSs shall be placed at a distance from the walls and the ceilings in such a way as to enable visual inspection of connections during assembly and to facilitate insertion of the branch units.
If possible, it is preferable to install the BTS edge-on so as to improve mechanical resistance and reduce any possible deposit of powder and polluting substances that might affect the level of internal insulation.

Load current calculation for three-phase system

Load current I_b for a three-phase system is calculated by the following formula:

$$I_b = \frac{P_t \cdot b}{\sqrt{3} \cdot U_r \cdot \cos\varphi_m} \ [A] \qquad (1)$$

where:
- P_t is the sum of the active power of all the installed loads [W];
- b is the supply factor, which is:
  - 1 if the BTS is supplied from one side only;
  - 1/2 if the BTS is supplied from the centre or from both ends simultaneously;
- U_r is the operating voltage [V];
- $\cos\varphi_m$ is the average power factor of the loads.

Choice of BTS current carrying capacity

A BTS shall be chosen so that its current carrying capacity I_z complies with the following formula:

$$I_b \leq I_{Z0} \cdot k_t = I_Z \qquad (2)$$

where:
- I_{Z0} is the current that the BTS can carry for an indefinite time at the reference temperature (40 °C);
- I_b is the load current;
- k_t is the correction factor for ambient temperature values other than the reference ambient temperature shown on Table 1.

Table 1: Correction factor k_t for ambient temperature other than 40 °C

Ambient Temperature [°C]	15	20	25	30	35	40	45	50
k_t	1.2	1.17	1.12	1.08	1.05	1	0.95	0.85

2 Protection of feeders

Note: the following tables show typical parameters of the BTS present on the market

Table 2: Current carrying capacity I_{Z0} of copper BTS

Size	Generic type	Number of conductors	I_{Z0} [A]	r_{ph}* [mΩ/m]	x_{ph} [mΩ/m]	U_r [V]
25	25A 4 cond. Cu	4	25	6.964	1.144	400
25	25A 4 cond. Cu	4	25	6.876	1.400	400
25	25A 4+4 cond. Cu	4+4	25	6.876	1.400	400
40	40A 4 cond. Cu	4	40	3.556	0.792	400
40	40A 4 cond. Cu	4	40	3.516	1.580	400
40	40A 4+4 cond. Cu	4+4	40	3.516	1.580	400
40	40A 4 cond. Cu	4	40	2.173	0.290	400
63	63A 4 cond. Cu	4	63	1.648	0.637	400
100	100A 4 cond. Cu	4	100	0.790	0.366	400
160	160A 4 cond. Cu	4	160	0.574	0.247	400
160	160A 4 cond. Cu	4	160	0.335	0.314	500
160	160A 5 cond. Cu	5	160	0.335	0.314	500
250	250A 4 cond. Cu	4	250	0.285	0.205	1000
250	250A 5 cond. Cu	5	250	0.285	0.205	1000
250	250A 4 cond. Cu	4	250	0.194	0.205	500
250	250A 5 cond. Cu	5	250	0.194	0.205	500
315	315A 4 cond. Cu	4	315	0.216	0.188	1000
315	315A 5 cond. Cu	5	315	0.216	0.188	1000
350	350A 4 cond. Cu	4	350	0.142	0.188	500
350	350A 5 cond. Cu	5	350	0.142	0.188	500
400	400A 4 cond. Cu	4	400	0.115	0.129	1000
400	400A 5 cond. Cu	5	400	0.115	0.129	1000
500	500A 4 cond. Cu	4	500	0.092	0.129	500
500	500A 5 cond. Cu	5	500	0.092	0.129	500
630	630A 4 cond. Cu	4	630	0.073	0.122	1000
630	630A 5 cond. Cu	5	630	0.073	0.122	1000
700	700A 4 cond. Cu	4	700	0.077	0.122	500
700	700A 5 cond. Cu	5	700	0.077	0.122	500
700	700A 5 cond. Cu	5	700	0.077	0.122	500
700	700A 4 cond. Cu	4	700	0.077	0.122	500

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Size	Generic type	Number of conductors	I_{Z0} [A]	r_{ph}* [mΩ/m]	x_{ph} [mΩ/m]	U_r [V]
800	800A 4 cond. Cu	4	800	0.047	0.122	1000
800	800A 5 cond. Cu	5	800	0.047	0.122	1000
800	800A 4 cond. Cu	4	800	0.038	0.027	1000
800	800A 4 cond. Cu	4	800	0.072	0.122	500
800	800A 5 cond. Cu	5	800	0.072	0.122	500
1000	1000A 4 cond. Cu	4	1000	0.038	0.120	1000
1000	1000A 5 cond. Cu	5	1000	0.038	0.120	1000
1000	1000A 4 cond. Cu	4	1000	0.037	0.026	1000
1000	1000A 4 cond. Cu	4	1000	0.038	0.097	1000
1000	1000A 4 cond. Cu	4	1000	0.068	0.120	500
1000	1000A 5 cond. Cu	5	1000	0.068	0.120	500
1200	1200A 4 cond. Cu	4	1200	0.035	0.021	1000
1250	1250A 4 cond. Cu	4	1250	0.034	0.023	1000
1250	1250A 4 cond. Cu	4	1250	0.035	0.076	1000
1500	1500A 4 cond. Cu	4	1500	0.030	0.022	1000
1600	1600A 4 cond. Cu	4	1600	0.025	0.018	1000
1600	1600A 4 cond. Cu	4	1600	0.034	0.074	1000
2000	2000A 4 cond. Cu	4	2000	0.020	0.015	1000
2000	2000A 4 cond. Cu	4	2000	0.025	0.074	1000
2400	2400A 4 cond. Cu	4	2400	0.019	0.012	1000
2500	2500A 4 cond. Cu	4	2500	0.016	0.011	1000
2500	2500A 4 cond. Cu	4	2500	0.019	0.040	1000
3000	3000A 4 cond. Cu	4	3000	0.014	0.011	1000
3000	3000A 4 cond. Cu	4	3000	0.017	0.031	1000
3200	3200A 4 cond. Cu	4	3200	0.013	0.009	1000
3200	3200A 4 cond. Cu	4	3200	0.015	0.031	1000
4000	4000A 4 cond. Cu	4	4000	0.011	0.007	1000
4000	4000A 4 cond. Cu	4	4000	0.011	0.026	1000
5000	5000A 4 cond. Cu	4	5000	0.008	0.005	1000
5000	5000A 4 cond. Cu	4	5000	0.008	0.023	1000

*phase resistance at I_{z0}

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Table 3: Current carrying capacity I_{Z0} of aluminium BTS

Size	Generic type	Number of conductors	I_{Z0} [A]	r_{ph}* [mΩ/m]	x_{ph} [mΩ/m]	U_r [V]
160	160A 4 cond. Al	4	160	0.591	0.260	1000
160	160A 5 cond. Al	5	160	0.591	0.260	1000
160	160A 4 cond. Al	4	160	0.431	0.260	500
160	160A 5 cond. Al	5	160	0.431	0.260	500
250	250A 4 cond. Al	4	250	0.394	0.202	1000
250	250A 5 cond. Al	5	250	0.394	0.202	1000
250	250A 4 cond. Al	4	250	0.226	0.202	500
250	250A 5 cond. Al	5	250	0.226	0.202	500
315	315A 4 cond. Al	4	315	0.236	0.186	1000
315	315A 5 cond. Al	5	315	0.236	0.186	1000
315	315A 4 cond. Al	4	315	0.181	0.186	500
315	315A 5 cond. Al	5	315	0.181	0.186	500
400	400A 4 cond. Al	4	400	0.144	0.130	1000
400	400A 5 cond. Al	5	400	0.144	0.130	1000
400	400A 4 cond. Al	4	400	0.125	0.130	500
400	400A 5 cond. Al	5	400	0.125	0.130	500
500	500A 4 cond. Al	4	500	0.102	0.127	500
500	500A 5 cond. Al	5	500	0.102	0.127	500
630	630A 4 cond. Al	4	630	0.072	0.097	1000
630	630A 5 cond. Al	5	630	0.072	0.097	1000
630	630A 4 cond. Al	4	630	0.072	0.029	1000
630	630A 4 cond. Al	4	630	0.073	0.097	500
630	630A 5 cond. Al	5	630	0.073	0.097	500
800	800A 4 cond. Al	4	800	0.062	0.096	1000

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Size	Generic type	Number of conductors	I_{Z0} [A]	r_{ph}* [mΩ/m]	x_{ph} [mΩ/m]	U_r [V]
800	800A 5 cond. Al	5	800	0.062	0.096	1000
800	800A 4 cond. Al	4	800	0.067	0.027	1000
800	800A 4 cond. Al	4	800	0.071	0.096	500
800	800A 5 cond. Al	5	800	0.071	0.096	500
1000	1000A 4 cond. Al	4	1000	0.062	0.023	1000
1000	1000A 4 cond. Al	4	1000	0.068	0.087	1000
1200	1200A 4 cond. Al	4	1200	0.054	0.023	1000
1250	1250A 4 cond. Al	4	1250	0.044	0.021	1000
1250	1250A 4 cond. Al	4	1250	0.044	0.066	1000
1500	1500A 4 cond. Al	4	1500	0.041	0.023	1000
1600	1600A 4 cond. Al	4	1600	0.035	0.017	1000
1600	1600A 4 cond. Al	4	1600	0.041	0.066	1000
2000	2000A 4 cond. Al	4	2000	0.029	0.016	1000
2000	2000A 4 cond. Al	4	2000	0.034	0.053	1000
2250	2250A 4 cond. Al	4	2250	0.032	0.049	1000
2400	2400A 4 cond. Al	4	2400	0.028	0.012	1000
2500	2500A 4 cond. Al	4	2500	0.022	0.011	1000
2500	2500A 4 cond. Al	4	2500	0.022	0.034	1000
3000	3000A 4 cond. Al	4	3000	0.020	0.011	1000
3200	3200A 4 cond. Al	4	3200	0.017	0.009	1000
3200	3200A 4 cond. Al	4	3200	0.020	0.034	1000
4000	4000A 4 cond. Al	4	4000	0.014	0.008	1000
4000	4000A 4 cond. Al	4	4000	0.017	0.024	1000
4500	4500A 4 cond. Al	4	4500	0.014	0.024	1000

*phase resistance at I_{Z0}

2 Protection of feeders

BTS protection

Protection against overload

BTSs are protected against overload by using the same criterion as that used for the cables. The following formula shall be verified:

$$I_b \leq I_n \leq I_z \qquad (3)$$

where:
- I_b is the current for which the circuit is designed;
- I_n is the rated current of the protective device; for adjustable protective devices, the rated current I_n is the set current;
- I_z is the continuous current carrying capacity of the BTS.

NOTE - The protection against short-circuit does not need to be checked if MCBs up to 63 A are used whenever correctly dimensioned for overload protection. In such cases, in fact, protection against both thermal and electrodynamic effects is certainly adequate because of the energy and peak limitations offered by these protective devices.

Protection against short-circuit

The BTS must be protected against thermal overload and electrodynamic effects due to the short-circuit current.

Protection against thermal overload
The following formula shall be fulfilled:

$$I^2t_{CB} \leq I^2t_{BTS} \quad (4)$$

where:
- I^2t_{CB} is the specific let-through energy of the circuit-breaker at the maximum short-circuit current value at the installation point. This can be extrapolated from the curves shown in Volume 1 Chapter 3.4;
- I^2t_{BTS} is the withstood energy of the BTS and it is normally given by the manufacturer (see Tables 4 and 5).

Protection against electrodynamic effects
The following formula shall be fulfilled:

$$I_{kp\ CB} \leq I_{kp\ BTS} \quad (5)$$

where:
- $I_{kp\ CB}$ is the peak limited by the circuit-breaker at the maximum short-circuit current value at the installation point. This can be extrapolated from the limitation curves shown in Volume 1, Chapter 3.3;
- $I_{kp\ BTS}$ is the maximum peak current value of the BTS (see Tables 4 and 5).

2 Protection of feeders

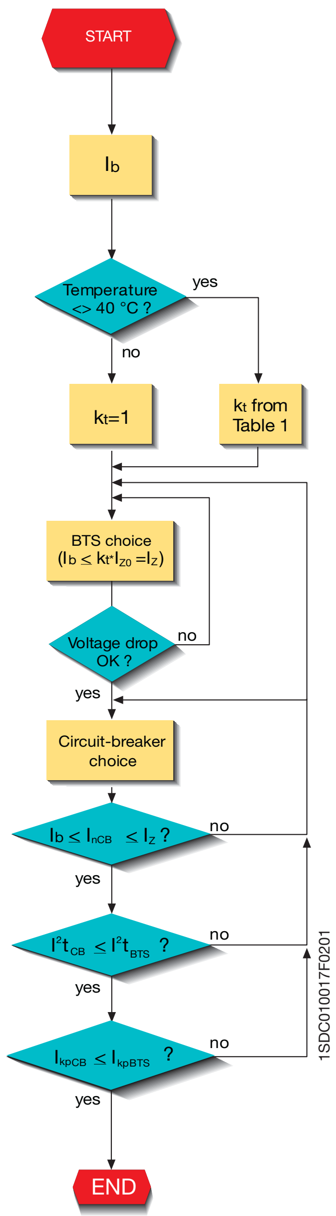

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Table 4: Values of the withstood energy and peak current of copper BTS

Size	Generic type	I^2t_{ph} [(kA)^{2}s]	I^2t_N [(kA)^{2}s]	I^2t_{PE} [(kA)^{2}s]	I_{peakph} [kA]	I_{peakN} [kA]
25	25A 4 cond. Cu	0.48	0.48	0.48	10	10
25	25A 4 cond. Cu	0.64	0.64	0.64	10	10
25	25A 4+4 cond. Cu	0.64	0.64	0.64	10	10
40	40A 4 cond. Cu	0.73	0.73	0.73	10	10
40	40A 4 cond. Cu	1	1	1	10	10
40	40A 4+4 cond. Cu	1	1	1	10	10
40	40A 4 cond. Cu	7.29	7.29	7.29	10	10
63	63A 4 cond. Cu	7.29	7.29	7.29	10	10
100	100A 4 cond. Cu	20.25	20.25	20.25	10	10
160	160A 4 cond. Cu	30.25	30.25	30.25	10	10
160	160A 4 cond. Cu	100	60	60	17	10.2
160	160A 5 cond. Cu	100	100	100	17	10.2
160	160A 4 cond. Cu	100	100	100	17	10.2
250	250A 4 cond. Cu	312.5	187.5	187.5	52.5	31.5
250	250A 5 cond. Cu	312.5	312.5	312.5	52.5	31.5
250	250A 4 cond. Cu	169	101.4	101.4	26	15.6
250	250A 5 cond. Cu	169	169	169	26	15.6
250	250A 4 cond. Cu	169	169	169	26	15.6
315	315A 4 cond. Cu	312.5	187.5	187.5	52.5	31.5
315	315A 5 cond. Cu	312.5	312.5	312.5	52.5	31.5
350	350A 4 cond. Cu	169	101.4	101.4	26	15.6
350	350A 5 cond. Cu	169	169	169	26	15.6
350	350A 4 cond. Cu	169	169	169	26	15.6
400	400A 4 cond. Cu	900	540	540	63	37.8
400	400A 5 cond. Cu	900	900	900	63	37.8
500	500A 4 cond. Cu	756.25	453.75	453.75	58	34.8
500	500A 5 cond. Cu	756.25	756.25	756.25	58	34.8
500	500A 4 cond. Cu	756.25	756.25	756.25	58	34.8
630	630A 4 cond. Cu	1296	777.6	777.6	75.6	45.4
630	630A 5 cond. Cu	1296	1296	1296	75.6	45.4
700	700A 4 cond. Cu	756.25	453.75	453.75	58	34.8
700	700A 5 cond. Cu	756.25	756.25	756.25	58	34.8
700	700A 4 cond. Cu	756.25	756.25	756.25	58	34.8

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Size	Generic type	I^2t_{ph} [(kA)^{2}s]	I^2t_N [(kA)^{2}s]	I^2t_{PE} [(kA)^{2}s]	I_{peakph} [kA]	I_{peakN} [kA]
800	800A 4 cond. Cu	1296	777.6	777.6	75.6	45.4
800	800A 5 cond. Cu	1296	1296	1296	75.6	45.4
800	800A 4 cond. Cu	3969	3969	2381.4	139	83.4
800	800A 4 cond. Cu	756.25	453.75	453.75	58	34.8
800	800A 5 cond. Cu	756.25	756.25	756.25	58	34.8
800	800A 4 cond. Cu	756.25	756.25	756.25	58	34.8
1000	1000A 4 cond. Cu	1296	777.6	777.6	75.6	45.4
1000	1000A 5 cond. Cu	1296	1296	1296	75.6	45.4
1000	1000A 4 cond. Cu	3969	3969	2381.4	139	83.4
1000	1000A 4 cond. Cu	1600	1600	960	84	50.4
1000	1000A 4 cond. Cu	1024	614.4	614.4	60	36
1000	1000A 5 cond. Cu	1024	1024	1024	60	36
1000	1000A 4 cond. Cu	1024	1024	1024	60	36
1200	1200A 4 cond. Cu	7744	7744	4646.4	194	116.4
1250	1250A 4 cond. Cu	7744	7744	4646.4	194	116.4
1250	1250A 4 cond. Cu	2500	2500	1500	105	63
1500	1500A 4 cond. Cu	7744	7744	4646.4	194	116.4
1600	1600A 4 cond. Cu	7744	7744	4646.4	194	116.4
1600	1600A 4 cond. Cu	2500	2500	1500	105	63
2000	2000A 4 cond. Cu	7744	7744	4646.4	194	116.4
2000	2000A 4 cond. Cu	3600	3600	2160	132	79.2
2400	2400A 4 cond. Cu	7744	7744	4646.4	194	116.4
2500	2500A 4 cond. Cu	7744	7744	4646.4	194	116.4
2500	2500A 4 cond. Cu	4900	4900	2940	154	92.4
3000	3000A 4 cond. Cu	30976	30976	18585.6	387	232.2
3000	3000A 4 cond. Cu	8100	8100	4860	198	118.8
3200	3200A 4 cond. Cu	30976	30976	18585.6	387	232.2
3200	3200A 4 cond. Cu	8100	8100	4860	198	118.8
4000	4000A 4 cond. Cu	30976	30976	18585.6	387	232.2
4000	4000A 4 cond. Cu	8100	8100	4860	198	118.8
5000	5000A 4 cond. Cu	30976	30976	18585.6	387	232.2
5000	5000A 4 cond. Cu	10000	10000	6000	220	132

2 Protection of feeders

Table 5: Values of the withstood energy and peak current of aluminium BTS

Size	Generic type	I^2t_{ph} [(kA)²s]	I^2t_N [(kA)²s]	I^2t_{PE} [(kA)²s]	I_{peakph} [kA]	I_{peakN} [kA]
160	160A 4 cond. Al	112.5	67.5	67.5	30	18
160	160A 5 cond. Al	112.5	112.5	112.5	30	18
160	160A 4 cond. Al	100	60	60	17	10.2
160	160A 5 cond. Al	100	100	100	17	10.2
160	160A 4 cond. Al	100	100	100	17	10.2
250	250A 4 cond. Al	312.5	187.5	187.5	52.5	31.5
250	250A 5 cond. Al	312.5	312.5	312.5	52.5	31.5
250	250A 4 cond. Al	169	101.4	101.4	26	15.6
250	250A 5 cond. Al	169	169	169	26	15.6
250	250A 4 cond. Al	169	169	169	26	15.6
315	315A 4 cond. Al	625	375	375	52.5	31.5
315	315A 5 cond. Al	625	625	625	52.5	31.5
315	315A 4 cond. Al	169	101.4	101.4	26	15.6
315	315A 5 cond. Al	169	169	169	26	15.6
315	315A 4 cond. Al	169	169	169	26	15.6
400	400A 4 cond. Al	900	540	540	63	37.8
400	400A 5 cond. Al	900	900	900	63	37.8
400	400A 4 cond. Al	625	375	375	52.5	31.5
400	400A 5 cond. Al	625	625	625	52.5	31.5
400	400A 4 cond. Al	625	625	625	52.5	31.5
500	500A 4 cond. Al	625	375	375	52.5	31.5
500	500A 5 cond. Al	625	625	625	52.5	31.5
500	500A 4 cond. Al	625	625	625	52.5	31.5
630	630A 4 cond. Al	1296	777.6	777.6	75.6	45.4
630	630A 5 cond. Al	1296	1296	1296	75.6	45.4
630	630A 4 cond. Al	1444	1444	866.4	80	48
630	630A 4 cond. Al	1024	614.4	614.4	67.5	40.5
630	630A 5 cond. Al	1024	1024	1024	67.5	40.5

2 Protection of feeders

Size	Generic type	I^2t_{ph} [(kA)²s]	I^2t_N [(kA)²s]	I^2t_{PE} [(kA)²s]	I_{peakph} [kA]	I_{peakN} [kA]
630	630A 4 cond. Al	1024	1024	1024	67.5	40.5
800	800A 4 cond. Al	1296	777.6	777.6	75.6	45.4
800	800A 5 cond. Al	1296	1296	1296	75.6	45.4
800	800A 4 cond. Al	1764	1764	1058.4	88	52.8
800	800A 4 cond. Al	1024	614.4	614.4	67.5	40.5
800	800A 5 cond. Al	1024	1024	1024	67.5	40.5
800	800A 4 cond. Al	1024	1024	1024	67.5	40.5
1000	1000A 4 cond. Al	6400	6400	3840	176	105.6
1000	1000A 4 cond. Al	1600	1600	960	84	50.4
1200	1200A 4 cond. Al	6400	6400	3840	176	105.6
1250	1250A 4 cond. Al	6400	6400	3840	176	105.6
1250	1250A 4 cond. Al	2500	2500	1500	105	63
1500	1500A 4 cond. Al	6400	6400	3840	176	105.6
1600	1600A 4 cond. Al	6400	6400	3840	176	105.6
1600	1600A 4 cond. Al	2500	2500	1500	105	63
2000	2000A 4 cond. Al	6400	6400	3840	176	105.6
2000	2000A 4 cond. Al	3600	3600	2160	132	79.2
2250	2250A 4 cond. Al	4900	4900	2940	154	92.4
2400	2400A 4 cond. Al	25600	25600	15360	352	211.2
2500	2500A 4 cond. Al	25600	25600	15360	352	211.2
2500	2500A 4 cond. Al	8100	8100	4860	198	118.8
3000	3000A 4 cond. Al	25600	25600	15360	352	211.2
3200	3200A 4 cond. Al	25600	25600	15360	352	211.2
3200	3200A 4 cond. Al	8100	8100	4860	198	118.8
4000	4000A 4 cond. Al	25600	25600	15360	352	211.2
4000	4000A 4 cond. Al	8100	8100	4860	198	118.8
4500	4500A 4 cond. Al	10000	10000	6000	220	132

2 Protection of feeders

Protection of the outgoing feeders

If the outgoing feeder, which generally consists of cable duct, is not already protected against short-circuit and overload by the device located upstream of the cable, the following measures shall be taken:

- protection against short-circuit:
there is no need to protect the feeder against the short-circuit if simultaneously:
a. the length does not exceed 3 metres;
b. the risk of short-circuit is minimized;
c. there is no inflammable material nearby.

In explosive environments and environments with greater risk of fire, protection against short-circuit is always required;

- protection against overload:
the current carrying capacity of the feeder is generally lower than that of the BTS. It is therefore necessary to protect also the feeder against overload.
The protection device against overload can be placed inside the pull box or on the incoming panel.
In the latter case, protection against overload can also be provided by the circuit-breakers protecting the single outgoing feeder from the panel only if the sum of their rated currents is lower or equal to the current carrying capacity I_z of the outgoing feeder.
In locations with greater risk of fire, the overload protection device shall be installed at the outgoing point, i.e. inside the pull box.

Voltage drop

If a BTS is particularly long, the value of the voltage drop must be verified.
For three-phase systems with a power factor ($\cos\varphi_m$) not lower than 0.8, the voltage drop can be calculated by using the following simplified formula:

$$\Delta u = \frac{a \cdot \sqrt{3} \cdot I_b \cdot L \cdot (r_t \cdot \cos\varphi_m + x \cdot \sin\varphi_m)}{1000} \text{ [V]} \qquad (6a)$$

For single-phase BTS the formula is:

$$\Delta u = \frac{a \cdot 2 \cdot I_b \cdot L \cdot (r_t \cdot \cos\varphi_m + x \cdot \sin\varphi_m)}{1000} \text{ [V]} \qquad (6b)$$

where:
- *a* is the current distribution factor, which depends on the circuit supply and the arrangement of the electric loads along the BTS, as shown in Table 6:

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Table 6: Current distribution factor

Type of supply	Arrangement of loads	Current distribution factor
From one end only	Load concentrated at the end	1
	Evenly distributed load	0.5
From both ends	Evenly distributed load	0.25
Central	Load concentrated at the ends	0.25
	Evenly distributed load	0.125

- I_b is the load current [A];
- L is the BTS length [m];
- r_t is the phase resistance per unit of length of BTS, measured under thermal steady-state conditions [mΩ/m];
- x is the phase reactance per unit of length of BTS [mΩ/m];
- $\cos\varphi_m$ is average power factor of the loads.

Percentage voltage drop is obtained from:

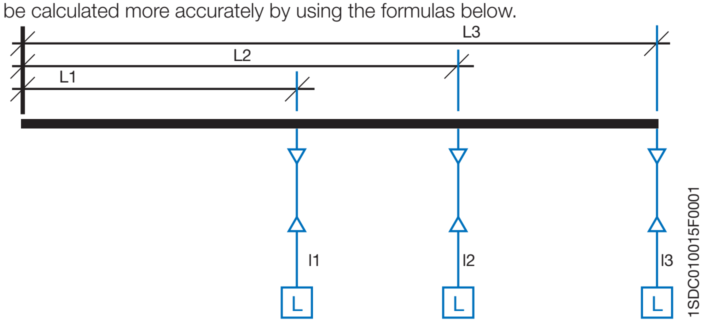
$$\Delta u\% = \frac{\Delta u}{U_r} \cdot 100 \qquad (7)$$

where U_r is rated voltage.

To reduce the voltage drop in very long BTS the power can be supplied at an intermediate position rather than at the end (see Table 6).

Calculation of voltage drop for unevenly distributed loads

If the loads cannot be considered to be evenly distributed, the voltage drop can be calculated more accurately by using the formulas below.



For the distribution of the three-phase loads shown in the figure, the voltage drop can be calculated by the following formula if the BTS has a constant cross section (as usual):

$$\Delta u = \sqrt{3}[r_t(I_1L_1\cos\varphi_1 + I_2L_2\cos\varphi_2 + I_3L_3\cos\varphi_3) + x(I_1L_1\sin\varphi_1 + I_2L_2\sin\varphi_2 + I_3L_3\sin\varphi_3)]$$

2 Protection of feeders

Generally speaking, this formula becomes:

$$\Delta u = \frac{\sqrt{3}\ r_t \cdot \sum I_i \cdot L_i \cdot \cos\varphi_{mi} + x \cdot \sum I_i \cdot L_i \cdot \sin\varphi_{mi}}{1000}\ [V] \qquad (8)$$

where:
- r_t is the phase resistance per unit of length of BTS, measured under thermal steady-state conditions [mΩ/m];
- x is the phase reactance per unit of length of BTS [mΩ/m];
- $\cos\varphi_m$ is average power factor of the i-th load;
- I_i is i-th load current [A];
- L_i is the distance of the i-th load from the beginning of the BTS [m].

Joule-effect losses

Joule-effect losses are due to the electrical resistance of the BTS.
The losses are dissipated in heat and contribute to the heating of the trunking and of the environment. Calculation of power losses is useful for correctly dimensioning the air-conditioning system for the building.
Three-phase losses are:

$$P_j = \frac{3 \cdot r_t \cdot I_b^2 \cdot L}{1000}\ [W] \quad (9a)$$

while single-phase losses are:

$$P_j = \frac{2 \cdot r_t \cdot I_b^2 \cdot L}{1000}\ [W] \quad (9b)$$

where:
- I_b is the current used [A];
- r_t is the phase resistance per unit of length of BTS measured under thermal steady-state conditions [mΩ/m];
- L is the length of BTS [m].

For accurate calculations, losses must be assessed section by section on the basis of the currents flowing through them; e.g. in the case of distribution of loads shown in the previous figure:

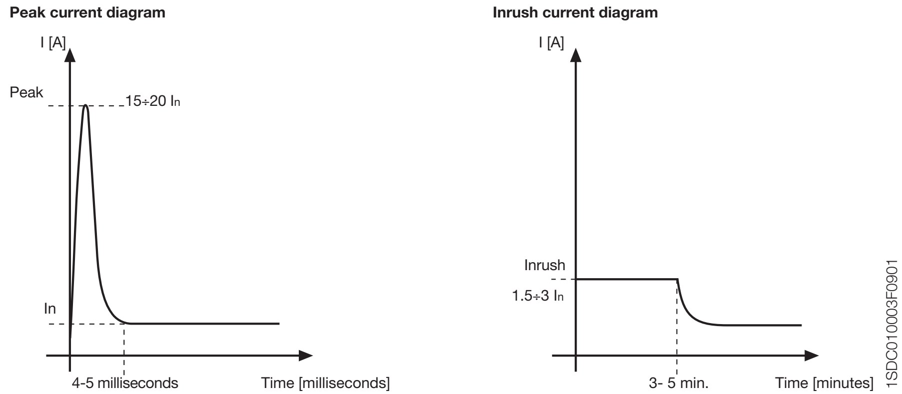
	Length	Current	Losses
1° section	L_1	$I_1+I_2+I_3$	$P_1=3r_tL_1(I_1+I_2+I_3)^2$
2° section	L_2-L_1	I_2+I_3	$P_2=3r_t(L_2-L_1)(I_2+I_3)^2$
3° section	L_3-L_2	I_3	$P_3=3r_t(L_3-L_2)(I_3)^2$
Total losses in BTS			$P_{tot}=P_1+P_2+P_3$

3 Protection of electrical equipment

3.1 Protection and switching of lighting circuits

Introduction

Upon supply of a lighting installation, for a brief period an initial current exceeding the rated current (corresponding to the power of the lamps) circulates on the network. This possible peak has a value of approximately 15÷20 times the rated current, and is present for a few milliseconds; there may also be an inrush current with a value of approximately 1.5÷3 times the rated current, lasting up to some minutes. The correct dimensioning of the switching and protection devices must take these problems into account.



The most commonly used lamps are of the following types:
- incandescent;
- halogen;
- fluorescent;
- high intensity discharge: mercury vapour, metal halide and sodium vapour.

Incandescent lamps

Incandescent lamps are made up of a glass bulb containing a vacuum or inert gas and a tungsten filament. The current flows through this filament, heating it until light is emitted.
The electrical behaviour of these lamps involves a high peak current, equal to approximately 15 times the rated current; after a few milliseconds the current returns to the rated value. The peak is caused by the lamp filament which, initially cold, presents a very low electrical resistance. Subsequently, due to the very fast heating of the element, the resistance value increases considerably, causing the decrease in the current absorbed.

3 Protection of electrical equipment

Halogen lamps

Halogen lamps are a special type of incandescent lamp in which the gas contained within the bulb prevents the vaporized material of the tungsten filament from depositing on the surface of the bulb and forces re-deposition on the filament. This phenomenon slows the deterioration of the filament, improves the quality of the light emitted and increases the life of the lamp.
The electrical behaviour of these lamps is the same as that of incandescent lamps.

Fluorescent lamps

Fluorescent lamps are a so-called discharge light source. The light is produced by a discharge within a transparent enclosure (glass, quartz, etc. depending on the type of lamp) which contains mercury vapour at low pressure.
Once the discharge has started, the gas within the enclosure emits energy in the ultraviolet range which strikes the fluorescent material; in turn, this material transforms the ultraviolet radiation into radiation which has a wavelength within the visible spectrum. The colour of the light emitted depends upon the fluorescent material used.
The discharge is created by an appropriate peak in voltage, generated by a starter. Once the lamp has been switched on, the gas offers an ever lower resistance, and it is necessary to stabilize the intensity of the current, using a controller (reactor); this lowers the power factor to approximately 0.4÷0.6; normally a capacitor is added to increase the power factor to a value of more than 0.9
There are two types of controllers, magnetic (conventional) and electronic, which absorb from 10% to 20% of the rated power of the lamp. Electronic controllers offer specific advantages such as a saving in the energy absorbed, a lower dissipation of heat, and ensure a stable, flicker-free light. Some types of fluorescent lamps with electronic reactors do not need a starter.
Compact fluorescent lamps are made up of a folded tube and a plastic base which contains, in some cases, a conventional or electronic controller.
The value of the inrush current depends upon the presence of a power factor correction capacitor:
- non PFC lamps have inrush currents equal to approximately twice the rated current and a turn-on time of about ten seconds;
- in PFC lamps, the presence of the capacitor allows the reduction of the turn-on time to a few seconds, but requires a high peak current, determined by the charge of the capacitor, which can reach 20 times the rated current.

If the lamp is fitted with an electronic controller, the initial transient current may lead to peak currents equal to, at maximum, 10 times the rated current.

3 Protection of electrical equipment

High intensity discharge lamps: mercury vapour, metal halide and sodium vapour

The functioning of high intensity discharge lamps is the same as that of fluorescent lamps with the difference that the discharge occurs in the presence of a gas at high pressure. In this case, the arc is able to vaporize the metallic elements contained in the gas, releasing energy in the form of radiation which is both ultraviolet and within the visible spectrum. The special type of bulb glass blocks the ultraviolet radiation and allows only the visible radiation to pass through. There are three main types of high intensity discharge lamps: mercury vapour, metal halide and sodium vapour. The colour characteristics and the efficiency of the lamp depend upon the different metallic elements present in the gas, which are struck by the arc.
High intensity discharge lamps require a suitably sized controller and a heating period which can last some minutes before the emission of the rated light output. A momentary loss of power makes the restarting of the system and the heating necessary.
Non PFC lamps have inrush currents of up to twice the rated current for approximately 5 minutes.
PFC lamps have a peak current equal to 20 times the rated current, and an inrush current of up to twice the rated current for approximately 5 minutes.

Lamp type		Peak current	Inrush current	Turn-on time
Incandescent lamps		15In	-	-
Halogen lamps		15In	-	-
Fluorescent	Non PFC	–	2In	10 s
lamp	PFC	20In		1÷6 s
High intensity	Non PFC	–	2In	2÷8 min
discharge lamps	PFC	20In	2In	2÷8 min

Protection and switching devices

IEC 60947-4-1 identifies two specific utilization categories for lamp control contactors:
- AC-5a switching of electric discharge lamps;
- AC-5b switching of incandescent lamps.

The documentation supplied by the manufacturer includes tables for contactor selection, according to the number of lamps to be controlled, and to their type.

3 Protection of electrical equipment

For the selection of a protection device the following verifications shall be carried out:

- the trip characteristic curve shall be above the turning-on characteristic curve of the lighting device to avoid unwanted trips; an approximate example is shown in Figure1;

- coordination shall exist with the contactor under short-circuit conditions (lighting installations are not generally characterized by overloads).

With reference to the above verification criteria, the following tables show the maximum number of lamps per phase which can be controlled by the combination of ABB circuit-breakers and contactors for some types of lamps, according to their power and absorbed current I_b(*) , for three phase installations with a rated voltage of 400 V and a maximum short-circuit current of 15 kA.

(*) For calculation see Annex B Calculation of load current I_b

3 Protection of electrical equipment

Figure 1: Approximate diagram for the coordination of lamps with protection and switching devices

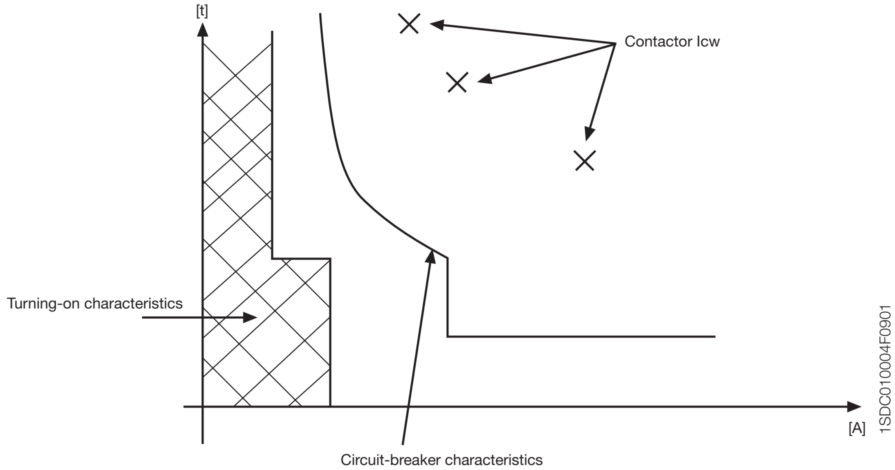


Table 1: Incandescent and halogen lamps

U_r= 400 V	I_k= 15 kA												
Incandescent/halogen lamps													
Circuit-breaker type		S200M D20	S200M D20	S200M D25	S200M D32	S200M D50		T2N160 In63	T2N160 In63	T2N160 In100	T2N160 In100	T2N160 In100	T2N160 In160
Setting PR221 DS		----	----	----	----	----		L= 0.68- A S= 8- B	L= 0.92- A S= 10- B	L= 0.68- A S= 8- B	L= 0.76- A S= 8- B	L= 1- A S= 10- B	L= 0.68- A S= 7- B
Contactor type		A26	A26	A26	A26	A30		A40	A50	A63	A75	A95	A110
Rated Power [W]	Rated current I_b [A]	N° lamps per phase											
60	0.27	57	65	70	103	142		155	220	246	272	355	390
100	0.45	34	38	42	62	85		93	132	147	163	210	240
200	0.91	17	19	20	30	42		46	65	73	80	105	120
300	1.37	11	12	13	20	28		30	43	48	53	70	80
500	2.28	6	7	8	12	16		18	26	29	32	42	48
1000	4.55	3	4	4	6	8		9	13	14	16	21	24

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3.1 Protection and switching of lighting circuits
3 Protection of electrical equipment

Table 2: Fluorescent lamps

U_r= 400 V	I_k= 15 kA											
Fluorescent lamps non PFC												
Circuit-breaker type		S200M D16	S200M D20	S200M D20	S200M D32	S200M D40	S200M D50	S200M D63	T2N160 In100	T2N160 In100	T2N160 In100	T2N160 In160
Setting PR221 DS									L= 0.68- A S= 10- B	L= 0.76- A S= 10- B	L= 0.96- A- S= 10- B	S= 0.68- A S= 10- B
Contactor type		A26	A26	A26	A26	A30	A40	A50	A63	A75	A95	A110
Rated Power [W]	Rated current I_b [A]	N° lamps per phase										
20	0.38	40	44	50	73	100	110	157	173	192	250	278
40	0.45	33	37	42	62	84	93	133	145	162	210	234
65	0.7	21	24	27	40	54	60	85	94	104	135	150
80	0.8	18	21	23	35	47	52	75	82	91	118	132
100	1.15	13	14	16	24	33	36	52	57	63	82	92
110	1.2	12	14	15	23	31	35	50	55	60	79	88

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U_r= 400 V	I_k= 15 kA											
Fluorescent lamps PFC												
Circuit-breaker type			S200M D25	S200M D25	S200M D32	S200M D40	S200M D63	T2N160 In63	T2N160 In63	T2N160 In100	T2N160 In100	T2N160 In100
Setting PR221 DS			---	---	---	---	---	L= 0.68- A S= 8- B	L= 1- A S= 10- B	L= 0.68- A S= 10- B	L= 0.76- A S= 10- B	L= 0.96- A S= 10- B
Contactor type			A26	A26	A26	A26	A30	A40	A50	A63	A75	A95
Rated Power [W]	Rated current I_b [A]	Capacitor [μF]	N° lamps per phase									
20	0.18	5	83	94	105	155	215	233	335	360	400	530
40	0.26	5	58	65	75	107	150	160	230	255	280	365
65	0.42	7	35	40	45	66	92	100	142	158	173	225
80	0.52	7	28	32	36	53	74	80	115	126	140	180
100	0.65	16	23	26	29	43	59	64	92	101	112	145
110	0.7	18	21	24	27	40	55	59	85	94	104	135

3 Protection of electrical equipment

3.1 Protection and switching of lighting circuits

3 Protection of electrical equipment

Table 3: High intensity discharge lamps

U_r= 400 V	I_k= 15 kA											
Fluorescent lamps non PFC												
Circuit-breaker type		S200M D16	S200M D20	S200M D20	S200M D32	S200M D40	S200M D40	S200M D50	S200M	T2N160 In100	T2N160 In100	T2N160 In160
Setting PR221 DS										L= 0.8- B S= 6.5- B	L= 1- B S= 8- B	L= 0.8- B S= 6.5- B
Contactor type		A26	A26	A26	A26	A30	A40	A50	A63	A75	A95	A110
Rated Power [W]	Rated current I_b [A]	N° lamps per phase										
150	1.8	6	7	8	11	15	17	23	26	29	38	41
250	3	4	4	5	7	9	10	14	16	17	23	25
400	4.4	3	3	3	4	6	7	9	10	12	15	17
600	6.2	1	2	2	3	4	5	7	8	8	11	12
1000	10.3	-	1	1	2	3	3	4	5	5	6	7

U_r= 400 V	I_k= 15 kA												
Fluorescent lamps PFC													
Circuit-breaker type			S200M D16	S200M D20	S200M D20	S200M D32	S200M D40	S200M D40	T2N160 In100	T2N160 In100	T2N160 In100	T2N160 In160	T2N160 In160
Setting PR221 DS			---	---	---	---	---	---	L= 0.8- B S= 6.5- B	L= 0.88- B S= 6.5- B	L= 1- B S= 6.5- B	L= 0.84- B S= 4.5- B	L= 0.88- B S= 4.5- B
Contactor type			A26	A26	A26	A26	A30	A40	A50	A63	A75	A95	A110
Rated Power [W]	Rated current I_b [A]	Capacitor [μF]	N° lamps per phase										
150	1	20	13	14	15	23	28	30	50	58	63	81	88
250	1.5	36	8	9	10	15	18	20	33	38	42	54	59
400	2.5	48	5	5	6	9	11	12	20	23	25	32	36
600	3.3	65	4	4	5	7	8	9	15	17	19	24	27
1000	6.2	100	-	-	-	4	4	5	8	9	10	13	14

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Example:

Switching and protection of a lighting system, supplied by a three phase network at 400 V 15 kA, made up of 55 incandescent lamps, of 200 W each, per phase. In Table 1, on the row corresponding to 200 W, select the cell showing the number of controllable lamps immediately above the number of lamps per phase present in the installation. In the specific case, corresponding to the cell for 65 lamps per phase the following equipment are suggested:

- ABB Tmax T2N160 In63 circuit-breaker with PR221/DS type electronic release, with protection L set at 0.92, curve A and protection S set at 10, curve B;
- A50 contactor.

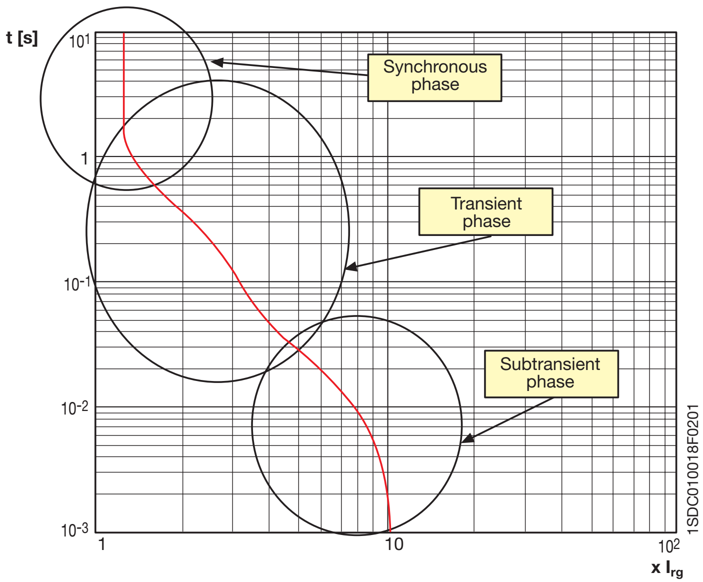
3.2 Protection and switching of generators

The need to guarantee an ever greater continuity of service has led to an increase in the use of emergency supply generators, either as an alternative to, or in parallel with the public utility supply network.

Typical configurations include:
- "Island supply" (independent functioning) of the priority loads in the case of a lack of energy supply through the public network;
- supply to the user installation in parallel with the public supply network.

Unlike the public supply network, which has a constant contribution, in case of a short-circuit, the current supplied by the generator is a function of the parameters of the machine itself, and decreases with time; it is possible to identify the following successive phases:

1. a subtransient phase: with a brief duration (10÷50 ms), characterized by the subtransient reactance X''_d (5÷20% of the rated impedance value), and by the subtransient time constant T''_d (5÷30 ms);
2. a transitory phase: may last up to some seconds (0.5÷2.5 s), and is characterized by the transitory reactance X'_d (15÷40% of the rated impedance value), and by the transitory time constant T'_d (0.03÷2.5 s);
3. a synchronous phase: may persist until the tripping of external protection, and is characterized by the synchronous reactance X_d (80÷300% of the rated impedance value).



As a first approximation, it can be estimated that the maximum value of the short-circuit current of a generator, with rated power S_{rg}, at the rated voltage of the installation U_r, is equal to:

$$I_{kg} = \frac{I_{rg} \cdot 100}{X''_d \%}$$

where

I_{rg} is the rated current of the generator:

$$I_{rg} = \frac{S_{rg}}{\sqrt{3} \cdot U_r}$$

The circuit-breaker for the protection of the generator shall be selected according to the following criteria:
- the set current higher than the rated current of the generator: $I_1 \geq I_{rg}$;
- breaking capacity I_{cu} or I_{cs} higher than the maximum value of short-circuit current at the installation point:
  - in the case of a single generator: $I_{cu}(I_{cs}) \geq I_{kg}$;
  - in the case of *n* identical generators in parallel: $I_{cu}(I_{cs}) \geq I_{kg} \cdot (n\text{-}1)$;
  - in the case of operation in parallel with the network: $I_{cu}(I_{cs}) \geq I_{kNet}$, as the short-circuit contribution from the network is normally greater than the contribution from the generator;
- for circuit-breakers with thermomagnetic releases: low magnetic trip threshold: $I_3 = 2.5/3 \cdot I_n$;
- for circuit-breakers with electronic releases:
  - trip threshold of the delayed short-circuit protection function (S), set between 1.5 and 4 times the rated current of the generator, in such a way as to "intercept" the decrement curve of the generator: $I_2 = (1.5÷4) \cdot I_{rg}$; if the function S is not present, function I can be set at the indicated values $I_3 = (1.5÷4) \cdot I_{rg}$;
  - trip threshold of the instantaneous short-circuit protection function (I_3) set at a value greater than the rated short-circuit current of the generator, so as to achieve discrimination with the devices installed downstream, and to allow fast tripping in the event of a short-circuit upstream of the device (working in parallel with other generators or with the network):

$$I_3 \geq I_{kg}$$

3 Protection of electrical equipment

The following tables give ABB SACE suggestions for the protection and switching of generators; the tables refer to 400 V (Table 1), 440 V (Table 2), 500 V (Table 3) and 690 V (Table 4). Molded-case circuit-breakers can be equipped with both thermomagnetic (TMG) as well as electronic releases.

Table 1 400 V

<table>
<tr><th>S_{rg} [kVA]</th><th>MCB</th><th>MCCB</th><th>ACB</th></tr>
<tr><td>4</td><td>S200 B6</td><td rowspan="22">T2 160</td><td rowspan="38"></td></tr>
<tr><td>6</td><td>S200 B10</td></tr>
<tr><td>7</td><td rowspan="2">S200 B13</td></tr>
<tr><td>9</td></tr>
<tr><td>11</td><td>S200 B16</td></tr>
<tr><td>14</td><td rowspan="2">S200 B25</td></tr>
<tr><td>17</td></tr>
<tr><td>19</td><td rowspan="3">S200 B32</td></tr>
<tr><td>21</td></tr>
<tr><td>22</td></tr>
<tr><td>28</td><td rowspan="2">S200 B50</td></tr>
<tr><td>31</td></tr>
<tr><td>35</td><td rowspan="3">S200 B63</td></tr>
<tr><td>38</td></tr>
<tr><td>42</td></tr>
<tr><td>44</td><td rowspan="3">S280 B80</td></tr>
<tr><td>48</td></tr>
<tr><td>55</td></tr>
<tr><td>69</td><td>S280 B100</td></tr>
<tr><td>80</td><td rowspan="33"></td></tr>
<tr><td>87</td></tr>
<tr><td>100</td></tr>
<tr><td>111</td><td rowspan="2">T4 250</td></tr>
<tr><td>138</td></tr>
<tr><td>159</td><td rowspan="2">T3 250
T4 250</td></tr>
<tr><td>173</td></tr>
<tr><td>180</td><td rowspan="4">T4 320</td></tr>
<tr><td>190</td></tr>
<tr><td>208</td></tr>
<tr><td>218</td></tr>
<tr><td>242</td><td rowspan="2">T5 400</td></tr>
<tr><td>277</td></tr>
<tr><td>308</td><td rowspan="6">T5 630
T6 630
T6 800</td></tr>
<tr><td>311</td></tr>
<tr><td>346</td></tr>
<tr><td>381</td></tr>
<tr><td>415</td></tr>
<tr><td>436</td></tr>
<tr><td>484</td><td rowspan="2">T6 800
S7 1250</td><td rowspan="4">E1/E2 1250</td></tr>
<tr><td>554</td></tr>
<tr><td>692</td><td rowspan="3">S7 1250</td></tr>
<tr><td>727</td></tr>
<tr><td>865</td><td>E2/E3 1600</td></tr>
<tr><td>1107</td><td>S7 1600</td><td>E2/E3 2000</td></tr>
<tr><td>1730</td><td rowspan="3">S8 3200</td><td>E3 3200</td></tr>
<tr><td>2180</td><td>E3 3200/E4 4000</td></tr>
<tr><td>2214</td><td rowspan="3">E4 4000</td></tr>
<tr><td>2250</td><td rowspan="5"></td></tr>
<tr><td>2500</td></tr>
<tr><td>2800</td><td rowspan="3">E6 5000/6300</td></tr>
<tr><td>3150</td></tr>
<tr><td>3500</td></tr>
</table>

Table 2 440 V

<table>
<tr><th>S_{rg} [kVA]</th><th>MCB</th><th>MCCB</th><th>ACB</th></tr>
<tr><td>4</td><td>S200 B6</td><td rowspan="23">T2 160</td><td rowspan="38"></td></tr>
<tr><td>6</td><td>S200 B8</td></tr>
<tr><td>7</td><td>S200 B10</td></tr>
<tr><td>9</td><td>S200 B13</td></tr>
<tr><td>11</td><td>S200 B16</td></tr>
<tr><td>14</td><td>S200 B20</td></tr>
<tr><td>17</td><td>S200 B25</td></tr>
<tr><td>19</td><td rowspan="3">S200 B32</td></tr>
<tr><td>21</td></tr>
<tr><td>22</td></tr>
<tr><td>28</td><td>S200 B40</td></tr>
<tr><td>31</td><td rowspan="2">S200 B50</td></tr>
<tr><td>35</td></tr>
<tr><td>38</td><td rowspan="3">S200 B63</td></tr>
<tr><td>42</td></tr>
<tr><td>44</td></tr>
<tr><td>48</td><td rowspan="2">S280 B80</td></tr>
<tr><td>55</td></tr>
<tr><td>69</td><td>S280 B100</td></tr>
<tr><td>80</td><td rowspan="33"></td></tr>
<tr><td>87</td></tr>
<tr><td>100</td></tr>
<tr><td>111</td></tr>
<tr><td>138</td><td>T4 250</td></tr>
<tr><td>159</td><td rowspan="2">T3 250
T4 250</td></tr>
<tr><td>173</td></tr>
<tr><td>180</td><td rowspan="5">T4 320</td></tr>
<tr><td>190</td></tr>
<tr><td>208</td></tr>
<tr><td>218</td></tr>
<tr><td>242</td></tr>
<tr><td>277</td><td>T5 400</td></tr>
<tr><td>308</td><td rowspan="6">T5 630
T6 630
T6 800</td></tr>
<tr><td>311</td></tr>
<tr><td>346</td></tr>
<tr><td>381</td></tr>
<tr><td>415</td></tr>
<tr><td>436</td></tr>
<tr><td>484</td><td rowspan="2">T6 800
S7 1250</td><td rowspan="5">E1/E2 1250</td></tr>
<tr><td>554</td></tr>
<tr><td>692</td><td rowspan="3">S7 1250</td></tr>
<tr><td>727</td></tr>
<tr><td>865</td></tr>
<tr><td>1107</td><td>S7 1600</td><td>E2/E3 1600</td></tr>
<tr><td>1730</td><td rowspan="3">S8 3200</td><td>E3 2500</td></tr>
<tr><td>2180</td><td rowspan="3">E3 3200</td></tr>
<tr><td>2214</td></tr>
<tr><td>2250</td><td rowspan="5"></td></tr>
<tr><td>2500</td><td rowspan="2">E4 4000</td></tr>
<tr><td>2800</td></tr>
<tr><td>3150</td><td rowspan="2">E6 5000/6300</td></tr>
<tr><td>3500</td></tr>
</table>

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3.2 Protection and switching of generators

3 Protection of electrical equipment

Table 3 500 V

<table>
<tr><th>S_{rg} [kVA]</th><th>MCB</th><th>MCCB</th><th>ACB</th></tr>
<tr><td>4</td><td rowspan="52"></td><td rowspan="24">T2 160</td><td rowspan="38"></td></tr>
<tr><td>6</td></tr>
<tr><td>7</td></tr>
<tr><td>9</td></tr>
<tr><td>11</td></tr>
<tr><td>14</td></tr>
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<tr><td>80</td></tr>
<tr><td>87</td></tr>
<tr><td>100</td></tr>
<tr><td>111</td></tr>
<tr><td>138</td></tr>
<tr><td>159</td><td rowspan="2">T3 250
T4 250</td></tr>
<tr><td>173</td></tr>
<tr><td>180</td><td rowspan="3">T4 250</td></tr>
<tr><td>190</td></tr>
<tr><td>208</td></tr>
<tr><td>218</td><td rowspan="3">T4 320</td></tr>
<tr><td>242</td></tr>
<tr><td>277</td></tr>
<tr><td>308</td><td rowspan="3">T5 400</td></tr>
<tr><td>311</td></tr>
<tr><td>346</td></tr>
<tr><td>381</td><td rowspan="4">T5 630
T6 630
T6 800</td></tr>
<tr><td>415</td></tr>
<tr><td>436</td></tr>
<tr><td>484</td><td rowspan="5">E1/E2 1250</td></tr>
<tr><td>554</td><td rowspan="2">T6 800
S7 1250</td></tr>
<tr><td>692</td></tr>
<tr><td>727</td><td rowspan="2">S7 1250</td></tr>
<tr><td>865</td></tr>
<tr><td>1107</td><td>S7 1600</td><td>E2/E3 1600</td></tr>
<tr><td>1730</td><td>S8 2500</td><td>E3 2500</td></tr>
<tr><td>2180</td><td rowspan="4">S8 3200</td><td rowspan="4">E3 3200</td></tr>
<tr><td>2214</td></tr>
<tr><td>2250</td></tr>
<tr><td>2500</td></tr>
<tr><td>2800</td><td rowspan="3"></td><td rowspan="2">E4 4000</td></tr>
<tr><td>3150</td></tr>
<tr><td>3500</td><td>E6 5000/6300</td></tr>
</table>

Table 4 690 V

<table>
<tr><th></th><th>MCB</th><th>MCCB</th><th>ACB</th></tr>
<tr><td>4</td><td rowspan="52"></td><td rowspan="26">T2 160</td><td rowspan="38"></td></tr>
<tr><td>6</td></tr>
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<tr><td>42</td></tr>
<tr><td>44</td></tr>
<tr><td>48</td></tr>
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<tr><td>69</td></tr>
<tr><td>80</td></tr>
<tr><td>87</td></tr>
<tr><td>100</td></tr>
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<tr><td>138</td></tr>
<tr><td>159</td></tr>
<tr><td>173</td></tr>
<tr><td>180</td><td rowspan="2">T3 250</td></tr>
<tr><td>190</td></tr>
<tr><td>208</td><td rowspan="4">T4 250</td></tr>
<tr><td>218</td></tr>
<tr><td>242</td></tr>
<tr><td>277</td></tr>
<tr><td>308</td><td rowspan="4">T4 320</td></tr>
<tr><td>311</td></tr>
<tr><td>346</td></tr>
<tr><td>381</td></tr>
<tr><td>415</td><td rowspan="2">T5 400</td></tr>
<tr><td>436</td></tr>
<tr><td>484</td><td>T5 630</td><td rowspan="5">E1 800</td></tr>
<tr><td>554</td><td rowspan="3">T5 630
T6 630
T6 800</td></tr>
<tr><td>692</td></tr>
<tr><td>727</td></tr>
<tr><td>865</td><td>T6 800</td></tr>
<tr><td>1107</td><td>S7 1250</td><td>E1/E2 1250</td></tr>
<tr><td>1730</td><td>S7 1600</td><td>E2/E3 1600</td></tr>
<tr><td>2180</td><td rowspan="5">S8 2500</td><td rowspan="3">E2 2000
E3 2500</td></tr>
<tr><td>2214</td></tr>
<tr><td>2250</td></tr>
<tr><td>2500</td><td rowspan="2">E3 2500</td></tr>
<tr><td>2800</td></tr>
<tr><td>3150</td><td rowspan="2">S8 3200</td><td rowspan="2">E3 3200</td></tr>
<tr><td>3500</td></tr>
</table>

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Note: It is always advisable to check that the settings of the releases are correct with respect to the effective decrement curve of the current of the generator to be protected.

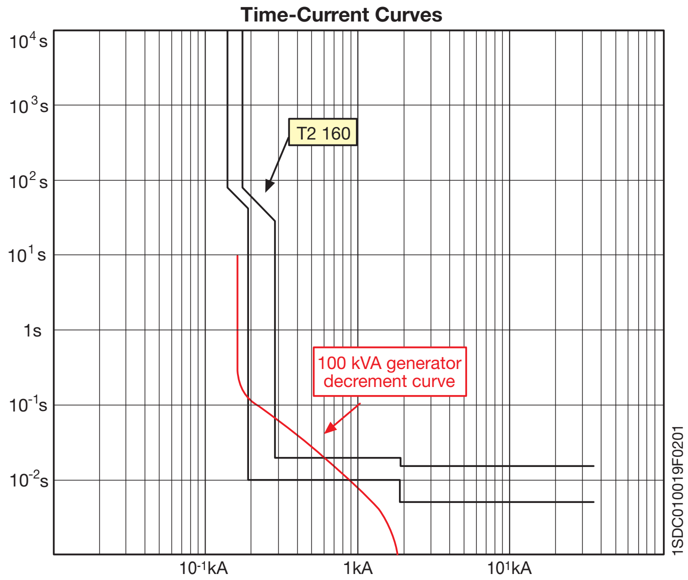
3 Protection of electrical equipment

Example:

Protection of a generator with S_{rg} = 100 kVA, in a system with a rated voltage of 440 V.
The generator parameters are:
U_r = 440 V
S_{rg} = 100 kVA
f = 50 Hz
I_{rg} = 131.2 A
X''_d = 6.5 % (subtransient reactance)
X'_d = 17.6 % (transient reactance)
X_d = 230 % (synchronous reactance)
T''_d = 5.5 ms (subtransient time constant)
T'_d = 39.3 ms (transient time constant)

From table 2, an ABB SACE T2N160 circuit-breaker is selected, with I_n = 160 A, with electronic release PR221-LS. For correct protection of the generator, the following settings are selected:

function L: 0.84 – A, corresponding to 134.4 A, value greater than I_{rg}
function I: 1.5



3 Protection of electrical equipment

3.3 Protection and switching of motors

Electromechanical starter

The starter is designed to:
- start motors;
- ensure continuous functioning of motors;
- disconnect motors from the supply line;
- guarantee protection of motors against working overloads.

The starter is typically made up of a switching device (contactor) and an overload protection device (thermal release).
The two devices must be coordinated with equipment capable of providing protection against short-circuit (typically a circuit-breaker with magnetic release only), which is not necessarily part of the starter.

The characteristics of the starter must comply with the international Standard IEC 60947-4-1, which defines the above as follows:

Contactor: a mechanical switching device having only one position of rest, operated otherwise than by hand, capable of making, carrying and breaking currents under normal circuit conditions including operating overload conditions.

Thermal release: thermal overload relay or release which operates in the case of overload and also in case of loss of phase.

Circuit-breaker: defined by IEC 60947-2 as a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions.

The main types of motor which can be operated and which determine the characteristics of the starter are defined by the following utilization categories:

Table 1: Utilization categories and typical applications

Current type	Utilization categories	Typical applications
Alternating Current ac	AC-2	Slip-ring motors: starting, switching off
	AC-3	Squirrel-cage motors: starting, switching off during running(1)
	AC-4	Squirrel-cage motors: starting, plugging, inching

(1) AC-3 categories may be used for occasionally inching or plugging for limited time periods such as machine set-up; during such limited time periods the number of such operations should not exceed five per minutes or more than ten in a 10 minutes period.

3 Protection of electrical equipment

The choice of the starting method and also, if necessary, of the type of motor to be used depends on the typical resistant torque of the load and on the short-circuit power of the motor supplying network.

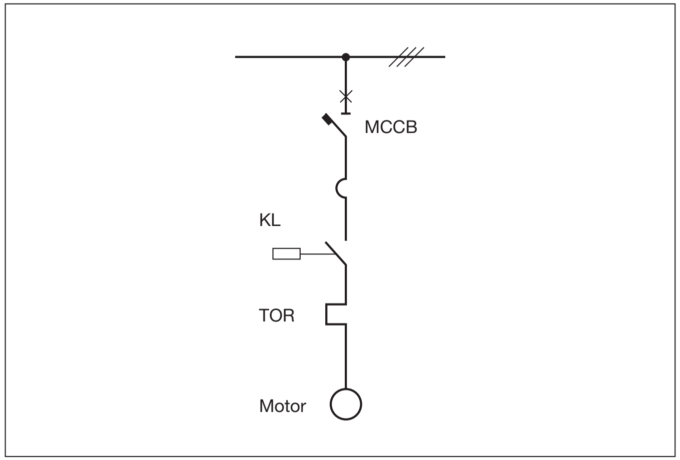
With alternating current, the most commonly used motor types are as follows:
- asynchronous three-phase squirrel-cage motors (AC-3): the most widespread type due to the fact that they are of simple construction, economical and sturdy; they develop high torque with short acceleration times, but require elevated starting currents;
- slip-ring motors (AC-2): characterized by less demanding starting conditions, and have quite a high starting torque, even with a supply network of low power.

Starting methods

The most common starting methods for asynchronous squirrel-cage motors are detailed below:

Direct starting

With direct starting, the DOL (Direct On Line) starter, with the closing of line contactor KL, the line voltage is applied to the motor terminals in a single operation. Hence a squirrel-cage motor develops a high starting torque with a relatively reduced acceleration time. This method is generally used with small and medium power motors which reach full working speed in a short time. These advantages are, however, accompanied by a series of drawbacks, including, for example:
- high current consumption and associated voltage drop which may cause damages to the other parts of the system connected to the network;
- violent acceleration which has negative effects on mechanical transmission components (belts, chains and mechanical joints), reducing working life.



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3 Protection of electrical equipment

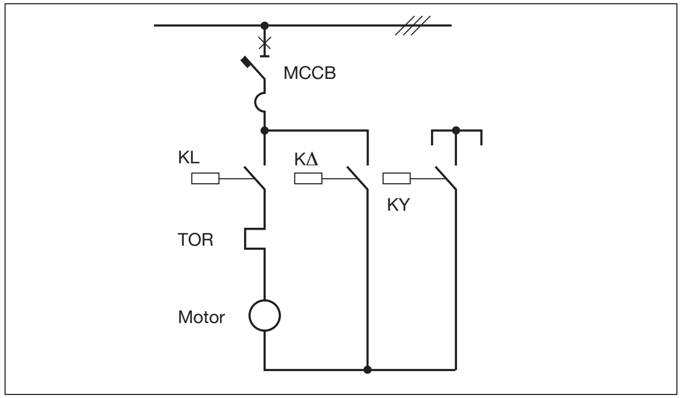
Other types of starting for squirrel-cage motors are accomplished by reducing the supply voltage of the motor: this leads to a reduction in the starting current and of the motor torque, and an increase in the acceleration time.

Star-Delta starter

The most common reduced voltage starter is the Star-Delta starter (Y-Δ), in which:
- on starting, the stator windings are star-connected, thus achieving the reduction of peak inrush current;
- once the normal speed of the motor is nearly reached, the switchover to delta is carried out.

After the switchover, the current and the torque follow the progress of the curves associated with normal service connections (delta).

As can be easily checked, starting the motor with star-connection gives a voltage reduction of √3, and the current absorbed from the line is reduced by 1/3 compared with that absorbed with delta-connection.
The start-up torque, proportional to the square of the voltage, is reduced by 3 times, compared with the torque that the same motor would supply when delta-connected.
This method is generally applied to motors with power from 15 to 355 kW, but intended to start with a low initial resistant torque.



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Starting sequence

By pressing the start button, contactors KL and KY are closed. The timer starts to measure the start time with the motor connected in star. Once the set time has elapsed, the first contact of the timer opens the KY contactor and the second contact, delayed by approximately 50 ms, closes the KΔ contactor. With this new configuration, contactors KL and KΔ closed, the motor becomes delta-connected.

3 Protection of electrical equipment

The thermal release TOR, inserted in the delta circuit, can detect any 3rd harmonic currents, which may occur due to saturation of the magnetic pack and by adding to the fundamental current, overload the motor without involving the line.

With reference to the connection diagram, the equipment used for a Star/Delta starter must be able to carry the following currents:

$\frac{I_r}{\sqrt{3}}$ KL line contactor and KΔ delta contactor

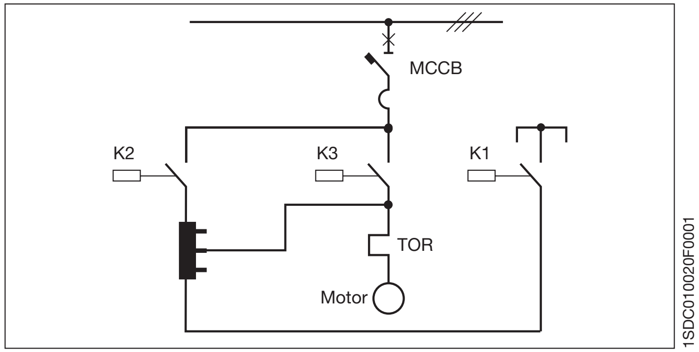
$\frac{I_r}{3}$ KY star contactor

$\frac{I_r}{\sqrt{3}}$ overload protection release

where I_r is the rated current of the motor.

Starting with autotransformers

Starting with autotransformers is the most functional of the methods used for reduced voltage starting, but is also the most expensive. The reduction of the supply voltage is achieved by using a fixed tap autotransformer or a more expensive multi tap autotransformer.
Applications can be found with squirrel-cage motors which generally have a power from 50 kW to several hundred kilowatts, and higher power double-cage motors.



The autotransformer reduces the network voltage by the factor K (K=1.25÷1.8), and as a consequence the start-up torque is reduced by K^2 times compared with the value of the full rated voltage.
On starting, the motor is connected to the taps of the autotransformer and the contactors K2 and K1 are closed.

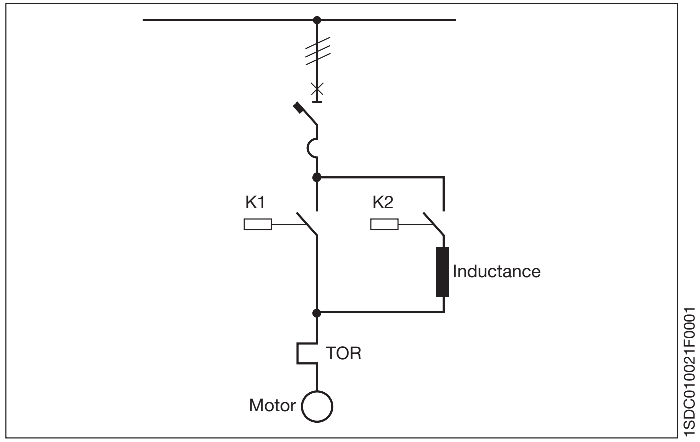
3.3 Protection and switching of motors

3 Protection of electrical equipment

Therefore, the motor starts at a reduced voltage, and when it has reached approximately 80% of its normal speed, contactor K1 is opened and main contactor K3 is closed. Subsequently, contactor K2 is opened, excluding the autotransformer so as to supply the full network voltage.

Starting with inductive reactors or resistors

This type of starting is used for simple or double-cage rotors. The reduction of the supply voltage is achieved by the insertion of inductive reactors or resistors, in series to the stator. On start-up, the current is limited to 2.5÷3.5 times the rated value.
On starting, the motor is supplied via contactor K2; once the normal speed is reached, the reactors are short-circuited by the closing of contactor K1, and are then excluded by the opening of contactor K2.
It is possible to achieve exclusions by step of the resistors or reactors with time-delayed commands, even for motors with power greater than 100 kW.
The use of reactors notably reduces the power factor, while the use of resistors causes the dissipation of a high power (Joule effect), even if limited to the starting phase.
For a reduction K (0.6÷0.8) of the motor voltage, the torque is reduced by K^2 times (0.36÷0.64).



In compliance with the above mentioned Standard, starters can also be classified according to tripping time (trip classes), and according to the type of coordination achieved with the short-circuit protection device (Type 1 and Type 2).

3 Protection of electrical equipment

Trip classes

The trip classes differentiate between the thermal releases according to their trip curve.
The trip classes are defined in the following table 2:

Table 2: Trip class

Trip Class	Tripping time in seconds (Tp)
10A	2 < Tp ≤ 10
10	4 < Tp ≤ 10
20	6 < Tp ≤ 20
30	9 < Tp ≤ 30

where Tp is the cold trip time of the thermal release at 7.2 times the set current value (for example: a release in class 10 at 7.2 times the set current value must not trip within 4 s, but must trip within 10 s).
It is normal procedure to associate class 10 with a normal start-up type, and class 30 with a heavy duty start-up type.

Coordination type

Type 1

It is acceptable that in the case of short-circuit the contactor and the thermal release may be damaged. The starter may still not be able to function and must be inspected; if necessary, the contactor and/or the thermal release must be replaced, and the breaker release reset.

Type 2

In the case of short-circuit, the thermal release must not be damaged, while the welding of the contactor contacts is allowed, as they can easily be separated (with a screwdriver, for example), without any significant deformation.

In order to clearly determine a coordination type, and therefore the equipment necessary to achieve it, the following must be known:
- power of the motor in kW and type;
- rated system voltage;
- rated motor current;
- short-circuit current at installation point;
- starting type: DOL or Y/Δ - normal or heavy duty – Type 1 or Type 2.

The requested devices shall be coordinated with each other in accordance with the prescriptions of the Standard.
For the most common voltages and short-circuit values (400 V - 440 V - 500 V - 690 V 35 kA - 50 kA) and for the most frequently used starting types, such as direct starting and Star/Delta starting, for asynchronous squirrel-cage motor (AC-3), ABB supplies solutions with:
- magnetic circuit-breaker - contactor - thermal release;
- thermomagnetic circuit-breaker - contactor;
- thermomagnetic circuit-breaker with PR222 MP electronic release – contactor.

3 Protection of electrical equipment

The following is an example of the type of tables available:

Table 3: 400 V 50 kA DOL Normal Type 2
(Tmax – Contactor – TOR)

Motor		MCCB		Contactor	Thermal Overload Release		
						Current setting	
P_e	I_r	Type	I_3	Type	Type	min.	max.
[kW]	[A]		[A]			[A]	[A]
0.37	1.1	**T2S160 MF 1.6**	21	**A9**	**TA25DU1.4**	1	1.4
0.55	1.5	**T2S160 MF 1.6**	21	**A9**	**TA25DU1.8**	1.3	1.8
0.75	1.9	**T2S160 MF 2**	26	**A9**	**TA25DU2.4**	1.7	2.4
1.1	2.8	**T2S160 MF 3.2**	42	**A9**	**TA25DU4**	2.8	4
1.5	3.5	**T2S160 MF 4**	52	**A16**	**TA25DU5**	3.5	5
2.2	5	**T2S160 MF 5**	65	**A26**	**TA25DU6.5**	4.5	6.5
3	6.6	**T2S160 MF 8.5**	110	**A26**	**TA25DU8.5**	6	8.5
4	8.6	**T2S160 MF 11**	145	**A30**	**TA25DU11**	7.5	11
5.5	11.5	**T2S160 MF 12.5**	163	**A30**	**TA25DU14**	10	14
7.5	15.2	**T2S160 MA 20**	210	**A30**	**TA25DU19**	13	19
11	22	**T2S160 MA 32**	288	**A30**	**TA42DU25**	18	25
15	28.5	**T2S160 MA 52**	392	**A50**	**TA75DU42**	29	42
18.5	36	**T2S160 MA 52**	469	**A50**	**TA75DU52**	36	52
22	42	**T2S160 MA 52**	547	**A50**	**TA75DU52**	36	52
30	56	**T2S160 MA 80**	840	**A63**	**TA75DU80**	60	80
37	68	**T2S160 MA 80**	960	**A75**	**TA75DU80**	60	80
45	83	**T2S160 MA 100**	1200	**A95**	**TA110DU110**	80	110
55	98	**T3S250 MA 160**	1440	**A110**	**TA110DU110**	80	110
75	135	**T3S250 MA 200**	1800	**A145**	**TA200DU175**	130	175
90	158	**T3S250 MA 200**	2400	**A185**	**TA200DU200**	150	200
110	193	**T4S320 PR221-I In320**	2720	**A210**	**E320DU320**	100	320
132	232	**T5S400 PR221-I In400**	3200	**A260**	**E320DU320**	100	320
160	282	**T5S400 PR221-I In400**	4000	**A300**	**E320DU320**	100	320
200	349	**T5S630 PR221-I In630**	5040	**AF400**	**E500DU500**	150	500
250	430	**T5S630 PR221-I In630**	6300	**AF460**	**E500DU500**	150	500
290	520	**T6S800 PR221-I In800**	7200	**AF580**	**E800DU800**	250	800
315	545	**T6S800 PR221-I In800**	8000	**AF580**	**E800DU800**	250	800
355	610	**T6S800 PR221-I In800**	8000	**AF750**	**E800DU800**	250	800

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MA: magnetic only adjustable release
MF: fixed magnetic only release

3 Protection of electrical equipment

Table 4: 400 V 50 kA DOL Heavy duty Type 2 (Tmax – Contactor – TOR)

Motor		MCCB		Contactor	Thermal Overload Release			
P_e [kW]	I_r [A]	Type	I_3 [A]	Type	Type**	No. of turns of the CT primary coil	Current setting min. [A]	Current setting max. [A]
0.37	1.1	**T2S160 MF 1.6**	21	**A9**	**TA25DU1.4***		1	1.4
0.55	1.5	**T2S160 MF 1.6**	21	**A9**	**TA25DU1.8***		1.3	1.8
0.75	1.9	**T2S160 MF 2**	26	**A9**	**TA25DU2.4***		1.7	2.4
1.1	2.8	**T2S160 MF 3.2**	42	**A9**	**TA25DU4***		2.8	4
1.5	3.5	**T2S160 MF 4**	52	**A16**	**TA25DU5***		3.5	5
2.2	5	**T2S160 MF 5**	65	**A26**	**TA25DU6.5***		4.5	6.5
3	6.6	**T2S160 MF 8.5**	110	**A26**	**TA25DU8.5***		6	8.5
4	8.6	**T2S160 MF 11**	145	**A30**	**TA25DU11***		7.5	11
5.5	11.5	**T2S160 MF 12.5**	163	**A30**	**TA450SU60**	**4**	10	15
7.5	15.2	**T2S160 MA 20**	210	**A30**	**TA450SU60**	**3**	13	20
11	22	**T2S160 MA 32**	288	**A30**	**TA450SU60**	**2**	20	30
15	28.5	**T2S160 MA 52**	392	**A50**	**TA450SU80**	**2**	23	40
18.5	36	**T2S160 MA 52**	469	**A50**	**TA450SU80**	**2**	23	40
22	42	**T2S160 MA 52**	547	**A50**	**TA450SU60**		40	60
30	56	**T2S160 MA 80**	840	**A63**	**TA450SU80**		55	80
37	68	**T2S160 MA 80**	960	**A95**	**TA450SU80**		55	80
45	83	**T2S160 MA 100**	1200	**A110**	**TA450SU105**		70	105
55	98	**T3S250 MA 160**	1440	**A145**	**TA450SU140**		95	140
75	135	**T3S250 MA 200**	1800	**A185**	**TA450SU185**		130	185
90	158	**T3S250 MA 200**	2400	**A210**	**TA450SU185**		130	185
110	193	**T4S320 PR221-I In320**	2720	**A260**	**E320DU320**		100	320
132	232	**T5S400 PR221-I In400**	3200	**A300**	**E320DU320**		100	320
160	282	**T5S400 PR221-I In400**	4000	**AF400**	**E500DU500**		150	500
200	349	**T5S630 PR221-I In630**	5040	**AF460**	**E500DU500**		150	500
250	430	**T5S630 PR221-I In630**	6300	**AF580**	**E500DU500*****		150	500
290	520	**T6S800 PR221-I In800**	7200	**AF750**	**E800DU800**		250	800
315	545	**T6S800 PR221-I In800**	8000	**AF750**	**E800DU800**		250	800
355	610	**T6S800 PR221-I In800**	8000	**AF750**	**E800DU800**		250	800

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* Provide a by-pass contactor of the same size during motor start-up
** For type E releases choose tripping class 30
*** Connecting kit not available. To use the connecting kit, replacement with release E800DU800 is necessary

MA: magnetic only adjustable release
MF: fixed magnetic only release

3 Protection of electrical equipment

Table 5: 400 V 50 kA Y/Δ Normal Type 2 (Tmax – Contactor – TOR)

Motor		MCCB		Contactor			Thermal Overload Release	
P_e [kW]	I_r [A]	Type	I_3 [A]	LINE Type	DELTA Type	STAR Type	Type	Current setting [A]
18.5	36	**T2S160 MA52**	469	**A50**	**A50**	**A26**	**TA75DU25**	18-25
22	42	**T2S160 MA52**	547	**A50**	**A50**	**A26**	**TA75DU32**	22-32
30	56	**T2S160 MA80**	720	**A63**	**A63**	**A30**	**TA75DU42**	29-42
37	68	**T2S160 MA80**	840	**A75**	**A75**	**A30**	**TA75DU52**	36-52
45	83	**T2S160 MA100**	1050	**A75**	**A75**	**A30**	**TA75DU63**	45 - 63
55	98	**T2S160 MA100**	1200	**A75**	**A75**	**A40**	**TA75DU63**	45 - 63
75	135	**T3S250 MA160**	1700	**A95**	**A95**	**A75**	**TA110DU90**	66 - 90
90	158	**T3S250 MA200**	2000	**A110**	**A110**	**A95**	**TA110DU110**	80 - 110
110	193	**T3S250 MA200**	2400	**A145**	**A145**	**A95**	**TA200DU135**	100 - 135
132	232	**T4S320 PR221-I In320**	2880	**A145**	**A145**	**A110**	**E200DU200**	60 - 200
160	282	**T5S400 PR221-I In400**	3600	**A185**	**A185**	**A145**	**E200DU200**	60 - 200
200	349	**T5S630 PR221-I In630**	4410	**A210**	**A210**	**A185**	**E320DU320**	100 - 320
250	430	**T5S630 PR221-I In630**	5670	**A260**	**A260**	**A210**	**E320DU320**	100 - 320
290	520	**T6S630 PR221-I In630**	6300	**AF400**	**AF400**	**A260**	**E500DU500**	150 - 500
315	545	**T6S800 PR221-I In800**	7200	**AF400**	**AF400**	**A260**	**E500DU500**	150 - 500
355	610	**T6S800 PR221-I In800**	8000	**AF400**	**AF400**	**A260**	**E500DU500**	150 - 500

MA: magnetic only adjustable release

Table 6: 400 V 50 kA DOL Normal and Heavy duty Type 2 (Tmax with MP release-Contactor)

Motor		MCCB			Contactor	Group
P_e [kW]	I_r [A]	Type	I_1* range [A]	I_3 [A]	Type	I_{max} [A]
30	56	**T4S250 PR222MP In100**	40-100	600	A95	95
37	68	**T4S250 PR222MP In100**	40-100	700	A95	95
45	83	**T4S250 PR222MP In100**	40-100	800	A95	95
55	98	**T4S250 PR222MP In160**	64-160	960	A145	145
75	135	**T4S250 PR222MP In160**	64-160	1280	A145	145
90	158	**T4S250 PR222MP In200**	80-200	1600	A185	185
110	193	**T5S320 PR222MP In320**	128-320	1920	A210	210
132	232	**T5S320 PR222MP In320**	128-320	2240	A260	260
160	282	**T5S320 PR222MP In320**	128-320	2560	AF400**	320
200	349	**T5S400 PR222MP In400**	160-400	3200	AF400	400
250	430	**T6S800 PR222MP In630**	252-630	5040	AF460	460
290	520	**T6S800 PR222MP In630**	252-630	5670	AF580	580
315	545	**T6S800 PR222MP In630**	252-630	5670	AF580	580
355	610	**T6S800 PR222MP In630**	252-630	5670	AF750	630

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(*) for heavy-duty start set the electronic release tripping class to class 30
(**) in case of normal start use AF300

3 Protection of electrical equipment

Table 7: 440 V 50 kA DOL Normal Type 2 (Tmax – Contactor – TOR)

Motor		MCCB		Contactor	Thermal Overload Release		
P_e [kW]	I_r [A]	Type	I3 [A]	Type	Type	Current setting min. [A]	Current setting max. [A]
0.37	1	**T2H160 MF 1**	13	**A9**	**TA25DU1.4**	1	1.4
0.55	1.4	**T2H160 MF 1.6**	21	**A9**	**TA25DU1.8**	1.3	1.8
0.75	1.7	**T2H160 MF 2**	26	**A9**	**TA25DU2.4**	1.7	2.4
1.1	2.2	**T2H160 MF 2.5**	33	**A9**	**TA25DU3.1**	2.2	3.1
1.5	3	**T2H160 MF 3.2**	42	**A16**	**TA25DU4**	2.8	4
2.2	4.4	**T2H160 MF 5**	65	**A26**	**TA25DU5**	3.5	5
3	5.7	**T2H160 MF 6.5**	84	**A26**	**TA25DU6.5**	4.5	6.5
4	7.8	**T2H160 MF 8.5**	110	**A30**	**TA25DU11**	7.5	11
5.5	10.5	**T2H160 MF 11**	145	**A30**	**TA25DU14**	10	14
7.5	13.5	**T2H160 MA 20**	180	**A30**	**TA25DU19**	13	19
11	19	**T2H160 MA 32**	240	**A30**	**TA42DU25**	18	25
15	26	**T2H160 MA 32**	336	**A50**	**TA75DU32**	22	32
18.5	32	**T2H160 MA 52**	469	**A50**	**TA75DU42**	29	42
22	38	**T2H160 MA 52**	547	**A50**	**TA75DU52**	36	52
30	52	**T2H160 MA 80**	720	**A63**	**TA75DU63**	45	63
37	63	**T2H160 MA 80**	840	**A75**	**TA75DU80**	60	80
45	75	**T2H160 MA 100**	1050	**A95**	**TA110DU90**	65	90
55	90	**T4H250 PR221-I In160**	1200	**A110**	**TA110DU110**	80	110
75	120	**T4H250 PR221-I In250**	1750	**A145**	**E200DU200**	60	200
90	147	**T4H250 PR221-I In250**	2000	**A185**	**E200DU200**	60	200
110	177	**T4H250 PR221-I In250**	2500	**A210**	**E320DU320**	100	320
132	212	**T4H320 PR221-I In320**	3200	**A260**	**E320DU320**	100	320
160	260	**T5H400 PR221-I In400**	3600	**A300**	**E320DU320**	100	320
200	320	**T5H630 PR221-I In630**	4410	**AF 400**	**E500DU500**	150	500
250	410	**T5H630 PR221-I In630**	5355	**AF 460**	**E500DU500**	150	500
290	448	**T6H630 PR221-I In630**	6300	**AF 580**	**E500DU500***	150	500
315	500	**T6H800 PR221-I In800**	7200	**AF 580**	**E800DU800**	250	800
355	549	**T6H800 PR221-I In800**	8000	**AF 580**	**E800DU800**	250	800

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* Connection kit not available. To use the connection kit, replace with relay E800DU800.
MA: magnetic only adjustable release
MF: fixed magnetic only release

3 Protection of electrical equipment

Table 8: 440 V 50 kA DOL Heavy duty Type 2 (Tmax – Contactor – TOR)

Motor		MCCB		Contactor	Thermal Overload Release			
P_e [kW]	I_r [A]	Type	I3 [A]	Type	Type**	No. of turns of the CT primary coil	Current setting min. [A]	Current setting max. [A]
0.37	1	**T2H160 MF 1**	13	**A9**	**TA25DU1.4***		1	1.4
0.55	1.4	**T2H160 MF 1.6**	21	**A9**	**TA25DU1.8***		1.3	1.8
0.75	1.7	**T2H160 MF 2**	26	**A9**	**TA25DU2.4***		1.7	2.4
1.1	2.2	**T2H160 MF 2.5**	33	**A9**	**TA25DU3.1***		2.2	3.1
1.5	3	**T2H160 MF 3.2**	42	**A16**	**TA25DU4***		2.8	4
2.2	4.4	**T2H160 MF 5**	65	**A26**	**TA25DU5***		3.5	5
3	5.7	**T2H160 MF 6.5**	84	**A26**	**TA25DU6.5***		4.5	6.5
4	7.8	**T2H160 MF 8.5**	110	**A30**	**TA25DU11***		7.5	11
5.5	10.5	**T2H160 MF 11**	145	**A30**	**TA25DU14***		10	14
7.5	13.5	**T2H160 MA 20**	180	**A30**	**TA450SU60**	**4**	10	15
11	19	**T2H160 MA 32**	240	**A30**	**TA450SU80**	**3**	18	27
15	26	**T2H160 MA 32**	336	**A50**	**TA450SU60**	**2**	20	30
18.5	32	**T2H160 MA 52**	469	**A50**	**TA450SU80**	**2**	28	40
22	38	**T2H160 MA 52**	547	**A50**	**TA450SU80**	**2**	28	40
30	52	**T2H160 MA 80**	720	**A63**	**TA450SU60**		40	60
37	63	**T2H160 MA 80**	840	**A95**	**TA450SU80**		55	80
45	75	**T2H160 MA 100**	1050	**A110**	**TA450SU105**		70	105
55	90	**T4H250 PR221-I In160**	1200	**A145**	**E200DU200**		60	200
75	120	**T4H250 PR221-I In250**	1750	**A185**	**E200DU200**		60	200
90	147	**T4H250 PR221-I In250**	2000	**A210**	**E320DU320**		100	320
110	177	**T4H250 PR221-I In250**	2500	**A260**	**E320DU320**		100	320
132	212	**T4H320 PR221-I In320**	3200	**A300**	**E320DU320**		100	320
160	260	**T5H400 PR221-I In400**	3600	**AF400**	**E500DU500**		150	500
200	320	**T5H630 PR221-I In630**	4410	**AF460**	**E500DU500**		150	500
250	410	**T5H630 PR221-I In630**	5355	**AF580**	**E500DU500*****		150	500
290	448	**T6H630 PR221-I In630**	6300	**AF750**	**E500DU500*****		150	500
315	500	**T6H800 PR221-I In800**	7200	**AF 750**	**E800DU800**		250	800
355	549	**T6H800 PR221-I In800**	8000	**AF 750**	**E800DU800**		250	800

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* Provide a by-pass contactor of the same size during motor start-up
** For type E releases choose tripping class 30
*** Connecting kit not available. To use the connecting kit, replacement with release E800DU800 is necessary

MA: magnetic only adjustable release
MF: fixed magnetic only release

3 Protection of electrical equipment

Table 9: 440 V 50 kA Y/Δ Normal Type 2
(Tmax – Contactor – TOR)

Motor		MCCB		Contactor			Thermal Overload Release	
P_e [kW]	I_r [A]	Type	I3 [A]	LINE Type	DELTA Type	STAR Type	Type	Current setting [A]
18.5	32	**T2H160 MA52**	392	**A 50**	**A 50**	**A 16**	**TA75DU25**	18-25
22	38	**T2H160 MA52**	469	**A 50**	**A 50**	**A 26**	**TA75DU25**	18-25
30	52	**T2H160 MA80**	720	**A 63**	**A 63**	**A 26**	**TA75DU42**	29-42
37	63	**T2H160 MA80**	840	**A 75**	**A 75**	**A 30**	**TA75DU42**	29-42
45	75	**T2H160 MA80**	960	**A 75**	**A 75**	**A30**	**TA75DU52**	36-52
55	90	**T2H160 MA100**	1150	**A 75**	**A 75**	**A40**	**TA75DU63**	45 - 63
75	120	**T4H250 PR221-I In250**	1625	**A95**	**A95**	**A75**	**TA80DU80**	60-80
90	147	**T4H250 PR221-I In250**	1875	**A95**	**A95**	**A75**	**TA110DU110**	80-110
110	177	**T4H250 PR221-I In250**	2250	**A145**	**A145**	**A95**	**E200DU200**	60-200
132	212	**T4H320 PR221-I In320**	2720	**A145**	**A145**	**A110**	**E200DU200**	60-200
160	260	**T5H400 PR221-I In400**	3200	**A185**	**A185**	**A145**	**E200DU200**	60-200
200	320	**T5H630 PR221-I In630**	4095	**A210**	**A210**	**A185**	**E320DU320**	100-320
250	410	**T5H630 PR221-I In630**	5040	**A260**	**A260**	**A210**	**E320DU320**	100-320
290	448	**T6H630 PR221-I In630**	5670	**AF400**	**AF400**	**A260**	**E500DU500**	150 - 500
315	500	**T6H630 PR221-I In630**	6300	**AF400**	**AF400**	**A260**	**E500DU500**	150 - 500
355	549	**T6H800 PR221-I In800**	7200	**AF400**	**AF400**	**A260**	**E500DU500**	150 - 500

MA : Magnetic only adjustable release

Table 10: 440 V 50 kA DOL Normal and Heavy duty Type 2
(Tmax with MP release-Contactor)

Motor		MCCB			Contactor	Group
P_e [kW]	I_r [A]	Type	I_1* range [A]	I3 [A]	Type	Imax [A]
30	52	**T4H250 PR222MP In100**	40-100	600	A95	93
37	63	**T4H250 PR222MP In100**	40-100	700	A95	93
45	75	**T4H250 PR222MP In100**	40-100	800	A95	93
55	90	**T4H250 PR222MP In160**	64-160	960	A145	145
75	120	**T4H250 PR222MP In160**	64-160	1120	A145	145
90	147	**T4H250 PR222MP In200**	80-200	1400	A185	185
110	177	**T5H320 PR222MP In320**	128-320	1920	A210	210
132	212	**T5H320 PR222MP In320**	128-320	2240	A260	240
160	260	**T5H320 PR222MP In320**	128-320	2560	AF400**	320
200	320	**T5H400 PR222MP In400**	160-400	3200	AF400	400
250	370	**T6H800 PR222MP In630**	252-630	4410	AF460	460
290	436	**T6H800 PR222MP In630**	252-630	5040	AF460	460
315	500	**T6H800 PR222MP In630**	252-630	5040	AF580	580
355	549	**T6H800 PR222MP In630**	252-630	5670	AF580	580

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(*) for heavy-duty start set the electronic release tripping class to class 30
(**) in case of normal start use AF300

3 Protection of electrical equipment

Table 11: 500 V 50 kA DOL Normal Type 2
(Tmax – Contactor – TOR)

Motor		MCCB		Contactor	Thermal Overload Release		
P_e [kW]	I_r [A]	Type	I3 [A]	Type	Type	Current setting min. [A]	Current setting max. [A]
0.37	0.88	**T2L160 MF 1**	13	**A9**	**TA25DU1.0**	0.63	1
0.55	1.2	**T2L160 MF 1.6**	21	**A9**	**TA25DU1.4**	1	1.4
0.75	1.5	**T2L160 MF 1.6**	21	**A9**	**TA25DU1.8**	1.3	1.8
1.1	2.2	**T2L160 MF 2.5**	33	**A9**	**TA25DU3.1**	2.2	3.1
1.5	2.8	**T2L160 MF 3.2**	42	**A16**	**TA25DU4**	2.8	4
2.2	4	**T2L160 MF 4**	52	**A26**	**TA25DU5**	3.5	5
3	5.2	**T2L160 MF 6.5**	84	**A26**	**TA25DU6.5**	4.5	6.5
4	6.9	**T2L160 MF 8.5**	110	**A30**	**TA25DU8.5**	6	8.5
5.5	9.1	**T2L160 MF 11**	145	**A30**	**TA25DU11**	7.5	11
7.5	12.2	**T2L160 MF 12.5**	163	**A30**	**TA25DU14**	10	14
11	17.5	**T2L160 MA 20**	240	**A30**	**TA25DU19**	13	19
15	23	**T2L160 MA 32**	336	**A50**	**TA75DU25**	18	25
18.5	29	**T2L160 MA 52**	392	**A50**	**TA75DU32**	22	32
22	34	**T2L160 MA 52**	469	**A50**	**TA75DU42**	29	42
30	45	**T2L160 MA 52**	624	**A63**	**TA75DU52**	36	52
37	56	**T2L160 MA 80**	840	**A75**	**TA75DU63**	45	63
45	67	**T2L160 MA 80**	960	**A95**	**TA80DU80**	60	80
55	82	**T2L160 MA 100**	1200	**A110**	**TA110DU90**	65	90
75	110	**T4H250 PR221-I In160**	1440	**A145**	**E200DU200**	60	200
90	132	**T4H250 PR221-I In250**	1875	**A145**	**E200DU200**	60	200
110	158	**T4H250 PR221-I In250**	2250	**A185**	**E200DU200**	60	200
132	192	**T4H320 PR221-I In320**	2720	**A210**	**E320DU320**	100	320
160	230	**T5H400 PR221-I In400**	3600	**A260**	**E320DU320**	100	320
200	279	**T5H400 PR221-I In400**	4000	**A300**	**E320DU320**	100	320
250	335	**T5H630 PR221-I In630**	4725	**AF 400**	**E 500DU500**	150	500
290	394	**T5H630 PR221-I In630**	5040	**AF 460**	**E 500DU500**	150	500
315	440	**T6L630 PR221-I In630**	6300	**AF 580**	**E 500DU500***	150	500
355	483	**T6L630 PR221-I In630**	6300	**AF 580**	**E 800DU800**	250	800

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* Connection kit not available. To use the connection kit, replace with relay E800DU800.
MA: magnetic only adjustable release
MF: fixed magnetic only release

3 Protection of electrical equipment

Table 12: 500 V 50 kA DOL Heavy duty Type 2 (Tmax – Contactor – TOR)

Motor		MCCB		Contactor	Thermal Overload Release			
P_e [kW]	I_r [A]	Type	I3 [A]	Type	Type**	No. of turns of the CT primary coil	Current setting min. [A]	Current setting max. [A]
0.37	0.88	**T2L160 MF 1**	13	**A9**	**TA25DU1.0***		0.63	1
0.55	1.2	**T2L160 MF 1.6**	21	**A9**	**TA25DU1.4***		1	1.4
0.75	1.5	**T2L160 MF 1.6**	21	**A9**	**TA25DU1.8***		1.3	1.8
1.1	2.2	**T2L160 MF 2.5**	33	**A9**	**TA25DU3.1***		2.2	3.1
1.5	2.8	**T2L160 MF 3.2**	42	**A16**	**TA25DU4***		2.8	4
2.2	4	**T2L160 MF 4**	52	**A26**	**TA25DU5***		3.5	5
3	5.2	**T2L160 MF 6.5**	84	**A26**	**TA25DU6.5***		4.5	6.5
4	6.9	**T2L160 MF 8.5**	110	**A30**	**TA25DU8.5***		6	8.5
5.5	9.1	**T2L160 MF 11**	145	**A30**	**TA25DU11***		7.5	11
7.5	12.2	**T2L160 MF 12.5**	163	**A30**	**TA450SU60**	**4**	10	15
11	17.5	**T2L160 MA 20**	240	**A30**	**TA450SU60**	**3**	13	20
15	23	**T2L160 MA 32**	336	**A50**	**TA450SU60**	**2**	20	30
18.5	29	**T2L160 MA 52**	392	**A50**	**TA450SU80**	**2**	27.5	40
22	34	**T2L160 MA 52**	469	**A50**	**TA450SU80**	**2**	27.5	40
30	45	**T2L160 MA 52**	624	**A63**	**TA450SU60**		40	60
37	56	**T2L160 MA 80**	840	**A75**	**TA450SU60**		40	60
45	67	**T2L160 MA 80**	960	**A95**	**TA450SU80**		55	80
55	82	**T2L160 MA 100**	1200	**A145**	**TA450SU105**		70	105
75	110	**T4H250 PR221-I In160**	1440	**A145**	**E200DU200**		60	200
90	132	**T4H250 PR221-I In250**	1875	**A185**	**E200DU200**		60	200
110	158	**T4H250 PR221-I In250**	2123	**A210**	**E320DU320**		100	320
132	192	**T4H320 PR221-I In320**	2720	**A260**	**E320DU320**		100	320
160	230	**T5H400 PR221-I In400**	3200	**A300**	**E320DU320**		100	320
200	279	**T5H400 PR221-I In400**	3600	**AF400**	**E500DU500**		150	500
250	335	**T5H630 PR221-I In630**	4725	**AF460**	**E500DU500**		150	500
290	394	**T5H630 PR221-I In630**	5040	**AF580**	**E500DU500*****		150	500
315	440	**T6L630 PR221-I In630**	6300	**AF750**	**E500DU500*****		150	500
355	483	**T6L630 PR221-I In630**	6300	**AF750**	**E500DU500**		150	500

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* Provide a by-pass contactor of the same size during motor start-up
** For type E releases choose tripping class 30
*** Connecting kit not available. To use the connecting kit, replacement with release E800DU800 is necessary

MA: magnetic only adjustable release
MF: fixed magnetic only release

3 Protection of electrical equipment

Table 13: 500 V 50 kA Y/Δ Normal Type 2 (Tmax – Contactor – TOR)

Motor		MCCB		Contactor			Thermal Overload Release	
P_e [kW]	I_r [A]	Type	I3 [A]	LINE Type	DELTA Type	STAR Type	Type	Current setting
22	34	**T2L160 MA52**	430	**A 50**	**A 50**	**A 16**	**TA75DU25**	18-25
30	45	**T2L160 MA52**	547	**A 63**	**A 63**	**A 26**	**TA75DU32**	22-32
37	56	**T2L160 MA80**	720	**A 75**	**A 75**	**A 30**	**TA75DU42**	29-42
45	67	**T2L160 MA80**	840	**A 75**	**A 75**	**A30**	**TA75DU52**	36 - 52
55	82	**T2L160 MA100**	1050	**A 75**	**A 75**	**A30**	**TA75DU52**	36 - 52
75	110	**T4H250 PR221-I In250**	1375	**A95**	**A95**	**A50**	**TA80DU80**	60-80
90	132	**T4H250 PR221-I In250**	1750	**A95**	**A95**	**A75**	**TA110DU90**	65-90
110	158	**T4H250 PR221-I In250**	2000	**A110**	**A110**	**A95**	**TA110DU110**	80-110
132	192	**T4H320 PR221-I In320**	2560	**A145**	**A145**	**A95**	**E200DU200**	60-200
160	230	**T4H320 PR221-I In320**	2880	**A145**	**A145**	**A110**	**E200DU200**	60-200
200	279	**T5H400 PR221-I In400**	3400	**A210**	**A210**	**A145**	**E320DU320**	100-320
250	335	**T5H630 PR221-I In630**	4410	**A210**	**A210**	**A185**	**E320DU320**	100-320
290	394	**T5H630 PR221-I In630**	5040	**A260**	**A260**	**A210**	**E320DU320**	100-320
315	440	**T6L630 PR221-I In630**	5760	**AF400**	**AF400**	**A210**	**E500DU500**	150 - 500
355	483	**T6L630 PR221-I In630**	6300	**AF400**	**AF400**	**A260**	**E500DU500**	150 - 500

MA: magnetic only adjustable release

Table 14: 500 V 50 kA DOL Normal and Heavy duty Type 2 (Tmax with MP release-Contactor)

Motor		MCCB			Contactor	Group
P_e [kW]	I_r [A]	Type	I_1* range [A]	I3 [A]	Type	[A]
30	45	**T4H250 PR222MP In100**	40-100	600	A95	80
37	56	**T4H250 PR222MP In100**	40-100	600	A95	80
45	67	**T4H250 PR222MP In100**	40-100	700	A145	100
55	82	**T4H250 PR222MP In100**	40-100	800	A145	100
75	110	**T4H250 PR222MP In160**	64-160	1120	A145	145
90	132	**T4H250 PR222MP In160**	64-160	1280	A145	145
110	158	**T4H250 PR222MP In200**	80-200	1600	A185	170
132	192	**T5H320 PR222MP In320**	128-320	1920	A210	210
160	230	**T5H320 PR222MP In320**	128-320	2240	A260	260
200	279	**T5H400 PR222MP In400**	160-400	2800	AF400**	400
250	335	**T5H400 PR222MP In400**	160-400	3200	AF400	400
290	395	**T6L800 PR222MP In630**	252-630	5040	AF460	460
315	415	**T6L800 PR222MP In630**	252-630	5040	AF460	460
355	451	**T6L800 PR222MP In630**	252-630	5670	AF580	580

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(*) for heavy duty start set the electronic release tripping class to class 30
(**) in case of normal start use AF300

3 Protection of electrical equipment

Table 15: 690 V 50kA DOL Normal Type 2
(Tmax-Contactor-CT-TOR)

Motor		MCCB		Contactor	CT		Thermal Overload Release		
P_e [kW]	I_e [A]	Type	I3 [A]	Type	KORC	N° of primary turns	Type	Current setting min. [A]	Current setting max. [A]
0.37	0.6	**T2L160 MF1**	13	**A9**			**TA25DU0.63**	0.4	0.63
0.55	0.9	**T2L160 MF1**	13	**A9**			**TA25DU1**	0.63	1
0.75	1.1	**T2L160 MF1.6**	21	**A9**			**TA25DU1.4**	1	1.4
1.1	1.6	**T2L160 MF1.6**	21	**A9**			**TA25DU1.8**	1.3	1.8
1.5	2	**T2L160 MF2.5**	33	**A9**			**TA25DU2.4**	1.7	2.4
2.2	2.9	**T2L160 MF3.2**	42	**A9**			**TA25DU3.1***	2.2	3.1
3	3.8	**T2L160 MF4**	52	**A9**			**TA25DU4***	2.8	4
4	5	**T2L160 MF5**	65	**A9**			**TA25DU5***	3.5	5
5.5	6.5	**T2L160 MF6.5**	84	**A9**			**TA25DU6.5***	4.5	6.5
		T4L250 PR221-I In 100	150	**A95**	4L185R/4	13**	**TA25DU2.4**	6	8.5
7.5	8.8	**T4L250 PR221-I In 100**	150	**A95**	4L185R/4	10**	**TA25DU2.4**	7.9	11.1
11	13	**T4L250 PR221-I In 100**	200	**A95**	4L185R/4	7**	**TA25DU2.4**	11.2	15.9
15	18	**T4L250 PR221-I In 100**	250	**A95**	4L185R/4	7**	**TA25DU3.1**	15.2	20.5
18.5	21	**T4L250 PR221-I In 100**	300	**A95**	4L185R/4	6	**TA25DU3.1**	17.7	23.9
22	25	**T4L250 PR221-I In 100**	350	**A95**	4L185R/4	6	**TA25DU4**	21.6	30.8
30	33	**T4L250 PR221-I In 100**	450	**A145**	4L185R/4	6	**TA25DU5**	27	38.5
37	41	**T4L250 PR221-I In 100**	550	**A145**	4L185R/4	4	**TA25DU4**	32.4	46.3
45	49	**T4L250 PR221-I In 100**	700	**A145**	4L185R/4	4	**TA25DU5**	40.5	57.8
55	60	**T4L250 PR221-I In 100**	800	**A145**	4L185R/4	3	**TA25DU5**	54	77.1
75	80	**T4L250 PR221-I In 160**	1120	**A145**			**E200DU200**	65	200
90	95	**T4L250 PR221-I In 160**	1280	**A145**			**E200DU200**	65	200
110	115	**T4L250 PR221-I In 250**	1625	**A145**			**E200DU200**	65	200
132	139	**T4L250 PR221-I In 250**	2000	**A185**			**E200DU200**	65	200
160	167	**T4L250 PR221-I In 250**	2250	**A185**			**E200DU200**	65	200
200	202	**T4L320 PR221-I In 320**	2720	**A210**			**E320DU320**	105	320
250	242	**T5L400 PR221-I In 400**	3400	**A300**			**E320DU320**	105	320
290	301	**T5L630 PR221-I In 630**	4410	**AF400**			**E500DU500**	150	500
315	313	**T5L630 PR221-I In 630**	4410	**AF400**			**E500DU500**	150	500
355	370	**T5L630 PR221-I In 630**	5355	**AF580**			**E500DU500*** **	150	500
400	420	**T5L630 PR221-I In 630**	5670	**AF580**			**E500DU500*** **	150	500

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For further information about the KORK, please see the “brochure KORK 1GB00-04” catalogue.
(*) Type 1 coordination
(**) Cable cross section equal to 4 mm^2
(***) No mounting kit to contactor is available;to use mounting kit provide E800DU800

3 Protection of electrical equipment

Table 16: 690 V 50 kA DOL Heavy duty Type 2
(Tmax – Contactor – TOR)

Motor		MCCB		Contactor	Thermal Overload Release			
P_e [kW]	I_r [A]	Type	I3 [A]	Type	Type	N° of primary turns	Current setting min. [A]	Current setting max. [A]
0.37	0.6	**T2L160 MF1**	13	**A9**	**TA25DU0.63(X)**		0.4	0.63
0.55	0.9	**T2L160 MF1**	13	**A9**	**TA25DU1(X)**		0.63	1
0.75	1.1	**T2L160 MF1.6**	21	**A9**	**TA25DU1.4(X)**		1	1.4
1.1	1.6	**T2L160 MF1.6**	21	**A9**	**TA25DU1.8(X)**		1.3	1.8
1.5	2	**T2L160 MF2.5**	33	**A9**	**TA25DU2.4(X)**		1.7	2.4
2.2	2.9	**T2L160 MF3.2**	42	**A9**	**TA25DU3.1 *(X)**		2.2	3.1
3	3.8	**T2L160 MF4**	52	**A9**	**TA25DU4 *(X)**		2.8	4
4	5	**T2L160 MF5**	65	**A9**	**TA25DU5 *(X)**		3.5	5
5.5	6.5	**T2L160 MF6.5**	84	**A9**	**TA25DU6.5 *(X)**		4.5	6.5
		T4L250 PR221-I In 100	150	**A95**	**TA450SU60**	7**	5.7	8.6
7.5	8.8	**T4L250 PR221-I In 100**	150	**A95**	**TA450SU60**	5**	8	12
11	13	**T4L250 PR221-I In 100**	200	**A95**	**TA450SU60**	4**	10	15
15	18	**T4L250 PR221-I In 100**	250	**A95**	**TA450SU60**	3**	13	20
18.5	21	**T4L250 PR221-I In 100**	300	**A95**	**TA450SU80**	3	18	27
22	25	**T4L250 PR221-I In 100**	350	**A95**	**TA450SU60**	2	20	30
30	33	**T4L250 PR221-I In 100**	450	**A145**	**TA450SU80**	2	27.5	40
37	41	**T4L250 PR221-I In 100**	550	**A145**	**TA450SU60**		40	60
45	49	**T4L250 PR221-I In 100**	700	**A145**	**TA450SU60**		40	60
55	60	**T4L250 PR221-I In 100**	800	**A145**	**TA450SU80**		55	80
75	80	**T4L250 PR221-I In 160**	1120	**A145**	**TA450SU105**		70	105
90	95	**T4L250 PR221-I In 160**	1280	**A145**	**TA450SU105**		70	105
110	115	**T4L250 PR221-I In 250**	1625	**A185**	**TA450SU140**		95	140
132	139	**T4L250 PR221-I In 250**	2000	**A210**	**E320DU320**		105	320
160	167	**T4L250 PR221-I In 250**	2250	**A210**	**E320DU320**		105	320
200	202	**T4L320 PR221-I In 320**	2720	**A260**	**E320DU320**		105	320
250	242	**T5L400 PR221-I In 400**	3400	**AF400**	**E500DU500**		150	500
290	301	**T5L630 PR221-I In 630**	4410	**AF400**	**E500DU500**		150	500
315	313	**T5L630 PR221-I In 630**	4410	**AF460**	**E500DU500**		150	500
355	370	**T5L630 PR221-I In 630**	5355	**AF580**	**E500DU500*** **		150	500
400	420	**T5L630 PR221-I In 630**	5670	**AF580**	**E500DU500*** **		150	500

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(*) Type 1 coordination
(**) Cable cross section equal to 4 mm^2
(***) No mounting kit to contactor is available;to use mounting kit provide E800DU800
(X) Provide by-pass contactor during motor start-up

3 Protection of electrical equipment

Table 17: 690 V 50 kA Y/Δ Normal Type 2 (Tmax – Contactor – CT – TOR)

Motor		MCCB		Contactor			CT		Overload Release	
P_e [kW]	I_r [A]	Type	I3 [A]	Line Type	Delta Type	Star Type	KORC	N° of primary turns	Type	Current setting [A]
5.5	6.5*	T4L250PR221-I In100	150	A95	A95	A26	4L185R/4**	13	TA25DU2.4**	6-8.5
7.5	8.8*	T4L250PR221-I In100	150	A95	A95	A26	4L185R/4**	10	TA25DU2.4**	7.9-11.1
11	13*	T4L250PR221-I In100	200	A95	A95	A26	4L185R/4**	7	TA25DU2.4**	11.2-15.9
15	18*	T4L250PR221-I In100	250	A95	A95	A26	4L185R/4**	7	TA25DU3.1**	15.2-20.5
18.5	21	T4L250PR221-I In100	300	A95	A95	A30	4L185R/4**	6	TA25DU3.1**	17.7-23.9
22	25	T4L250PR221-I In100	350	A95	A95	A30	4L185R/4**	6	TA25DU4**	21.6-30.8
30	33	T4L250PR221-I In100	450	A145	A145	A30	4L185R/4**	6	TA25DU5**	27-38.5
37	41	T4L250PR221-I In100	550	A145	A145	A30			TA75DU52**	36-52
45	49	T4L250PR221-I In100	650	A145	A145	A30			TA75DU52**	36-52
55	60	T4L250PR221-I In100	800	A145	A145	A40			TA75DU52**	36-52
75	80	T4L250PR221-I In160	1120	A145	A145	A50			TA75DU52	36-52
90	95	T4L250PR221-I In160	1280	A145	A145	A75			TA75DU63	45-63
110	115	T4L250PR221-I In160	1600	A145	A145	A75			TA75DU80	60-80
132	139	T4L250PR221-I In250	1875	A145	A145	A95			TA200DU110	80-110
160	167	T4L250PR221-I In250	2125	A145	A145	A110			TA200DU110	80-110
200	202	T4L320PR221-I In320	2720	A185	A185	A110			TA200DU135	100-135
250	242	T5L400PR221-I In400	3200	AF400	AF400	A145			E500DU500	150 -500
290	301	T5L400PR221-I In400	4000	AF400	AF400	A145			E500DU500	150 -500
315	313	T5L630PR221-I In630	4410	AF400	AF400	A185			E500DU500	150 -500
355	370	T5L630PR221-I In630	5040	AF400	AF400	A210			E500DU500	150 -500
400	420	T5L630PR221-I In630	5670	AF460	AF460	A210			E500DU500	150 -500
450	470	T5L630PR221-I In630	6300	AF460	AF460	A260			E500DU500	150 -500

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For further information about the KORK, please see the “brochure KORK 1GB00-04” catalogue.

(*) Cable cross section equal to 4 mm^2

(**) Connect the overload/relay upstream the line-delta node

3 Protection of electrical equipment

Table 18: 690 V 50 kA DOL Normal and Heavy duty Type 2 (Tmax with MP release-Contactor)

Motor		MCCB			Contactor	Group
P_e [kW]	I_r [A]	Type	I_1* range [A]	I3 [A]	Type	[A]
45	49	T4L250 PR222MP In100	40-100	600	A145	100
55	60	T4L250 PR222MP In100	40-100	600	A145	100
75	80	T4L250 PR222MP In100	40-100	800	A145	100
90	95	T4L250 PR222MP In160	64-160	960	A145	120
110	115	T4L250 PR222MP In160	64-160	1120	A145	120
132	139	T4L250 PR222MP In160	64-160	1440	A185	160
160	167	T4L250 PR222MP In200	80-200	1600	A185	170
200	202	T5L320 PR222MP In320	128-320	1920	A210	210
250	242	T5L320 PR222MP In320	128-320	2240	A300	280
290	301	T5L400 PR222MP In400	160-400	2800	AF400	350
315	313	T5L400 PR222MP In400	160-400	3200	AF400	350

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(*) for heavy duty start set the electronic release tripping class to class 30

3 Protection of electrical equipment

Example:

For a Y/Δ Normal starting Type 2, of a three phase asynchronous squirrel-cage motor with the following data:
rated voltage U_r = 400 V
short-circuit current I_k = 50 kA
rated motor power P_e = 200 kW
from Table 5, on the relevant row, the following information can be found:

- I_r (rated current): 349 A;
- short-circuit protection device: circuit-breaker T5S630 PR221-I In630;
- magnetic trip threshold: I_3 = 4410 A;
- line contactor: A210;
- delta contactor: A210;
- star contactor: A185;
- thermal release E320DU320, setting range 100÷320 A (to be set at $\frac{I_r}{\sqrt{3}}$ = 202 A).

For a DOL heavy-duty starting Type 2 with MP protection of a three phase asynchronous squirrel-cage motor with the following data:
rated voltage Ur = 400 V
short-circuit current Ik = 50 kA
rated motor power Pe = 55 kW
from Table 6, on the relevant row, the following information can be found:

- Ir (rated current): 98 A;
- short-circuit protection device: circuit breaker T4S250 PR222MP* In160;
- magnetic trip threshold: I3 = 960 A;
- contactor: A145;

* for heavy-duty start set the electronic release tripping class to class 30

3 Protection of electrical equipment

3.4 Protection and switching of transformers

General aspects

Transformers are used to achieve a change in the supply voltage, for both medium and low voltage supplies.
The choice of the protection devices must take into account transient insertion phenomena, during which the current may reach values higher than the rated full load current; the phenomenon decays in a few seconds.

The curve which represents these transient phenomena in the time-current diagram, termed “inrush current I0”, depends on the size of the transformer and can be evaluated with the following formula (the short-circuit power of the network is assumed to be equal to infinity)

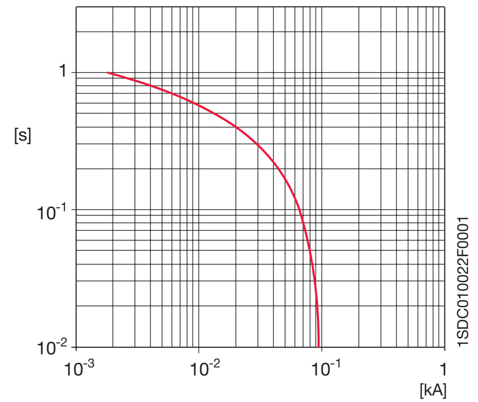
$$I_0 = \frac{K \cdot I_{r1} \cdot e^{(-t/\tau)}}{\sqrt{2}}$$

where:
K ratio between the maximum peak inrush current value (I_0) and the rated current of the transformer (I_{1r}): (K= I_0 / I_{1r});
τ time constant of the inrush current;
I_{1r} rated current of the primary;
t time.

The table below shows the indicative values for t and K parameters referred to rated power Sr for oil transformers.

Sr [kVA]	50	100	160	250	400	630	1000	1600	2000
$K = I_o/I_{1r}$	15	14	12	12	12	11	10	9	8
τ [s]	0.10	0.15	0.20	0.22	0.25	0.30	0.35	0.40	0.45

Further to the above consideration, the follwing diagram shows the inrush current curve for a 20/0.4kV of 400kVA transformer. This transformer has an inrush current during the very first moments equal to about 8 times the rated current; this transient phenomenon stops after a few tenths of a second.



3 Protection of electrical equipment

The transformer protection devices must also guarantee that the transformer cannot operate above the point of maximum thermal overload under short-circuit conditions; this point is defined on the time-current diagram by the value of short-circuit current which can pass through the transformer and by a time equal to 2 s, as stated by Standard IEC 60076-5. The short-circuit current (I_k) flowing for a fault with low impedance at the LV terminals of the transformer is calculated by using the following formula:

$$I_k = \frac{U_r}{\sqrt{3}\cdot(Z_{Net}+Z_t)} \quad [A] \qquad (1)$$

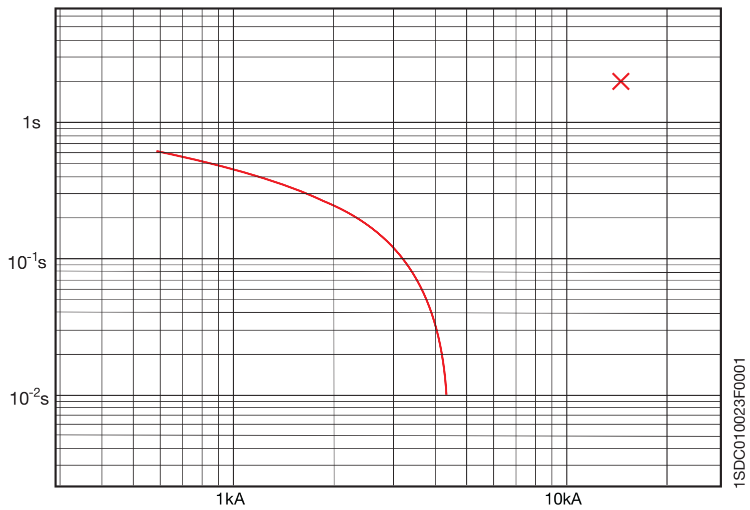
where:
- U_r is the rated voltage of the transformer [V];
- Z_{Net} is the short-circuit impedance of the network [Ω];
- Z_t is the short-circuit impedance of the transformer; from the rated power of the transformer (S_r [VA]) and the percentage short-circuit voltage (u_k%) it is equal to:

$$Z_t = \frac{u_k\%}{100}\cdot\frac{U_r^2}{S_r} \quad [\Omega] \qquad (2)$$

Considering the upstream short-circuit power of the network to be infinite (Z_{Net}=0), formula (1) becomes:

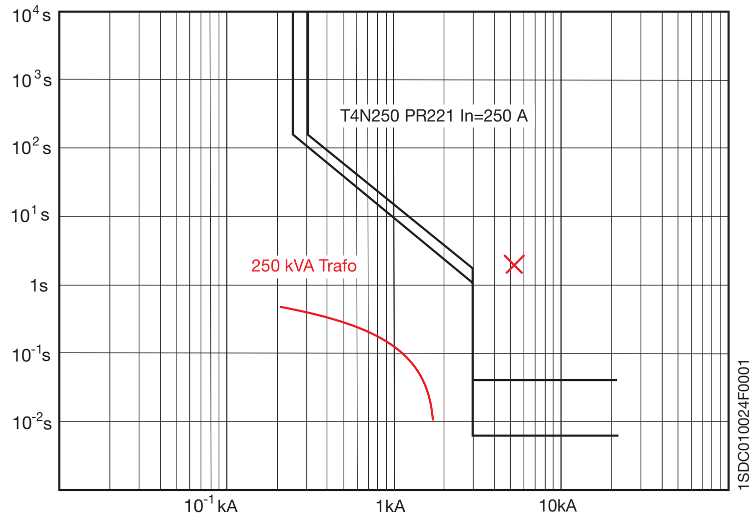
$$I_k = \frac{U_r}{\sqrt{3}\cdot(Z_t)} = \frac{U_r}{\sqrt{3}\cdot\left(\frac{u_k\%}{100}\cdot\frac{U_r^2}{S_r}\right)} = \frac{100\, S_r}{\sqrt{3}\cdot u_k\%\cdot U_r} \quad [A] \qquad (3)$$

The diagram below shows the inrush current curve for a 20/0.4 kV of 400 kVA transformer (u_k% = 4 %) and the point referred to the thermal ability to withstand the short-circuit current (Ik; 2 sec.).



3 Protection of electrical equipment

In summary: for the correct protection of the transformer and to avoid unwanted trips, the trip curve of the protection device must be above the inrush current curve and below the overload point.
The diagram below shows a possible position of the time-current curve of an upstream protection device of a 690/400 V, 250 kVA transformer with u_k% = 4 %.



Criteria for the selection of protection devices

For the protection at the LV side of MV/LV transformers, the selection of a circuit-breaker shall take into account:
- the rated current at LV side of the protected transformer (this value is the reference value for the rated current of the circuit-breaker and the setting of the protections);
- the maximum short-circuit current at the point of installation (this value determines the minimum breaking capacity (I_{cu}/I_{cs}) of the protection device).

MV/LV unit with single transformer
The rated current at the LV side of the transformer (I_r) is determined by the following formula:

$$I_r = \frac{1000\cdot S_r}{\sqrt{3}\cdot U_{r20}} \quad [A] \qquad (4)$$

where:
- S_r is the rated power of the transformer [kVA];
- U_{r20} is the rated LV no-load voltage of the transformer [V].

3 Protection of electrical equipment

The full voltage three-phase short-circuit current (I_k), at the LV terminals of the transformer, can be expressed as (assuming that the short-circuit power of the network is infinite):

$$I_k = \frac{100 \cdot I_r}{u_k\%} \text{ [A]} \qquad (5)$$

where:
$u_k\%$ is the short-circuit voltage of the transformer, in %.

The protection circuit-breaker must have: (*)
$I_n \geq I_r$;
I_{cu} (I_{cs}) $\geq I_k$.

If the short-circuit power of the upstream network is not infinite and cable or busbar connections are present, it is possible to obtain a more precise value for I_k by using formula (1), where Z_{Net} is the sum of the impedance of the network and of the impedance of the connection.

MV/LV substation with more than one transformer in parallel
For the calculation of the rated current of the transformer, the above applies (formula 4).

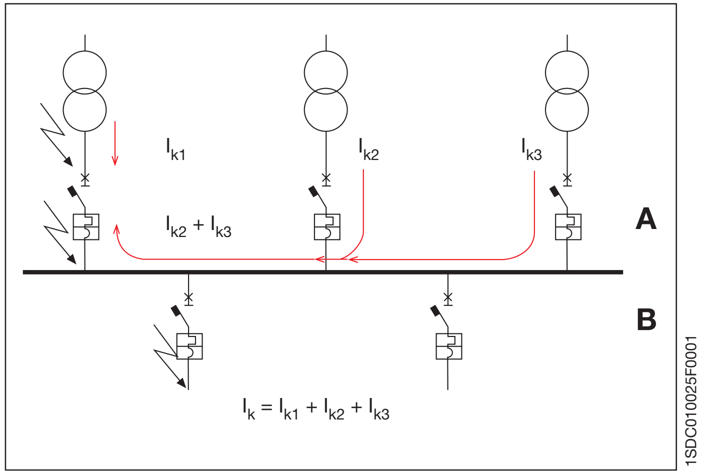
The breaking capacity of each protection circuit-breaker on the LV side shall be higher than the short-circuit current equivalent to the short-circuit current of each equal transformer multiplied by the number of them minus one.
As can be seen from the diagram below, in the case of a fault downstream of a transformer circuit-breaker (circuit-breaker A), the short-circuit current that flows through the circuit-breaker is equal to the contribution of a single transformer. In the case of a fault upstream of the same circuit-breaker, the short-circuit current that flows is equal to the contribution of the other two transformers in parallel.

(*) To carry out correct protection against overload it is advisable to use thermometric equipment or other protection devices able to monitor temperature inside transformers.

3 Protection of electrical equipment

For a correct dimensioning, a circuit-breaker with a breaking capacity higher than twice the short-circuit current of one of the transformers must be chosen (assuming that all the transformers are equal and the loads are passive).

The circuit-breakers positioned on the outgoing feeders (circuit-breakers B) shall have a breaking capacity higher than the sum of the short-circuit currents of the three transformers, according to the hypothesis that the upstream network short-circuit power is 750 MVA and the loads are passive.



3 Protection of electrical equipment

Selection of the circuit-breaker

The following tables show some possible choices of ABB SACE circuit-breakers, according to the characteristics of the transformer to be protected.

Table 1: Protection and switching of 230 V transformers

Transformer S_r [kVA]	u_k [%]	Trafo I_r [A]	Busbar I_b [A]	Trafo feeder I_k [kA]	Circuit-breaker "A" (LV side) ABB SACE Circuit-breaker	Release size	Release setting	Busbar I_k [kA]	32 A	63 A	125 A	160 A	250 A	400 A
1 x 63	4	158	158	3.9	T1B160	In=160	1	3.9	S200		T1B160			
2 x 63		158	316	3.9	T1B160	In=160	1	7.9	S200		T1B160		T3N250	
1 x 100	4	251	251	6.3	T4N320	In=320	0.8	6.3	S200		T1B160			
2 x 100		251	502	6.2	T4N320	In=320	0.8	12.5	S200M		T1B160		T3N250	T5N400
1 x 125	4	314	314	7.8	T5N400	In=400	0.8	7.8	S200		T1B160		T3N250	
2 x 125		314	628	7.8	T5N400	In=400	0.8	15.6	S200P		T1B160		T3N250	T5N400
1 x 160	4	402	402	10.0	T5N630	In=630	0.64	10.0	S200		T1B160		T3N250	
2 x 160		402	803	9.9	T5N630	In=630	0.64	19.9	T1B160				T3N250	T5N400
1 x 200	4	502	502	12.5	T5N630	In=630	0.8	12.5	S200M		T1B160		T3N250	T5N400
2 x 200		502	1004	12.4	T5N630	In=630	0.8	24.8	T1B160				T3N250	T5N400
1 x 250	4	628	628	15.6	T5N630	In=630	1	15.6	S200P		T1B160		T3N250	T5N400
2 x 250		628	1255	15.4	T5N630	In=630	1	30.9	T1C160				T3N250	T5N400
1 x 315	4	791	791	19.6	T6N800	In=800	1	19.6	T1B160				T3N250	T5N400
2 x 315		791	1581	19.4	T6N800	In=800	1	38.7	T1C160				T3N250	T5N400
1 x 400	4	1004	1004	24.8	S7S1250/E1B1250	In=1250	0.85/0.825	24.8	T1B160				T3N250	T5N400
2 x 400		1004	2008	24.5	S7S1250/E1B1250	In=1250	0.85/0.825	48.9	T1N160				T3N250	T5N400
1 x 500	4	1255	1255	30.9	S7S1600/E2B1600	In=1600	0.8	30.9	T1C160				T3N250	T5N400
2 x 500		1255	2510	30.4	S7S1600/E2B1600	In=1600	0.8	60.7	T2N160				T3S250	T5N400
1 x 630		1581	1581	38.7	S7S1600/E2B1600	In=1600	1	38.7	T1C160				T3N250	T5N400
2 x 630	4	1581	3163	37.9	S7S1600/E2B1600	In=1600	1	75.9	T2S160				T3S250	T5S400
3 x 630		1581	4744	74.4	S7S1600/E3S1600	In=1600	1	111.6	T2L160				T4L250	T5L400
1 x 800		2008	2008	39.3	E3N2500	In=2500	0.825	39.3	T1C160				T3N250	T5N400
2 x 800	5	2008	4016	38.5	E3N2500	In=2500	0.825	77.0	T2S160				T3S250	T5S400
3 x 800		2008	6025	75.5	E3H2500	In=2500	0.825	113.2	T2L160				T4L250	T5L400
1 x 1000		2510	2510	48.9	E3N3200	In=3200	0.8	48.9	T1N160				T3N250	T5N400
2 x 1000	5	2510	5020	47.7	E3N3200	In=3200	0.8	95.3	T4L250				T4H250	T5H400
3 x 1000		2510	7531	93.0	E3H3200	In=3200	0.8	139.5	T2H160				T4L250	T5L400
1 x 1250		3138	3138	60.7	E3N3200	In=3200	1	60.7	T4L250				T3S250	T5N400
2 x 1250	5	3138	6276	58.8	E3N3200	In=3200	1	117.7	T2N160				T4L250	T5L400
3 x 1250		3138	9413	114.1	S8V3200/E4V3200	In=3200	1	171.2	T2L160				T4L250	T5L400

3.4 Protection and switching of transformers

3 Protection of electrical equipment

Circuit-breaker "B" (Feeder circuit-breaker) – Feeder circuit-breaker type and rated current

S_r [kVA]	630 A	800 A	1000 A	1250 A	1600 A	2000 A	2500 A	3200 A	4000 A
1 x 63									
2 x 63									
1 x 100									
2 x 100									
1 x 125									
2 x 125									
1 x 160									
2 x 160	T5N630								
1 x 200									
2 x 200	T5N630								
1 x 250									
2 x 250	T5N630	T6N800							
1 x 315	T5N630								
2 x 315	T5N630	T6N800	S7S1250/E1B1000	S7S1250/E1B1250					
1 x 400	T5N630	T6N800							
2 x 400	T5N630	T6N800	S7S1250/E1N1000	S7S1250/E1N1250	S7S1600/E1N1600				
1 x 500	T5N630	T6N800							
2 x 500	T5N630	T6N800	S7S1250/E2N1000	S7S1250/E2N1250	S7S1600/E2N1600	E2N2000			
1 x 630	T5N630	T6N800	S7S1250/E1B1000	S7S1250/E1B1250					
2 x 630	T5S630	T6S800	S7S1250/E2S1000	S7S1250/E2S1250	S7S1600/E2S1600	E2S2000	E3H2500		
3 x 630	T5L630	T6L800	S7L1250/E3V1250	S7L1250/E3V1250	S7L1600/E3V1600	E3V2000	E3V2500	E4V3200	
1 x 800	T5N630	T6N800	S7S1250/E1B1000	S7S1250/E1B1250	S7S1600/E2B1600				
2 x 800	T5S630	T6S800	S7S1250/E2S1000	S7S1250/E2S1250	S7S1600/E2S1600	E2S2000	E3H2500	E3H3200	
3 x 800	T5L630	T6L800	S7L1250/E3V1250	S7L1250/E3V1250	S7L1600/E3V1600	E3V2000	E3V2500	E4V3200	
1 x 1000	T5N630	T6N800	S7S1250/E1N1000	S7S1250/E1N1250	S7S1600/E1N1600	E2N2000			
2 x 1000	T5H630	T6H800	S7H1250/E3H1000	S7H1250/E3H1250	S7H1600/E3H1600	E3H2000	E3H2500	E3H3200	E4H4000
3 x 1000	T5L630	T6L800	S7L1250		S7L1600	E4V3200	E4V3200	E4V3200	E4V4000
1 x 1250	T5N630	T6N800	S7S1250/E2N1000	S7S1250/E2N1250	S7S1600/E2N1600	E2N2000	E3N2500		
2 x 1250	T5L630	T6L800	S7L1250/E3V1250	S7L1250/E3V1250	S7L1600/E3V1600	E3V2000	E4V2500	E4V3200	E4V4000
3 x 1250	T5L630	T6L800	S7L1250		S7L1600				

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3 Protection of electrical equipment

Table 2: Protection and switching of 400 V transformers

Transformer				Circuit-breaker “A” (LV side)											
S_r	u_k	Trafo I_r	Busbar I_b	Trafo feeder I_k	ABB SACE Circuit-breaker	Release		Busbar I_k							
[kVA]	[%]	[A]	[A]	[kA]		size	setting	[kA]	32 A	63 A	125 A	160 A	250 A	400 A
1 x 63	4	91	91	2.2	T1B/T2N160	In=100	0.96	2.2	S200					
2 x 63		91	182	2.2	T1B/T2N160	In=100	0.96	4.4	S200		T1B160			
1 x 100	4	144	144	3.6	T1B/T2N160	In=160	0.92	3.6	S200		T1B160			
2 x 100		144	288	3.6	T1B/T2N160	In=160	0.92	7.2	S200		T1B160			
1 x 125	4	180	180	4.5	T3N250	In=250	0.72	4.5	S200		T1B160			
2 x 125		180	360	4.4	T3N250	In=250	0.72	8.8	S200		T1B160			
1 x 160	4	231	231	5.7	T3N250	In=250	0.94	5.7	S200		T1B160			
2 x 160		231	462	5.7	T3N250	In=250	0.94	11.4	T1B160				T3N250	
1 x 200	4	289	289	7.2	T4N320	In=320	0.92	7.2	S200		T1B160		T3N250	
2 x 200		289	578	7.1	T4N320	In=320	0.92	14.2	T1B160				T3N250	T5N400
1 x 250	4	361	361	8.9	T5N400	In=400	0.92	8.9	S200		T1B160		T3N250	
2 x 250		361	722	8.8	T5N400	In=400	0.92	17.6	T4L250				T3N250	T5N400
1 x 315	4	455	455	11.2	T5N630	In=630	0.74	11.2	T2H160				T3N250	T5N400
2 x 315		455	910	11.1	T5N630	In=630	0.74	22.2	T2S160				T3N250	T5N400
1 x 400	4	577	577	14.2	T5N630/T6N630	In=630	0.92	14.2	T4L250				T3N250	T5N400
2 x 400		577	1154	14	T5N630/T6N630	In=630	0.92	28	T4L250				T3N250	T5N400
1 x 500	4	722	722	17.7	T6N800/S7S1250	In=800/1000	0.92/0.74	17.7	T2H160				T3N250	T5N400
2 x 500		722	1444	17.5	T6N800/S7S1250	In=800/1000	0.92/0.74	35.9	T1N160				T3N250	T5N400
1 x 630		909	909	22.3	S7S1250/E1B1000	In=1000	0.925	22.3	T2H160				T3N250	T5N400
2 x 630	4	909	1818	21.8	S7S1250/E1B1000	In=1000	0.925	43.6	T2L160				T3S250	T5S400
3 x 630		909	2727	42.8	S7S1250/E1B1000	In=1000	0.925	64.2	T1N160				T4H250	T5H400
1 x 800		1155	1155	22.6	S7S1250/E1B1250	In=1250	0.925	22.6	T1C160				T3N250	T5N400
2 x 800	5	1155	2310	22.1	S7S1250/E1B1250	In=1250	0.925	44.3	T1N160				T3S250	T5S400
3 x 800		1155	3465	43.4	S7S1250/E1N1250	In=1250	0.925	65	T1C160				T4H250	T5H400
1 x 1000		1443	1443	28.1	S7S1600/E2B1600	In=1600	0.925	28.1	T1B160				T3N250	T5N400
2 x 1000	5	1443	2886	27.4	S7S1600/E2B1600	In=1600	0.925	54.8	T1C160				T4H250	T5H400
3 x 1000		1443	4329	53.5	S7H1600/E2N1600	In=1600	0.925	80.2	T1B160				T4L250	T5L400
1 x 1250		1804	1804	34.9	E2B2000	In=2000	0.925	34.9	T1C160				T3N250	T5N400
2 x 1250	5	1804	3608	33.8	E2B2000	In=2000	0.925	67.7	T2S160				T4H250	T5H400
3 x 1250		1804	5412	65.6	E2S2000	In=2000	0.925	98.4	T2H160				T4L250	T5L400
1 x 1600		2309	2309	35.7	E3N2500	In=2500	0.925	35.7	T2H160				T3N250	T5N400
2 x 1600	6.25	2309	4618	34.6	E3N2500	In=2500	0.925	69.2	T2S160				T4H250	T5H400
3 x 1600		2309	6927	67	E3S2500	In=2500	0.925	100.6	T1C160				T4L250	T5L400
1 x 2000		2887	2887	44.3	E3N3200	In=3200	0.925	44.3	T1N160				T3S250	T5S400
2 x 2000	6.25	2887	5774	42.6	E3N3200	In=3200	0.925	85.1	T2H160				T4L250	T5L400
3 x 2000		2887	8661	81.9	E3H3200	In=3200	0.925	122.8	T2N160				T4V250	T5V400
1 x 2500	6.25	3608	3608	54.8	E4S4000	In=4000	0.925	54.8	T4L250				T4H250	T5H400
1 x 3125	6.25	4510	4510	67.7	E6H5000	In=5000	0.925	67.7	T2H160				T4H250	T5H400

3 Protection of electrical equipment

S_r [kVA]	Circuit-breaker “B” (Feeder circuit-breaker)								
	Feeder circuit-breaker type and rated current								
	630 A	800 A	1000 A	1250 A	1600 A	2000 A	2500 A	3200 A	4000 A
1 x 63									
2 x 63									
1 x 100									
2 x 100									
1 x 125									
2 x 125									
1 x 160									
2 x 160									
1 x 200									
2 x 200									
1 x 250									
2 x 250									
1 x 315									
2 x 315	T5N630								
1 x 400									
2 x 400	T5N630								
1 x 500	T5N630								
2 x 500	T5N630	T6N800							
1 x 630	T5N630	T6N800/E1B800							
2 x 630	T5S630	T6S800/E1N800	S7S1250/E1N1000	S7S1250/E1N1250					
3 x 630	T5H630	T6H800/E2N1000	S7H1250/E2N1000	S7L1250/E2N1250	S7L1600/E2N1600				
1 x 800	T5N630	T6N800/E1B800							
2 x 800	T5S630	T6S800/E1N800	S7S1250/E1N1000	S7S1250/E1N1250	S7S1600/E1N1600				
3 x 800	T5H630	T6H800/E2N1000	S7H1250/E2N1000	S7L1250/E2N1250	S7L1600/E2N1600	E2N2000	E3N2500		
1 x 1000	T5N630	T6N800/E1B800	S7S1250/E1B1000	S7S1250/E1B1250					
2 x 1000	T5H400	T6H800/E2N1000	S7H1250/E2N1000	S7H1250/E2N1250	S7H1600/E2N1600	E2N2000			
3 x 1000	T5L630	T6L800/E2S800	S7L1250/E2N1000	S7L1250/E2S1250	S7L1600/E2S1600	E2S2000	E3H2500	E3H3200	
1 x 1250	T5N630	T6N800/E1B800	S7S1250/E1B1000	S7S1250/E1B1250	S7S1600/E1B1600				
2 x 1250	T5H630	T6H800/E2S800	S7L1250/E2S1000	S7L1250/E2S1250	S7L1600/E2S1600	E2S2000	E3S2500	E3S3200	
3 x 1250	T5L630	T6L800/E3H800	S7L1250/E3H1000	S7L1250/E3H1250	S7L1600/E3H1600	E3H2000	E3H2500	E3H3200	E4H4000
1 x 1600	T5N630	T6N800/E1B800	S7S1250/E1B1000	S7S1250/E1B1250	S7S1600/E1B1600				
2 x 1600	T5H630	T6H800/E2S800	S7L1250/E2S1000	S7L1250/E2S1250	S7L1600/E2S1600	E2S2000	E3S2500	E3S3200	E4S4000
3 x 1600	T5L630	S8V2000/E3V800	S8V2000/E3V1250		S8V2000/E3V1600	E3V2000	E3V2500	E4V3200	E4V4000
1 x 2000	T5S630	T6S800/E1N800	S7S1250/E1N1000	S7S1250/E1N1250	S7S1600/E1N1600	E2N2000			
2 x 2000	T5L630	T6L800/E3H800	S7L1250/E3H1000	S7L1250/E3H1250	S7L1600/E3H1600	E3H2000	E3H2500	E3H3200	E4H4000
3 x 2000	T5V630	E3V800	E3V1250		E3V1600	E3V2000	E3V2500	E4V3200	E4V4000
1 x 2500	T5H630	T6H800/E2N1000	S7H1250/E2N1000	S7H1250/E2N1250	S7H1600/E2N1600	E2N2000	E3N2500	E3N3200	
1 x 3125	T5H630	T6H800/E2S800	S7L1250/E2S1000	S7L1250/E2S1250	S7L1600/E2S1600	E2S2000	E3S2500	E3S3200	E4S4000

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3 Protection of electrical equipment

Table 3: Protection and switching of 440 V transformers

Transformer				Circuit-breaker "A" (LV side)											
S_r	u_k	Trafo I_r	Busbar I_b	Trafo feeder I_k	ABB SACE Circuit-breaker	Release		Busbar I_k							
[kVA]	[%]	[A]	[A]	[kA]		size	setting	[kA]	32 A	63 A	125 A	160 A	250 A	400 A
1 x 63	4	83	83	2.1	T1B/T2N160	In=100	0.9/0.88	2.1	S200					
2 x 63		83	165	2.1	T1B/T2N160	In=100	0.9/0.88	4.1	S200		T1B160			
1 x 100	4	131	131	3.3	T1B/T2N160	In=160	0.85/0.84	3.3	S200					
2 x 100		131	262	3.3	T1B/T2N160	In=160	0.85/0.84	6.5	T1B160					
1 x 125	4	164	164	4.1	T3N/T4N250	In=250	0.7	4.1	S200		T1B160			
2 x 125		164	328	4.1	T3N/T4N250	In=250	0.7	8.1	T1B160				T3N250	
1 x 160	4	210	210	5.2	T3N/T4N250	In=250	0.84	5.2	S200		T1B160			
2 x 160		210	420	5.2	T3N/T4N250	In=250	0.84	10.4	T2L160				T3N250	
1 x 200	4	262	262	6.5	T5N400	In=320	0.82	6.5	T4V250					
2 x 200		262	525	6.5	T5N400	In=320	0.82	12.9	T4L250				T3N250	T5N400
1 x 250	4	328	328	8.1	T5N400	In=400	0.82	8.1	T4L250				T3N250	
2 x 250		328	656	8.1	T5N400	In=400	0.82	16.1	T2H160				T3N250	T5N400
1 x 315	4	413	413	10.2	T5N630	In=630	0.66	10.2	T2L160				T3N250	
2 x 315		413	827	10.1	T5N630	In=630	0.66	20.2	T2S160				T3N250	T5N400
1 x 400	4	525	525	12.9	T5N630	In=630	0.84	12.9	S4L160				T3N250	T5N400
2 x 400		525	1050	12.8	T5N630	In=630	0.84	25.6	T1C160				T3S250	T5N400
1 x 500	4	656	656	16.1	T6N800	In=800	0.84	16.1	T1C160				T3N250	T5N400
2 x 500		656	1312	15.9	T6N800	In=800	0.84	31.7	T1B160				T3S250	T5S400
1 x 630		827	827	20.2	S7S1250/E1B1000	In=1000	0.9	20.2	T1N160				T3N250	T5N400
2 x 630	4	827	1653	19.8	S7S1250/E1B1000	In=1000	0.9	39.7	T1C160				T3S250	T5S400
3 x 630		827	2480	38.9	S7S1250/E1B1000	In=1000	0.9	58.3	T1N160				T4H250	T5H400
1 x 800		1050	1050	20.6	S7S1250/E1B1250	In=1250	0.85	20.6	T1C160				T3N250	T5N400
2 x 800	5	1050	2099	20.1	S7S1250/E1B1250	In=1250	0.85	40.3	T2L160				T4H250	T5H400
3 x 800		1050	3149	39.5	S7S1250/E1B1250	In=1250	0.85	59.2	T1N160				T4H250	T5H400
1 x 1000		1312	1312	25.6	S7S1600/E2B1600	In=1600	0.85/0.825	25.6	T2S160				T3S250	T5N400
2 x 1000	5	1312	2624	24.9	S7S1600/E2B1600	In=1600	0.85/0.825	49.8	T2N160				T4H250	T5H400
3 x 1000		1312	3936	48.6	S7H1600/E2N1600	In=1600	0.85/0.825	72.9	T1N160				T4L250	T5L400
1 x 1250		1640	1640	31.7	E2B2000	In=2000	0.825	31.7	T2S160				T3S250	T5S400
2 x 1250	5	1640	3280	30.8	E2B2000	In=2000	0.825	61.5	T1N160				T4H250	T5H400
3 x 1250		1640	4921	59.6	E2N2000	In=2000	0.825	89.5	T1B160				T4L250	T5L400
1 x 1600		2099	2099	32.5	E3N2500	In=2500	0.85	32.5	T2L160				T3S250	T5S400
2 x 1600	6.25	2099	4199	31.4	E3N2500	In=2500	0.85	62.9	T2S160				T4H250	T5H400
3 x 1600		2099	6298	60.9	E3N2500	In=2500	0.85	91.4	T2S160				T4L250	T5L400
1 x 2000		2624	2624	40.3	E3N3200	In=3200	0.85	40.3	T2L160				T4H250	T5H400
2 x 2000	6.25	2624	5249	38.7	E3N3200	In=3200	0.85	77.4	T2N160				T4L250	T5L400
3 x 2000		2624	7873	74.4	E3S3200	In=3200	0.85	111.7	T2H160				T4V250	T5V400
1 x 2500	6.25	3280	3280	49.8	E4S4000	In=4000	0.85	49.8	T2L160				T4H250	T5H400
1 x 3125	6.25	4100	4100	61.5	E6H5000	In=5000	0.85	61.5	T2S160				T4H250	T5H400

3 Protection of electrical equipment

	Circuit-breaker "B" (Feeder circuit-breaker)								
	Feeder circuit-breaker type and rated current								
S_r [kVA]	630 A	800 A	1000 A	1250 A	1600 A	2000 A	2500 A	3200 A	4000 A
1 x 63									
2 x 63									
1 x 100									
2 x 100									
1 x 125									
2 x 125									
1 x 160									
2 x 160									
1 x 200									
2 x 200									
1 x 250									
2 x 250									
1 x 315									
2 x 315	T5N630								
1 x 400									
2 x 400	T5N630								
1 x 500									
2 x 500	T5S630	T6S800							
1 x 630	T5N630								
2 x 630	T5S630	T6S800/E1B800	S7S1250/E1B1000	S7S1250/E1B1250					
3 x 630	T5H630	T6L800/E2N1000	S7L1250/E2N1000	S7L1250/E2N1250	S7L1600/E2N1600	E2N2000			
1 x 800	T5N630	T6N800/E1B800							
2 x 800	T5H630	T6S800/E1B800	S7H1250/E1B1000	S7H1250/E1B1250	S7H1600/E1B1600				
3 x 800	T5H630	T6L800/E2N1000	S7L1250/E2N1000	S7L1250/E2N1250	S7L1600/E2N1600	E2N2000	E3N2500	E3N3200	E4S4000
1 x 1000	T5N630	T6N800/E1B800							
2 x 1000	T5H630	T6L800/E1N800	S7S1250/E1N1000	S7H1250/E1N1250	S7H1600/E1N1600	E2N2000			
3 x 1000	T5L630	T6L800/E2S800	S7L1250/E2S1000	S7L1250/E2S1250	S7L1600/E2S1600	E2S2000	E3S2500	E3S3200	
1 x 1250	T5S630	T6S800/E1B800	S7S1250/E1B1000	S7S1250/E1B1250					
2 x 1250	T5H630	T6L800/E2N1000	S7H1250/E2N1000	S7L1250/E2N1250	S7L1600/E2N1600	E2N2000	E3N2500		
3 x 1250	T5L630	S8V2000/E3H1000		S8V2000/E3H1250	S8V2000/E3H1600	E3H2000	E3H2500	E3H3200	E4H4000
1 x 1600	T5S630	T6S800/E1B800	S7S1250/E1B1000	S7S1250/E1B1250	S7S1600/E1B1600				
2 x 1600	T5H630	T6L800/E2N1000	S7L1250/E2N1000	S7L1250/E2N1250	S7L1600/E2N1600	E2N2000	E3N2500	E3N3200	
3 x 1600	T5L630	S8V2000/E3H800	S8V2000/E3H1000	S8V2000/E3H1250	S8V2000/E3H1600	E3H2000	E3H2500	E3H3200	E4H4000
1 x 2000	T5H630	T6S800/E1B800	S7H1250/E1B1000	S7H1250/E1B1250	S7H1600/E1B1600	E2B2000			
2 x 2000	T5L630	T6L800/E2S800	S7L1250/E2S1000	S7L1250/E2S1250	S7L1600/E2S1600	E2S2000	E3H2500	E3H3200	E4H4000
3 x 2000	T5V630	E3V800	E3V1250		E3V1600	E3V2000	E3V2500	E3V3200	E4V4000
1 x 2500	T5H630	T6L800/E1N800	S7S1250/E1N1000	S7H1250/E1N1250	S7H1600/E1N1600	E2N2000	E3N2500		
1 x 3125	T5H630	T6L800/E2N1000	S7L1250/E2N1000	S7L1250/E2N1250	S7L1600/E2N1600	E2N2000	E3N2500	E3N3200	

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3 Protection of electrical equipment

Table 4: Protection and switching of 690 V transformers

Transformer				Circuit-breaker "A" (LV side)										
S_r	u_k	Trafo I_r	Busbar I_b	Trafo feeder I_k	ABB SACE Circuit-breaker	Release size	Release setting	Busbar I_k	32 A	63 A	125 A	160 A	250 A	400 A
[kVA]	[%]	[A]	[A]	[kA]				[kA]						
1 x 63	4	53	53	1.3	T1B/T2N160	In=63	0.9/0.88	1.3	T1B160					
2 x 63		53	105	1.3	T1B/T2N160	In=63	0.9/0.88	2.6	T1B160					
1 x 100	4	84	84	2.1	T1B/T2N160	In=100	0.9/0.86	2.1	T1B160					
2 x 100		84	167	2.1	T1B/T2N160	In=100	0.9/0.86	4.2	T1N160					
1 x 125	4	105	105	2.6	T1B/T2N160	In=160	0.7	2.6	T1B160					
2 x 125		105	209	2.6	T1B/T2N160	In=160	0.7	5.2	T1N160					
1 x 160	4	134	134	3.3	T1C/T2N160	In=160	0.9/0.86	3.3	T1C160					
2 x 160		134	268	3.3	T1C/T2N160	In=160	0.9/0.86	6.6	T2S160					
1 x 200	4	167	167	4.2	T3N250/T4N250	In=250	0.7	4.2	T1N160					
2 x 200		167	335	4.1	T3N250/T4N250	In=250	0.7	8.3	T4H250				T4N250	
1 x 250	4	209	209	5.2	T3S250/T4N250	In=250	0.9/0.86	5.2	T4L250					
2 x 250		209	418	5.1	T3S250/T4N250	In=250	0.9/0.86	10.3	T4L250				T4N250	
1 x 315	4	264	264	6.5	T4N320	In=320	0.84	6.5	T4L250					
2 x 315		264	527	6.5	T4N320	In=320	0.84	12.9	T4H250				T4N250	T5N400
1 x 400	4	335	335	8.3	T5N400	In=400	0.86	8.3	T4H250				T4N250	
2 x 400		335	669	8.2	T5N400	In=400	0.86	16.3	T4H250				T4N250	T5N400
1 x 500	4	418	418	10.3	T5N630	In=630	0.68	10.3	T4V250				T4N250	
2 x 500		418	837	10.1	T5N630	In=630	0.68	20.2	T4L250				T4S250	T5S400
1 x 630		527	527	12.9	T5N630	In=630	0.84	12.9	T4S250				T4N250	T5N400
2 x 630	4	527	1054	12.6	T5N630	In=630	0.84	25.3	T4H250				T4H250	T5H400
3 x 630		527	1581	24.8	T5S630	In=630	0.84	37.2	T4S250				T4H250	T5H400
1 x 800		669	669	13.1	T6N800	In=800	0.84	13.1	T4N250				T4N250	T5N400
2 x 800	5	669	1339	12.8	T6N800	In=800	0.84	25.7	T4H250				T4H250	T5H400
3 x 800		669	2008	25.2	T6L800	In=800	0.84	37.7	T4N250				T4H250	T5H400
1 x 1000		837	837	16.3	S7S1250/E1B1000	In=1000	0.85	16.3	T2L160				T4N250	T5N400
2 x 1000	5	837	1673	15.9	S7S1250/E1B1000	In=1000	0.85	31.8	T1N160				T4H250	T5H400
3 x 1000		837	2510	31.0	S7L1250/E1B1000	In=1000	0.85	46.5	T4N250				T4L250	T5L400
1 x 1250		1046	1046	20.2	S7H1250/E1B1250	In=1250	0.85	20.2	T2S160				T4S250	T5S400
2 x 1250	5	1046	2092	19.6	S7S1250/E1B1250	In=1250	0.85	39.2	T4N250				T4H250	T5H400
3 x 1250		1046	3138	38.0	E2B1600	In=1250	0.85	57.1	T2L160				T4L250	T5L400
1 x 1600		1339	1339	20.7	E1B1600	In=1600	0.85	20.7	T4N250				T4S250	T5S400
2 x 1600	6.25	1339	2678	20.1	E1B1600	In=1600	0.85	40.1	T4N250				T4L250	T5L400
3 x 1600		1339	4016	38.9	E2B1600	In=1600	0.85	58.3	T4H250				T4L250	T5L400
1 x 2000		1673	1673	25.7	E2B2000	In=2000	0.85	25.7	T4N250				T4H250	T5H400
2 x 2000	6.25	1673	3347	24.7	E2B2000	In=2000	0.85	49.3	T4H250				T4L250	T5L400
3 x 2000		1673	5020	47.5	E2B2000	In=2000	0.85	71.2	T4H250				T4V250	T5V400
1 x 2500	6.25	2092	2092	31.8	E3N2500	In=2500	0.85	31.8	T4S250				T4H250	T5H400
1 x 3125	6.25	2615	2615	39.2	E3N3200	In=3200	0.825	39.2	T4L250				T4H250	T5H400

3 Protection of electrical equipment

S_r	Circuit-breaker "B" (Feeder circuit-breaker) – Feeder circuit-breaker type and rated current: 630 A	800 A	1000 A	1250 A	1600 A	2000 A	2500 A	3200 A	4000 A
1 x 63									
2 x 63									
1 x 100									
2 x 100									
1 x 125									
2 x 125									
1 x 160									
2 x 160									
1 x 200									
2 x 200									
1 x 250									
2 x 250									
1 x 315									
2 x 315									
1 x 400									
2 x 400									
1 x 500									
2 x 500	T5S630								
1 x 630									
2 x 630	T5H630								
3 x 630	T5H630	E2B1600							
1 x 800									
2 x 800	T5H630	T6L800/E1B800							
3 x 800	T5H630	E2B1600							
1 x 1000	T5N630								
2 x 1000	T5H630	E1B800	S7L1250/E1B1000	S7L1250/E1B1250					
3 x 1000	T5L630	S8V2000/E2N1000		S8V2000/E2N1250	S8V2000/E2N1600	E2N2000			
1 x 1250	T5S630	T6S800/E1B800							
2 x 1250	T5H630	S8H2000/E2B1600							
3 x 1250	T5L630	E2S800	E2S1000	E2S1250	E2S1600	E2S2000			
1 x 1600	T5S630	T6S800/E1B800	E1B1000						
2 x 1600	T5L630	S8V2000/E2B1600				E2B2000			
3 x 1600	T5L630	E2S800	E2S1000	E2S1250	E2S1600	E2S2000	E3N2500	E3N3200	
1 x 2000	T5H630	T6L800/E1B800	S7L1250/E1B1000	S7L1250/E1B1250					
2 x 2000	T5L630	S8V2000/E2N1000	S8V2000/E2N1000	S8V2000/E2N1250	S8V2000/E2N1600	E2N2000	E3N2500		
3 x 2000	T5V630	E3S1000	E3S1000	E3S1250	E3S1600	E3S2000	E3S2500	E3S3200	E4S4000
1 x 2500	T5H630	S7L1250/E1B800	S7L1250/E1B1000	S7L1250/E1B1250	S7L1250/E1B1600				
1 x 3125	T5H630	S8H2000/E2B1600				E2B2000			

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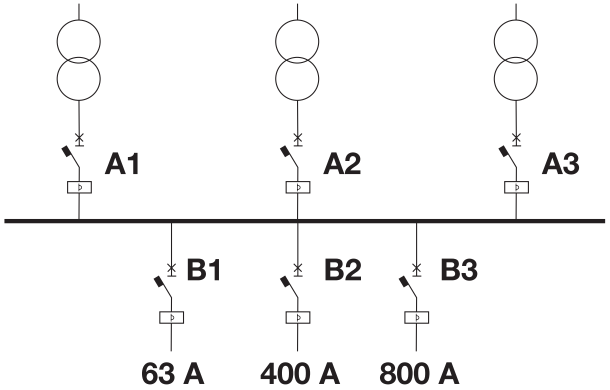
3 Protection of electrical equipment

NOTE

The tables refer to the previously specified conditions; the information for the selection of circuit-breakers is supplied only with regard to the current in use and the prospective short-circuit current. For a correct selection, other factors such as selectivity, back-up protection, the decision to use limiting circuit-breakers etc. must also be considered. Therefore, it is essential that the design engineers carry out precise checks.
It must also be noted that the short-circuit currents given are determined using the hypothesis of 750 MVA power upstream of the transformers, disregarding the impedances of the busbars or the connections to the circuit-breakers.

Example:

Supposing the need to size breakers A1/A2/A3, on the LV side of the three transformers of 630 kVA 20/0.4 kV with u_k% equal to 4% and outgoing feeder circuit-breakers B1/B2/B3 of 63-400-800 A:



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3 Protection of electrical equipment

From Table 2, corresponding to the row relevant to 3x630 kVA transformers, it can be read that:

Level A circuit-breakers (LV side of transformer)

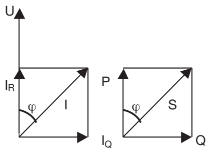
- Trafo I_r (909 A) is the current that flows through the transformer circuit-breakers;
- Busbar I_b (2727 A) is the maximum current that the transformers can supply;
- Trafo Feeder I_k (42.8 kA) is the value of the short-circuit current to consider for the choice of the breaking capacity of each of the transformer circuit-breakers;
- S7S1250 or E1N1000 is the size of the transformer circuit-breaker;
- In (1000 A) is the rated current of the transformer circuit-breaker (electronic release chosen by the user);
- Settings 0.95 and 0.925 indicate the set value of function L of the electronic releases for CBs S7S1250 and E1N1000 respectively.

Level B circuit-breakers (outgoing feeder)

- Busbar I_k (64.2 kA) is the short-circuit current due to the contribution of all three transformers;
- corresponding to 63 A, read circuit-breaker B1 Tmax T2H160;
- corresponding to 400 A, read circuit-breaker B2 Tmax T5H400;
- corresponding to 800 A, read circuit-breaker B3 Isomax S6L800 or E2N1000.

The choice made does not take into account discrimination/back-up requirements. Refer to the relevant chapters for selections appropriate to the various cases.

4.1 General aspects



In alternating current circuits, the current absorbed by the user can be represented by two components:
- the active component I_R, in phase with the supply voltage, is directly correlated to the output (and therefore to the part of electrical energy transformed into energy of a different type, usually electrical with different characteristics, mechanical, light and/or thermal);
- the reactive component I_Q, in quadrature to the voltage, is used to produce the flow necessary for the conversion of powers through the electric or magnetic field. Without this, there could be no flow of power, such as in the core of a transformer or in the air gap of a motor.

In the most common case, in the presence of ohmic-inductive type loads, the total current (I) lags in comparison with the active component I_R.
In an electrical installation, it is necessary to generate and transmit, other than the active power P, a certain reactive power Q, which is essential for the conversion of electrical energy, but not available to the user. The complex of the power generated and transmitted constitutes the apparent power *S*.

Power factor (cosφ) is defined as the ratio between the active component I_R and the total value of the current I; φ is the phase shifting between the voltage U and the current I.
It results:

$$\cos\varphi = \frac{I_R}{I} = \frac{P}{S} \quad (1)$$

The reactive demand factor (tanφ) is the relationship between the reactive power and the active power:

$$\tan\varphi = \frac{Q}{P} \quad (2)$$

4 Power factor correction

Table 1 shows some typical power factors:

Table 1: Typical power factor

Load	**cosφ power factor**	**tanφ reactive demand factor**
Transformers (no load condition)	0.1÷0.15	9.9÷6.6
Motor (full load)	0.7÷0.85	1.0÷0.62
Motor (no load)	0.15	6.6
Metal working apparatuses:		
- Arc welding	0.35÷0.6	2.7÷1.3
- Arc welding compensated	0.7÷0.8	1.0÷0.75
- Resistance welding:	0.4÷0.6	2.3÷1.3
- Arc melting furnace	0.75÷0.9	0.9÷0.5
Fluorescent lamps		
- compensated	0.9	0.5
- uncompensated	0.4÷0.6	2.3÷1.3
Mercury vapour lamps	0.5	1.7
Sodium vapour lamp	0.65÷0.75	1.2÷0.9
AC DC converters	0.6÷0.95	1.3÷0.3
DC drives	0.4÷0.75	2.3÷0.9
AC drives	0.95÷0.97	0.33÷0.25
Resistive load	1	0

The power factor correction is the action increasing the power factor in a specific section of the installation by locally supplying the necessary reactive power, so as to reduce the current value to the equivalent of the power required, and therefore the total power absorbed from the upstream side. Thus, both the line as well as the supply generator can be sized for a lower apparent power value required by the load.
In detail, as shown by Figure 1 and Figure 2, increasing the power factor of the load:
- decreases the relative voltage drop u_{rp} per unit of active power transmitted;
- increases the transmittable active power and decreases the losses, the other dimensioning parameters remaining equal.

4 Power factor correction

Figure 1: Relative voltage drop

Voltage drop per unit of active power transmitted

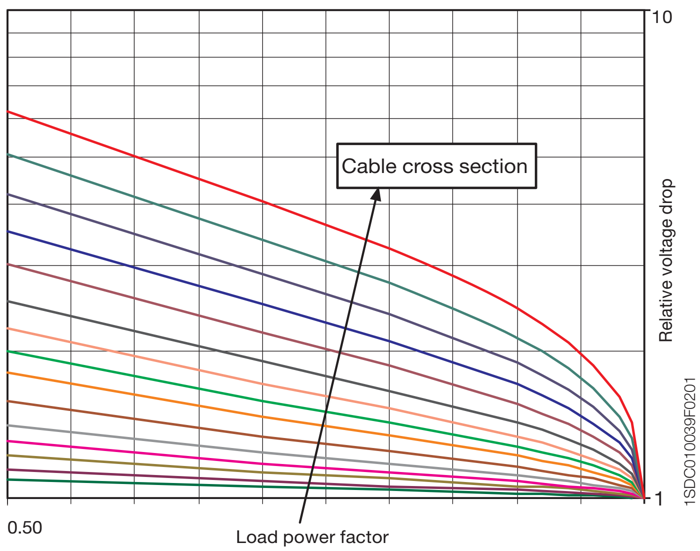
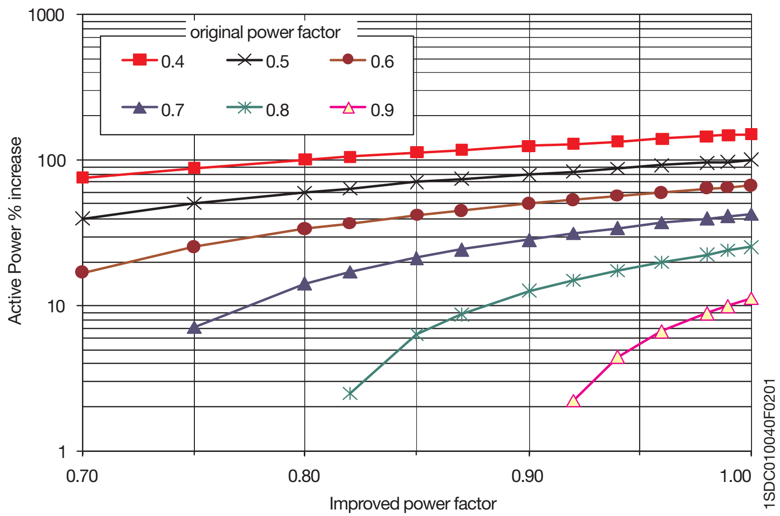


Figure 2: Transmittable active power

Active power increase with equal dimensioning factors



4 Power factor correction

The distribution authority is responsible for the production and transmission of the reactive power required by the user installations, and therefore has a series of further inconveniences which can be summarized as:
- oversizing of the conductors and of the components of the transmission lines;
- higher Joule-effect losses and higher voltage drops in the components and lines.

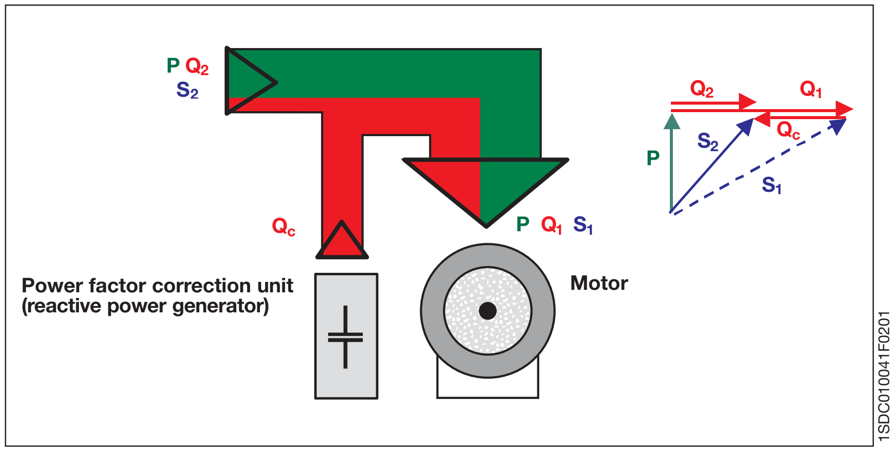
The same inconveniences are present in the distribution installation of the final user. The power factor is an excellent index of the size of the added costs and is therefore used by the distribution authority to define the purchase price of the energy for the final user.
The ideal situation would be to have a cosφ slightly higher than the set reference so as to avoid payment of legal penalties, and at the same time not to risk having, with a cosφ too close to the unit, a leading power factor when the power factor corrected device is working with a low load.
The distribution authority generally does not allow others to supply reactive power to the network, also due to the possibility of unexpected overvoltages.

In the case of a sinusoidal waveform, the reactive power necessary to pass from one power factor cosφ_1 to a power factor cosφ_2 is given by the formula:

$$Q_c = Q_2 - Q_1 = P \cdot (\tan\varphi_1 - \tan\varphi_2) \quad (3)$$

where:

- P is the active power;
- Q_1, φ_1 are the reactive power and the phase shifting before power factor correction;
- Q_2, φ_2 are the reactive power and the phase shifting after power factor correction;
- Q_c is the reactive power for the power factor correction.



4 Power factor correction

Table 2 shows the value of the relationship

$$K_c = \frac{Q_c}{P} = \tan\varphi_1 - \tan\varphi_2 \quad (4)$$

for different values of the power factor before and after the correction.

Table 2: Factor K_c

K_c	$\cos\varphi_2$												
$\cos\varphi_1$	0.80	0.85	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
0.60	0.583	0.714	0.849	0.878	0.907	0.938	0.970	1.005	1.042	1.083	1.130	1.191	1.333
0.61	0.549	0.679	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.157	1.299
0.62	0.515	0.646	0.781	0.810	0.839	0.870	0.903	0.937	0.974	1.015	1.062	1.123	1.265
0.63	0.483	0.613	0.748	0.777	0.807	0.837	0.870	0.904	0.941	0.982	1.030	1.090	1.233
0.64	0.451	0.581	0.716	0.745	0.775	0.805	0.838	0.872	0.909	0.950	0.998	1.058	1.201
0.65	0.419	0.549	0.685	0.714	0.743	0.774	0.806	0.840	0.877	0.919	0.966	1.027	1.169
0.66	0.388	0.519	0.654	0.683	0.712	0.743	0.775	0.810	0.847	0.888	0.935	0.996	1.138
0.67	0.358	0.488	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.966	1.108
0.68	0.328	0.459	0.594	0.623	0.652	0.683	0.715	0.750	0.787	0.828	0.875	0.936	1.078
0.69	0.299	0.429	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.907	1.049
0.70	0.270	0.400	0.536	0.565	0.594	0.625	0.657	0.692	0.729	0.770	0.817	0.878	1.020
0.71	0.242	0.372	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
0.72	0.214	0.344	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.186	0.316	0.452	0.481	0.510	0.541	0.573	0.608	0.645	0.686	0.733	0.794	0.936
0.74	0.159	0.289	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.132	0.262	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.105	0.235	0.371	0.400	0.429	0.460	0.492	0.526	0.563	0.605	0.652	0.713	0.855
0.77	0.079	0.209	0.344	0.373	0.403	0.433	0.466	0.500	0.537	0.578	0.626	0.686	0.829
0.78	0.052	0.183	0.318	0.347	0.376	0.407	0.439	0.474	0.511	0.552	0.599	0.660	0.802
0.79	0.026	0.156	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.634	0.776
0.80		0.130	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.608	0.750
0.81		0.104	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82		0.078	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.556	0.698
0.83		0.052	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.530	0.672
0.84		0.026	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
0.85			0.135	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86			0.109	0.138	0.167	0.198	0.230	0.265	0.302	0.343	0.390	0.451	0.593
0.87			0.082	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88			0.055	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
0.89			0.028	0.057	0.086	0.117	0.149	0.184	0.221	0.262	0.309	0.370	0.512
0.90				0.029	0.058	0.089	0.121	0.156	0.193	0.234	0.281	0.342	0.484

4 Power factor correction

Example

Supposing the need to change from 0.8 to 0.93 the power factor of a three-phase installation (U_r= 400 V) which absorbs an average power of 300 kW. From Table 2, at the intersection of the column corresponding to the final power factor (0.93), and the row corresponding to the starting power factor (0.8), the value of K_c (0.355) can be read. The reactive power Q_c which must be generated locally shall be:

$$Q_c = K_c \cdot P = 0.355 \cdot 300 = 106.5 \text{ Kvar}$$

Due to the effect of power factor correction, the current absorbed decreases from 540 A to 460 A (a reduction of approximately 15%).

Characteristics of power factor correction capacitor banks

The most economical means of increasing the power factor, especially for an installation which already exists, is installing capacitors.
Capacitors have the following advantages:
- low cost compared with synchronous compensators and electronic power converters;
- ease of installation and maintenance;
- reduced losses (less than 0.5 W/kvar in low voltage);
- the possibility of covering a wide range of powers and different load profiles, simply supplying in parallel different combinations of components, each with a relatively small power.

The disadvantages are sensitivity to overvoltages and to the presence of non-linear loads.

The Standards applicable to power factor correction capacitors are as follows:

- IEC 60831-1 *"Shunt power capacitors of the self-healing type for a.c. systems having a rated voltage up to and including 1000 V - Part 1: General - Performance, testing and rating - Safety requirements - Guide for installation and operation"*;

- IEC 60931-1 *"Shunt power capacitors of the non-self-healing type for a.c. systems having a rated voltage up to and including 1000 V - Part 1: General-Performance, testing and rating - Safety requirements - Guide for installation and operation"*.

4 Power factor correction

The characteristics of a capacitor, given on its nameplate, are:

- rated voltage U_r, which the capacitor must withstand indefinitely;
- rated frequency f_r (usually equal to that of the network);
- rated power Q_C, generally expressed in kvar (reactive power of the capacitor bank).

From this data it is possible to find the size characteristics of the capacitors by using the following formulae (5):

	Single-phase connection	Three-phase star-connection	Three-phase delta-connection
Capacity of the capacitor bank	$C = \frac{Q_c}{2\pi f_r \cdot U_r^2}$	$C = \frac{Q_c}{2\pi f_r \cdot U_r^2}$	$C = \frac{Q_c}{2\pi f_r \cdot U_r^2 \cdot 3}$
Rated current of the components	$I_{rc} = 2\pi f_r \cdot C \cdot U_r$	$I_{rc} = 2\pi f_r \cdot C \cdot U_r / \sqrt{3}$	$I_{rc} = 2\pi f_r \cdot C \cdot U_r$
Line current	$I_l = I_{rc}$	$I_l = I_{rc}$	$I_l = I_{rc} \cdot \sqrt{3}$

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U_r = line voltage system

In a three-phase system, to supply the same reactive power, the star connection requires a capacitor with a capacitance three times higher than the delta-connected capacitor.

In addition, the capacitor with the star connection results to be subjected to a voltage √3 lower and flows through by a current √3 higher than a capacitor inserted and delta connected.

Capacitors are generally supplied with connected discharge resistance, calculated so as to reduce the residual voltage at the terminals to 75 V in 3 minutes, as stated in the reference Standard.

4.2 Power factor correction method

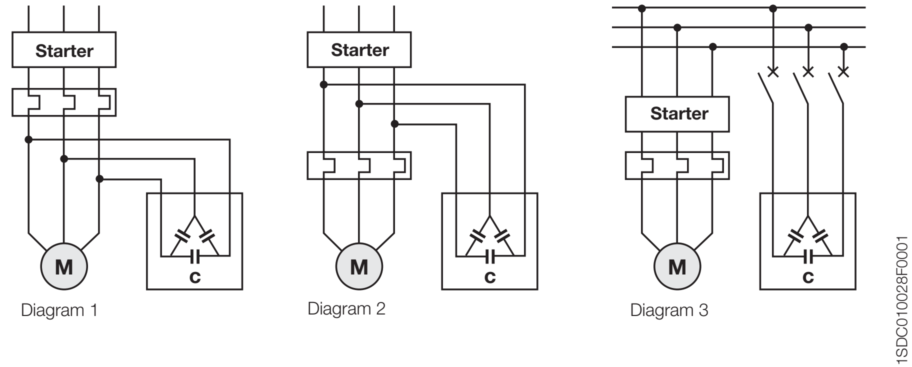
Single PFC

Single or individual power factor correction is carried out by connecting a capacitor of the correct value directly to the terminals of the device which absorbs reactive power.
Installation is simple and economical: capacitors and load can use the same overload and short-circuit protection, and are connected and disconnected simultaneously.
The adjustment of cosφ is systematic and automatic with benefit not only to the energy distribution authority, but also to the whole internal distribution system of the user.
This type of power factor correction is advisable in the case of large users with constant load and power factor and long connection times.
Individual PFC is usually applied to motors and fluorescent lamps. The capacitor units or small lighting capacitors are connected directly to loads.

4 Power factor correction

Individual PFC of motors

The usual connection diagrams are shown in the following figure:



In the case of direct connection (diagrams 1 and 2) there is a risk that after disconnection of the supply, the motor will continue to rotate (residual kinetic energy) and self-excite with the reactive energy supplied by the capacitor bank, acting as an asynchronous generator. In this case, the voltage is maintained on the load side of the switching and control device, with the risk of dangerous overvoltages of up to twice the rated voltage value.

However, in the case of diagram 3, to avoid the risk detailed above, the normal procedure is to connect the PFC bank to the motor only when it is running, and to disconnect it before the disconnection of the motor supply.

As a general rule, for a motor with power P_r, it is advisable to use a PFC with reactive power Q_c below 90% of the reactive power absorbed by the no-load motor Q_0, at rated voltage U_r, to avoid a leading power factor.
Considering that under no-load conditions, the current absorbed I_0 [A] is solely reactive, if the voltage is expressed in volts, it results:

$$Q_c = 0.9 \cdot Q_0 = 0.9 \cdot \frac{\sqrt{3} \cdot U_r \cdot I_0}{1000} \text{ [kvar] (6)}$$

The current I_0 is generally given in the documentation supplied by the manufacturer of the motor.

4 Power factor correction

Table 3 shows the values of reactive power for power factor correction of some ABB motors, according to the power and the number of poles.

Table 3: Reactive power for power factor motor correction

P_r [kW]	Q_c [kvar]	Before PFC cosφ_r	Before PFC I_r [A]	After PFC cosφ_2	After PFC I_2 [A]
400V / 50 Hz / 2 poles / 3000 r/min					
7.5	2.5	0.89	13.9	0.98	12.7
11	2.5	0.88	20	0.95	18.6
15	5	0.9	26.5	0.98	24.2
18.5	5	0.91	32	0.98	29.7
22	5	0.89	38.5	0.96	35.8
30	10	0.88	53	0.97	47.9
37	10	0.89	64	0.97	58.8
45	12.5	0.88	79	0.96	72.2
55	15	0.89	95	0.97	87.3
75	15	0.88	131	0.94	122.2
90	15	0.9	152	0.95	143.9
110	20	0.86	194	0.92	181.0
132	30	0.88	228	0.95	210.9
160	30	0.89	269	0.95	252.2
200	30	0.9	334	0.95	317.5
250	40	0.92	410	0.96	391.0
315	50	0.92	510	0.96	486.3
400V / 50 Hz / 4 poles / 1500 r/min					
7.5	2.5	0.86	14.2	0.96	12.7
11	5	0.81	21.5	0.96	18.2
15	5	0.84	28.5	0.95	25.3
18.5	7.5	0.84	35	0.96	30.5
22	10	0.83	41	0.97	35.1
30	15	0.83	56	0.98	47.5
37	15	0.84	68	0.97	59.1
45	20	0.83	83	0.97	71.1
55	20	0.86	98	0.97	86.9
75	20	0.86	135	0.95	122.8
90	20	0.87	158	0.94	145.9
110	30	0.87	192	0.96	174.8
132	40	0.87	232	0.96	209.6
160	40	0.86	282	0.94	257.4
200	50	0.86	351	0.94	320.2
250	50	0.87	430	0.94	399.4
315	60	0.87	545	0.93	507.9

4 Power factor correction

P_r [kW]	Q_c [kvar]	Before PFC cosφ_r	Before PFC I_r [A]	After PFC cosφ_2	After PFC I_2 [A]
400V / 50 Hz / 6 poles / 1000 r/min					
7.5	5	0.79	15.4	0.98	12.4
11	5	0.78	23	0.93	19.3
15	7.5	0.78	31	0.94	25.7
18.5	7.5	0.81	36	0.94	30.9
22	10	0.81	43	0.96	36.5
30	10	0.83	56	0.94	49.4
37	12.5	0.83	69	0.94	60.8
45	15	0.84	82	0.95	72.6
55	20	0.84	101	0.96	88.7
75	25	0.82	141	0.93	123.9
90	30	0.84	163	0.95	144.2
110	35	0.83	202	0.94	178.8
132	45	0.83	240	0.95	210.8
160	50	0.85	280	0.95	249.6
200	60	0.85	355	0.95	318.0
250	70	0.84	450	0.94	404.2
315	75	0.84	565	0.92	514.4
400V / 50 Hz / 8 poles / 750 r/min					
7.5	5	0.7	18.1	0.91	13.9
11	7.5	0.76	23.5	0.97	18.4
15	7.5	0.82	29	0.97	24.5
18.5	7.5	0.79	37	0.93	31.5
22	10	0.77	45	0.92	37.5
30	12.5	0.79	59	0.93	50.0
37	15	0.78	74	0.92	62.8
45	20	0.78	90	0.93	75.4
55	20	0.81	104	0.93	90.2
75	30	0.82	140	0.95	120.6
90	30	0.82	167	0.93	146.6
110	35	0.83	202	0.94	178.8
132	50	0.8	250	0.93	214.6

4 Power factor correction

Example

For a three-phase asynchronous motor, 110 kW (400 V - 50 Hz - 4 poles), the PFC power suggested in the table is 30 kvar.

Individual power factor correction of three-phase transformers

A transformer is an electrical device of primary importance which, due to the system requirements, is often constantly in service.
In particular, in installations constituted by several transformer substations, it is advisable to carry out power factor correction directly at the transformer.
In general, the PFC power (Q_c) for a transformer with rated power S_r [kVA] should not exceed the reactive power required under minimum reference load conditions.
Reading the data from the transformer nameplate, the percentage value of the no-load current i_0%, the percentage value of the short-circuit voltage u_k%, the iron losses P_{fe} and the copper losses P_{cu} [kW], the PFC power required is approximately:

$$Q_c = \sqrt{\left(\frac{i_0\%}{100}\cdot S_r\right)^2 - P_{fe}^2} + K_L^2 \cdot \sqrt{\left(\frac{u_k\%}{100}\cdot S_r\right)^2 - P_{cu}^2} \approx \left(\frac{i_0\%}{100}\cdot S_r\right) + K_L^2 \cdot \left(\frac{u_k\%}{100}\cdot S_r\right) \text{ [kvar] } (7)$$

where K_L is the load factor, defined as the relationship between the minimum reference load and the rated power of the transformer.

Example

Supposing the need for PFC of a 630 kVA oil-distribution transformer which supplies a load which is less than 60% of its rated power.
From the data on the transformer nameplate:
i_0% = 1.8%
u_k% = 4%
P_{cu} = 8.9 kW
P_{fe} = 1.2 kW
The PFC power of the capacitor bank connected to the transformer is:

$$Q_c = \sqrt{\left(\frac{i_0\%}{100}\cdot S_r\right)^2 - P_{fe}^2} + K_L^2 \cdot \sqrt{\left(\frac{u_k\%}{100}\cdot S_r\right)^2 - P_{cu}^2} = \sqrt{\left(\frac{1.8\%}{100}\cdot 630\right)^2 - 1.2^2} + 0.6^2 \cdot \sqrt{\left(\frac{4\%}{100}\cdot 630\right)^2 - 8.9^2} = 19.8 \text{ kvar}$$

while, when using the simplified formula, the result is:

$$Q_c = \left(\frac{i_0\%}{100}\cdot S_r\right) + K_L^2 \cdot \left(\frac{u_k\%}{100}\cdot S_r\right) = \left(\frac{1.8\%}{100}\cdot 630\right) + 0.6^2 \cdot \left(\frac{4\%}{100}\cdot 630\right) = 20.4 \text{ kvar}$$

4 Power factor correction

Table 4 shows the reactive power of the capacitor bank Q_C [kvar] to be connected on the secondary side of an ABB transformer, according to the different minimum estimated load levels.

Table 4: PFC reactive power for ABB transformers

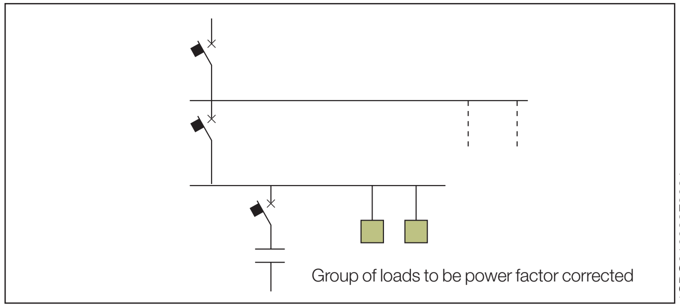
S_r [kVA]	u_k% [%]	i_o% [%]	P_{fe} [kW]	P_{cu} [kW]	Q_c [kvar] load factor K_L 0	0.25	0.5	0.75	1
Oil Distribution Transformer MV-LV									
50	4	2.9	0.25	1.35	1.4	1.5	1.8	2.3	2.9
100	4	2.5	0.35	2.30	2.5	2.7	3.3	4.3	5.7
160	4	2.3	0.48	3.20	3.6	4	5	6.8	9.2
200	4	2.2	0.55	3.80	4.4	4.8	6.1	8.3	11
250	4	2.1	0.61	4.50	5.2	5.8	7.4	10	14
315	4	2	0.72	5.40	6.3	7	9.1	13	18
400	4	1.9	0.85	6.50	7.6	8.5	11	16	22
500	4	1.9	1.00	7.40	9.4	11	14	20	28
630	4	1.8	1.20	8.90	11	13	17	25	35
800	6	1.7	1.45	10.60	14	16	25	40	60
1000	6	1.6	1.75	13.00	16	20	31	49	74
1250	6	1.6	2.10	16.00	20	24	38	61	93
1600	6	1.5	2.80	18.00	24	30	47	77	118
2000	6	1.2	3.20	21.50	24	31	53	90	142
2500	6	1.1	3.70	24.00	27	37	64	111	175
3150	7	1.1	4.00	33.00	34	48	89	157	252
4000	7	1.4	4.80	38.00	56	73	125	212	333
Cast Resin Distribution Transformer MV-LV									
100	6	2.3	0.50	1.70	2.2	2.6	3.7	5.5	8
160	6	2	0.65	2.40	3.1	3.7	5.5	8.4	12
200	6	1.9	0.85	2.90	3.7	4.4	6.6	10	15
250	6	1.8	0.95	3.30	4.4	5.3	8.1	13	19
315	6	1.7	1.05	4.20	5.3	6.4	9.9	16	24
400	6	1.5	1.20	4.80	5.9	7.3	12	19	29
500	6	1.4	1.45	5.80	6.8	8.7	14	23	36
630	6	1.3	1.60	7.00	8	10	17	29	45
800	6	1.1	1.94	8.20	8.6	12	20	35	56
1000	6	1	2.25	9.80	9.7	13	25	43	69
1250	6	0.9	3.30	13.00	11	15	29	52	85
1600	6	0.9	4.00	14.50	14	20	38	67	109
2000	6	0.8	4.60	15.50	15	23	45	82	134
2500	6	0.7	5.20	17.50	17	26	54	101	166
3150	8	0.6	6.00	19.00	18	34	81	159	269

Example

For a 630 kVA oil-distribution transformer with a load factor of 0.5, the necessary PFC power is 17 kvar.

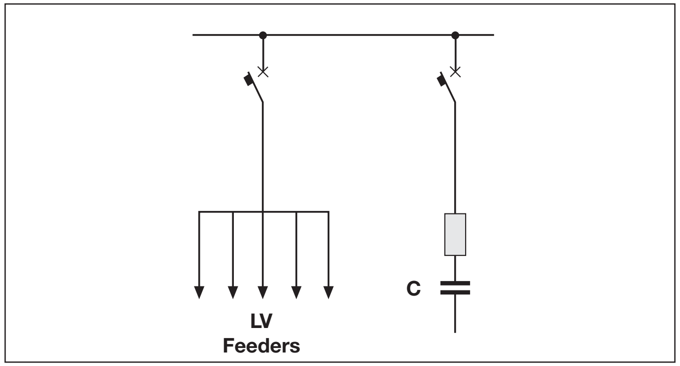
4 Power factor correction

PFC in groups



This consists of local power factor correction of groups of loads with similar functioning characteristics by installing a dedicated capacitor bank.
This method achieves a compromise between the economical solution and the correct operation of the installation, since only the line downstream of the installation point of the capacitor bank is not correctly exploited.

Centralized PFC



The daily load profile is of fundamental importance for the choice of the most suitable type of power factor correction.
In installations, in which not all loads function simultaneously and/or in which some loads are connected for only a few hours a day, the solution of using single PFC becomes unsuitable as many of the capacitors installed could stay idle for long periods.
In the case of installations with many loads occasionally functioning, thus having a high installed power and a quite low average power absorption by the loads which function simultaneously, the use of a single PFC system at the installation origin ensures a remarkable decrease in the total power of the capacitors to be installed.

4 Power factor correction

Centralized PFC normally uses automatic units with capacitor banks divided into several steps, directly installed in the main distribution switchboards; the use of a permanently connected capacitor bank is only possible if the absorption of reactive energy is fairly regular throughout the day.
The main disadvantage of centralized PFC is that the distribution lines of the installation, downstream of the PFC device, must be dimensioned taking into account the full reactive power required by the loads.

4.3 Circuit-breakers for the protection and switching of capacitor banks

The circuit-breakers for the protection and switching of capacitor banks in LV shall:

1. withstand the transient currents which occur when connecting and disconnecting the banks. In particular, the instantaneous magnetic and electronic releases shall not trip due to these peak currents;
2. withstand the periodic or permanent overcurrents due to the voltage harmonics and to the tolerance (+15%) of the rated value of capacity;
3. perform a high number of no-load and on-load operations, also with high frequency;
4. be coordinated with any external device (contactors).

Furthermore, the making and breaking capacity of the circuit-breaker must be adequate to the short- circuit current values of the installation.

Standards IEC 60831-1 and 60931-1 state that:
- the capacitors shall normally function with an effective current value up to 130% of their rated current I_{rc} (due to the possible presence of voltage harmonics in the network);
- a tolerance of +15% on the value of the capacity is allowed.

The maximum current which can be absorbed by the capacitor bank I_{cmax} is:

$$I_{cmax} = 1.3 \cdot 1.15 \cdot \frac{Q_c}{\sqrt{3} \cdot U_r} \approx 1.5 \cdot I_{rc} \quad (8)$$

Therefore:
- the rated current of the circuit-breaker shall be greater than $1.5 \cdot I_{rc}$;
- the overload protection setting shall be equal to $1.5 \cdot I_{rc}$.

The connection of a capacitor bank, similar to a closing operation under short-circuit conditions, associated with transient currents with high frequency (1÷15 kHz), of short duration (1÷3 ms), with high peak (25÷200 I_{rc}).
Therefore:
- the circuit-breaker shall have an adequate making capacity;
- the setting of the instantaneous short-circuit protection must not cause unwanted trips.

4 Power factor correction

The second condition is generally respected:

- for thermomagnetic releases, the magnetic protection shall be set at a value not less than $10 \cdot I_{cmax}$

$$I_3 \geq 10 \cdot I_{cmax} = 15 \cdot I_{rc} = 15 \cdot \frac{Q_r}{\sqrt{3} \cdot U_r} \quad (9)$$

- for electronic releases, the instantaneous short-circuit protection shall be deactivated (I_3 = OFF).

Hereunder, the selection tables for circuit-breakers: for the definition of the version according to the required breaking capacity, refer to Volume 1, Chapter 3.1 “General characteristics”.

The following symbols are used in the tables (they refer to maximum values):

- I_{nCB} = rated current of the protection release [A];
- I_{rc}= rated current of the connected capacitor bank [A];
- Q_C= power of the capacitor bank which can be connected [kvar] with reference to the indicated voltage and 50 Hz frequency;
- N_{mech} = number of mechanical operations;
- f_{mech} = frequency of mechanical operations [op/h];
- N_{el} = number of electrical operations with reference to a voltage of 415 V for Tmax and Isomax moulded-case circuit breakers (Tables 5 and 6), and to a voltage of 440 V for Emax air circuit-breakers (Table 7);
- f_{el} = frequency of electrical operations [op/h].

Table 5: Selection table for Tmax moulded-case circuit-breakers

	I_{nCB}	I_{rc}	Q_C [kvar]				N_{mech}	f_{mech}	N_{el}	f_{el}
CB Type	[A]	[A]	400 V	440 V	500 V	690 V		[op/h]		[op/h]
T1 B-C-N 160	160	107	74	81	92	127	25000	240	8000	120
T2 N-S-H-L 160*	160	107	74	81	92	127	25000	240	8000	120
T3 N-S 250*	250	167	115	127	144	199	25000	240	8000	120
T4 N-S-H-L-V 250	250	167	115	127	144	199	20000	240	8000	120
T4 N-S-H-L-V 320	320	213	147	162	184	254	20000	240	6000	120
T5 N-S-H-L-V 400	400	267	185	203	231	319	20000	120	7000	60
T5 N-S-H-L-V 630	630	420	291	320	364	502	20000	120	5000	60
T6 N-S-H-L 630	630	420	291	320	364	502	20000	120	7000	60
T6 N-S-H-L 800	830	533	369	406	462	637	20000	120	5000	60
T6 N-S-H-L 1000	1000	666	461	507	576	795	20000	120	4000	60

* for plug-in version reduce the maximum power of the capacitor bank by 10%

Table 6: Selection table for SACE Isomax S moulded-case circuit-breakers

	I_{nCB}	I_{rc}		Q_C [kvar]			N_{mech}	f_{mech}	N_{el}	f_{el}
S7 S-H-L 1250	1250	833	577	635	722	996	10000	120	7000	20
S7 S-H-L 1600	1600	1067	739	813	924	1275	10000	120	5000	20
S8 H-V 2000	2000	1333	924	1016	1155	1593	10000	120	3000	20
S8 H-V 2500	2500	1667	1155	1270	1443	1992	10000	120	2500	20
S8 H-V 3200	3200	2133	1478	1626	1847	2550	10000	120	1500	10

4 Power factor correction

Table 7: Selection table for SACE Emax air circuit-breakers

	I_{nCB}	I_{rc}	Q_C [kvar]				N_{mech}	f_{mech}	N_{el}	f_{el}
CB Type	[A]	[A]	400 V	440 V	500 V	690 V		[op/h]		[op/h]
E1 B N	1000	666	461	507	576	795	25000	60	10000	30
E1 B N	1250	834	578	636	722	997	25000	60	10000	30
E2 B-N-S	1250	834	578	636	722	997	25000	60	15000	30
E2 B-N-S	1600	1067	739	813	924	1275	25000	60	12000	30
E2 B-N-S	2000	1334	924	1017	1155	1594	25000	60	10000	30
E3 N-S-H-V	1250	834	578	636	722	997	20000	60	12000	20
E3 N-S-H-V	1600	1067	739	813	924	1275	20000	60	10000	20
E3 N-S-H-V	2000	1334	924	1017	1155	1594	20000	60	9000	20
E3 N-S-H-V	2500	1667	1155	1270	1444	1992	20000	60	8000	20
E3 N-S-H-V	3200	2134	1478	1626	1848	2550	20000	60	6000	20
E4 S-H-V	3200	2134	1478	1626	1848	2550	15000	60	7000	10
E6 H-V	3200	2134	1478	1626	1848	2550	12000	60	5000	10

5 Protection of human beings

5.1 General aspects: effects of current on human beings

Danger to persons due to contact with live parts is caused by the flow of the current through the human body. The effects are:

- **tetanization:** the muscles affected by the current flow involuntary contract and letting go of gripped conductive parts is difficult. Note: very high currents do not usually induce muscular tetanization because, when the body touches such currents, the muscular contraction is so sustained that the involuntary muscle movements generally throw the subject away from the conductive part;

- **breathing arrest:** if the current flows through the muscles controlling the lungs, the involuntary contraction of these muscles alters the normal respiratory process and the subject may die due to suffocation or suffer the consequences of traumas caused by asphyxia;

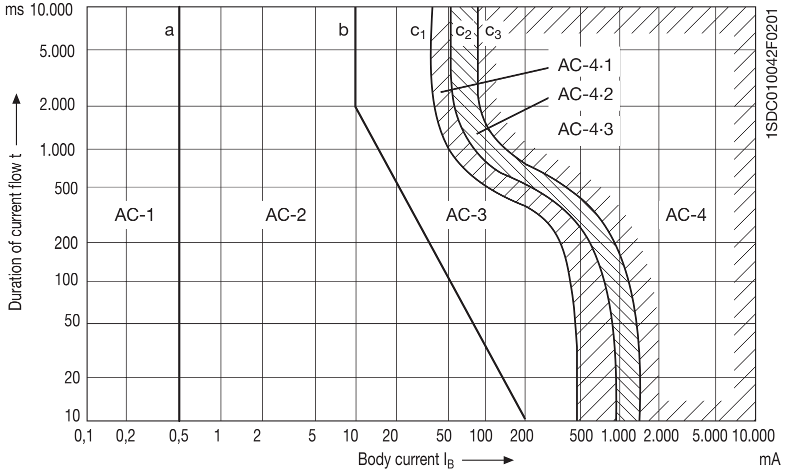
- **ventricular fibrillation:** the most dangerous effect is due to the superposition of the external currents with the physiological ones which, by generating uncontrolled contractions, induce alterations of the cardiac cycle. This anomaly may become an irreversible phenomenon since it persists even when the stimulus has ceased;

- **burns:** they are due to the heating deriving, by Joule effect, from the current passing through the human body.

The Standard IEC 60479-1 *"Effects of current on human being and livestock"* is a guide about the effects of current passing through the human body to be used for the definition of electrical safety requirements. This Standard shows, on a time-current diagram, four zones to which the physiological effects of alternating current (15 ÷100 Hz) passing through the human body have been related.

5 Protection of human beings

Figure 1: Time-current zones of the effects of alternating current on the human body



Zone designation	Zone limits	Physiological effects
AC-1	Up to 0.5 mA line a	Usually no reaction.
AC-2	0.5 mA up to line b*	Usually no harmful physiological effects.
AC-3	Line b up to curve c_1	Usually no organic damage to be expected. Likelihood of cramplike muscular contractions and difficulty in breathing for durations of current-flow longer than 2 s. Reversible disturbances of formation and conduction of impulses in the heart, including atrial fibrillation and transient cardiac arrest without ventricular fibrillation increasing with current magnitude and time.
AC-4	Above curve c_1	Increasing with magnitude and time, dangerous pathophysiological effects such as cardiac arrest, breathing arrest and severe burns may occur in addition to the effects of zone 3.
AC-4.1	c_1 - c_2	Probability of ventricular fibrillation increasing up to about 5%.
AC-4.2	c_2 - c_3	Probability of ventricular fibrillation up to about 50%.
AC-4.3	Beyond curve c_3	Probability of ventricular fibrillation above 50%.

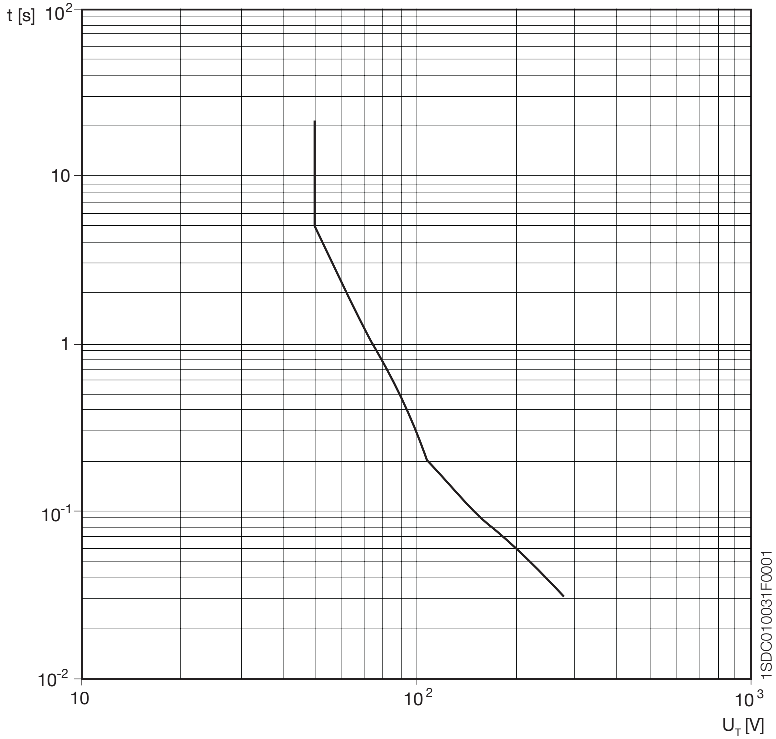
* For durations of current-flow below 10 ms, the limit for the body current for line b remains constant at a value of 200 mA.

This Standard gives also a related figure for direct current.
By applying Ohm's law it is possible to define the safety curve for the allowable voltages, once the human body impedance has been calculated. The electrical impedance of the human body depends on many factors. The above mentioned Standard gives different values of impedance as a function of the touch voltage and of the current path.

5 Protection of human beings

The Standard IEC 60479-1 has adopted precautionary values for the impedance reported in the figure so as to get the time-voltage safety curve (Figure 2) related to the total touch voltage U_T (i.e. the voltage which, due to an insulation failure, is present between a conductive part and a point of the ground sufficiently far, with zero potential).
This represents the maximum no-load touch voltage value; thus, the most unfavorable condition is taken into consideration for safety's sake.

Figure 2: Safety curve



From this safety curve it results that for all voltage values below 50 V, the tolerance time is indefinite; at 50 V the tolerance time is 5 s. The curve shown in the figure refers to an ordinary location; in particular locations, the touch resistance of the human body towards earth changes and consequently the tolerable voltage values for an indefinite time shall be lower than 25 V.
Therefore, if the protection against indirect contact is obtained through the disconnection of the circuit, it is necessary to ensure that such breaking is carried out in compliance with the safety curve for any distribution system.

5 Protection of human beings

5.2 Distribution systems

The earth fault modalities and the consequences caused by contact with live parts, are strictly related to the neutral conductor arrangement and to the connections of the exposed conductive parts.

For a correct choice of the protective device, it is necessary to know which is the distribution system of the plant.
IEC 60364-1 classifies the distribution systems with two letters.

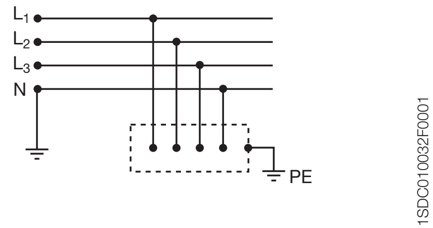
The first letter represents the relationship of the power system to earth:
- T: direct connection of one point to earth, in alternating current systems, generally the neutral point;
- I: all live parts isolated from earth, or one point, in alternating current systems, generally the neutral point, connected to earth through an impedance.

The second letter represents the relationship of the exposed conductive parts of the installation to earth:
- T: direct electrical connection of the exposed conductive parts to earth;
- N: direct electrical connection of the exposed conductive parts to the earthed point of the power system.

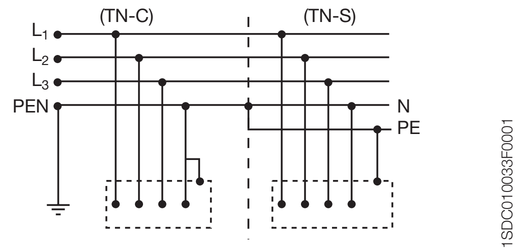
Subsequent letters, if any, represent the arrangement of neutral and protective conductors:
- S: protective function is provided by a conductor separate from the neutral conductor;
- C: neutral and protective functions combined as a single conductor (PEN conductor).

Three types of distribution system are considered:

TT System

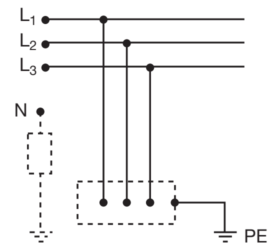


TN System



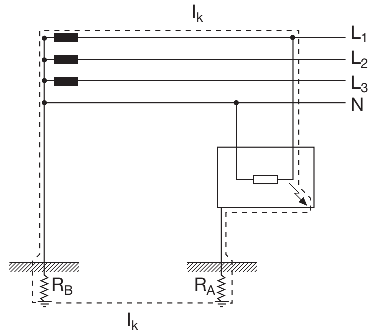
5 Protection of human beings

IT System



In **TT** systems, the neutral conductor and the exposed conductive parts are connected to earth electrodes electrically independent; the fault current flows towards the power supply neutral point through earth (Fig. 1):

Figure 1: Earth fault in TT systems



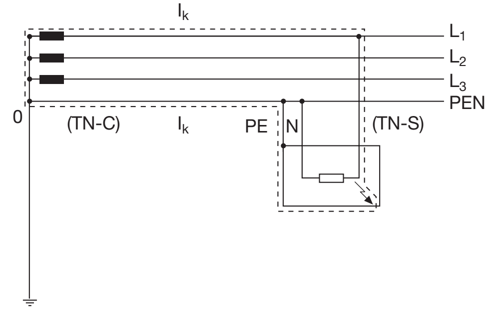
In **TT** installations, the neutral conductor is connected to the supply star center, it is usually distributed and has the function of making the phase voltage (e.g. 230 V) available, useful for single-phase load supply. The exposed conductive parts, on the contrary, singularly or collectively, are locally connected to earth. **TT** systems are generally used for civil installations.
TN systems are typically used when the power supply is distributed to loads having their own electrical substation. The neutral conductor is directly earthed in the substation; the exposed conductive parts are connected to the same earthing point of the neutral conductor, and can be locally earthed.
Three types of TN system are considered according to the arrangement of neutral and protective conductors:

1. TN-C neutral and protective functions are combined in a single conductor (PEN conductor);
2. TN-S neutral and protective conductors are always separated;
3. TN-C-S neutral and protective functions are combined in a single conductor in a part of the system (PEN) and are separated in another part (PE + N).

5 Protection of human beings

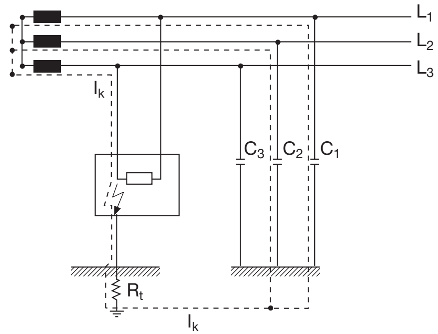
In **TN** systems, the fault current flows towards the power supply neutral point through a solid metallic connection, practically without involving the earth electrode (Figure 2).

Figure 2: Earth fault in TN systems



IT systems have no live parts directly connected to earth, but they can be earthed through a sufficiently high impedance. Exposed conductive parts shall be earthed individually, in groups or collectively to an independent earthing electrode.
The earth fault current flows towards the power supply neutral point through the earthing electrode and the line conductor capacitance (Figure 3).

Figure 3: Earth fault in IT systems



These distribution systems are used for particular plants, where the continuity of supply is a fundamental requirement, where the absence of the supply can cause hazards to people or considerable economical losses, or where a low value of a first earth fault is required. In these cases, an insulation monitoring device shall be provided for optical or acoustic signalling of possible earth faults, or failure of the supplied equipment.

5 Protection of human beings

5.3 Protection against both direct and indirect contact

Contacts of a person with live parts can be divided in two categories:
- direct contacts;
- indirect contacts.

A direct contact occurs when a part of the human body touches a part of the plant, usually live (bare conductors, terminals, etc.).
A contact is indirect when a part of the human body touches an exposed conductive parts, usually not live, but with voltage presence due to a failure or wear of the insulating materials.

The measures of protection against **direct contact** are:
- insulation of live parts with an insulating material which can only be removed by destruction (e.g. cable insulation);
- barriers or enclosures: live parts shall be inside enclosures or behind barriers providing at least the degree of protection IPXXB or IP2X; for horizontal surfaces the degree of protection shall be of at least IPXXD or IP4X (for the meaning of the degree of protection codes please refer to Volume 1, Chapter 6.1 Electrical switchboards);
- obstacles: the interposition of an obstacle between the live parts and the operator prevents unintentional contacts only, but not an intentional contact by the removal of the obstacle without particular tools;
- placing out of reach: simultaneously accessible parts at different potentials shall not be within arm's reach.

An additional protection against direct contact can be obtained by using residual current devices with a rated operating residual current not exceeding 30 mA. It must be remembered that the use of a residual current device as a mean of protection against direct contacts does not obviate the need to apply one of the above specified measures of protection.

The measures of protection against **indirect contact** are:
- automatic disconnection of the supply: a protective device shall automatically disconnect the supply to the circuit so that the touch voltage on the exposed conductive part does not persist for a time sufficient to cause a risk of harmful physiological effect for human beings;
- supplementary insulation or reinforced insulation, e.g. by the use of Class II components;

5 Protection of human beings

- non-conducting locations: locations with a particular resistance value of insulating floors and walls (≥ 50 kΩ for U_r ≤ 500 V; ≥ 100 kΩ for U_r > 500 V) and without protective conductors inside
- electrical separation, e.g. by using an isolating transformer to supply the circuit;
- earth-free local equipotential bonding: locations where the exposed conductive parts are connected together but not earthed.

Finally, the following measures provide combined protection against both direct and indirect contact:
- SELV (Safety Extra Low Voltage) system and PELV (Protective Extra Low Voltage) system;
- FELV (Functional Extra Low Voltage) system.

The protection against both direct and indirect contact is ensured if the requirements stated in 411 from IEC 60364-4-41 are fulfilled; particularly:
- the rated voltage shall not exceeds 50 V ac r.m.s. and 120 V ripple-free dc;
- the supply shall be a SELV or PELV source;
- all the installation conditions provided for such types of electrical circuits shall be fulfilled.

A SELV circuit has the following characteristics:
1) it is supplied by an independent source or by a safety source. Independent sources are batteries or diesel-driven generators. Safety sources are supplies obtained through an isolating transformer;
2) there are no earthed points. The earthing of both the exposed conductive parts as well as of the live parts of a SELV circuit is forbidden;
3) it shall be separated from other electrical systems. The separation of a SELV system from other circuits shall be guaranteed for all the components; for this purpose, the conductors of the SELV circuit may be contained in multi-conductor cables or may be provided with an additional insulating sheath.

A PELV circuit has the same prescription of a SELV system, except for the prohibition of earthed points; in fact in PELV circuits, at least one point is always earthed.

5 Protection of human beings

FELV circuits are used when for functional reasons the requirements for SELV or PELV circuits cannot be fulfilled; they require compliance with the following rules:

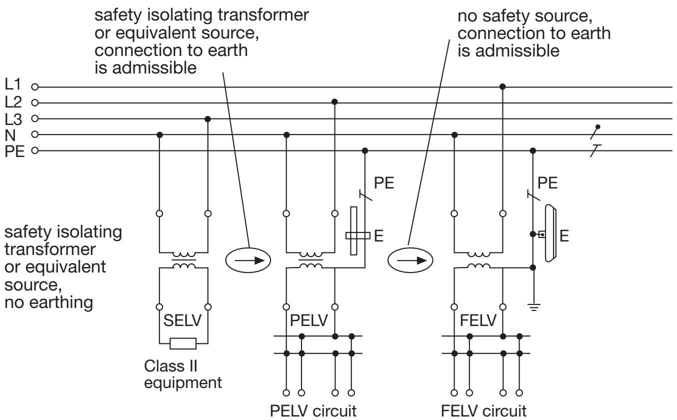
a) protection against direct contact shall be provided by either:
  - barriers or enclosures with degree of protection in accordance with what stated above (measures of protection against direct contact);
  - insulation corresponding to the minimum test voltage specified for the primary circuit. If this test is not passed, the insulation of accessible non-conductive parts of the equipment shall be reinforced during erection so that it can withstand a test voltage of 1500 V ac r.m.s. for 1 min.;

b) protection against indirect contact shall be provided by:
  - connection of the exposed conductive parts of the equipment of the FELV circuit to the protective conductor of the primary circuit, provided that the latter is subject to one of the measures of protection against direct contact;
  - connection of a live conductor of the FELV circuit to the protective conductor of the primary circuit provided that an automatic disconnection of the supply is applied as measure of protection;

c) plugs of FELV systems shall not be able to enter socket-outlets of other voltage systems, and plugs of other voltage systems shall not be able to enter socket-outlets of FELV systems.

Figure 1 shows the main features of SELV, PELV and FELV systems.

Figure 1: SELV, PELV, FELV systems



voltage limits for extra-low voltages:	E	earth connections by estraneous conductive parts, e.g. by metal pipe or structural steelwork
50 V ac 120 V dc	PE ⏚	protective conductor earth electrode

Note 1: Overcurrent protective devices are not shown in this figure.

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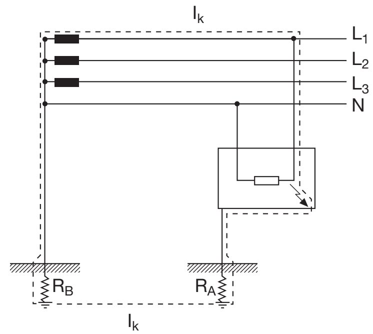
5.4 TT System

An earth fault in a TT system involves the circuit represented in Figure 1:

Figure 1: Earth fault in TT system



The fault current involves the secondary winding of the transformer, the phase conductor, the fault resistance, the protective conductor and the earth electrode resistance (plant earthing system (R_A) and earthing system which the neutral is connected to (R_B)).

According to IEC 60364-4 requirements, the protective devices must be co-ordinated with the earthing system in order to rapidly disconnect the supply, if the touch voltage reaches harmful values for the human body.

Assuming 50 V (25 V for particular locations) as limit voltage value, the condition to be fulfilled in order to limit the touch voltage on the exposed conductive parts under this limit value is:

$$R_t \leq \frac{50}{I_a} \quad \text{or} \quad R_t \leq \frac{50}{I_{\Delta n}}$$

where:

- R_t is the total resistance, equal to the sum of the earth electrode (R_A) and the protective conductor for the exposed conductive parts [Ω];
- I_a is the current causing the automatic operation within 5 s of the overcurrent protective device, read from the tripping curve of the device [A];
- $I_{\Delta n}$ is the rated residual operating current, within one second, of the circuit-breaker [A].

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From the above, it is clear that R_t value is considerably different when using automatic circuit-breakers instead of residual current devices.
In fact, with the former, it is necessary to obtain very low earth resistance values (usually less than 1 Ω) since the 5 s tripping current is generally high, whereas, with the latter, it is possible to realize earthing systems with resistance value of thousands of ohms, which are easier to be carried out.

Table 1 reports the maximum earth resistance values which can be obtained using residual current devices, with reference to an ordinary location (50 V):

Table 1: Earth resistance values

$I_{\Delta n}$ [A]	R_t [Ω]
0.01	5000
0.03	1666
0.1	500
0.3	166
0.5	100
3	16
10	5
30	1.6

Example:
Assuming to provide protection by using an automatic circuit-breaker Tmax T1B160 In125, the trip current value in less than 5 s, read from the tripping characteristic curve, is about 750 A, when starting from cold conditions (the worst case for thermomagnetic releases).

So:

$$R_t \leq \frac{50}{750} = 0.06\,\Omega$$

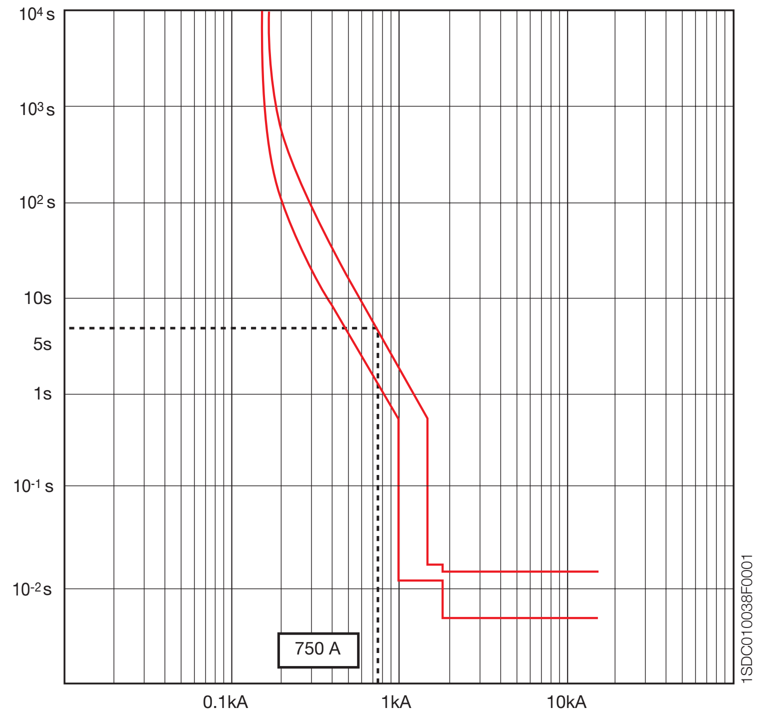
In order to provide the required protection, it must be necessary to carry out an earthing system with an earth resistance $R_t \leq 0.06$ Ω, which is not an easily obtainable value.

On the contrary, by using the same circuit-breaker mounting ABB SACE RC221 residual current release, with rated residual operating current $I_{\Delta n} = 0.03$ A, the required value of earth resistance is:

$$R_t \leq \frac{50}{0.03} = 1666.6\,\Omega$$

which can be easily obtained in practice.

5 Protection of human beings



In an electrical installation with a common earthing system and loads protected by devices with different tripping currents, for the achievement of the coordination of all the loads with the earthing system, the worst case - represented by the device with the highest tripping current - shall be considered.

As a consequence, when some feeders are protected by overcurrent devices and some others by residual current devices, all the advantages deriving from the use of residual current releases are nullified, since the R_t shall be calculated on the basis of the I_{5s} of the overcurrent device and since it is the highest tripping current between these two kind of devices.

Therefore, it is advisable to protect all the loads of a TT system by means of residual current circuit-breakers coordinated with the earthing system to obtain the advantages of both a quick disconnection of the circuit when the fault occurs as well as an earthing system which can be easily accomplished.

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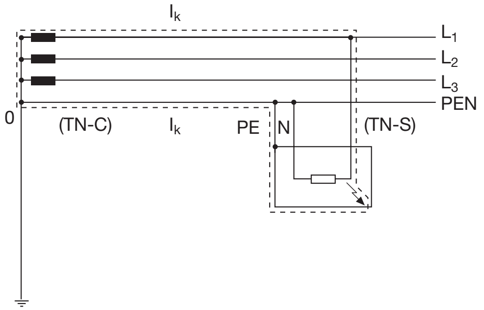
5.5 TN System

An earth fault in a TN system involves the circuit represented in Figure 1:

Figure 1: Earth fault in TN system



The fault loop does not affect the earthing system and is basically formed by the connection in series of the phase conductor and of the protective conductor. To provide a protection with automatic disconnection of the circuit, according to IEC 60364-4 prescriptions, the following condition shall be fulfilled:

$$Z_s \cdot I_a \leq U_0$$

where:

- Z_S is the impedance of the fault loop comprising the source, the live conductor up to the point of the fault and the protective conductor between the point of the fault and the source [Ω];
- U_0 is the nominal ac r.m.s. voltage to earth [V];
- I_a is the current causing the automatic operation of the disconnecting protective device within the time stated in Table 1, as a function of the rated voltage U_0 or, for distribution circuits, a conventional disconnecting time not exceeding 5 s is permitted [A]; if the protection is provided by means of a residual current device, I_a is the rated residual operating current $I_{\Delta n}$.

Table 1: Maximum disconnecting times for TN system

U_0 [V]	Disconnecting time [s]
120	0.8
230	0.4
400	0.2
> 400	0.1

5 Protection of human beings

In TN installations, an earth fault with low impedance occurring on the LV side causes a short circuit current with quite high value, due to the low value of the impedance of the fault loop. The protection against indirect contact can be provided by automatic circuit-breakers: it is necessary to verify that the operating current within the stated times is lower than the short-circuit current.

The use of residual current devices improves the conditions for protection in particular when the fault impedance doesn't have a low value, thus limiting the short-circuit current; this current can persist for quite long time causing overheating of the conductors and fire risks.

Finally, it is important to highlight the fact that the residual current devices cannot be used in TN-C system, since the neutral and protective functions are provided by a unique conductor: this configuration prevents the residual current device from working.

Example:

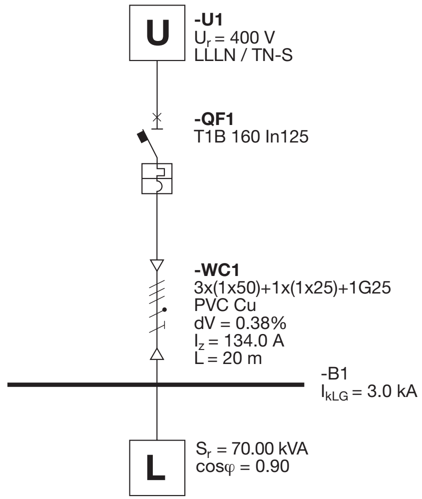
In the plant represented in Figure 2, the earth fault current is:

$$I_{kLG} = 3 \text{ kA}$$

The rated voltage to earth is 230 V, therefore, according to Table 1, it shall be verified that:

$$I_a\,(0.4s) \leq \frac{U_0}{Z_s} = I_{kLG} = 3 \text{ kA}$$

Figure 2



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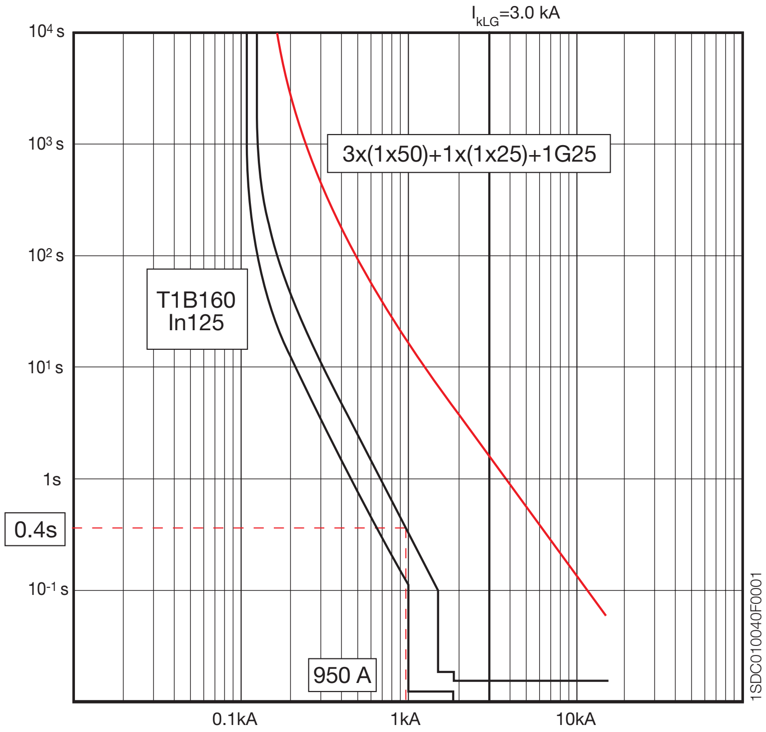
From the tripping curve (Figure 3), it is clear that the circuit-breaker trips in 0.4 s for a current value lower than 950 A. As a consequence, the protection against indirect contact is provided by the same circuit-breaker which protects the cable against short-circuit and overload, without the necessity of using an additional residual current device.

Figure 3: LG Time-Current curves



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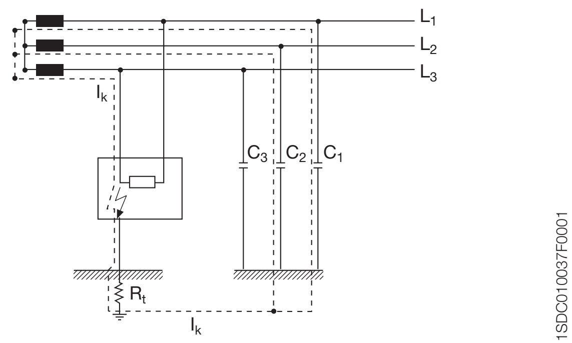
5.6 IT System

As represented in Figure 1, the earth fault current in an IT system flows through the line conductor capacitance to the power supply neutral point. For this reason, the first earth fault is characterized by such an extremely low current value to prevent the overcurrent protections from disconnecting; the deriving touch voltage is very low.

Figure1: Earth fault in IT system



According to IEC 60364-4, the automatic disconnection of the circuit in case of the first earth fault is not necessary only if the following condition is fulfilled:

$$R_t \cdot I_d \leq U_L$$

where:

- R_t is the resistance of the earth electrode for exposed conductive parts [Ω];
- I_d is the fault current, of the first fault of negligible impedance between a phase conductor and an exposed conductive part [A];
- U_L is 50 V for ordinary locations (25 V for particular locations).

If this condition is fulfilled, after the first fault, the touch voltage value on the exposed conductive parts is lower than 50 V, tolerable by the human body for an indefinite time, as shown in the safety curve (see Chapter 5.1 “General aspects: effects of current on human beings”).
In IT system installations, an insulation monitoring device shall be provided to

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indicate the occurrence of a first earth fault; in the event of a second fault, the supply shall be disconnected according to the following modalities:

a) where exposed conductive parts are earthed in groups or individually, the conditions for protection are the same as for TT systems (see Chapter 5.4 "TT system");
b) where exposed conductive parts are interconnected by a protective conductor collectively earthed, the conditions of a TN system apply; in particular, the following conditions shall be fulfilled:
if the neutral is not distributed:

$$Z_s \leq \frac{U_r}{2 \cdot I_a}$$

if the neutral is distributed:

$$Z'_s \leq \frac{U_0}{2 \cdot I_a}$$

where
- U_0 is the rated voltage between phase and neutral [V];
- U_r is the rated voltage between phases [V];
- Z_s is the impedance of the fault loop comprising the phase conductor and the protective conductor of the circuit [Ω];
- Z'_s is the impedance of the fault loop comprising the neutral conductor and the protective conductor of the circuit [Ω];
- I_a is the operating current of the protection device in the disconnecting time specified in Table 1, or within 5 s for distribution circuits.

Table 1: Maximum disconnecting time in IT systems

Rated voltage U_0/U_r [V]	disconnecting time [s] neutral not distributed	neutral distributed
120/240	0.8	5
230/400	0.4	0.8
400/690	0.2	0.4
580/1000	0.1	0.2

IEC 60364-4 states that, if the requirements mentioned at point b) cannot be fulfilled by using an overcurrent protective device, the protection of every supplied load shall be provided by means of a residual current device.

The residual current device threshold shall be carefully chosen in order to avoid unwanted tripping, due also to the particular path followed by the first fault current through the line conductor capacitance to the power supply neutral point (instead of the faulted line, another sound line with higher capacitance could be affected by a higher fault current value).

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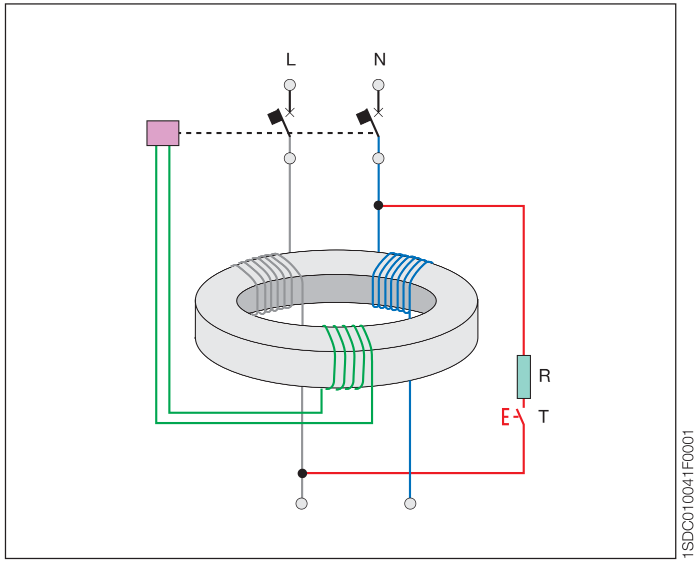
5.7 Residual current devices (RCDs)

Generalities on residual current circuit-breakers

The operating principle of the residual current release is basically the detection of an earth fault current, by means of a toroid transformer which embraces all the live conductors, included the neutral if distributed.

Figure 1: Operating principle of the residual current device



In absence of an earth fault, the vectorial sum of the currents I_Δ is equal to zero; in case of an earth fault if the I_Δ value exceeds the rated residual operating current $I_{\Delta n}$, the circuit at the secondary side of the toroid sends a command signal to a dedicated opening coil causing the tripping of the circuit-breaker.
A first classification of RCDs can be made according to the type of the fault current they can detect:
- AC type: the tripping is ensured for residual sinusoidal alternating currents, whether suddenly applied or slowly rising;
- A type: tripping is ensured for residual sinusoidal alternating currents and residual pulsating direct currents, whether suddenly applied or slowly rising;
- B type: tripping is ensured for residual direct currents, for residual sinusoidal alternating currents and residual pulsating direct currents, whether suddenly applied or slowly rising.

Another classification referred to the operating time delay is:
- undelayed type;
- time delayed S-type.

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RCDs can be coupled, or not, with other devices; it is possible to distinguish among:
- pure residual current circuit-breakers (RCCBs): they have only the residual current release and can protect only against earth fault. They must be coupled with thermomagnetic circuit-breakers or fuses, for the protection against thermal and dynamical stresses;
- residual current circuit-breakers with overcurrent protection (RCBOs): they are the combination of a thermomagnetic circuit-breaker and a RCD; for this reason, they provide the protection against both overcurrents as well as earth fault current;
- residual current circuit-breakers with external toroid: they are used in industrial plants with high currents. They are composed by a release connected to an external toroid with a winding for the detection of the residual current; in case of earth fault, a signal commands the opening mechanism of a circuit-breaker or a line contactor.

Given $I_{\Delta n}$ the operating residual current, a very important parameter for residual current devices is the residual non-operating current, which represents the maximum value of the residual current which does not cause the circuit-breaker trip; it is equal to 0.5 $I_{\Delta n}$. Therefore, it is possible to conclude that:
- for $I_{\Delta} < 0.5 \cdot I_{\Delta n}$ the RCD shall not operate;
- for $0.5 \cdot I_{\Delta n} < I_{\Delta} < I_{\Delta n}$ the RCD could operate;
- for $I_{\Delta} > I_{\Delta n}$ the RCD shall operate.

For the choice of the rated operating residual current, it is necessary to consider, in addition to the coordination with the earthing system, also the whole of the leakage currents in the plant; their vectorial sums on each phase shall not be greater than $0.5 \cdot I_{\Delta n}$. in order to avoid unwanted tripping.

Discrimination between RCDs

The Standard IEC 60364-5-53 states that discrimination between residual current protective devices installed in series may be required for service reasons, particularly when safety is involved, to provide continuity of supply to the parts of the installation not involved by the fault, if any. This discrimination can be achieved by selecting and installing RCDs in order to provide the disconnection from the supply by the RCD closest to the fault.
There are two types of discrimination between RCDs:
- horizontal discrimination: it provides the protection of each line by using a dedicated residual current circuit-breaker; in this way, in case of earth fault, only the faulted line is disconnected, since the other RCDs do not detect any fault current. However, it is necessary to provide protective measures against indirect contacts in the part of the switchboard and of the plant upstream the RCD;
- vertical discrimination: it is realized by using RCDs connected in series.

Figure 2: Horizontal discrimination between RCDs

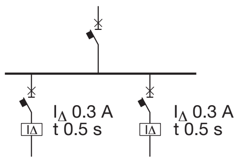

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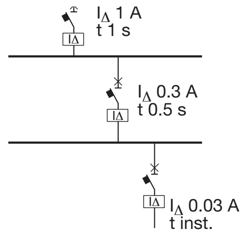
Figure 3: Vertical discrimination between RCDs



According to IEC 60364-5-53, to ensure discrimination between two residual current protective devices in series, these devices shall satisfy both the following conditions:
- the non-actuating time-current characteristic of the residual current protective device located on the supply side (upstream) shall lie above the total operating time-current characteristic of the residual current protective device located on the load side (downstream);
- the rated residual operating current on the device located on the supply side shall be higher than that of the residual current protective device located on the load side.

The non-actuating time-current characteristic is the curve reporting the maximum time value during which a residual current greater than the residual non-operating current (equal to $0.5 \cdot I_{\Delta n}$) involves the residual current circuit-breaker without causing the tripping.
As a conclusion, discrimination between two RCDs connected in series can be achieved:
- for S type residual current circuit-breakers, located on the supply side, (complying with IEC 61008-1 and IEC 61009), time-delayed type, by choosing general type circuit-breakers located downstream with $I_{\Delta n}$ equal to one third of $I_{\Delta n}$ of the upstream ones;
- for electronic residual current releases (RC221/222/223, RCQ) by choosing the upstream device with time and current thresholds directly greater than the downstream device, keeping carefully into consideration the tolerances (see Vol. 1, Chapter 2.3: Type of release).

For the protection against indirect contacts in distribution circuits in TT system, the maximum disconnecting time at $I_{\Delta n}$ shall not exceed 1 s (IEC 60364-4-41,§ 413.1)

5 Protection of human beings

5.8 Maximum protected length for the protection of human beings

As described in the previous chapters, the Standards give indications about the maximum disconnecting time for the protective devices, in order to avoid pathophysiological effects for people touching live parts.
For the protection against indirect contact, it shall be verified that the circuit-breaker trips within a time lower than the maximum time stated by the Standard; this verification is carried out by comparing the minimum short-circuit current of the exposed conductive part to be protected with the operating current corresponding to the time stated by the Standard.
The minimum short-circuit current occurs when there is a short-circuit between the phase and the protective conductors at the farthest point on the protected conductor.
For the calculation of the minimum short-circuit current, an approximate method can be used, assuming that:

- a 50 % increasing of the conductors resistance, with respect to the 20 °C value, is accepted, due to the overheating caused by the short-circuit current;
- a 80 % reduction of the supply voltage is considered as effect of the short-circuit current;
- the conductor reactance is considered only for cross sections larger than 95 mm^2.

The formula below is obtained by applying Ohm's law between the protective device and the fault point.

Legend of the symbols and constants of the formula:

- 0.8 is the coefficient representing the reduction of the voltage;
- 1.5 is the coefficient representing the increasing in the resistance;
- U_r is the rated voltage between phases;
- U_0 is the rated voltage between phase and ground;
- S is the phase conductor cross section;
- S_N is the neutral conductor cross section;
- S_{PE} is the protection conductor cross section;
- ρ is the conductor resistivity at 20 °C;
- L is the length of the cable;
- $m=\frac{S\cdot n}{S_{PE}}$ is the ratio between the total phase conductor cross section (single phase conductor cross section S multiplied by n, number of conductors in parallel) and the protective conductor cross section S_{PE} assuming they are made of the same conductor material;
- $m_1=\frac{S_N\cdot n}{S_{PE}}$ is the ratio between the total neutral conductor cross section (single neutral conductor cross section S_N multiplied by n, number of conductors in parallel) and the protective conductor cross section S_{PE} assuming they are made of the same conductor material;
- k_1 is the correction factor which takes into account the reactance of cables with cross section larger than 95 mm^2, obtainable from the following table:

Phase conductor cross section [mm^2]	120	150	185	240	300
k_1	0.90	0.85	0.80	0.75	0.72

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- k_2 is the correction factor for conductors in parallel, obtainable by the following formula:

$$k_2 = 4\frac{n-1}{n}$$

where n is the number of conductor in parallel per phase;
- 1.2 is the magnetic threshold tolerance allowed by the Standard.

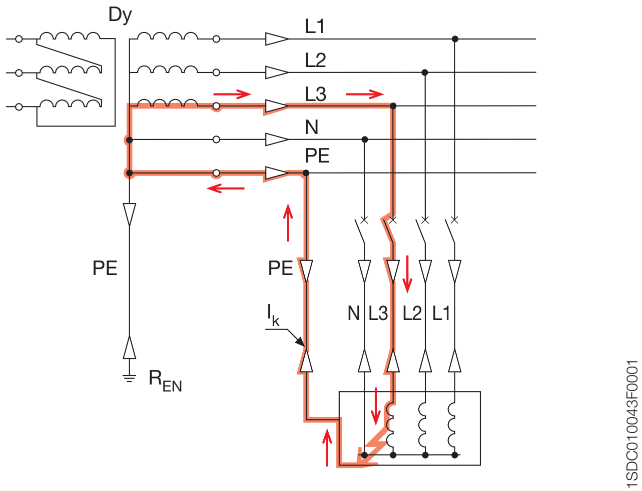
TN system

The formula for the evaluation of the minimum short circuit current is:

$$I_{k\,min} = \frac{0.8\cdot U_0\cdot S}{1.5\cdot 1.2\cdot \rho\cdot(1+m)\cdot L}\cdot k_1\cdot k_2$$

and consequently:

$$L = \frac{0.8\cdot U_0\cdot S}{1.5\cdot 1.2\cdot \rho\cdot(1+m)\cdot I_{k\,min}}\cdot k_1\cdot k_2$$



IT system

The formulas below are valid when a second fault turns the IT system into a TN system.
It is necessary to separately examine installations with neutral not distributed and neutral distributed.

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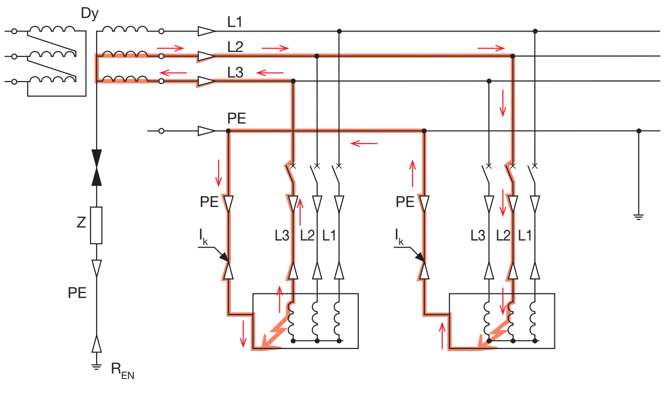
Neutral not distributed

When a second fault occurs, the formula becomes:

$$I_{k\,min} = \frac{0.8 \cdot U_r \cdot S}{2 \cdot 1.5 \cdot 1.2 \cdot \rho \cdot (1+m) \cdot L} \cdot k_1 \cdot k_2$$

and consequently:

$$L = \frac{0.8 \cdot U_r \cdot S}{2 \cdot 1.5 \cdot 1.2 \cdot \rho \cdot (1+m) \cdot I_{k\,min}} \cdot k_1 \cdot k_2$$



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Neutral distributed

Case A: three-phase circuits in IT system with neutral distributed
The formula is:

$$I_{k\,min} = \frac{0.8 \cdot U_0 \cdot S}{2 \cdot 1.5 \cdot 1.2 \cdot \rho \cdot (1+m) \cdot L} \cdot k_1 \cdot k_2$$

and consequently:

$$L = \frac{0.8 \cdot U_0 \cdot S}{2 \cdot 1.5 \cdot 1.2 \cdot \rho \cdot (1+m) \cdot I_{k\,min}} \cdot k_1 \cdot k_2$$

Case B: three-phase + neutral circuits in IT system with neutral distributed

The formula is:

$$I_{k\,min} = \frac{0.8 \cdot U_0 \cdot S_N}{2 \cdot 1.5 \cdot 1.2 \cdot \rho \cdot (1+m_1) \cdot L} \cdot k_1 \cdot k_2$$

and consequently:

$$L = \frac{0.8 \cdot U_0 \cdot S_N}{2 \cdot 1.5 \cdot 1.2 \cdot \rho \cdot (1+m_1) \cdot I_{k\,min}} \cdot k_1 \cdot k_2$$

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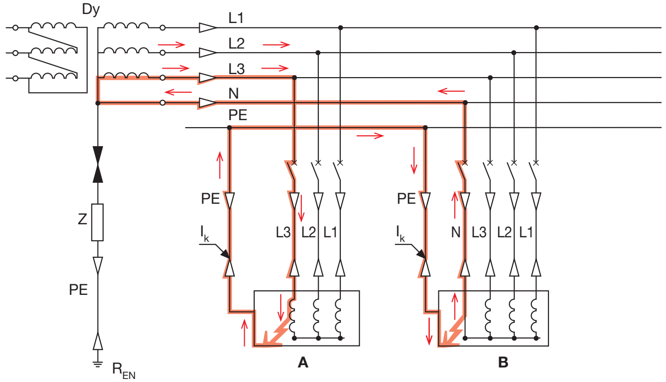

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Note for the use of the tables

The tables showing the maximum protected length (MPL) have been defined considering the following conditions:

- one cable per phase;
- rated voltage equal to 400 V (three-phase system);
- copper cables;
- neutral not distributed, for IT system only;
- protective conductor cross section according to Table 1:

Table 1: Protective conductor cross section

Phase conductor cross section S [mm²]	Protective conductor cross section S_{PE} [mm²]
S ≤ 16	S
16 < S ≤ 35	16
S > 35	S/2

Note: phase and protective conductors having the same isolation and conductive materials

Whenever the S function (delayed short-circuit) of electronic releases is used for the definition of the maximum protected length, it is necessary to verify that the tripping time is lower than the time value reported in Chapter 5.5 Table 1 for TN systems and in Chapter 5.6 Table 1 for IT systems.

For conditions different from the reference ones, the following correction factors shall be applied.

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Correction factors

Correction factor for cable in parallel per phase: the value of the maximum protected length read in Table 2 (TN system) or Table 3 (IT system) shall be multiplied by the following factor:

n	2	3	4	5	6	7	8
k_p	2	2.7	3	3.2	3.3	3.4	3.5

n is the number of conductors in parallel per phase.

Correction factor for three-phase voltage different from 400 V: the value of the maximum protected length read in Table 2 (TN system) or Table 3 (IT system) shall be multiplied by the following factor:

voltage [V]	230	400	440	500	690
k_V	0.58	1	1.1	1.25	1.73

For 230 V single-phase systems, no correction factor is necessary.

Correction factor for aluminium cables: the value of the maximum protected length read in Table 2 (TN system) or Table 3 (IT system) shall be multiplied by the following factor:

k_{Al}	0.64

Correction factor for protective conductor cross section S_{PE} different from the cross sections stated in Table 1: the value of the maximum protected length shall be multiplied by the coefficient corresponding to the phase conductor cross section and to the ratio between the protective conductor (PE) and the phase cross sections:

S_{PE}/S	0.5	0.55	0.6	0.66	0.75	0.87	1	1.25	1.5	2
S					k_{PE}					
≤16 mm²	0.67	0.71	0.75	0.80	0.86	0.93	1.00	1.11	1.20	1.33
25 mm²	0.85	0.91	0.96	1.02	1.10	1.19	1.28	1.42	1.54	1.71
35 mm²	1.06	1.13	1.20	1.27	1.37	1.48	1.59	1.77	1.91	2.13
>35 mm²	1.00	1.06	1.13	1.2	1.29	1.39	1.5	1.67	1.8	2.00

Correction factor for neutral distributed in IT systems (for Table 3 only): the value of the maximum protected length shall be multiplied by 0.58.

5.8 Maximum protected length for the protection of human beings

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TN system MPL by MCB

Table 2.1: Curve Z

CURVE		Z	Z	Z	Z	Z	Z	Z	Z	Z
In		**≤10**	**13**	**16**	**20**	**25**	**32**	**40**	**50**	**63**
I3		**30**	**39**	**48**	**60**	**75**	**96**	**120**	**150**	**189**
S	**S_{PE}**									
1.5	1.5	173	133	108	86	69	54	43		
2.5	2.5	288	221	180	144	115	90	72	58	45
4	4	461	354	288	231	185	144	115	92	72
6	6	692	532	432	346	277	216	173	138	108
10	10	1153	886	721	577	461	360	288	231	180
16	16	1845	1419	1153	923	738	577	461	369	288
25	16	2250	1730	1406	1125	900	703	563	450	352

Table 2.2: Curve B

CURVE		B	B	B	B	B	B	B	B	B	B	B	B	B
In		**≤6**	**8**	**10**	**13**	**16**	**20**	**25**	**32**	**40**	**50**	**63**	**80**	**100**
I3		**30**	**40**	**50**	**65**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**
S	**S_{PE}**													
1.5	1.5	173	130	104	80	65	52	42	32	26				
2.5	2.5	288	216	173	133	108	86	69	54	43	35	27		
4	4	461	346	277	213	173	138	111	86	69	55	44	35	28
6	6	692	519	415	319	259	208	166	130	104	83	66	52	42
10	10	1153	865	692	532	432	346	277	216	173	138	110	86	69
16	16	1845	1384	1107	852	692	554	443	346	277	221	176	138	111
25	16	2250	1688	1350	1039	844	675	540	422	338	270	214	169	135
35	16												190	152

Table 2.3: Curve C

CURVE		C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
In		**≤3**	**4**	**6**	**8**	**10**	**13**	**16**	**20**	**25**	**32**	**40**	**50**	**63**	**80**	**100**	**125**
I3		**30**	**40**	**60**	**80**	**100**	**130**	**160**	**200**	**250**	**320**	**400**	**500**	**630**	**800**	**1000**	**1250**
S	**S_{PE}**																
1.5	1.5	173	130	86	65	52	40	32	26	21	16	13					
2.5	2.5	288	216	144	108	86	67	54	43	35	27	22	17	14			
4	4	461	346	231	173	138	106	86	69	55	43	35	28	22	17	14	11
6	6	692	519	346	259	208	160	130	104	83	65	52	42	33	26	21	17
10	10	1153	865	577	432	346	266	216	173	138	108	86	69	55	43	35	28
16	16	1845	1384	923	692	554	426	346	277	221	173	138	111	88	69	55	44
25	16	2250	1688	1125	844	675	519	422	338	270	211	169	135	107	84	68	54
35	16														95	76	61

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Table 2.4: Curve K

CURVE		K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K
In		≤2	≤3	4	4.2	5.8	6	8	10	11	13	15	16	20	25	26	32	37	40	41	45	50	63
I3		28	42	56	59	81	84	112	140	154	182	210	224	280	350	364	448	518	560	574	630	700	882
S	S_{PE}																						
1.5	1.5	185	123	92	88	64	62	46	37	34	28	25	23	18	15	14	12	10	9				
2.5	2.5	308	205	154	146	106	103	77	62	56	47	41	38	31	25	24	19	17	15	15	14		
4	4	492	328	246	234	170	164	123	98	89	76	66	62	49	39	38	31	27	25	24	22	20	16
6	6	738	492	369	350	255	246	185	148	134	114	98	92	74	59	57	46	40	37	36	33	30	23
10	10	1231	820	615	584	425	410	308	246	224	189	164	154	123	98	95	77	67	62	60	55	49	39
16	16	1969	1313	984	934	681	656	492	394	358	303	263	246	197	158	151	123	106	98	96	88	79	63
25	16	2401	1601	1201	1140	830	800	600	480	437	369	320	300	240	192	185	150	130	120	117	107	96	76

Table 2.5: Curve D

CURVE		D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
In		≤2	3	4	6	8	10	13	16	20	25	32	40	50	63	80	100
I3		40	60	80	120	160	200	260	320	400	500	640	800	1000	1260	1600	2000
S	S_{PE}																
1.5	1.5	130	86	65	43	32	26	20	16	13	10	8	6				
2.5	2.5	216	144	108	72	54	43	33	27	22	17	14	11	9	7		
4	4	346	231	173	115	86	69	53	43	35	28	22	17	14	11	9	7
6	6	519	346	259	173	130	104	80	65	52	42	32	26	21	16	13	10
10	10	865	577	432	288	216	173	133	108	86	69	54	43	35	27	22	17
16	16	1384	923	692	461	346	277	213	173	138	111	86	69	55	44	35	28
25	16	1688	1125	844	563	422	338	260	211	169	135	105	84	68	54	42	34
35	16															47	38

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Table 2.6: TmaxT1 TMD

		T1	T1	T1	T1	T1	T1
	In	≤50	63	80	100	125	160
	I3	500 A	10 In	10 In	10 In	10 In	10 In
S	S_{PE}						
1.5	1.5	6					
2.5	2.5	10					
4	4	15	12	10	8	6	
6	6	23	18	14	12	9	7
10	10	38	31	24	19	15	12
16	16	62	49	38	31	25	19
25	16	75	60	47	38	30	23
35	16	84	67	53	42	34	26
50	25	128	102	80	64	51	40
70	35	179	142	112	90	72	56
95	50	252	200	157	126	101	79

Table 2.7: Tmax T2 TMD

		T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2
	In	1.6	2	2.5	3.2	4	5	6.3	8	10	12.5	16÷50	63	80	100	125	160
	I3	10 In	10 In	10 In	10 In	10 In	10 In	10 In	10 In	10 In	10 In	500 A	10 In	10 In	10 In	10 In	10 In
S	S_{PE}																
1.5	1.5	246	197	157	123	98	79	62	49	39	31	8					
2.5	2.5	410	328	262	205	164	131	104	82	66	52	13					
4	4	655	524	419	328	262	210	166	131	105	84	21	17	13	10	8	
6	6	983	786	629	491	393	315	250	197	157	126	31	25	20	16	13	10
10	10	1638	1311	1048	819	655	524	416	328	262	210	52	42	33	26	21	16
16	16	2621	2097	1677	1311	1048	839	666	524	419	335	84	67	52	42	34	26
25	16				1598	1279	1023	812	639	511	409	102	81	64	51	41	32
35	16						1151	914	720	576	460	115	91	72	58	46	36
50	25								1092	874	699	175	139	109	87	70	55
70	35										979	245	194	153	122	98	76
95	50											343	273	215	172	137	107
120	70											417	331	261	209	167	130
150	95											518	411	324	259	207	162
185	95											526	418	329	263	211	165

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Table 2.8: Tmax T3 TMD

		T3	T3	T3	T3	T3	T3	T3
	In	**63**	**80**	**100**	**125**	**160**	**200**	**250**
	I3	**10 In**	**10 In**	**10 In**	**10 In**	**10 In**	**10 In**	**10 In**
S	**S_{PE}**							
4	4	17	13	10	8			
6	6	25	20	16	13	10	8	
10	10	42	33	26	21	16	13	10
16	16	67	52	42	34	26	21	17
25	16	81	64	51	41	32	26	20
35	16	91	72	58	46	36	29	23
50	25	139	109	87	70	55	44	35
70	35	194	153	122	98	76	61	49
95	50	273	215	172	137	107	86	69
120	70	331	261	209	167	130	104	83
150	95	411	324	259	207	162	130	104
185	95	418	329	263	211	165	132	105
240	120	499	393	315	252	197	157	126

Table 2.9: Tmax T4 TMD/TMA

		T4	T4	T4	T4	T4	T4	T4	T4	T4
	In	**20**	**32**	**50**	**80**	**100**	**125**	**160**	**200**	**250**
	I_3	**320 A**	**10 In**	**10 In**	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**
S	**S_{PE}**									
1.5	1.5	14	14	9	11…5	9…4	7…3	5…3	4…2	3…2
2.5	2.5	23	23	14	18…9	14…7	12…6	9…5	7…4	6…3
4	4	36	36	23	29…14	23…12	18…9	14…7	12…6	9…5
6	6	54	54	35	43…22	35…17	28…14	22…11	17…9	14…7
10	10	90	90	58	72…36	58…29	46…23	36…18	29…14	23…12
16	16	144	144	92	115…58	92…46	74…37	58…29	46…23	37…18
25	16	176	176	113	141…70	113…56	90…45	70…35	56…28	45…23
35	16	198	198	127	158…79	127…63	101…51	79…40	63…32	51…25
50	25	300	300	192	240…120	192…96	154…77	120…60	96…48	77…38
70	35	420	420	269	336…168	269…135	215…108	168…84	135…67	108…54
95	50	590	590	378	472…236	378…189	302…151	236…118	189…94	151…76
120	70	717	717	459	574…287	459…229	367…184	287…143	229…115	184…92
150	95	891	891	570	713…356	570…285	456…228	356…178	285…143	228…114
185	95	905	905	579	724…362	579…290	463…232	362…181	290…145	232…116
240	120	1081	1081	692	865…432	692…346	554…277	432…216	346…173	277…138
300	150	1297	1297	830	1038…519	830…415	664…332	519…259	415…208	332…166

5.8 Maximum protected length for the protection of human beings

5 Protection of human beings

TN system MPL by MCCB

Table 2.10: Tmax T5-T6 TMA

		T5	T5	T5	T6	T6
	In	**320**	**400**	**500**	**630**	**800**
	I_3	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**
S	**S_{PE}**					
1,5	1,5	3…1	2…1	2…1	1…1	1…1
2,5	2,5	5…2	4…2	3…1	2…1	2…1
4	4	7…4	6…3	5…2	4…2	3…1
6	6	11…5	9…4	7…3	5…3	4…2
10	10	18…9	14…7	12…6	9…5	7…4
16	16	29…14	23…12	18…9	15…7	12…6
25	16	35…18	28…14	23…11	18…9	14…7
35	16	40…20	32…16	25…13	20…10	16…8
50	25	60…30	48…24	38…19	31…15	24…12
70	35	84…42	67…34	54…27	43…21	34…17
95	50	118…59	94…47	76…38	60…30	47…24
120	70	143…72	115…57	92…46	73…36	57…29
150	95	178…89	143…71	114…57	91…45	71…36
185	95	181…90	145…72	116…58	92…46	72…36
240	120	216…108	173…86	138…69	110…55	86…43
300	150	259…130	208…104	166…83	132…66	104…52

Table 2.11: Tmax T2 with PR221 DS-LS

		T2	T2	T2	T2	T2
	In	**10**	**25**	**63**	**100**	**160**
	I3	**5.5 In**	**5.5 In**	**5.5 In**	**5.5 In**	**5.5 In**
S	**S_{PE}**					
1.5	1.5	79	31	12		
2.5	2.5	131	52	21		
4	4	210	84	33	21	
6	6	315	126	50	31	20
10	10	524	210	83	52	33
16	16	839	335	133	84	52
25	16	1023	409	162	102	64
35	16	1151	460	183	115	72
50	25	1747	699	277	175	109
70	35	2446	979	388	245	153
95	50	3434	1374	545	343	215
120	70	4172	1669	662	417	261
150	95	5183	2073	823	518	324
185	95	5265	2106	836	526	329

Note: if the setting of function I is different from the reference value (5.5), the value of the MPL shall be multiplied by the ratio between the reference value and the set value.

5 Protection of human beings

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Table 2.12: Tmax T4-T5-T6 with PR221 - PR222 - PR223

		T4	T4	T4	T4	T5	T5	T5	T6	T6	T6
	In	**100**	**160**	**250**	**320**	**320**	**400**	**630**	**630**	**800**	**1000**
	I_3	**6.5 In**	**6.5 In**	**6.5 In**	**6.5 In**	**6.5 In**	**6.5 In**	**6.5 In**	**6.5 In**	**6.5 In**	**6.5 In**
S	**S_{PE}**										
1,5	1,5										
2,5	2,5										
4	4										
6	6	29	18								
10	10	48	30	19							
16	16	77	48	31	24	24	19				
25	16	94	59	38	30	30	24	15			
35	16	106	66	43	33	33	27	17			
50	25	161	101	65	50	50	40	26	26	20	
70	35	226	141	90	71	71	56	36	36	28	23
95	50	317	198	127	99	99	79	50	50	40	32
120	70	385	241	154	120	120	96	61	61	48	39
150	95	478	299	191	150	150	120	76	76	60	48
185	95	486	304	194	152	152	121	77	77	61	49
240	120	581	363	232	181	181	145	92	92	73	58
300	150	697	435	279	218	218	174	111	111	87	70

Note: if the setting of function I is different from the reference value (6.5), the value of the MPL shall be multiplied by the ratio between the reference value and the set value.

Table 2.13: SACE Isomax S6÷S8 with PR211- PR212

		S7	S7	S7	S8	S8	S8	S8
	In	**1000**	**1250**	**1600**	**1600**	**2000**	**2500**	**3200**
	I3	**6 In**	**6 In**	**6 In**	**6 In**	**6 In**	**6 In**	**6 In**
S	**S_{PE}**							
2.5	2.5							
4	4							
6	6							
10	10							
16	16							
25	16							
35	16							
50	25							
70	35	22	18	14	14			
95	50	31	25	20	20	16	13	10
120	70	38	31	24	24	19	15	12
150	95	48	38	30	30	24	19	15
185	95	48	39	30	30	24	19	15
240	120	58	46	36	36	29	23	18
300	150	69	55	43	43	35	28	22

Note: if the setting of function S or I is different from the reference value (6), the MPL value shall be multiplied by the ratio between the reference value and the set value. Besides, using function S the MPL shall be multiplied by 1.1.

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Table 3.1: Curve Z

CURVE		**Z**	**Z**	**Z**	**Z**	**Z**	**Z**	**Z**	**Z**	**Z**	**Z**
In		**≤8**	**10**	**13**	**16**	**20**	**25**	**32**	**40**	**50**	**63**
I3		**30**	**30**	**39**	**48**	**60**	**75**	**96**	**120**	**150**	**189**
S	**S_{PE}**										
1.5	1.5	150	150	115	94	75	60	47	37		
2.5	2.5	250	250	192	156	125	100	78	62	50	40
4	4	400	400	307	250	200	160	125	100	80	63
6	6	599	599	461	375	300	240	187	150	120	95
10	10	999	999	768	624	499	400	312	250	200	159
16	16	1598	1598	1229	999	799	639	499	400	320	254
25	16	1949	1949	1499	1218	974	780	609	487	390	309

Table 3.2: Curve B

CURVE		**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**
In		**≤6**	**8**	**10**	**13**	**16**	**20**	**25**	**32**	**40**	**50**	**63**	**80**	**100**
I3		**30**	**40**	**50**	**65**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**
S	**S_{PE}**													
1.5	1.5	150	112	90	69	56	45	36	28	22				
2.5	2.5	250	187	150	115	94	75	60	47	37	30	24		
4	4	400	300	240	184	150	120	96	75	60	48	38	30	24
6	6	599	449	360	277	225	180	144	112	90	72	57	45	36
10	10	999	749	599	461	375	300	240	187	150	120	95	75	60
16	16	1598	1199	959	738	599	479	384	300	240	192	152	120	96
25	16	1949	1462	1169	899	731	585	468	365	292	234	186	146	117
35	16												165	132

Table 3.3: Curve C

CURVE		**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**
In		**≤3**	**4**	**6**	**8**	**10**	**13**	**16**	**20**	**25**	**32**	**40**	**50**	**63**	**80**	**100**	**125**
I3		**30**	**40**	**60**	**80**	**100**	**130**	**160**	**200**	**250**	**320**	**400**	**500**	**630**	**800**	**1000**	**1250**
S	**S_{PE}**																
1.5	1.5	150	112	75	56	45	35	28	22	18	14	11					
2.5	2.5	250	187	125	94	75	58	47	37	30	23	19	15	12			
4	4	400	300	200	150	120	92	75	60	48	37	30	24	19	15	12	10
6	6	599	449	300	225	180	138	112	90	72	56	45	36	29	22	18	14
10	10	999	749	499	375	300	230	187	150	120	94	75	60	48	37	30	24
16	16	1598	1199	799	599	479	369	300	240	192	150	120	96	76	60	48	38
25	16	1949	1462	974	731	585	450	365	292	234	183	146	117	93	73	58	47
35	16														82	66	53

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Table 3.4: Curve K

CURVE		K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K
In		≤2	≤3	4	4.2	5.8	6	8	10	11	13	15	16	20	25	26	32	37	40	41	45	50	63
I3		28	42	56	59	81	84	112	140	154	182	210	224	280	350	364	448	518	560	574	630	700	882
S	S_{PE}																						
1.5	1.5	161	107	80	76	55	54	40	32	29	25	21	20	16	13	12	10	9	8				
2.5	2.5	268	178	134	127	92	89	67	54	49	41	36	33	27	21	21	17	14	13	13	12		
4	4	428	285	214	204	148	143	107	86	78	66	57	54	43	34	33	27	23	21	21	19	17	14
6	6	642	428	321	306	221	214	161	128	117	99	86	80	64	51	49	40	35	32	31	29	26	20
10	10	1070	713	535	510	369	357	268	214	195	165	143	134	107	86	82	67	58	54	52	48	43	34
16	16	1712	1141	856	815	590	571	428	342	311	263	228	214	171	137	132	107	93	86	84	76	68	54
25	16	2088	1392	1044	994	720	696	522	418	380	321	278	261	209	167	161	130	113	104	102	93	84	66

Table 3.5: Curve D

CURVE		D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
In		≤2	3	4	6	8	10	13	16	20	25	32	40	50	63	80	100
I3		40	60	80	120	160	200	260	320	400	500	640	800	1000	1260	1600	2000
S	S_{PE}																
1.5	1.5	112	75	56	37	28	22	17	14	11	9	7	6				
2.5	2.5	187	125	94	62	47	37	29	23	19	15	12	9	7	6		
4	4	300	200	150	100	75	60	46	37	30	24	19	15	12	10	7	6
6	6	449	300	225	150	112	90	69	56	45	36	28	22	18	14	11	9
10	10	749	499	375	250	187	150	115	94	75	60	47	37	30	24	19	15
16	16	1199	799	599	400	300	240	184	150	120	96	75	60	48	38	30	24
25	16	1462	974	731	487	365	292	225	183	146	117	91	73	58	46	37	29
35																41	33

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Table 3.6: Tmax T1 TMD

		T1	T1	T1	T1	T1	T1
	In	≤50	63	80	100	125	160
	I3	500 A	10 In	10 In	10 In	10 In	10 In
S	S_{PE}						
1.5	1.5	5					
2.5	2.5	8					
4	4	13	11	8	7	5	
6	6	20	16	12	10	8	6
10	10	33	26	21	17	13	10
16	16	53	42	33	27	21	17
25	16	65	52	41	32	26	20
35	16	73	58	46	37	29	23
50	25	111	88	69	55	44	35
70	35	155	123	97	78	62	49
95	50	218	173	136	109	87	68

Table 3.7: Tmax T2 TMD

		T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2	T2
	In	1.6	2	2.5	3.2	4	5	6.3	8	10	12.5	16÷50	63	80	100	125	160
	I3	10 In	10 In	10 In	10 In	10 In	10 In	10 In	10 In	10 In	10 In	500 A	10 In	10 In	10 In	10 In	10 In
S	S_{PE}																
1.5	1.5	213	170	136	106	85	68	54	43	34	27	7					
2.5	2.5	355	284	227	177	142	113	90	71	57	45	11					
4	4	567	454	363	284	227	182	144	113	91	73	18	14	11	9	7	
6	6	851	681	545	426	340	272	216	170	136	109	27	22	17	14	11	9
10	10	1419	1135	908	709	567	454	360	284	227	182	45	36	28	23	18	14
16	16	2270	1816	1453	1135	908	726	576	454	363	291	73	58	45	36	29	23
25	16				1384	1107	886	703	554	443	354	89	70	55	44	35	28
35	16						997	791	623	498	399	100	79	62	50	40	31
50	25								946	757	605	151	120	95	76	61	47
70	35										847	212	168	132	106	85	66
95	50											297	236	186	149	119	93
120	70											361	287	226	181	145	113
150	95											449	356	281	224	180	140
185	95											456	362	285	228	182	142

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Table 3.8: Tmax T3 TMD

		T3	T3	T3	T3	T3	T3	T3
In		**63**	**80**	**100**	**125**	**160**	**200**	**250**
I3		**10 In**	**10 In**	**10 In**	**10 In**	**10 In**	**10 In**	**10 In**
S	**S_{PE}**							
4	4	14	11	9	7			
6	6	22	17	14	11	9	7	
10	10	36	28	23	18	14	11	9
16	16	58	45	36	29	23	18	15
25	16	70	55	44	35	28	22	18
35	16	79	62	50	40	31	25	20
50	25	120	95	76	61	47	38	30
70	35	168	132	106	85	66	53	42
95	50	236	186	149	119	93	74	59
120	70	287	226	181	145	113	90	72
150	95	356	281	224	180	140	112	90
185	95	362	285	228	182	142	114	91
240	120	432	340	272	218	170	136	109

Table 3.9: Tmax T4 TMD/TMA

		T4	T4	T4	T4	T4	T4	T4	T4	T4
	In	**20**	**32**	**50**	**80**	**100**	**125**	**160**	**200**	**250**
	I_3	**320 A**	**10 In**	**10 In**	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**
S	**S_{PE}**									
1.5	1.5	12	12	7	9...5	7...4	6...3	5...2	4...2	3...1
2.5	2.5	20	20	12	16...8	12...6	10...5	8...4	6...3	5...2
4	4	31	31	20	25...12	20...10	16...8	12...6	10...5	8...4
6	6	47	47	30	37...19	30...15	24...12	19...9	15...7	12...6
10	10	78	78	50	62...31	50...25	40...20	31...16	25...12	20...10
16	16	125	125	80	100...50	80...40	64...32	50...25	40...20	32...16
25	16	152	152	97	122...61	97...49	78...39	61...30	49...24	39...19
35	16	171	171	110	137...69	110...55	88...44	69...34	55...27	44...22
50	25	260	260	166	208...104	166...83	133...67	104...52	83...42	67...33
70	35	364	364	233	291...146	233...117	186...93	146...73	117...58	93...47
95	50	511	511	327	409...204	327...164	262...131	204...102	164...82	131...65
120	70	621	621	397	497...248	397...199	318...159	248...124	199...99	159...79
150	95	772	772	494	617...309	494...247	395...198	309...154	247...123	198...99
185	95	784	784	502	627...313	502...251	401...201	313...157	251...125	201...100
240	120	936	936	599	749...375	599...300	479...240	375...187	300...150	240...120
300	150	1124	1124	719	899...449	719...360	575...288	449...225	360...180	288...144

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Table 3.10: Tmax T5-T6 TMA

		T5	T5	T5	T6	T6
	In	**320**	**400**	**500**	**630**	**800**
	I_3	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**	**5...10 In**
S	**S_{PE}**					
1.5	1.5	2…1	2…1	1…1	1…1	
2.5	2.5	4…2	3…2	2…1	2…1	2…1
4	4	6…3	5…2	4…2	3…2	2…1
6	6	9…5	7…4	6…3	5…2	4…2
10	10	16…8	12…6	10…5	8…4	6…3
16	16	25…12	20…10	16…8	13…6	10…5
25	16	30…15	24…12	19…10	15…8	12…6
35	16	34…17	27…14	22…11	17…9	14…7
50	25	52…26	42…21	33…17	26…13	21…10
70	35	73…36	58…29	47…23	37…18	29…15
95	50	102…51	82…41	65…33	52…26	41…20
120	70	124…62	99…50	79…40	63…32	50…25
150	95	154…77	123…62	99…49	78…39	62…31
185	95	157…78	125…63	100…50	80…40	63…31
240	120	187…94	150…75	120…60	95…48	75…37
300	150	225…112	180…90	144…72	114…57	90…45

Table 3.11: Tmax T2 with PR221 DS-LS

		T2	T2	T2	T2	T2
	In	**10**	**25**	**63**	**100**	**160**
	I3	**5.5 In**	**5.5 In**	**5.5 In**	**5.5 In**	**5.5 In**
S	**S_{PE}**					
1.5	1.5	68	27	11		
2.5	2.5	113	45	18		
4	4	182	73	29	18	
6	6	272	109	43	27	17
10	10	454	182	72	45	28
16	16	726	291	115	73	45
25	16	886	354	141	89	55
35	16	997	399	158	100	62
50	25	1513	605	240	151	95
70	35	2119	847	336	212	132
95	50	2974	1190	472	297	186
120	70	3613	1445	573	361	226
150	95	4489	1796	713	449	281
185	95	4559	1824	724	456	285

Note: if the setting of function I is different from the reference value (5.5), the MPL value shall be multiplied by the ratio between the reference value and the set value.

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Table 3.12: Tmax T4-T5-T6 with PR221 - PR222 - PR223

		T4	T4	T4	T4	T5	T5	T5	T6	T6	T6
	In	100	160	250	320	320	400	630	630	800	1000
	I_3	6.5 In	6.5 In	6.5 In	6.5 In	6.5 In	6.5 In	6.5 In	6.5 In	6.5 In	6.5 In
S	S_{PE}										
1.5	1.5										
2.5	2.5										
4	4										
6	6	25	16								
10	10	42	26	17							
16	16	67	42	27	21	21	17				
25	16	82	51	33	26	26	20	13	13		
35	16	92	58	37	29	29	23	15	15	12	
50	25	140	87	56	44	44	35	22	22	17	14
70	35	196	122	78	61	61	49	31	31	24	20
95	50	275	172	110	86	86	69	44	44	34	27
120	70	333	208	133	104	104	83	53	53	42	33
150	95	414	259	166	129	129	104	66	66	52	41
185	95	421	263	168	132	132	105	67	67	53	42
240	120	503	314	201	157	157	126	80	80	63	50
300	150	603	377	241	189	189	151	96	96	75	60

Note: if the setting of function I is different from the reference value (6.5), the value of the MPL shall be multiplied by the ratio between the reference value and the set value.

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Table 3.13: SACE Isomax S6-S8 with PR211-212

		S7	S7	S7	S8	S8	S8	S8
	In	1000	1250	1600	1600	2000	2500	3200
	I3	6 In	6 In	6 In	6 In	6 In	6 In	6 In
S	S_{PE}							
2.5	2.5							
4	4							
6	6							
10	10							
16	16							
25	16							
35	16							
50	25							
70	35	19	16	12	12			
95	50	27	22	17	17	14	11	9
120	70	33	26	21	21	17	13	10
150	95	41	33	26	26	21	16	13
185	95	42	33	26	26	21	17	13
240	120	50	40	31	31	25	20	16
300	150	60	48	37	37	30	24	19

Note: if the setting of function S or I is different from the reference value (6), the MPL value shall be multiplied by the ratio between the reference value and the set value. Besides, using function S, the MPL shall be multiplied by 1.1.

6 Calculation of short-circuit current

6.1 General aspects

A short-circuit is a fault of negligible impedance between live conductors having a difference in potential under normal operating conditions.

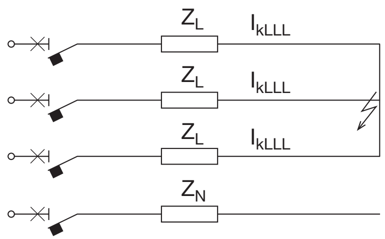
6.2 Fault typologies

In a three-phase circuit the following types of fault may occur:
- three-phase fault;
- two-phase fault;
- phase to neutral fault;
- phase to PE fault.

In the formulas, the following symbols are used:
- I_k short-circuit current;
- U_r rated voltage;
- Z_L phase conductor impedance;
- Z_N neutral conductor impedance;
- Z_{PE} protective conductor impedance.

The following table briefly shows the type of fault and the relationships between the value of the short-circuit current for a symmetrical fault (three phase) and the short-circuit current for asymmetrical faults (two phase and single phase) in case of faults far from generators.

Three-phase fault

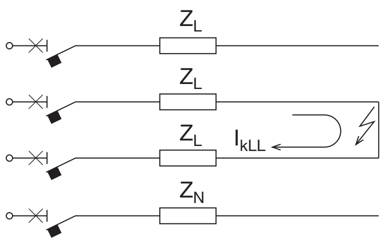


$$I_{kLLL} = \frac{Ur}{\sqrt{3}\,Z_L}$$

where

$$Z_L = \sqrt{R_L^2 + X_L^2}$$

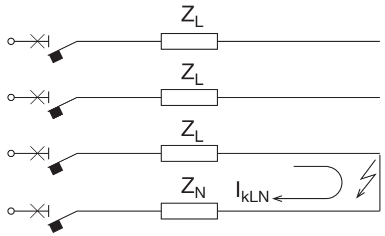
Two-phase fault



$$I_{kLL} = \frac{U_r}{2Z_L} = \frac{\sqrt{3}}{2} I_{kLLL} = 0.87\, I_{kLLL}$$

6 Calculation of short-circuit current

Phase to neutral fault



$$I_{kLN} = \frac{U_r}{\sqrt{3}(Z_L + Z_N)}$$

If $Z_L = Z_N$ (cross section of neutral conductor equal to the phase conductor one):

$$I_{kLN} = \frac{U_r}{\sqrt{3}(Z_L + Z_N)} = \frac{U_r}{\sqrt{3}(2Z_L)} = 0.5\, I_{kLLL}$$

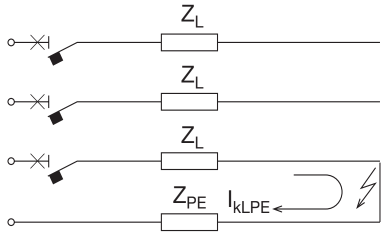
If $Z_N = 2Z_L$ (cross section of neutral conductor half the phase conductor one):

$$I_{kLN} = \frac{U_r}{\sqrt{3}(Z_L + Z_N)} = \frac{U_r}{\sqrt{3}(3Z_L)} = 0.33 I_{kLLL}$$

If $Z_N \cong 0$ limit condition:

$$I_{kLN} = \frac{U_r}{\sqrt{3}(Z_L + Z_N)} = \frac{U_r}{\sqrt{3}(Z_L)} = I_{kLLL}$$

Phase to PE fault



$$I_{kLPE} = \frac{U_r}{\sqrt{3}(Z_L + Z_{PE})}$$

If $Z_L = Z_{PE}$ (cross section of protective conductor equal to the phase conductor one):

$$I_{kLPE} = \frac{U_r}{\sqrt{3}(Z_L + Z_{PE})} = \frac{U_r}{\sqrt{3}(2Z_L)} = 0.5 I_{kLLL}$$

If $Z_{PE} = 2Z_L$ (cross section of protective conductor half to the phase conductor one):

$$I_{kLPE} = \frac{U_r}{\sqrt{3}(Z_L + Z_{PE})} = \frac{U_r}{\sqrt{3}(3Z_L)} = 0.33 I_{kLLL}$$

If $Z_{PE} \cong 0$ limit condition:

$$I_{kLPE} = \frac{U_r}{\sqrt{3}(Z_L + Z_{PE})} = \frac{U_r}{\sqrt{3}(Z_L)} = I_{kLLL}$$

The following table allows the approximate value of a short-circuit current to be found quickly.

Note	Three-phase short-circuit	Two-phase short-circuit	Phase to neutral short-circuit	Phase to PE short-circuit (TN system)
	I_{kLLL}	I_{kLL}	I_{kLN}	I_{kLPE}
I_{kLLL}	-	$I_{kLL}=0.87I_{kLLL}$	$I_{LN}=0.5I_{kLLL}$ $(Z_L = Z_N)$ $I_{LN}=0.33I_{kLLL}$ $(Z_L = 0,5Z_N)$ $I_{LN}=I_{kLLL}$ $(Z_N \cong 0)$	$I_{LPE}=0.5I_{kLLL}$ $(Z_L = Z_{PE})$ $I_{LPE}=0.33I_{kLLL}$ $(Z_L = 0.5Z_{PE})$ $I_{LPE}=I_{kLLL}$ $(Z_{PE} \cong 0)$
I_{kLL}	$I_{kLLL}=1.16I_{kLL}$	-	$I_{kLN}=0.58I_{kLL}$ $(Z_L = Z_N)$ $I_{kLN}=0.38I_{kLL}$ $(Z_L = 0,5Z_N)$ $I_{kLN}=1.16I_{kLL}$ $(Z_N \cong 0)$	$I_{kLPE}=0.58I_{kLL}$ $(Z_L = Z_{PE})$ $I_{kLPE}=0.38I_{kLL}$ $(Z_L = 0.5Z_{PE})$ $I_{kLPE}=1.16I_{kLL}$ $(Z_{PE} \cong 0)$
I_{kLN}	$I_{kLLL}=2I_{kLN}$ $(Z_L = Z_N)$ $I_{kLLL}=3I_{kLN}$ $(Z_L = 0,5Z_N)$ $I_{kLLL}=I_{kLN}$ $(Z_N \cong 0)$	$I_{kLL}=1.73I_{kLN}$ $(Z_L = Z_N)$ $I_{kLL}=2.6I_{kLN}$ $(Z_L = 0,5Z_N)$ $I_{kLL}=0.87I_{kLN}$ $(Z_N \cong 0)$	-	

6 Calculation of short-circuit current

6.3 Determination of the short-circuit current: “short-circuit power method”

The short-circuit current can be determined by using the “short-circuit power method”. This method allows the determination of the approximate short-circuit current at a point in an installation in a simple way; the resultant value is generally acceptable. However, this method is not conservative and gives more accurate values, the more similar the power factors of the considered components are (network, generators, transformers, motors and large section cables etc.).
The “short-circuit power method” calculates the short-circuit current I_k based on the formula:

Three-phase short-circuit $$I_k = \frac{S_k}{\sqrt{3} \cdot U_r}$$

Two-phase short-circuit $$I_k = \frac{S_k}{2 \cdot U_r}$$

where:
- S_k is the short-circuit apparent power seen at the point of the fault;
- U_r is the rated voltage.

To determine the short-circuit apparent power S_k, all the elements of the network shall be taken into account, which may be:
- elements which contribute to the short-circuit current: network, generators, motors;
- elements which limit the value of the short-circuit current: conductors and transformers.

The procedure for the calculation of the short-circuit current involves the following steps:
1. calculation of the short-circuit power for the different elements of the installation;
2. calculation of the short-circuit power at the fault point;
3. calculation of the short-circuit current.

6.3.1 Calculation of the short-circuit power for the different elements of the installation

The short-circuit apparent power S_k shall be determined for all the components which are part of the installation:

Network

An electrical network is considered to include everything upstream of the point of energy supply.

6 Calculation of short-circuit current

Generally, the energy distribution authority supplies the short-circuit apparent power (S_{knet}) value at the point of energy supply. However, if the value of the short-circuit current I_{knet} is known, the value of the power can be obtained by using, for three-phase systems, the following formula:

$$S_{knet} = \sqrt{3} U_r I_{knet}$$

where U_r is the rated voltage at the point of energy supply.

If the aforementioned data are not available, the values for S_{knet} given in the following table can be taken as reference values:

Net voltage U_r [kV]	Short-circuit power S_{knet} [MVA]
Up to 20	500
Up to 32	750
Up to 63	1000

Generator

The short-circuit power is obtained from:

$$S_{kgen} = \frac{S_r \cdot 100}{X^*_{d\%}}$$

where $X^*_{d\%}$ is the percentage value of the subtransient reactance (X_d”) or of the transient reactance (X_d’) or of the synchronous reactance (X_d), according to the instant in which the value of the short-circuit power is to be evaluated.
In general, the reactances are expressed in percentages of the rated impedance of the generator (Z_d) given by:

$$Z_d = \frac{U_r^2}{S_r}$$

where U_r and S_r are the rated voltage and power of the generator.
Typical values can be:
- X_d” from 10 % to 20 %;
- X_d’ from 15 % to 40 %;
- X_d from 80 % to 300 %.

Normally, the worst case is considered, that being the subtransient reactance.
The following table gives the approximate values of the short-circuit power of generators (X_d” = 12.5 %):

S_r [kVA]	50	63	125	160	200	250	320	400	500	630	800	1000	1250	1600	2000	2500	3200	4000
S_{kgen} [MVA]	0.4	0.5	1.0	1.3	1.6	2.0	2.6	3.2	4.0	5.0	6.4	8.0	10.0	12.8	16.0	20.0	25.6	32.0

6 Calculation of short-circuit current

Asynchronous three-phase motors

Under short-circuit conditions, electric motors contribute to the fault for a brief period (5-6 periods).
The power can be calculated according to the short-circuit current of the motor (I_k), by using the following expression:

$$S_{kmot} = \sqrt{3} \cdot U_r \cdot I_k$$

Typical values are:
$S_{kmot} = 5 \div 7\ S_{rmot}$
(I_k is about $5 \div 7\ I_{rmot}$: 5 for motors of small size, and 7 for larger motors).

Transformers

The short-circuit power of a transformer (S_{ktrafo}) can be calculated by using the following formula:

$$S_{ktrafo} = \frac{100}{u_k\,\%} \cdot S_r$$

The following table gives the approximate values of the short-circuit power of transformers:

S_r [kVA]	50	63	125	160	200	250	320	400	500	630	800	1000	1250	1600	2000	2500	3200	4000
u_k%	4	4	4	4	4	4	4	4	4	4	5	5	5	6	6	6	6	6
S_{ktrafo} [MVA]	1.3	1.6	3.1	4	5	6.3	8	10	12.5	15.8	16	20	25	26.7	33.3			

Cables

A good approximation of the short-circuit power of cables is:

$$S_{kcable} = \frac{U_r^2}{Z_c}$$

where the impedance of the cable (Z_c) is:

$$I_{kLLL} = \frac{Ur}{\sqrt{3}\, Z_L}$$
where
$$Z_L = \sqrt{R_L^2 + X_L^2}$$

The following table gives the approximate values of the short-circuit power of cables, at 50 and 60 Hz, according to the supply voltage (cable length = 10 m):

6 Calculation of short-circuit current

S [mm²]	230 [V]	400 [V]	440 [V]	500 [V]	690 [V]	230 [V]	400 [V]	440 [V]	500 [V]	690 [V]
	S_{kcable} [MVA] @50 Hz					S_{kcable} [MVA] @60 Hz				
1.5	0.44	1.32	1.60	2.07	3.94	0.44	1.32	1.60	2.07	3.94
2.5	0.73	2.20	2.66	3.44	6.55	0.73	2.20	2.66	3.44	6.55
4	1.16	3.52	4.26	5.50	10.47	1.16	3.52	4.26	5.50	10.47
6	1.75	5.29	6.40	8.26	15.74	1.75	5.29	6.40	8.26	15.73
10	2.9	8.8	10.6	13.8	26.2	2.9	8.8	10.6	13.7	26.2
16	4.6	14.0	16.9	21.8	41.5	4.6	13.9	16.9	21.8	41.5
25	7.2	21.9	26.5	34.2	65.2	7.2	21.9	26.4	34.1	65.0
35	10.0	30.2	36.6	47.3	90.0	10.0	30.1	36.4	47.0	89.6
50	13.4	40.6	49.1	63.4	120.8	13.3	40.2	48.7	62.9	119.8
70	19.1	57.6	69.8	90.1	171.5	18.8	56.7	68.7	88.7	168.8
95	25.5	77.2	93.4	120.6	229.7	24.8	75.0	90.7	117.2	223.1
120	31.2	94.2	114.0	147.3	280.4	29.9	90.5	109.5	141.5	269.4
150	36.2	109.6	132.6	171.2	326.0	34.3	103.8	125.6	162.2	308.8
185	42.5	128.5	155.5	200.8	382.3	39.5	119.5	144.6	186.7	355.6
240	49.1	148.4	179.5	231.8	441.5	44.5	134.7	163.0	210.4	400.7
300	54.2	164.0	198.4	256.2	488.0	48.3	146.1	176.8	228.3	434.7

With *n* cables in parallel, it is necessary to multiply the value given in the table by *n*. If the length of the cable (L_{act}) is other than 10 m, it is necessary to multiply the value given in the table by the following coefficient:

$$\frac{10}{L_{act}}$$

6.3.2 Calculation of the short-circuit power at the fault point

The rule for the determination of the short-circuit power at a point in the installation, according to the short-circuit power of the various elements of the circuit, is analogue to that relevant to the calculation of the equivalent admittance.
In particular:
- the power of elements in series is equal to the inverse of the sum of the inverses of the single powers (as for the parallel of impedances);

$$S_k = \frac{1}{\sum \frac{1}{S_i}}$$

- the short-circuit power of elements in parallel is equal to the sum of the single short-circuit powers (as for the series of impedances).

$$S_k = \sum S_i$$

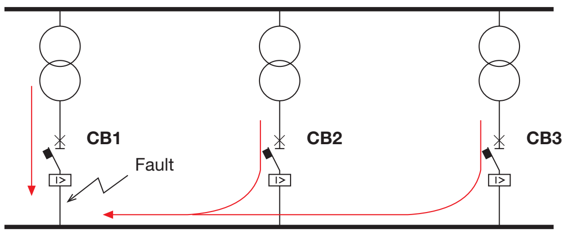
The elements of the circuit are considered to be in series or parallel, seeing the circuit from the fault point.
In the case of different branches in parallel, the distribution of the current between the different branches shall be calculated once the short-circuit current at the fault point has been calculated. This must be done to ensure the correct choice of protection devices installed in the branches.

6 Calculation of short-circuit current

6.3.3 Calculation of the short-circuit current

To determine the short-circuit current in an installation, both the fault point as well as the configuration of the system which maximize the short-circuit current involving the device shall be considered. If appropriate, the contribution of the motors shall be taken into account.
For example, in the case detailed below, for circuit-breaker CB1, the worst condition occurs when the fault is right upstream of the circuit-breaker itself. To determine the breaking capacity of the circuit-breaker, the contribution of two transformers in parallel must be considered.

Fault right downstream of CB1



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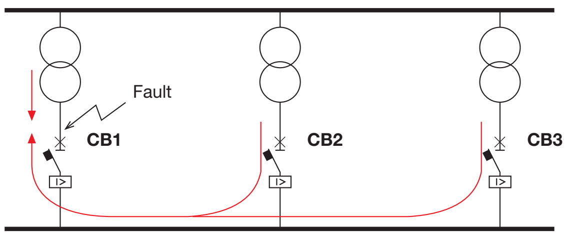
Fault right upstream of CB1
(worst condition for CB1)



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Once the short-circuit power equivalent at the fault point has been determined, the short-circuit current can be calculated by using the following formula:

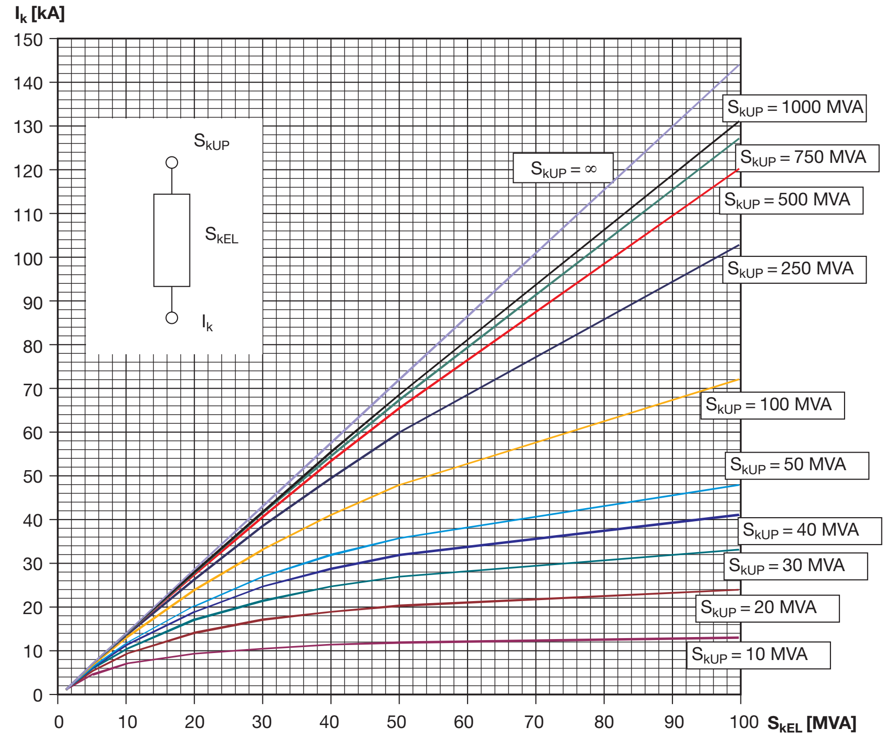
Three-phase short-circuit $$I_k = \frac{S_k}{\sqrt{3} \cdot U_r}$$

Two-phase short-circuit $$I_k = \frac{S_k}{2 \cdot U_r}$$

6 Calculation of short-circuit current

As a first approximation, by using the following graph, it is possible to evaluate the three-phase short-circuit current downstream of an object with short-circuit power (S_{kEL}) known; corresponding to this value, knowing the short-circuit power upstream of the object (S_{kUP}), the value of I_k can be read on the y-axis, expressed in kA, at 400 V.

Figure 1: Chart for the calculation of the three-phase short-circuit current at 400 V



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6 Calculation of short-circuit current

6.3.4 Examples

The following examples demonstrate the calculation of the short-circuit current in some different types of installation.

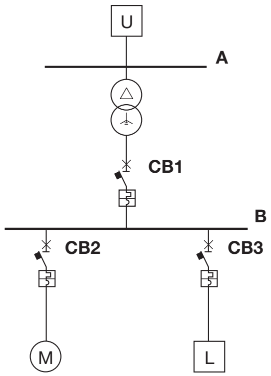
Example 1

Upstream network: U_r = 20000 V
S_{knet} = 500 MVA

Transformer: S_r = 1600 kVA
$u_k\%$ = 6%
U_{1r} / U_{2r} =20000/400

Motor: P_r = 220 kW
I_{kmot}/I_r = 6.6
$\cos\varphi_r$ = 0.9
η = 0.917

Generic load: I_{rL}= 1443.4 A
$\cos\varphi_r$= 0.9



Calculation of the short-circuit power of different elements

Network: S_{knet}= 500 MVA

Transformer: $$S_{ktrafo} = \frac{100}{u_k\%}\cdot S_r = 26.7\ \text{MVA}$$

Motor: $$S_{rmot} = \frac{P_r}{\eta \cdot \cos\varphi_r} = 267\ \text{kVA}$$

$S_{kmot} = 6.6{\cdot}S_{rmot}$ = 1.76 MVA for the first 5-6 periods (at 50 Hz about 100 ms)

Calculation of the short-circuit current for the selection of circuit-breakers

Selection of CB1
For circuit-breaker CB1, the worst condition arises when the fault occurs right downstream of the circuit-breaker itself. In the case of a fault right upstream, the circuit-breaker would be involved only by the fault current flowing from the motor, which is remarkably smaller than the network contribution.

6 Calculation of short-circuit current

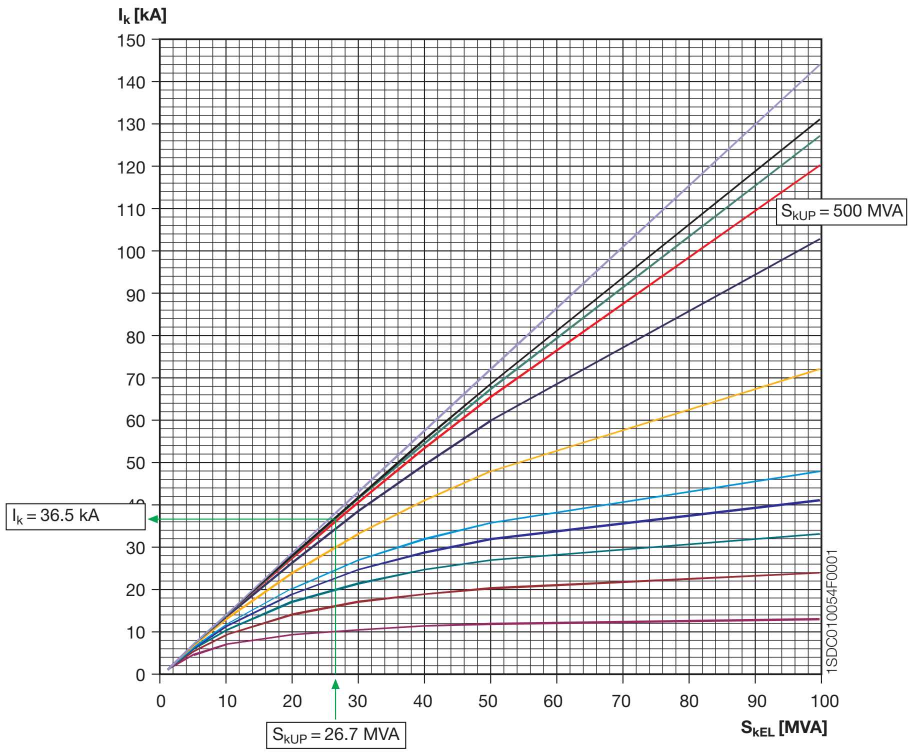
The circuit, seen from the fault point, is represented by the series of the network with the transformer. According to the previous rules, the short-circuit power is determined by using the following formula:

$$S_{kCB1} = \frac{S_{knet}\cdot S_{ktrafo}}{S_{knet} + S_{ktrafo}} = 25.35\ \text{MVA}$$

the maximum fault current is:

$$I_{kCB1} = \frac{S_{kCB1}}{\sqrt{3}\cdot U_r} = 36.6\ \text{kA}$$

The transformer LV side rated current is equal to 2309 A; therefore the circuit-breaker to select is an Emax E3N 2500.
Using the chart shown in Figure 1, it is possible to find I_{kCB1} from the curve with $S_{kUP} = S_{knet}$ = 500 MVA corresponding to $S_{kEL} = S_{ktrafo}$ = 26.7 MVA:



6 Calculation of short-circuit current

Selection of CB2

For circuit-breaker CB2, the worst condition arises when the fault occurs right downstream of the circuit-breaker itself. The circuit, seen from the fault point, is represented by the series of the network with the transformer. The short-circuit current is the same used for CB1.

$$I_{kCB1} = \frac{S_{kCB1}}{\sqrt{3} \cdot U_r} = 36.6 \text{ kA}$$

The rated current of the motor is equal to 385 A; the circuit-breaker to select is a Tmax T5H 400.

Selection of CB3

For CB3 too, the worst condition arises when the fault occurs right downstream of the circuit-breaker itself.

The circuit, seen from the fault point, is represented by two branches in parallel: the motor and the series of the network and transformer. According to the previous rules, the short-circuit power is determined by using the following formula:

Motor // (Network + Transformer)

$$S_{kCB3} = S_{kmot} + \frac{1}{\frac{1}{S_{knet}} + \frac{1}{S_{ktrafo}}} = 27.11 \text{MVA}$$

$$I_{kCB3} = \frac{S_{kCB3}}{\sqrt{3} \cdot U_r} = 39.13 \text{ kA}$$

The rated current of the load L is equal to 1443 A; the circuit-breaker to select is a SACE Isomax S7S 1600, or an E1B1600.

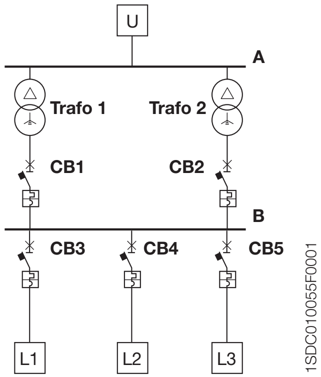
Example 2

The circuit shown in the diagram is constituted by the supply, two transformers in parallel and three loads.

Upstream network: U_{r1}=20000 V
S_{knet} = 500 MVA

Transformers 1 and 2: S_r = 1600 kVA
$u_k\%$ = 6%
U_{1r} /U_{2r} =20000/400

Load L1: S_r = 1500 kVA; cosφ = 0.9;
Load L2: S_r = 1000 kVA; cosφ = 0.9;
Load L3: S_r = 50 kVA; cosφ = 0.9.



6 Calculation of short-circuit current

Calculation of the short-circuit powers of different elements:

Network S_{knet} = 500 MVA

Transformers 1 and 2 $S_{ktrafo} = \frac{S_r}{u_k\ \%} \cdot 100 = 26.7 \text{ MVA}$

Selection of CB1 (CB2)

For circuit-breaker CB1 (CB2) the worst condition arises when the fault occurs right downstream of the circuit-breaker itself. According to the previous rules, the circuit seen from the fault point, is equivalent to the parallel of the two transformers in series with the network: Network + (Trafo 1 // Trafo 2).

The short-circuit current obtained in this way corresponds to the short-circuit current at the busbar. This current, given the symmetry of the circuit, is distributed equally between the two branches (half each). The current which flows through CB1 (CB2) is therefore equal to half of that at the busbar.

$$S_{kbusbar} = \frac{S_{knet} \cdot (S_{rtrafo1} + S_{ktrafo2})}{S_{knet} + (S_{ktrafo1} + S_{ktrafo2})} = 48.2 \text{ MVA}$$

$$I_{kbusbar} = \frac{S_{kbusbar}}{\sqrt{3} \cdot U_r} = 69.56 \text{ kA}$$

$$I_{kCB1(2)} = \frac{I_{kbusbar}}{2} = 34.78 \text{ kA}$$

The circuit-breakers CB1(CB2) to select, with reference to the rated current of the transformers, are Emax E3N 2500.

Selection of CB3-CB4-CB5

For these circuit-breakers the worst condition arises when the fault occurs right downstream of the circuit-breakers themselves. Therefore, the short-circuit current to be taken into account is that at the busbar:

$$I_{kCB3} = I_{kbusbar} = 69.56 \text{ kA}$$

The circuit-breakers to select, with reference to the current of the loads, are:

CB3: Emax E3S 2500
CB4: Emax E2S 1600
CB5: Tmax T2H 160

6.4 Determination of the short-circuit current I_k downstream of a cable as a function of the upstream one

The table below allows the determination, in a conservative way, of the three-phase short-circuit current at a point in a 400 V network downstream of a single pole copper cable at a temperature of 20 °C. Known values:
- the three-phase short-circuit current upstream of the cable;
- the length and cross section of the cable.

Cable section [mm²]	Length [m]																								
1.5																0.9	1.1	1.4	1.8	2.5	3.5	5.3	7	9.4	14
2.5													0.9	1	1.2	1.5	1.8	2.3	2.9	4.1	5.9	8.8	12	16	24
4											0.9	1.2	1.4	1.6	1.9	2.3	2.8	3.7	4.7	6.6	9.4	14	19	25	38
6									0.8	1.1	1.4	1.8	2.1	2.5	2.8	3.5	4.2	5.6	7	10	14	21	28	38	56
10							0.9	1.2	1.4	1.9	2.3	2.9	3.5	4.1	4.7	5.8	7	9.4	12	16	23	35	47	63	94
16					0.9	1.1	1.5	1.9	2.2	3	3.7	4.7	5.6	6.5	7.5	9.3	11	15	19	26	37	56	75	100	150
25			0.9	1.2	1.4	1.7	2.3	2.9	3.5	4.6	5.8	7.2	8.7	10	12	14	17	23	29	41	58	87	116	155	233
35			1.2	1.6	2	2.4	3.2	4	4.8	6.4	8	10	12	14	16	20	24	32	40	56	80	121	161	216	324
50		1.1	1.7	2.3	2.8	3.4	4.5	5.7	6.8	9	11	14	17	20	23	28	34	45	57	79	113	170	226	303	455
70	0.8	1.5	2.3	3.1	3.8	4.6	6.2	7.7	9.2	12	15	19	23	27	31	38	46	62	77	108	154	231	308	413	
95	1	2	3	4	5	6	8	10	12	16	20	25	30	35	40	50	60	80	100	140	200	300	400		
120	1.2	2.4	3.6	4.8	6	7.2	10	12	14	19	24	30	36	42	48	60	72	96	120	168	240	360	481		
150	1.4	2.8	4.2	5.6	7	8.4	11	14	17	23	28	35	42	49	56	70	84	113	141	197	281	422			
185	1.6	3.2	4.8	6.4	8	10	13	16	19	26	32	40	48	56	64	80	96	128	160	224	320	480			
240	1.8	3.7	5.5	7.3	9.1	11	15	18	22	29	37	46	55	64	73	91	110	146	183	256	366	549			
300	2	4	6	8	10	12	16	20	24	32	40	50	60	70	80	100	120	160	200	280	400				
2x120	2.4	4.8	7.2	10	12	14	19	24	29	38	48	60	72	84	96	120	144	192	240	336	481				
2x150	2.8	5.6	8.4	11	14	17	23	28	34	45	56	70	84	98	113	141	169	225	281	394	563				
2x185	3.2	6.4	10	13	16	19	26	32	38	51	64	80	96	112	128	160	192	256	320	448					
3x120	3.6	7.2	11	14	18	22	29	36	43	58	72	90	108	126	144	180	216	288	360	505					
3x150	4.2	8.4	13	17	21	25	34	42	51	68	84	105	127	148	169	211	253	338	422						
3x185	4.8	10	14	19	24	29	38	48	58	77	96	120	144	168	192	240	288	384	480						

I_k upstream [kA]	I_k downstream [kA]																								
100	96	92	89	85	82	78	71	65	60	50	43	36	31	27	24	20	17	13	11	7.8	5.6	3.7	2.7	2.0	1.3
90	86	83	81	78	76	72	67	61	57	48	42	35	31	27	24	20	17	13	11	7.8	5.6	3.7	2.7	2.0	1.3
80	77	75	73	71	69	66	62	57	53	46	40	34	30	27	24	20	17	13	10	7.7	5.5	3.7	2.7	2.0	1.3
70	68	66	65	63	62	60	56	53	49	43	38	33	29	26	23	19	16	13	10	7.6	5.5	3.7	2.7	2.0	1.3
60	58	57	56	55	54	53	50	47	45	40	36	31	28	25	23	19	16	12	10	7.5	5.4	3.7	2.7	2.0	1.3
50	49	48	47	46	45	44	43	41	39	35	32	29	26	23	21	18	15	12	10	7.3	5.3	3.6	2.6	2.0	1.3
40	39	39	38	38	37	37	35	34	33	31	28	26	24	22	20	17	15	12	10	7.1	5.2	3.6	2.6	2.0	1.3
35	34	34	34	33	33	32	32	31	30	28	26	24	22	20	19	16	14	11	10	7.1	5.1	3.5	2.6	2.0	1.3
30	30	29	29	29	28	28	28	27	26	25	23	22	20	19	18	16	14	11	9.3	7.0	5.0	3.5	2.6	1.9	1.3
25	25	24	24	24	24	24	23	23	22	21	21	19	18	17	16	14	13	11	9.0	6.8	5.0	3.4	2.6	1.9	1.3
20	20	20	20	19	19	19	19	18	18	18	17	16	15	15	14	13	12	10	8.4	6.5	4.8	3.3	2.5	1.9	1.3
15	15	15	15	15	15	14	14	14	14	14	13	13	12	12	12	11	10	8.7	7.6	6.1	4.6	3.2	2.5	1.9	1.3
12	12	12	12	12	12	12	12	11	11	11	11	11	10	10	10	9.3	8.8	7.8	7.0	5.7	4.4	3.1	2.4	1.9	1.3
10	10	10	10	10	10	10	10	9.5	9.4	9.2	9.0	8.8	8.5	8.3	8.1	7.7	7.3	6.5	5.9	5.0	3.9	2.9	2.3	1.8	1.2
8.0	8.0	7.9	7.9	7.9	7.8	7.8	7.7	7.7	7.6	7.5	7.4	7.2	7.1	6.9	6.8	6.5	6.2	5.7	5.2	4.5	3.7	2.8	2.2	1.7	1.2
6.0	6.0	5.9	5.9	5.9	5.9	5.8	5.8	5.8	5.7	5.6	5.5	5.4	5.3	5.2	5.1	4.9	4.8	4.4	4.1	3.6	3.1	2.4	2.0	1.6	1.1
3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.9	2.8	2.8	2.8	2.7	2.7	2.6	2.5	2.4	2.2	2.0	1.7	1.4	1.2	0.9

6 Calculation of short-circuit current

Note:

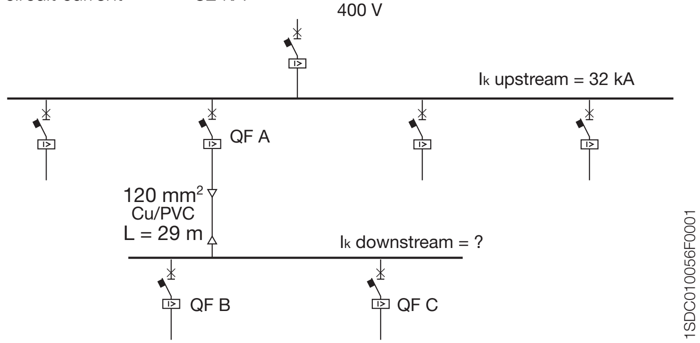
- In the case of the I_k upstream and the length of the cable not being included in the table, it is necessary to consider:
  - the value right above I_k upstream;
  - the value right below for the cable length.

These approximations allow calculations which favour safety.
- In the case of cables in parallel not present in the table, the length must be divided by the number of cables in parallel.

Example

Data
Rated voltage = 400 V
Cable section = 120 mm²
Conductor = copper
Length = 29 m

Upstream short-circuit current = 32 kA



Procedure

In the row corresponding to the cable cross section 120 mm², it is possible to find the column for a length equal to 29 m or right below (in this case 24). In the column of upstream short-circuit current it is possible to identify the row with a value of 32 kA or right above (in this case 35). From the intersection of this last row with the previously identified column, the value of the downstream short-circuit current can be read as being equal to 26 kA.

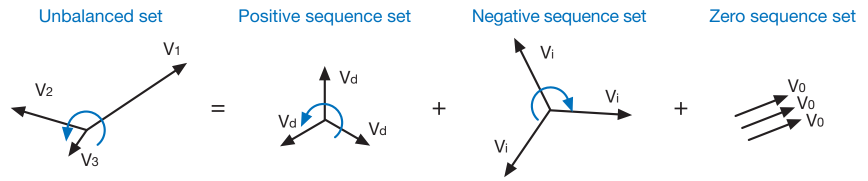
6 Calculation of short-circuit current

6.5 Algebra of sequences

6.5.1 General aspects

It is possible to study a symmetrical, balanced three-phase network in quite a simple way by reducing the three-phase network to a single-phase one having the same value of rated voltage as the three-phase system line-to-line voltage. Asymmetric networks cannot be reduced to the study of a single-phase network just because of this unbalance. In this case, being impossible any simplification, it is necessary to proceed according to the analysis methods typical for the solution of electrical systems.
The modelling technique allowing the calculation of an asymmetric and unbalanced network by converting it to a set of three balanced networks that each can be represented by a single-phase equivalent circuit easily solvable is the method of symmetrical components.
This method derives from mathematical considerations according to which any set of three phasors[1] can be divided into three sets of phasors with the following characteristics:
- a balanced set, called *positive sequence*, formed by three phasors of equal magnitude shifted by 120° and having the same phase sequence as the original system
- a balanced set, called *negative sequence*, formed by three phasors of equal magnitude shifted by 120° and having inverse phase sequence to that of the original system
- a *zero sequence* set formed by three phasors of equal magnitude in phase.

Figure 1



[1] The phasor is a vectorial representation of magnitude which varies in time. A signal of type $v(t)=\sqrt{2}\cdot V\cdot \cos(\omega\cdot t+\varphi)$ is represented by the phasor $\bar{v}=V\cdot e^{j\varphi}$

6 Calculation of short-circuit current

6.5.2 Positive, negative and zero sequence systems

The following relationships* represent the link between the quantities of the three-phase balanced network and the positive, negative and zero sequence systems:

$$\bar{V}_0=\frac{1}{3}(\bar{V}_1+\bar{V}_2+\bar{V}_3) \qquad \bar{I}_0=\frac{1}{3}(\bar{I}_1+\bar{I}_2+\bar{I}_3) \qquad \bar{V}_1=\bar{V}_0+\bar{V}_d+\bar{V}_i \qquad \bar{I}_1=\bar{I}_0+\bar{I}_d+\bar{I}_i$$

$$\bar{V}_d=\frac{1}{3}(\bar{V}_1+\alpha\cdot\bar{V}_2+\alpha^2\cdot\bar{V}_3) \qquad \bar{I}_d=\frac{1}{3}(\bar{I}_1+\alpha\cdot\bar{I}_2+\alpha^2\cdot\bar{I}_3) \qquad \bar{V}_2=\bar{V}_0+\alpha^2\cdot\bar{V}_d+\alpha\cdot\bar{V}_i \qquad \bar{I}_2=\bar{I}_0+\alpha^2\cdot\bar{I}_d+\alpha\cdot\bar{I}_i$$

$$\bar{V}_i=\frac{1}{3}(\bar{V}_1+\alpha^2\cdot\bar{V}_2+\alpha\cdot\bar{V}_3) \quad 1) \qquad \bar{I}_i=\frac{1}{3}(\bar{I}_1+\alpha^2\cdot\bar{I}_2+\alpha\cdot\bar{I}_3) \qquad \bar{V}_3=\bar{V}_0+\alpha\cdot\bar{V}_d+\alpha^2\cdot\bar{V}_i \quad 2) \qquad \bar{I}_3=\bar{I}_1+\alpha\cdot\bar{I}_2+\alpha^2\cdot\bar{I}_3$$

* In the formulas, the subscripts relevant to positive-sequence, negative-sequence and zero-sequence components are indicated by “d”, “i” and “0” respectively.

The complex constant $\alpha = -\frac{1}{2}+j\frac{\sqrt{3}}{2}$ is a versor which, multiplied by a vector, rotates the vector by 120° in a positive direction (counterclockwise).

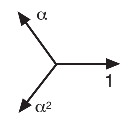
The complex constant $\alpha^2 = -\frac{1}{2}-j\frac{\sqrt{3}}{2}$ operates a -120° rotation.

Some useful properties of this set of three vectors are:

$1+\alpha+\alpha^2=0$

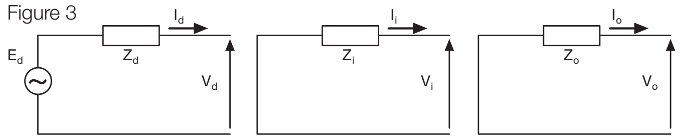
$|\alpha^2-\alpha|=\sqrt{3}$

Figure 2



Therefore, it is possible to state that a real three-phase network may be replaced by three single-phase networks related to the three positive, negative and zero sequences, by substituting each component with the corresponding equivalent circuit. If generators can be considered symmetrical as it occurs in plant practice, by considering as a positive sequence set the one they generate, the three single-phase networks are defined by the following circuits and equations:

Figure 3



$$\bar{E}_d-\bar{Z}_d\cdot\bar{I}_d=\bar{V}_d \qquad -\bar{Z}_i\cdot\bar{I}_i=\bar{V}_i \qquad -\bar{Z}_o\cdot\bar{I}_o=\bar{V}_o$$

Where:
- E_d is the line-to-neutral voltage ($E_d=\frac{U_r}{\sqrt{3}}$) of the section upstream the fault
- Z is the system impedance upstream the fault location
- I is the fault current
- V is the voltage measured at the fault location.

6 Calculation of short-circuit current

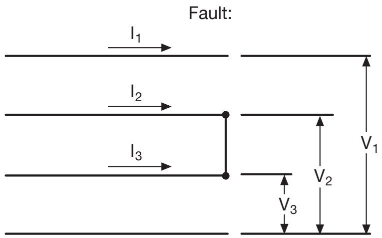
6.5.3 Calculation of short-circuit current with the algebra of sequences

Without going into the details of a theoretical treatment, it is possible to show the procedure to semplify and resolve the electrical network under a pre-estabilished fault condition thruogh an example.

Isolated line-to line fault

The diagram showing this fault typology and the link between currents and voltages, may be represented as follows:

Figure 4



Fault conditions (3)

$$\overline{V}_2 = \overline{V}_3 \qquad \overline{I}_2 = -\overline{I}_3 \qquad \overline{I}_1 = 0$$

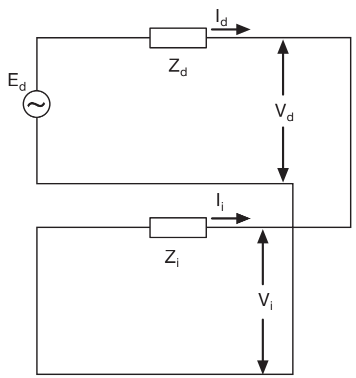
By using the given fault conditions and the formula 1), it follows that:

$$V_d = V_i \qquad I_d = -I_i \qquad (4)$$

$$I_o = 0 \text{ therefore } V_o = 0$$

These relationships applied to the three sequence circuits of Figure 3 allow the definition of the sequence network equivalent to the three-phase network under study and representing the initial fault condition. This network may be represented as follows:

Figure 5



6 Calculation of short-circuit current

By solving this simple network (constituted by series-connected elements) in relation to the current I_d, the following is obtained:

$$\overline{I}_d = \frac{\overline{E}_d}{\overline{Z}_d + \overline{Z}_i} \qquad 5)$$

By using formulas 2) referred to the current, and formulas 4), it follows that:

$$\overline{I}_2 = (\alpha^2 - \alpha)\cdot\overline{I}_d \qquad \overline{I}_3 = (\alpha - \alpha^2)\cdot\overline{I}_d$$

Since $|(\alpha^2 - \alpha)|$ results to be equal to $\sqrt{3}$, the value of the line-to-line short-circuit current in the two phases affected by the fault can be expressed as follows:

$$|\overline{I}_2| = |\overline{I}_3| = |\overline{I}_{k2}| = \sqrt{3}\cdot\left|\frac{\overline{E}_d}{\overline{Z}_d + \overline{Z}_i}\right|$$

Using formulas 2) referred to the voltage, and formulas 4) previously found, the following is obtained:

$\overline{V}_1 = 2\cdot\overline{V}_i$ 6) for the phase not affected by the fault

$\overline{V}_2 = \overline{V}_3 = (\alpha^2 + \alpha)\cdot\overline{V}_d = -\overline{V}_d$ 7) for the phases affected by the fault

Through the negative sequence circuit, relation 6) can be written as $\overline{V}_1 = -2\cdot\overline{Z}_i\cdot\overline{I}_i$.

Further to the above, and since $\overline{I}_d = -\overline{I}_i$, the phase not affected by the fault shall be:

$$\overline{V}_1 = \frac{2\cdot\overline{Z}_i}{\overline{Z}_d + \overline{Z}_i}\cdot\overline{E}_d \; .$$

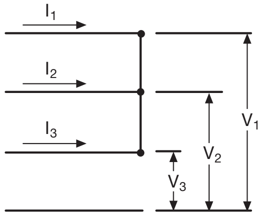
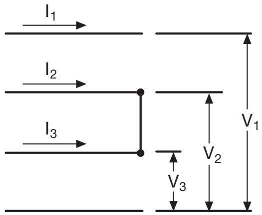
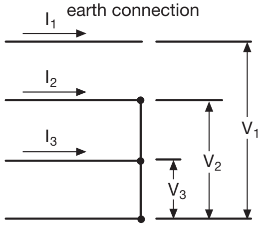
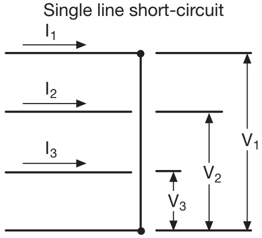
For the phases affected by the fault, being $\overline{V}_d = \overline{V}_i = \frac{\overline{V}_1}{2}$, it results:

$$\overline{V}_2 = \overline{V}_3 = -\frac{\overline{V}_1}{2} = \frac{\overline{Z}_i\cdot\overline{E}_d}{\overline{Z}_d + \overline{Z}_i}$$

Making reference to the previous example, it is possible to analyse all fault typologies and to express the fault currents and voltages as a function of the impedances of the sequence components.

6 Calculation of short-circuit current

A summary is given in Table 1 below:

Type of fault	Fault conditions:	Current	Voltage on phases
Three-phase short-circuit 	$\overline{V}_1=\overline{V}_2=\overline{V}_3$ $\overline{I}_1+\overline{I}_2+\overline{I}_3=0$	$\lvert\overline{I_{k3}}\rvert=\lvert\overline{I}_1\rvert=\dfrac{U_n}{\sqrt{3}\cdot\lvert\overline{Z}_d\rvert}$	$\overline{V}_1=\overline{V}_2=\overline{V}_3=0$
Line-to-line short-circuit 	$\overline{V}_2=\overline{V}_3$ $\overline{I}_2=-\overline{I}_3$	$\lvert\overline{I_{k2}}\rvert=\lvert\overline{I}_2\rvert=\dfrac{U_n}{\lvert\overline{Z}_d+\overline{Z}_i\rvert}$	$\lvert\overline{V}_1\rvert=\dfrac{2}{\sqrt{3}}\cdot U_n\cdot\left\lvert\dfrac{\overline{Z}_i}{\overline{Z}_d+\overline{Z}_i}\right\rvert$ $\lvert\overline{V}_2\rvert=\lvert\overline{V}_3\rvert=\dfrac{U_n}{\sqrt{3}}\cdot\left\lvert\dfrac{\overline{Z}_i}{\overline{Z}_d+\overline{Z}_i}\right\rvert$
Line-to-line short-circuit with earth connection 	$\overline{V}_2=\overline{V}_3=0$ $\overline{I}_1=0$	$\lvert\overline{I}_2\rvert=U_n\cdot\left\lvert\dfrac{(1+\alpha^2)\cdot\overline{Z}_i+\overline{Z}_o}{\overline{Z}_d\cdot\overline{Z}_i+\overline{Z}_i\cdot\overline{Z}_o+\overline{Z}_o\cdot\overline{Z}_d}\right\rvert$ $\lvert\overline{I}_3\rvert=U_n\cdot\left\lvert\dfrac{(1+\alpha)\cdot\overline{Z}_i+\overline{Z}_o}{\overline{Z}_d\cdot\overline{Z}_i+\overline{Z}_i\cdot\overline{Z}_o+\overline{Z}_o\cdot\overline{Z}_d}\right\rvert$ $\lvert\overline{I}_{ground}\rvert=\lvert\overline{I}_2+\overline{I}_3\rvert=U_n\cdot\left\lvert\dfrac{\overline{Z}_i}{\overline{Z}_d\cdot\overline{Z}_i+\overline{Z}_i\cdot\overline{Z}_o+\overline{Z}_o\cdot\overline{Z}_d}\right\rvert$	$\overline{V}_2=\overline{V}_3=0$ $\lvert\overline{V}_1\rvert=\sqrt{3}\cdot U_n\cdot\left\lvert\dfrac{\overline{Z}_i\cdot\overline{Z}_o}{\overline{Z}_d\cdot\overline{Z}_i+\overline{Z}_i\cdot\overline{Z}_o+\overline{Z}_o\cdot\overline{Z}_d}\right\rvert$
Single line short-circuit 	$\overline{V}_1=0$ $\overline{I}_2=\overline{I}_3=0$	$\lvert\overline{I_{k1}}\rvert=\lvert\overline{I}_1\rvert=\dfrac{\sqrt{3}\cdot U_n}{\lvert\overline{Z}_d+\overline{Z}_i+\overline{Z}_o\rvert}$	$\overline{V}_1=0$ $\lvert\overline{V}_2\rvert=U_n\cdot\left\lvert\dfrac{\overline{Z}_i-\alpha\cdot\overline{Z}_o}{\overline{Z}_d+\overline{Z}_i+\overline{Z}_o}\right\rvert$ $\lvert\overline{V}_3\rvert=U_n\cdot\left\lvert\dfrac{-\alpha\cdot\overline{Z}_i+\overline{Z}_o}{\overline{Z}_d+\overline{Z}_i+\overline{Z}_o}\right\rvert$

6 Calculation of short-circuit current

6.5.4 Positive, negative and zero sequence short-circuit impedances of electrical equipment

Each component of an electrical network (utility – transformer – generator – cable) may be represented by a positive, negative and zero sequence impedance value.

Utility

By utility it is meant the distribution supply network (usually MV) from which the plant is fed. It is characterized by positive and negative sequence elements, whereas the zero sequence impedance is not taken into consideration since the delta-connected windings of the primary circuit of the transformer impede the zero sequence current. As regards the existing impedances, it can be written:

$$Z_d = Z_i = Z_{NET}\ \frac{U_r}{\sqrt{3}\cdot I_{k3}}$$

Transformer

It is characterized by positive and negative sequence elements; besides, as a function of the connection of the windings and of the distribution system on the LV side, the zero sequence component may be present too.
Thus, it is possible to say that:

$$Z_d = Z_i = Z_T = \frac{uk\ \%}{100}\cdot\frac{U_r^2}{S_r}$$

whereas the zero sequence component can be expressed as:
$Z_o=Z_T$ when the flow of zero sequence currents in the two windings is possible
$Z_o=\infty$ when the flow of zero sequence currents in the two windings is impossible

Cable

It is characterized by positive, negative and zero sequence elements which vary as a function of the return path of the short-circuit current.

As regards the positive and negative sequence components, it is possible to say that:
$Z_d = Z_i = Z_C = R_C + j\ X_C$

To evaluate the zero sequence impedance, it is necessary to know the return path of the current:
$Z_o = Z_C + j3\cdot Z_{nC} = (R_C + 3\cdot R_{nC}) + j\,(X_C + 3\cdot X_{nC})$
Return through the neutral wire (phase-to-neutral fault)

$Z_o = Z_C + j3\cdot Z_{PEC} = (R_C + 3\cdot R_{PEC}) + j\,(X_C + 3\cdot X_{PEC})$
Return through PE (phase-to-PE conductor fault in TN-S system)

$Z_o = Z_{EC} + j3\cdot Z_{EC} = (R_C + 3\cdot R_{EC}) + j\,(X_C + 3\cdot X_{EC})$
Return through ground (phase-to-ground fault in TT system)

where:
- Z_C, R_C and X_C refer to the line conductor
- Z_{nC}, R_{nC} and X_{nC} refer to the neutral conductor
- Z_{PEC}, R_{PEC} and X_{PEC} refer to the protection conductor PE
- Z_{EC}, R_{EC} and X_{EC} refer to the ground.

6 Calculation of short-circuit current

Synchronous generators

Generally speaking, positive, negative and zero sequence reactances of synchronous generators (and also of rotating machines) have different values. For the positive sequence, only the sub transient reactance X''_d is used, since, in this case, the calculation of the fault current gives the highest value.
The negative sequence reactance is very variable, ranging between the values of X''_d and X''_q. In the initial instants of the short-circuit, X''_d and X''_q do not differ very much and therefore we may consider $X_i = X''_d$. On the contrary if X''_d and X''_q are remarkably different, it is possible to use a value equal to the average value of the two reactances; it follows that:

$$X_i = \frac{X''_d + X''_q}{2}.$$

The zero sequence reactance is very variable too and results to be lower than the other two above mentioned reactances. For this reactance, a value equal to 0.1 to 0.7 times the negative or positive sequence reactances may be assumed and can be calculated as follows:

$$X_o = \frac{x_o\%}{100} \cdot \frac{U_r^2}{S_r}$$

where $x_o\%$ is a typical parameter of the machine. Besides, the zero sequence component results to be influenced also by the grounding modality of the generator through the introduction of the parameters R_G and X_G, which represent, respectively, the grounding resistance and the reactance of the generator. If the star point of the generator is inaccessible or anyway non-earthed, the grounding impedance is ∞.

To summarize, the following expressions are to be considered for the sequence impedances:

$$Z_d = (R_a + j \cdot X''_d)$$
$$Z_i = (R_a + j \cdot X''_d)$$
$$Z_o = R_a + 3 \cdot R_G + j \cdot (X_o + 3 \cdot X_G)$$

where R_a is the stator resistance defined as $R_a = \dfrac{X''_d}{2 \cdot \pi \cdot f \cdot T_a}$, with T_a as stator time constant.

6.5 Algebra of sequences

6 Calculation of short-circuit current

Loads

If the load is passive, the impedance shall be considered as infinite.
If the load is not passive, as it could be for an asynchronous motor, it is possible to consider the machine represented by the impedance Z_M for the positive and negative sequence, whereas for the zero sequence the value Z_{oM} must be given by the manufacturer. Besides, if the motors are not earthed, the zero sequence impedance shall be ∞.
Therefore:

$$Z_d = Z_i = Z_M = (R_M + j \cdot X_M)$$

with Z_M equal to

$$Z_M = \frac{U_r^2}{\frac{I_{LR}}{I_r}} \cdot \frac{1}{S_r}$$

where:

I_{LR} is the current value when the rotor is blocked by the motor

I_r is the rated current of the motor

$S_r = \dfrac{P_r}{(\eta . \cos\varphi_r)}$ is the rated apparent power of the motor

The ratio $\dfrac{R_M}{X_M}$ is often known; for LV motors, this ratio can be considered equal to 0.42 with $X_M = \dfrac{Z_M}{\sqrt{1+\left(\frac{R_M}{X_M}\right)^2}}$, from which $X_M = 0.922 \cdot Z_M$ can be determined.

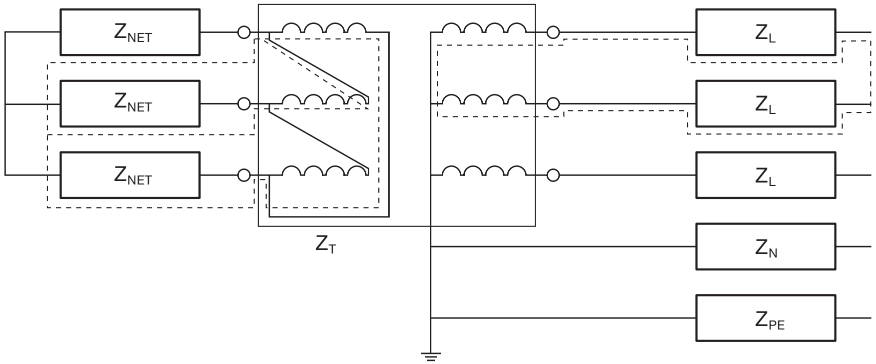
6 Calculation of short-circuit current

6.5.5 Formulas for the calculation of the fault currents as a function of the electrical parameters of the plant

Through Table 1 and through the formulas given for the sequence impedances expressed as a function of the electrical parameters of the plant components, it is possible to calculate the different short-circuit currents.

In the following example, a network with a MV/LV transformer with delta primary winding and secondary winding with grounded star point is taken into consideration and a line-to-line fault is assumed downstream the cable distribution line.

Figure 6



Applying the algebra of sequences:

$$I_{k2} = \frac{\sqrt{3} \cdot E_d}{(Z_d + Z_i)}$$

the impedances relevant to the positive and negative sequences under examination are:

$$Z_d = Z_i = Z_{NET} + Z_T + Z_L$$

considering that $E_d = \frac{U_r}{\sqrt{3}}$, the following is obtained:

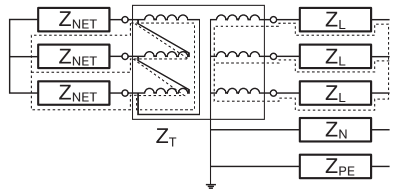
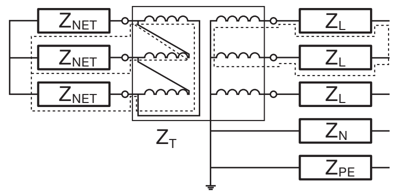
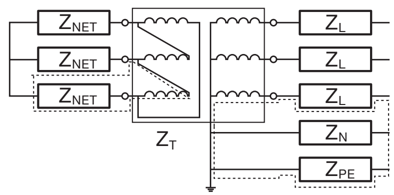
$$I_{k2} = \frac{\sqrt{3} \cdot E_d}{(Z_d + Z_i)} = \frac{U_r}{2 \cdot (Z_{NET} + Z_T + Z_L)}$$

where:
U_r is the rated voltage on the LV side
Z_T is the impedance of the transformer
Z_L is the impedance of the phase conductor
Z_{NET} is the impedance of the upstream network

By making reference to the previous example, it is possible to obtain Table 2 below, which gives the expressions for the short-circuit currents according to the different typologies of fault.

6 Calculation of short-circuit current

Table 2

Three-phase fault I_{k3}		$I_{k3} = \frac{U_r}{\sqrt{3} \cdot (Z_{NET} + Z_T + Z_L)}$
Line-to-line fault I_{k2}		$I_{k2} = \frac{U_r}{2 \cdot (Z_{NET} + Z_T + Z_L)}$
Single-phase fault I_{k1} (line-to-neutral or line-to- PE)		$I_{k1} = \frac{U_r}{\sqrt{3} \cdot \left(\frac{2}{3} \cdot Z_{NET} + Z_T + Z_L + Z_{PE}\right)}$ $I_{k1} = \frac{U_r}{\sqrt{3} \cdot \left(\frac{2}{3} \cdot Z_{NET} + Z_T + Z_L + Z_N\right)}$

Where:
U_r is the rated voltage on the LV side
Z_T is the impedance of the transformer
Z_L is the impedance of the phase conductor
Z_{NET} is the impedance of the upstream network
Z_{PE} is the impedance of the protection conductor (PE)
Z_N is the impedance of the neutral conductor

6 Calculation of short-circuit current

Table 3 below summarizes the relations for the fault currents, taking into account the upstream defined or infinite power network values and the distance of the fault from the transformer.

Table 3

	Upstream defined power network		Upstream infinite power network $Z_{NET} \rightarrow 0$	
	Far-from the transformer	Near the transformer $Z_L \rightarrow 0$, Z_{PE} (o Z_N) $\rightarrow 0$	Far-from the transformer	Near the transformer $Z_L \rightarrow 0$, Z_{PE} (o Z_N) $\rightarrow 0$
I_{k3}	$I_{k3}=\frac{U_r}{\sqrt{3}\cdot(Z_{NET}+Z_T+Z_L)}$	$I_{k3}=\frac{U_r}{\sqrt{3}\cdot(Z_{NET}+Z_T)}$	$I_{k3}=\frac{U_r}{\sqrt{3}\cdot(Z_T+Z_L)}$	$I_{k3}=\frac{U_r}{\sqrt{3}\cdot(Z_T)}$
I_{k2}	$I_{k2}=\frac{U_r}{2\cdot(Z_{NET}+Z_T+Z_L)}$	$I_{k2}=\frac{U_r}{2\cdot(Z_{NET}+Z_T)}$	$I_{k2}=\frac{U_r}{2\cdot(Z_T+Z_L)}$	$I_{k2}=\frac{U_r}{2\cdot(Z_T)}$
	$I_{k2}<I_{k3}$	$I_{k2}=0.87\cdot I_{k3}$	$I_{k2}=0.87\cdot I_{k3}$	$I_{k2}=0.87\cdot I_{k3}$
I_{k1}	$I_{k1}=\frac{U_r}{\sqrt{3}\cdot\left(\frac{2}{3}\cdot Z_{NET}+Z_T+Z_L+Z_{PE}\right)}$	$I_{k1}=\frac{U_r}{\sqrt{3}\cdot\left(\frac{2}{3}\cdot Z_{NET}+Z_T\right)}$	$I_{k1}=\frac{U_r}{\sqrt{3}\cdot(Z_T+Z_L+Z_{PE})}$	$I_{k1}=\frac{U_r}{\sqrt{3}\cdot(Z_T)}$
	$I_{k1}>I_{k3}$ if $Z_{NET}>3\cdot Z_{PE}$	$I_{k1}>I_{k3}$	$I_{k1}\leq I_{k3}$	$I_{k1}=I_{k3}$

6 Calculation of short-circuit current

6.6 Calculation of the peak value of the short-circuit current

The electrodynamical effects of the short-circuit currents are particularly dangerous for the bus ducts, but they can also damage cables.
The peak current is important also to evaluate the I_{cm} value of the circuit-breaker.
The I_{cm} value is also bound to the I_{cu} value, according to Table 16 of the Standard IEC 60947-1. With reference to the short-circuit current of the plant, it shall be $I_{cm} > I_{kp}$.

The peak current of a plant may be calculated by the following formula (see Std. IEC 60909-0):

$$I_{kp} = I''_k \cdot \sqrt{2} \cdot \left(1.02 + 0.98 \cdot e^{-\frac{3 \cdot R}{X}}\right)$$

where:
- I''_k is the short-circuit current (rms value) at the initial instant of the short-circuit
- R is the resistive component of the short-circuit impedance at the fault location
- X is the reactive component of the short-circuit current at the fault location

When the power factor $\cos\varphi_k$ is known, it is possible to write:

$$I_{kp} = I''_k \cdot \sqrt{2} \cdot \left(1.02 + 0.98 \cdot e^{-\frac{3}{\tan\varphi_k}}\right)$$

6.7 Considerations about UPS (Uninterruptible Power Supplies) contribution to short-circuit currents

In the following considerations particular attention is given to a double-conversion or UPS on-line, belonging to the category VFI (Voltage and Frequency Independent), for which the output voltage is independent of the mains voltage variations and frequency variations are controlled by this device within the standard limits prescribed by the Standards; this system is characterised by the following operating modalities:

- under normal operating conditions, in the presence of the network voltage, the load is fed by the network itself through the UPS;
- under emergency conditions (lack of network), power to the load is supplied by the battery and by the inverter (“island supply” with UPS disconnected from the mains);
- in case of temporary overcurrent required by the load (e.g. motor start-up), power supply to the load is guaranteed by the network through the static switch which excludes the UPS;
- in case of maintenance, for example due to a fault on the UPS, the load is fed by the network through a manual bypass switch, by temporarily giving up the availability of emergency power supply.

As regards the dimensioning of the protections on the supply side of the UPS, it is necessary to know the characteristics of the network voltage and of the short-circuit current; for the dimensioning of the protections on the load side, it is necessary to know the current values let through by the UPS.
If power supply of the loads is provided directly from the network through manual bypass, also the circuit-breaker on the load side must have a breaking capacity (Icu) suitable for the short-circuit current of the supply-side network.
Furthermore, if required, an evaluation of the protection co-ordination in relation to the operating conditions is necessary.

However, in order to choose the suitable protections, it is important to distinguish between two operating conditions for UPS:

1) UPS under normal operating conditions

a) Overload condition:
- if due to a possible fault on the battery, this condition affects only the circuit-breaker on the supply-side of the UPS (also likely the intervention of the protections inside the battery);
- if required by the load, this condition might not be supported by the UPS, which is bypassed by the static converter.

b) Short-circuit condition:
The short-circuit current is limited by the dimensioning of the thyristors of the bridge inverter. In the practice, UPS may supply a maximum short-circuit current equal to 150 to 200% of the rated value. In the event of a short-circuit, the inverter supplies the maximum current for a limited time (some hundreds of milliseconds) and then switches to the network, so that power to the load is supplied by the bypass circuit.
In this case, selectivity between the circuit-breaker on the supply side and the circuit-breaker on the load side is important in order to disconnect only the load affected by the fault.
The bypass circuit, which is also called static switch, and is formed by thyristors protected by extrarapid fuses, can feed the load with a higher current than the inverter; this current results to be limited by the dimensioning of the thyristors used, by the power installed and by the provided protections.
The thyristors of the bypass circuit are usually dimensioned to withstand the following overload conditions:

125%	for 600 seconds
150%	for 60 seconds
700%	for 600 milliseconds
1000%	for 100 milliseconds

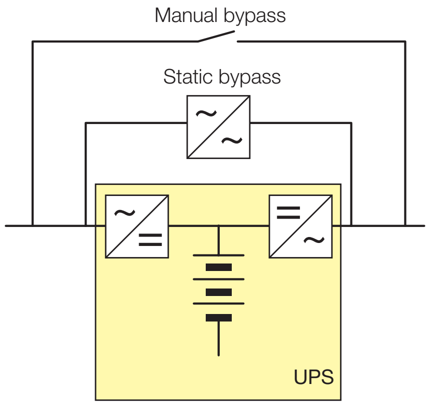
Generally, more detailed data can be obtained from the technical information given by the manufacturer.

2) UPS under emergency operating conditions

a) Overload condition:
this condition, involving the load-side circuit-breaker only, is supported by the battery with inverter, which presents an overload condition usually calculable in the following orders of magnitude:
1.15 x In for indefinite time
1.25 x In for 600 seconds
1.5 x In for 60 seconds
2 x In for 1 seconds
Generally, more detailed data can be obtained from the technical information given by the manufacturer.

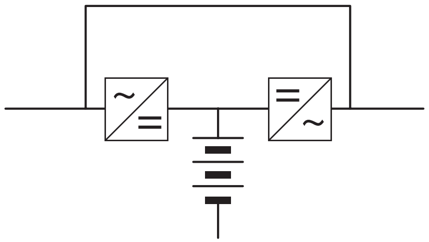
b) Short-circuit condition:
the maximum current towards the load is limited by the inverter circuit only (with a value from 150 to 200% of the nominal value). The inverter feeds the short-circuit for a certain period of time, usually limited to some milliseconds, after which the UPS unit disconnects the load leaving it without supply. In this operating modality, it is necessary to obtain selectivity between the circuit-breaker on the load side and the inverter, which is quite difficult due to the reduced tripping times of the protection device of the inverter.

Figure 7



UPS on-line with static switch

Figure 8



UPS off-line: loads directly fed by the network

A.1 Slide rules

These slide rules represent a valid instrument for a quick and approximate dimensioning of electrical plants.
All the given information is connected to some general reference conditions; the calculation methods and the data reported are gathered from the IEC Standards in force and from plant engineering practice. The instruction manual enclosed with the slide rules offers different examples and tables showing the correction coefficients necessary to extend the general reference conditions to those actually required.

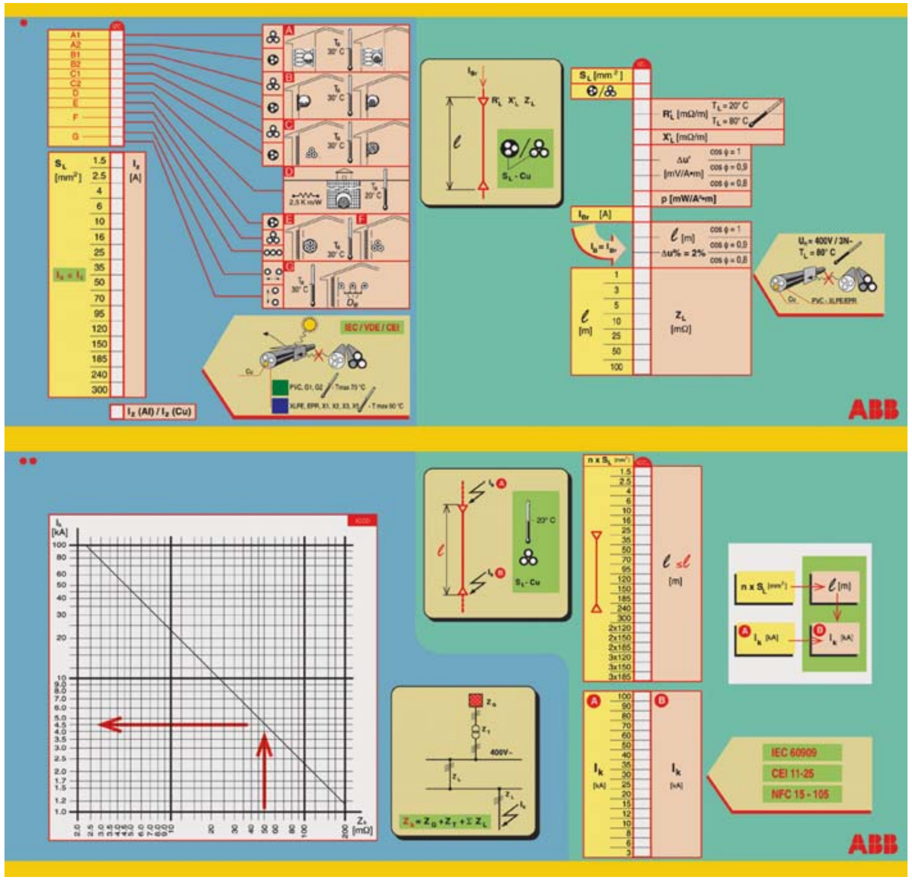
These two-sided slide rules are available in four different colors, easily identified by subject:
- yellow slide rule: cable sizing;
- orange slide rule: cable verification and protection;
- green slide rule: protection coordination;
- blue slide rule: motor and transformer protection.

Annex A: Calculation tools

Yellow slide rule: cable sizing

Side ●
Definition of the current carrying capacity, impedance and voltage drop of cables.

Side ● ●
Calculation of the short-circuit current for three-phase fault on the load side of a cable line with known cross section and length.
In addition, a diagram for the calculation of the short-circuit current on the load side of elements with known impedance.



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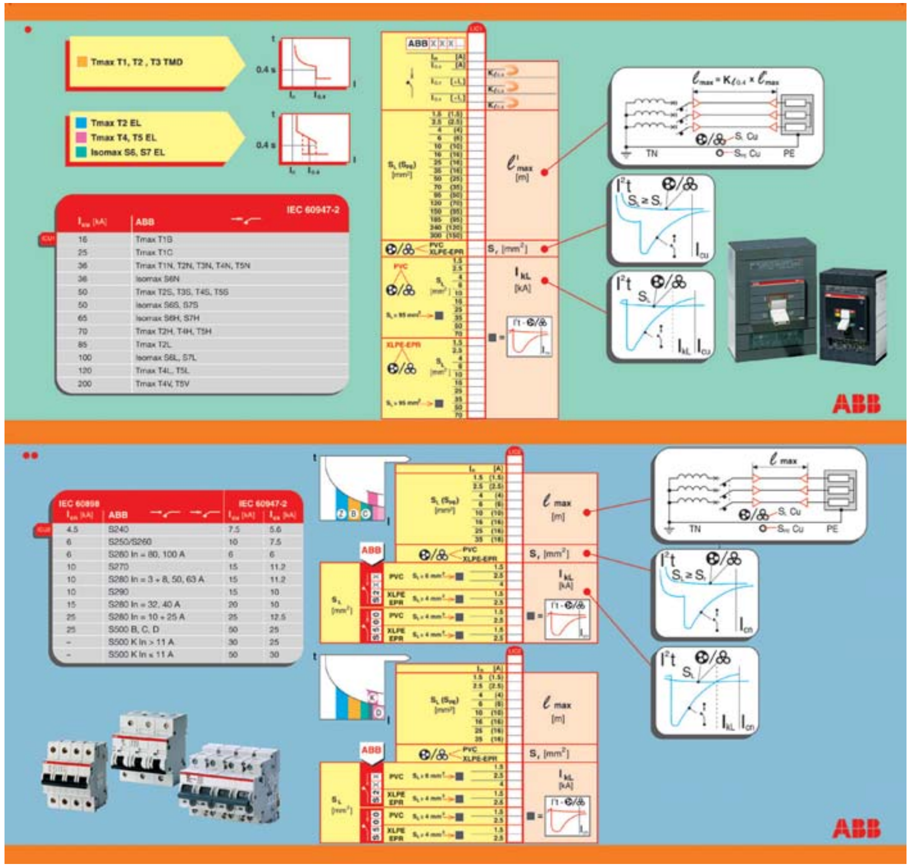
Annex A: Calculation tools

Orange slide rule: cable verification and protection

Side ●
Verification of cable protection against indirect contact and short-circuit with ABB SACE MCCBs (moulded-case circuit-breakers).

Side ● ●
Verification of cable protection against indirect contact and short-circuit with ABB MCBs (modular circuit-breakers).



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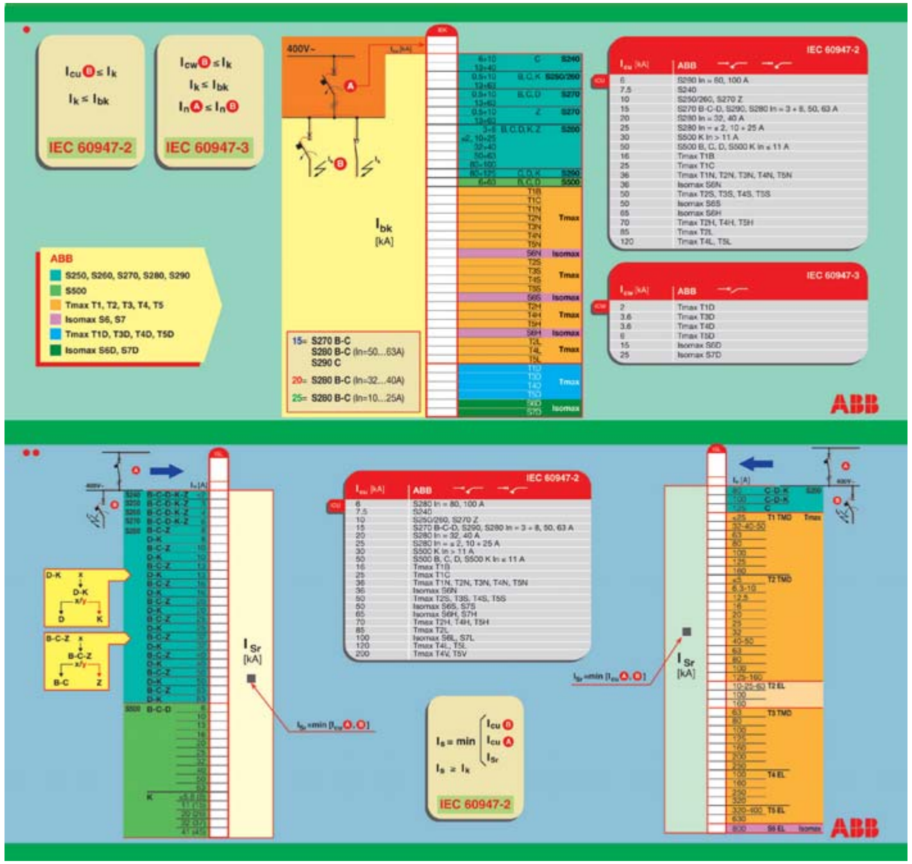
Annex A: Calculation tools

Green slide rule: protection coordination

Side ●
Selection of the circuit-breakers when back-up protection is provided.

Side ● ●
Definition of the limit selectivity current for the combination of two circuit-breakers in series.



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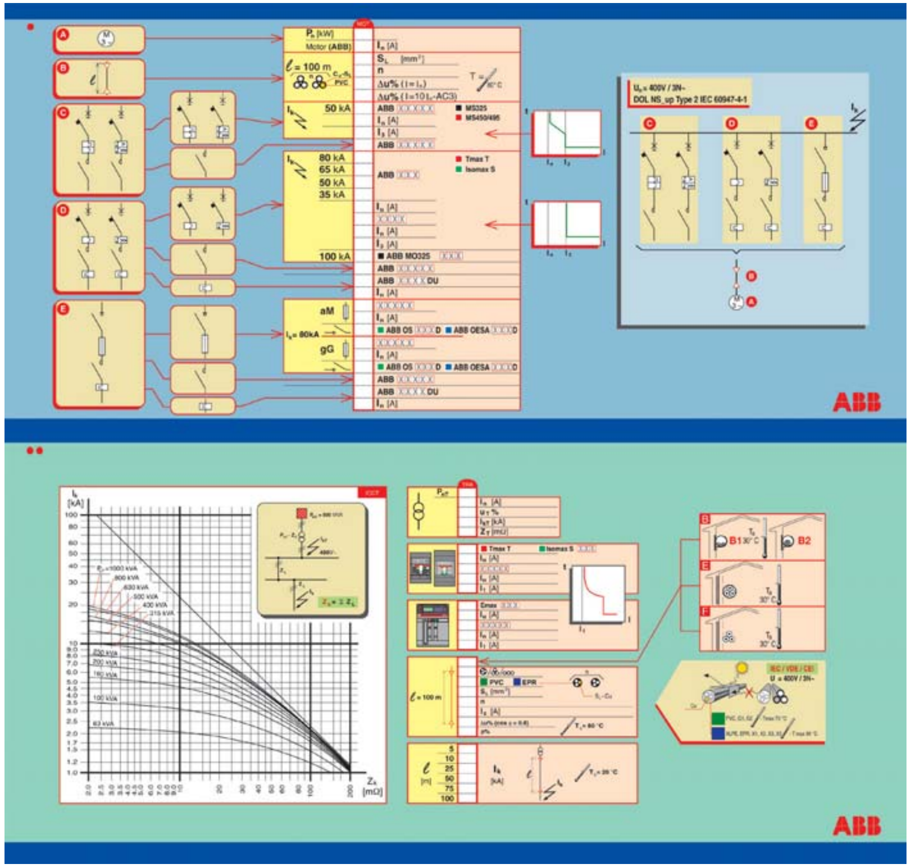
Annex A: Calculation tools

Blue slide rule: motor and transformer protection

Side ●
Selection and coordination of the protection devices for the motor starter, DOL start-up (type 2 coordination in compliance with the Standard IEC 60947-4-1).

Side ● ●
Sizing of a transformer feeder.
In addition, a diagram for the calculation of the short-circuit current on the load side of transformers with known rated power.



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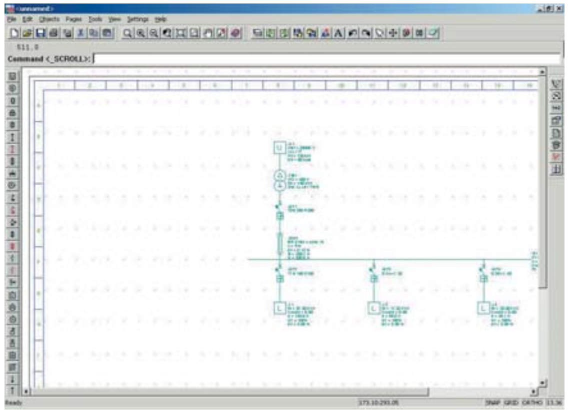
Annex A: Calculation tools

A.2 DOCWin

DOCWin is a software for the dimensioning of electrical networks, with low or medium voltage supply.
Networks can be completely calculated through simple operations starting from the definition of the single-line diagram and thanks to the drawing functions provided by an integrated CAD software.

Drawing and definition of networks

Creation of the single-line diagram, with no limits to the network complexity. Meshed networks can also be managed.
- The diagram can be divided into many pages.
- The program controls the coherence of drawings in real time.
- It is possible to enter and modify the data of the objects which form the network by using a table.
- It is possible to define different network configurations by specifying the status (open/closed) of the operating and protective devices.



Supplies

- There are no pre-defined limits: the software manages MV and LV power supplies and generators, MV/LV and LV/LV transformers, with two or three windings, with or without voltage regulator, according to the requirements.

Network calculation

- Load Flow calculation using the Newton-Raphson method. The software can manage networks with multiple slacks and unbalances due to single- or two-phase loads. Magnitude and phase shift of the node voltage and of the branch current are completely defined for each point of the network, for both MV as well as LV.
- Calculation of the active and reactive power required by each single power source.

Annex A: Calculation tools

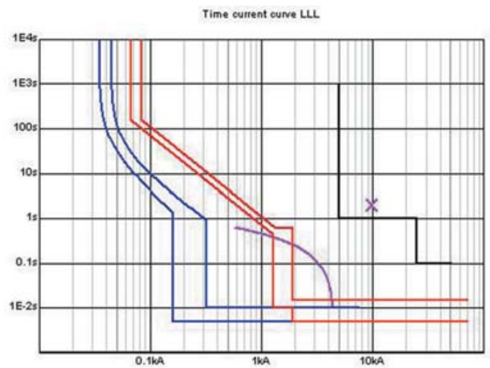
- Management of local (motors) and centralized power factor correction with capacitor banks.
- Management of the demand factor for each single node of the network and of the utilization factor on the loads.
- Short-circuit current calculation for three-phase, phase-to-phase, phase-to-neutral, phase-to-ground faults. The calculation is also carried out for MV sections, in compliance with the Standards IEC 60909-1, IEC 61363-1 (naval installations) or with the method of symmetric components, taking into account also the time-variance contribution of rotary machines (generators and motors).
- Calculation of switchboard overtemperature in compliance with Standard IEC 60890. The power dissipated by the single apparatus is automatically derived by the data files of the software, and can be considered as a function of the rated current or of the load current.

Cable line sizing

- Cable line sizing according to thermal criteria in compliance with the following Standards: CEI 64-8 (tables CEI UNEL 35024-35026), IEC 60364, VDE 298-4, NFC 15-100, IEC 60092 (naval installations) and IEC 60890.
- Possibility of setting, as additional calculation criterion, the economic criteria stated in the Standard IEC 60827-3-2.
- Possibility of setting, as additional calculation criterion, the maximum allowed voltage drop.
- Automatic sizing of busbar trunking system.
- Sizing and check on the dynamic withstand of busbars in compliance with the Standard IEC 60865.

Curves and verifications

- Representation of:
- time / current curves (I-t),
- current / let-through energy curves (I-I^2t),
- current limiting curves (peak): visual check of the effects of the settings on the trip characteristics of protection devices.

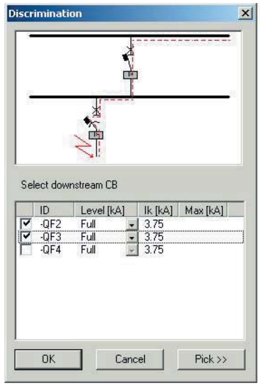


Annex A: Calculation tools

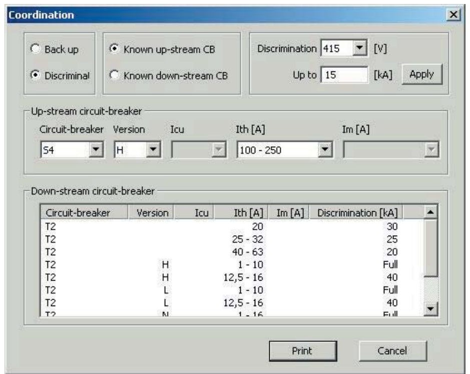
- Representation of the curves of circuit-breakers, cables, transformers, motors and generators.
- Possibility of entering the curve of the utility and of the MV components point by point, to verify the tripping discrimination of protection devices.
- Verification of the maximum voltage drop at each load.
- Verification of the protection devices, with control over the setting parameters of the adjustable releases (both thermomagnetic as well as electronic).

Selection of operating and protection devices

- Automatic selection of protection devices (circuit-breakers and fuses)
- Automatic selection of operating devices (contactors and switch disconnectors)
- Discrimination and back-up managed as selection criteria, with discrimination level adjustable for each circuit-breaker combination.

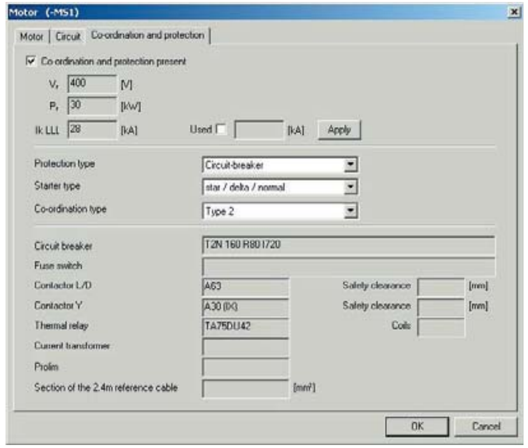


- Discrimination and back-up verification also through quick access to coordination tables.



Annex A: Calculation tools

- Motor coordination management through quick access to ABB tables.



Printouts

- Single-line diagram, curves and reports of the single components of the network can be printed by any printer supported by the hardware configuration.
- All information can be exported in the most common formats of data exchange.
- All print modes can be customized.

Annex B: Calculation of load current I_b

Generic loads

The formula for the calculation of the load current of a generic load is:

$$I_b = \frac{P}{k \cdot U_r \cdot \cos\varphi}$$

where:

- P is the active power [W];
- k is a coefficient which has the value:
  - 1 for single-phase systems or for direct current systems;
  - $\sqrt{3}$ for three-phase systems;
- U_r is the rated voltage [V] (for three-phase systems it is the line voltage, for single-phase systems it is the phase voltage);
- $\cos\varphi$ is the power factor.

Table 1 allows the load current to be determined for some power values according to the rated voltage. The table has been calculated considering $\cos\varphi$ to be equal to 0.9; for different power factors, the value from Table 1 must be multiplied by the coefficient given in Table 2 corresponding to the actual value of the power factor ($\cos\varphi_{act}$).

Table 1: Load current for three-phase systems with $\cos\varphi$ = 0.9

P [kW]	U_r [V] 230	400	415	440	500	600	690
	I_b [A]						
0.03	0.08	0.05	0.05	0.04	0.04	0.03	0.03
0.04	0.11	0.06	0.06	0.06	0.05	0.04	0.04
0.06	0.17	0.10	0.09	0.09	0.08	0.06	0.06
0.1	0.28	0.16	0.15	0.15	0.13	0.11	0.09
0.2	0.56	0.32	0.31	0.29	0.26	0.21	0.19
0.5	1.39	0.80	0.77	0.73	0.64	0.53	0.46
1	2.79	1.60	1.55	1.46	1.28	1.07	0.93
2	5.58	3.21	3.09	2.92	2.57	2.14	1.86
5	13.95	8.02	7.73	7.29	6.42	5.35	4.65
10	27.89	16.04	15.46	14.58	12.83	10.69	9.30
20	55.78	32.08	30.92	29.16	25.66	21.38	18.59
30	83.67	48.11	46.37	43.74	38.49	32.08	27.89
40	111.57	64.15	61.83	58.32	51.32	42.77	37.19
50	139.46	80.19	77.29	72.90	64.15	53.46	46.49
60	167.35	96.23	92.75	87.48	76.98	64.15	55.78
70	195.24	112.26	108.20	102.06	89.81	74.84	65.08
80	223.13	128.30	123.66	116.64	102.64	85.53	74.38
90	251.02	144.34	139.12	131.22	115.47	96.23	83.67
100	278.91	160.38	154.58	145.80	128.30	106.92	92.97
110	306.80	176.41	170.04	160.38	141.13	117.61	102.27
120	334.70	192.45	185.49	174.95	153.96	128.30	111.57
130	362.59	208.49	200.95	189.53	166.79	138.99	120.86
140	390.48	224.53	216.41	204.11	179.62	149.68	130.16
150	418.37	240.56	231.87	218.69	192.45	160.38	139.46
200	557.83	320.75	309.16	291.59	256.60	213.83	185.94

Annex B: Calculation of load current I_b

P [kW]	U_r [V] 230	400	415	440	500	600	690
	I_b[A]						
250	697.28	400.94	386.45	364.49	320.75	267.29	232.43
300	836.74	481.13	463.74	437.39	384.90	320.75	278.91
350	976.20	561.31	541.02	510.28	449.05	374.21	325.40
400	1115.65	641.50	618.31	583.18	513.20	427.67	371.88
450	1255.11	721.69	695.60	656.08	577.35	481.13	418.37
500	1394.57	801.88	772.89	728.98	641.50	534.58	464.86
550	1534.02	882.06	850.18	801.88	705.65	588.04	511.34
600	1673.48	962.25	927.47	874.77	769.80	641.50	557.83
650	1812.94	1042.44	1004.76	947.67	833.95	694.96	604.31
700	1952.39	1122.63	1082.05	1020.57	898.10	748.42	650.80
750	2091.85	1202.81	1159.34	1093.47	962.25	801.88	697.28
800	2231.31	1283.00	1236.63	1166.36	1026.40	855.33	743.77
850	2370.76	1363.19	1313.92	1239.26	1090.55	908.79	790.25
900	2510.22	1443.38	1391.21	1312.16	1154.70	962.25	836.74
950	2649.68	1523.56	1468.49	1385.06	1218.85	1015.71	883.23
1000	2789.13	1603.75	1545.78	1457.96	1283.00	1069.17	929.71

Table 2: Correction factors for load current with $\cos\varphi$ other than 0.9

$\cos\varphi_{act}$	1	0.95	0.9	0.85	0.8	0.75	0.7
$k_{\cos\varphi}$*	0.9	0.947	1	1.059	1.125	1.2	1.286

* For $\cos\varphi_{act}$ values not present in the table, $k_{\cos\varphi} = \frac{0.9}{\cos\varphi_{act}}$

Table 3 allows the load current to be determined for some power values according to the rated voltage. The table has been calculated considering $\cos\varphi$ to be equal to 1; for different power factors, the value from Table 3 must be multiplied by the coefficient given in Table 4 corresponding to the actual value of the power factor ($\cos\varphi_{act}$).

Table 3: Load current for single-phase systems with $\cos\varphi$ = 1 or dc systems

P [kW]	U_r [V] 230	400	415	440	500	600	690
	I_b [A]						
0.03	0.13	0.08	0.07	0.07	0.06	0.05	0.04
0.04	0.17	0.10	0.10	0.09	0.08	0.07	0.06
0.06	0.26	0.15	0.14	0.14	0.12	0.10	0.09
0.1	0.43	0.25	0.24	0.23	0.20	0.17	0.14
0.2	0.87	0.50	0.48	0.45	0.40	0.33	0.29
0.5	2.17	1.25	1.20	1.14	1.00	0.83	0.72
1	4.35	2.50	2.41	2.27	2.00	1.67	1.45
2	8.70	5.00	4.82	4.55	4.00	3.33	2.90
5	21.74	12.50	12.05	11.36	10.00	8.33	7.25
10	43.48	25.00	24.10	22.73	20.00	16.67	14.49
20	86.96	50.00	48.19	45.45	40.00	33.33	28.99

Annex B: Calculation of load current I_b

	U_r [V]						
	230	400	415	440	500	600	690
P [kW]	I_b [A]						
30	130.43	75.00	72.29	68.18	60.00	50.00	43.48
40	173.91	100.00	96.39	90.91	80.00	66.67	57.97
50	217.39	125.00	120.48	113.64	100.00	83.33	72.46
60	260.87	150.00	144.58	136.36	120.00	100.00	86.96
70	304.35	175.00	168.67	159.09	140.00	116.67	101.45
80	347.83	200.00	192.77	181.82	160.00	133.33	115.94
90	391.30	225.00	216.87	204.55	180.00	150.00	130.43
100	434.78	250.00	240.96	227.27	200.00	166.67	144.93
110	478.26	275.00	265.06	250.00	220.00	183.33	159.42
120	521.74	300.00	289.16	272.73	240.00	200.00	173.91
130	565.22	325.00	313.25	295.45	260.00	216.67	188.41
140	608.70	350.00	337.35	318.18	280.00	233.33	202.90
150	652.17	375.00	361.45	340.91	300.00	250.00	217.39
200	869.57	500.00	481.93	454.55	400.00	333.33	289.86
250	1086.96	625.00	602.41	568.18	500.00	416.67	362.32
300	1304.35	750.00	722.89	681.82	600.00	500.00	434.78
350	1521.74	875.00	843.37	795.45	700.00	583.33	507.25
400	1739.13	1000.00	963.86	909.09	800.00	666.67	579.71
450	1956.52	1125.00	1084.34	1022.73	900.00	750.00	652.17
500	2173.91	1250.00	1204.82	1136.36	1000.00	833.33	724.64
550	2391.30	1375.00	1325.30	1250.00	1100.00	916.67	797.10
600	2608.70	1500.00	1445.78	1363.64	1200.00	1000.00	869.57
650	2826.09	1625.00	1566.27	1477.27	1300.00	1083.33	942.03
700	3043.48	1750.00	1686.75	1590.91	1400.00	1166.67	1014.49
750	3260.87	1875.00	1807.23	1704.55	1500.00	1250.00	1086.96
800	3478.26	2000.00	1927.71	1818.18	1600.00	1333.33	1159.42
850	3695.65	2125.00	2048.19	1931.82	1700.00	1416.67	1231.88
900	3913.04	2250.00	2168.67	2045.45	1800.00	1500.00	1304.35
950	4130.43	2375.00	2289.16	2159.09	1900.00	1583.33	1376.81
1000	4347.83	2500.00	2409.64	2272.73	2000.00	1666.67	1449.28

Table 4: Correction factors for load current with cosφ other than 1

$\cos\varphi_{act}$	1	0.95	0.9	0.85	0.8	0.75	0.7
$k_{\cos\varphi}$*	1	1.053	1.111	1.176	1.25	1.333	1.429

* For $\cos\varphi_{act}$ values not present in the table, $k_{\cos\varphi} = \dfrac{1}{\cos\varphi_{act}}$

Lighting circuits

The current absorbed by the lighting system may be deduced from the lighting equipment catalogue, or approximately calculated using the following formula:

$$I_b = \frac{P_L n_L k_B k_N}{U_{rL} \cos\varphi}$$

where:

- P_L is the power of the lamp [W];
- n_L is the number of lamps per phase;
- k_B is a coefficient which has the value:
  - 1 for lamps which do not need any auxiliary starter;
  - 1.25 for lamps which need auxiliary starters;
- k_N is a coefficient which has the value:
  - 1 for star-connected lamps;
  - $\sqrt{3}$ for delta-connected lamps;
- U_{rL} is the rated voltage of the lamps;
- cosφ is the power factor of the lamps which has the value:
  - 0.4 for lamps without compensation;
  - 0.9 for lamps with compensation.

Annex B: Calculation of load current I_b

Motors

Table 5 gives the approximate values of the load current for some three-phase squirrel-cage motors, 1500 rpm at 50 Hz, according to the rated voltage.

Note: these values are given for information only, and may vary according to the motor manifacturer and depending on the number of poles

Table 5: Motor load current

Motor power		Rated current of the motor at:							
[kW]	PS = hp	220-230 V [A]	240 V [A]	380-400 V [A]	415 V [A]	440 V [A]	500 V [A]	600 V [A]	660-690 V [A]
0.06	1/12	0.38	0.35	0.22	0.20	0.19	0.16	0.12	–
0.09	1/8	0.55	0.50	0.33	0.30	0.28	0.24	0.21	–
0.12	1/6	0.76	0.68	0.42	0.40	0.37	0.33	0.27	–
0.18	1/4	1.1	1	0.64	0.60	0.55	0.46	0.40	–
0.25	1/3	1.4	1.38	0.88	0.85	0.76	0.59	0.56	–
0.37	1/2	2.1	1.93	1.22	1.15	1.06	0.85	0.77	0.7
0.55	3/4	2.7	2.3	1.5	1.40	1.25	1.20	1.02	0.9
0.75	1	3.3	3.1	2	2	1.67	1.48	1.22	1.1
1.1	1.5	4.9	4.1	2.6	2.5	2.26	2.1	1.66	1.5
1.5	2	6.2	5.6	3.5	3.5	3.03	2.6	2.22	2
2.2	3	8.7	7.9	5	5	4.31	3.8	3.16	2.9
2.5	3.4	9.8	8.9	5.7	5.5	4.9	4.3	3.59	3.3
3	4	11.6	10.6	6.6	6.5	5.8	5.1	4.25	3.5
3.7	5	14.2	13	8.2	7.5	7.1	6.2	5.2	4.4
4	5.5	15.3	14	8.5	8.4	7.6	6.5	5.6	4.9
5	6.8	18.9	17.2	10.5	10	9.4	8.1	6.9	6
5.5	7.5	20.6	18.9	11.5	11	10.3	8.9	7.5	6.7
6.5	8.8	23.7	21.8	13.8	12.5	12	10.4	8.7	8.1
7.5	10	27.4	24.8	15.5	14	13.5	11.9	9.9	9
8	11	28.8	26.4	16.7	15.4	14.4	12.7	10.6	9.7
9	12.5	32	29.3	18.3	17	15.8	13.9	11.6	10.6
11	15	39.2	35.3	22	21	19.3	16.7	14.1	13
12.5	17	43.8	40.2	25	23	21.9	19	16.1	15
15	20	52.6	48.2	30	28	26.3	22.5	19.3	17.5
18.5	25	64.9	58.7	37	35	32	28.5	23.5	21
20	27	69.3	63.4	40	37	34.6	30.6	25.4	23
22	30	75.2	68	44	40	37.1	33	27.2	25
25	34	84.4	77.2	50	47	42.1	38	30.9	28
30	40	101	92.7	60	55	50.1	44	37.1	33
37	50	124	114	72	66	61.9	54	45.4	42
40	54	134	123	79	72	67	60	49.1	44
45	60	150	136	85	80	73.9	64.5	54.2	49
51	70	168	154	97	90	83.8	73.7	61.4	56
55	75	181	166	105	96	90.3	79	66.2	60
59	80	194	178	112	105	96.9	85.3	71.1	66
75	100	245	226	140	135	123	106	90.3	82
80	110	260	241	147	138	131	112	96.3	86
90	125	292	268	170	165	146	128	107	98
100	136	325	297	188	182	162	143	119	107
110	150	358	327	205	200	178	156	131	118
129	175	420	384	242	230	209	184	153	135
132	180	425	393	245	242	214	186	157	140
140	190	449	416	260	250	227	200	167	145
147	200	472	432	273	260	236	207	173	152
160	220	502	471	295	280	256	220	188	170
180	245	578	530	333	320	289	254	212	190
184	250	590	541	340	325	295	259	217	200
200	270	626	589	370	340	321	278	235	215
220	300	700	647	408	385	353	310	260	235
250	340	803	736	460	425	401	353	295	268
257	350	826	756	475	450	412	363	302	280
295	400	948	868	546	500	473	416	348	320
315	430	990	927	580	535	505	445	370	337
355	480	1080	1010	636	580	549	483	405	366
400	545	1250	1130	710	650	611	538	450	410
450	610	1410	1270	800	740	688	608	508	460
475	645	1490	1340	850	780	730	645	540	485
500	680	1570	1420	890	830	770	680	565	510
560	760	1750	1580	1000	920	860	760	630	570
600	810	–	–	1080	990	920	810	680	610
670	910	–	–	1200	1100	1030	910	760	680

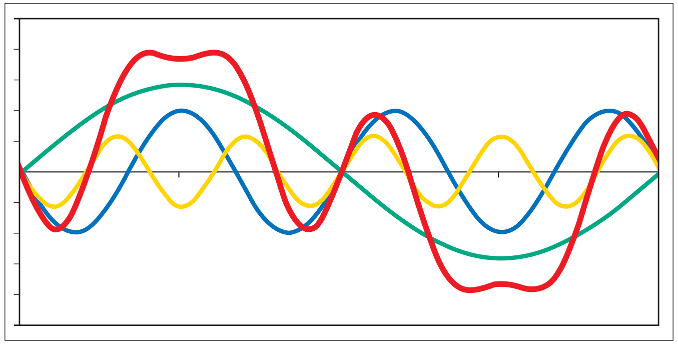
Annex C: Harmonics

What are they?

The harmonics allow to represent any periodic waveform; in fact, according to Fourier's theorem, any periodic function of a period T may be represented as a summation of:
- a sinusoid with the same period T;
- some sinusoids with the same frequency as whole multiples of the fundamental;
- a possible continuous component, if the function has an average value not null in the period.

The harmonic with frequency corresponding to the period of the original waveform is called fundamental and the harmonic with frequency equal to "n" times that of the fundamental is called harmonic component of order "n".
A perfectly sinusoidal waveform complying with Fourier's theorem does not present harmonic components of order different from the fundamental one. Therefore, it is understandable how there are no harmonics in an electrical system when the waveforms of current and voltage are sinusoidal. On the contrary, the presence of harmonics in an electrical system is an index of the distortion of the voltage or current waveform and this implies such a distribution of the electric power that malfunctioning of equipment and protective devices can be caused.
To summarize: the harmonics are nothing less than the components of a distorted waveform and their use allows us to analyse any periodic nonsinusoidal waveform through different sinusoidal waveform components.
Figure 1 below shows a graphical representation of this concept.

Figure 1



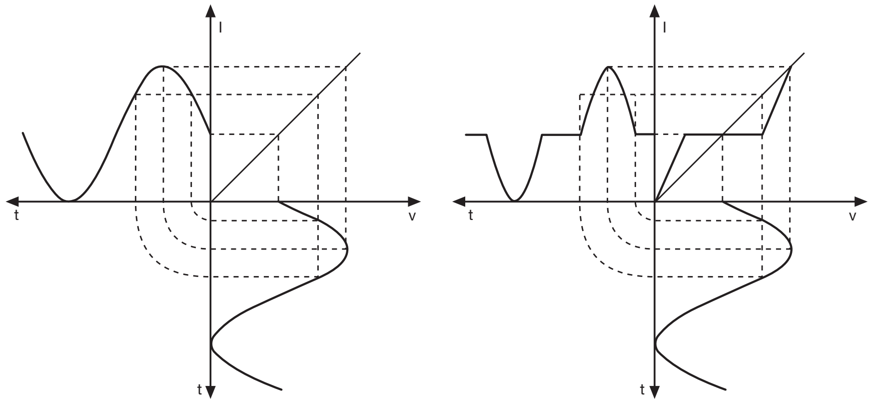
Caption:
- nonsinusoidal waveform
- first harmonic (fundamental)
- third harmonic
- fifth harmonic

Annex C: Harmonics

How harmonics are generated?

Harmonics are generated by nonlinear loads. When we apply a sinusoidal voltage to a load of this type, we shall obtain a current with non-sinusoidal waveform. The diagram of Figure 2 illustrates an example of nonsinusoidal current waveform due to a nonlinear load:

Figure 2



Linear load Nonlinear load

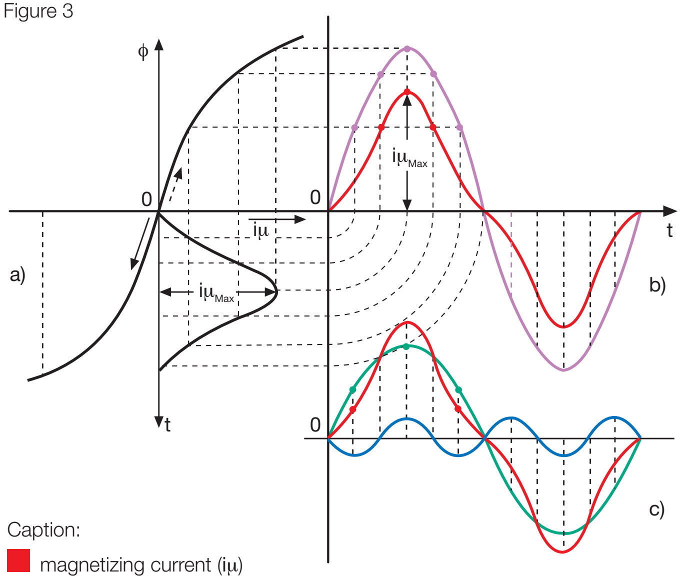
As already said, this nonsinusoidal waveform can be deconstructed into harmonics. If the network impedances are very low, the voltage distortion resulting from a harmonic current is low too and rarely it is above the pollution level already present in the network. As a consequence, the voltage can remain practically sinusoidal also in the presence of current harmonics.
To function properly, many electronic devices need a definite current waveform and thus they have to 'cut' the sinusoidal waveform so as to change its rms value or to get a direct current from an alternate value; in these cases the current on the line has a nonsinusoidal curve.
The main equipment generating harmonics are:
- personal computer
- fluorescent lamps
- static converters
- continuity groups
- variable speed drives
- welders

In general, waveform distortion is due to the presence, inside of these equipment, of bridge rectifiers, whose semiconductor devices carry the current only for a fraction of the whole period, thus originating discontinuous curves with the consequent introduction of numerous harmonics.

Annex C: Harmonics

Also transformers can be cause of harmonic pollution; in fact, by applying a perfectly sinusoidal voltage to a transformer, it results into a sinusoidal magnetizing flux, but, due to the phenomenon of the magnetic saturation of iron, the magnetizing current shall not be sinusoidal. Figure 3 shows a graphic representation of this phenomenon:

Figure 3



Caption:

- magnetizing current (iμ)
- first harmonic current (fundamental)
- third harmonic current
- flux variable in time: $\phi = \phi_{Max} \sin\omega t$

The resultant waveform of the magnetizing current contains numerous harmonics, the greatest of which is the third one. However, it should be noted that the magnetizing current is generally a little percentage of the rated current of the transformer and the distortion effect becomes more and more negligible the most loaded the transformer results to be.

Effects

The main problems caused by harmonic currents are:
1) overloading of neutrals
2) increase of losses in the transformers
3) increase of skin effect

The main effects of the harmonics voltages are:
4) voltage distortion
5) disturbances in the torque of induction motors

Annex C: Harmonics

1) Overloading of neutrals

In a three phase symmetric and balanced system with neutral, the waveforms between the phases are shifted by a 120° phase angle so that, when the phases are equally loaded, the current in the neutral is zero. The presence of unbalanced loads (phase-to-phase, phase-to-neutral etc.) allows the flowing of an unbalanced current in the neutral.

Figure 4

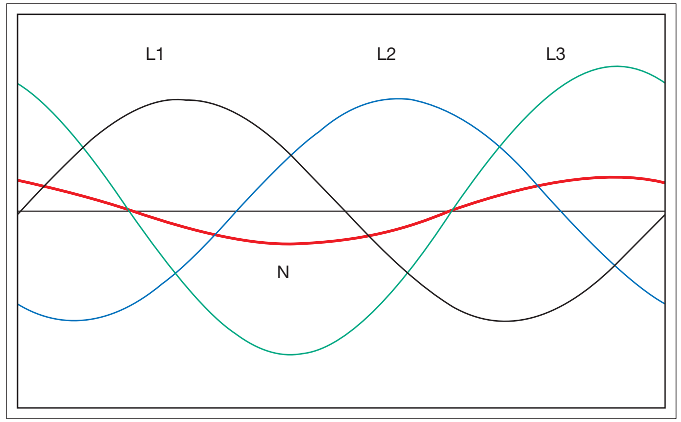
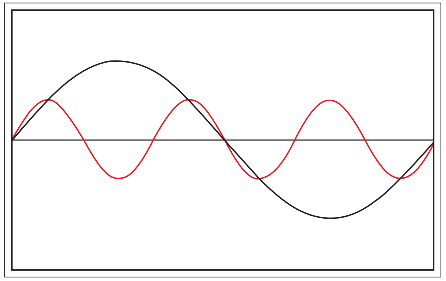


Figure 4 shows an unbalanced system of currents (phase 3 with a load 30% higher than the other two phases), and the current resultant in the neutral is highlighted in red. Under these circumstances, the Standards allow the neutral conductor to be dimensioned with a cross section smaller than the phase conductors. In the presence of distortion loads it is necessary to evaluate correctly the effects of harmonics.
In fact, although the currents at fundamental frequency in the three phases cancel each other out, the components of the third harmonic, having a period equal to a third of the fundamental, that is equal to the phase shift between the phases (see Figure 5), are reciprocally in phase and consequently they sum in the neutral conductor adding themselves to the normal unbalance currents.
The same is true also for the harmonics multiple of three (even and odd, although actually the odd ones are more common).

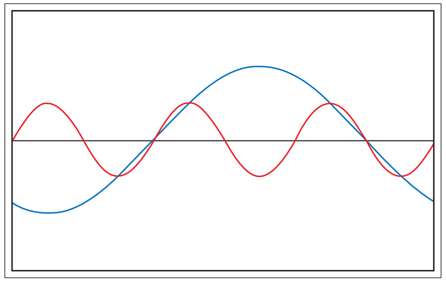
Annex C: Harmonics

Figure 5

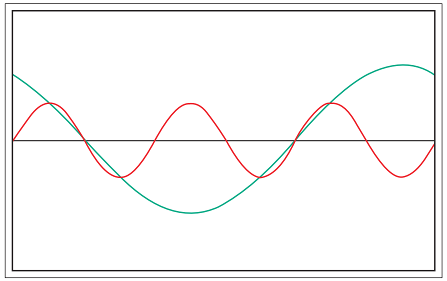
Phase 1:
fundamental harmonic and 3rd harmonic



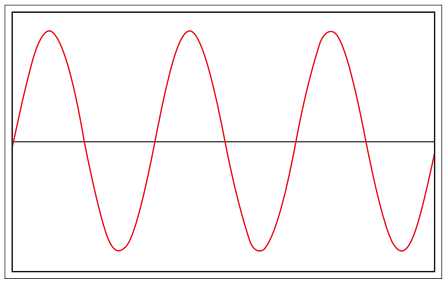
Phase 2:
fundamental harmonic and 3rd harmonic



Phase 3:
fundamental harmonic and 3rd harmonic



Resultant of the currents of the three phases



Annex C: Harmonics

2) Increase of losses in the transformers

The effects of harmonics inside the transformers involve mainly three aspects:

- a) increase of iron losses (or no-load losses)
- b) increase of copper losses
- c) presence of harmonics circulating in the windings

a) The iron losses are due to the hysteresis phenomenon and to the losses caused by eddy currents; the losses due to hysteresis are proportional to the frequency, whereas the losses due to eddy currents depend on the square of the frequency.

b) The copper losses correspond to the power dissipated by Joule effect in the transformer windings. As the frequency rises (starting from 350 Hz) the current tends to thicken on the surface of the conductors (skin effect); under these circumstances, the conductors offer a smaller cross section to the current flow, since the losses by Joule effect increase.

These two first aspects affect the overheating which sometimes causes a derating of the transformer.

c) The third aspect is relevant to the effects of the triple-N harmonics (homopolar harmonics) on the transformer windings. In case of delta windings, the harmonics flow through the windings and do not propagate upstream towards the network since they are all in phase; the delta windings therefore represent a barrier for triple-N harmonics, but it is necessary to pay particular attention to this type of harmonic components for a correct dimensioning of the transformer.

3) Increase of skin effect

When the frequency rises, the current tends to flow on the outer surface of a conductor. This phenomenon is known as skin effect and is more pronounced at high frequencies. At 50 Hz power supply frequency, skin effect is negligible, but above 350 Hz, which corresponds to the 7th harmonic, the cross section for the current flow reduces, thus increasing the resistance and causing additional losses and heating.
In the presence of high-order harmonics, it is necessary to take skin effect into account, because it affects the life of cables. In order to overcome this problem, it is possible to use multiple conductor cables or busbar systems formed by more elementary isolated conductors.

4) Voltage distortion

The distorted load current drawn by the nonlinear load causes a distorted voltage drop in the cable impedance. The resultant distorted voltage waveform is applied to all other loads connected to the same circuit, causing harmonic currents to flow in them, even if they are linear loads.
The solution consists in separating the circuits which supply harmonic generating loads from those supplying loads sensitive to harmonics.

5) Disturbances in the torque of induction motors

Harmonic voltage distortion causes increased eddy current losses in the motors, in the same way as seen for transformers. The additional losses are due to the generation of harmonic fields in the stator, each of which is trying to rotate the motor at a different speed, both forwards (1st, 4th, 7th, ...) as well as backwards (2nd, 5th, 8th, ...). High frequency currents induced in the rotor further increase losses.

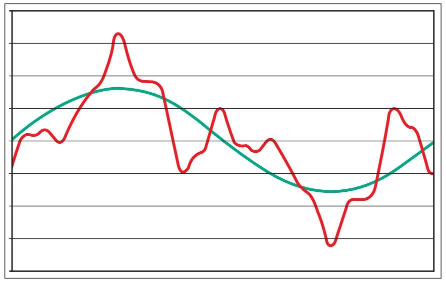
Annex C: Harmonics

Main formulas

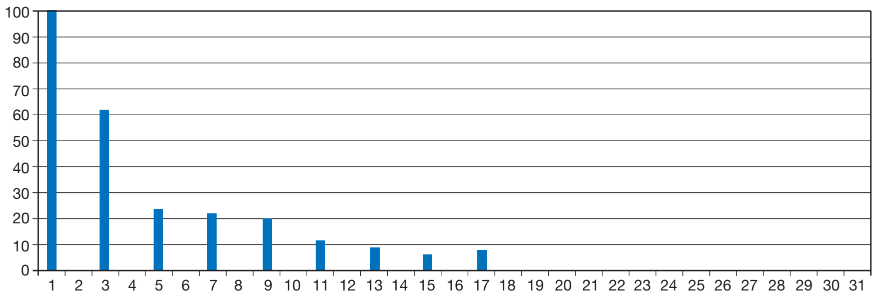
The definitions of the main quantities typically used in a harmonic analysis are given hereunder.

Frequency spectrum

The frequency spectrum is the classic representation of the harmonic content of a waveform and consists of a histogram reporting the value of each harmonic as a percentage of the fundamental component. For example, for the following waveform:



the frequency spectrum is:



The frequency spectrum provides the size of the existing harmonic components.

Peak factor

The peak factor is defined as the ratio between the peak value and the rms value of the waveform:

$$k = \frac{I_p}{I_{rms}}$$

in case of perfectly sinusoidal waveforms, it is worth $\sqrt{2}$, but in the presence of harmonics it can reach higher values.
High peak factors may cause the unwanted tripping of the protection devices.

Rms value

The rms value of a periodical waveform e(t) is defined as:

$$E_{rms} = \sqrt{\frac{1}{T}\int_0^T e^2(t)dt}$$

where T is the period.

Annex C: Harmonics

If the rms values of the harmonic components are known, the total rms value can be easily calculated by the following formula:

$$E_{rms} = \sqrt{\sum_{n=1}^{\infty} E_n^2}$$

Total harmonic distortion THD

The total harmonic distortion is defined as:

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \quad \text{THD in current}$$

$$THD_u = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \quad \text{THD in voltage}$$

The harmonic distortion ratio is a very important parameter, which gives information about the harmonic content of the voltage and current waveforms and about the necessary measures to be taken should these values be high. For $THD_i < 10\%$ and $THD_u < 5\%$, the harmonic content is considered negligible and such as not to require any provisions.

Standard references for circuit-breakers

IEC 60947 Low-voltage switchgear and controlgear

Annex F of the Standard IEC 60947-2 (third edition 2003) gives information about the tests to check the immunity of the overcurrent releases against harmonics.
In particular, it describes the waveform of the test current, at which, in correspondence with determinate values of injected current, the release shall have a behaviour complying with the prescriptions of this Standard.

Hereunder, the characteristics of the waveform of the test current are reported, which shall be formed, in alternative, as follows:
1) by the fundamental component and by a 3rd harmonic variable between 72% and 88% of the fundamental, with peak factor equal to 2 or by a 5th harmonic variable between 45% and 55% of the fundamental, with peak factor equal to 1.9
or
2) by the fundamental component and by a 3rd harmonic higher than 60% of the fundamental, by a 5th harmonic higher than 14% of the fundamental and by a 7th harmonic higher than 7% of the fundamental. This test current shall have a peak factor $\geq$ 2.1 and shall flow for a given time $\leq$ 42% of the period for each half period.

Annex D: Calculation of the coefficient k for the cables (k^2S^2)

By using the formula (1), it is possible to determine the conductor minimum section S, in the hypothesis that the generic conductor is submitted to an adiabatic heating from a known initial temperature up to a specific final temperature (applicable if the fault is removed in less than 5 s):

$$S = \frac{\sqrt{I^2 t}}{k} \qquad (1)$$

where:
- S is the cross section [mm²];
- I is the value (r.m.s) of prospective fault current for a fault of negligible impedance, which can flow through the protective device [A];
- t is the operating time of the protective device for automatic disconnection [s];

k can be evaluated using the tables 2÷7 or calculated according to the formula (2):

$$k = \sqrt{\frac{Q_c\,(B+20)}{\rho_{20}} \ln\left(1+\frac{\theta_f - \theta_i}{B+\theta_i}\right)} \qquad (2)$$

where:
- Q_c is the volumetric heat capacity of conductor material [J/°Cmm³] at 20 °C;
- B is the reciprocal of temperature coefficient of resistivity at 0 °C for the conductor [°C];
- ρ_{20} is the electrical resistivity of conductor material at 20 °C [Ωmm];
- θ_i initial temperature of conductor [°C];
- θ_f final temperature of conductor [°C].

Table 1 shows the values of the parameters described above.

Table 1: Value of parameters for different materials

Material	B [°C]	Q_c [J/°Cmm³]	ρ_{20} [Ωmm]	$\sqrt{\frac{Q_c(B+20)}{\rho_{20}}}$
Copper	234.5	$3.45\cdot10^{-3}$	$17.241\cdot10^{-6}$	226
Aluminium	228	$2.5\cdot10^{-3}$	$28.264\cdot10^{-6}$	148
Lead	230	$1.45\cdot10^{-3}$	$214\cdot10^{-6}$	41
Steel	202	$3.8\cdot10^{-3}$	$138\cdot10^{-6}$	78

Annex D: Calculation of the coefficient k for the cables (k^2S^2)

Table 2: Values of *k* for phase conductor

	Conductor insulation					
	PVC ≤ 300 mm²	**PVC ≤ 300 mm²**	**EPR XLPE**	**Rubber 60 °C**	**Mineral PVC**	**Mineral Bare**
Initial temperature °C	70	70	90	60	70	105
Final temperature °C	160	140	250	200	160	250
Material of conductor:						
copper	115	103	143	141	115	135/115 [a]
aluminium	76	68	94	93	-	-
tin-soldered joints in copper conductors	115	-	-	-	-	-

[a] This value shall be used for bare cables exposed to touch.

Table 3: Values of *k* for insulated protective conductors not incorporated in cables and not bunched with other cables

Conductor insulation	Temperature °C [b] Initial	Temperature °C [b] Final	Material of conductor: Copper	Aluminium	Steel
			Value for k		
70 °C PVC	30	160/140 [a]	143/133 [a]	95/88 [a]	52/49 [a]
90 °C PVC	30	160/140 [a]	143/133 [a]	95/88 [a]	52/49 [a]
90 °C thermosetting	30	250	176	116	64
60 °C rubber	30	200	159	105	58
85 °C rubber	30	220	166	110	60
Silicone rubber	30	350	201	133	73

[a] The lower value applies to PVC insulated conductors of cross section greater than 300 mm².
[b] Temperature limits for various types of insulation are given in IEC 60724.

Annex D: Calculation of the coefficient k for the cables (k^2S^2)

Table 4: Values of *k* for bare protective conductors in contact with cable covering but not bunched with other cables

Cable covering	Temperature °C [a] Initial	Final	Material of conductor Copper	Aluminium (Value for k)	Steel
PVC	30	200	159	105	58
Polyethylene	30	150	138	91	50
CSP	30	220	166	110	60

[a] Temperature limits for various types of insulation are given in IEC 60724.

Table 5: Values of *k* for protective conductors as a core incorporated in a cable or bunched with other cables or insulated conductors

Conductor insulation	Temperature °C [b] Initial	Final	Material of conductor Copper	Aluminium (Value for k)	Steel
70 °C PVC	70	160/140 [a]	115/103 [a]	76/68 [a]	42/37 [a]
90 °C PVC	90	160/140 [a]	100/86 [a]	66/57 [a]	36/31 [a]
90 °C thermosetting	90	250	143	94	52
60 °C rubber	60	200	141	93	51
85 °C rubber	85	220	134	89	48
Silicone rubber	180	350	132	87	47

[a] The lower value applies to PVC insulated conductors of cross section greater than 300 mm^2 .
[b] Temperature limits for various types of insulation are given in IEC 60724.

Annex D: Calculation of the coefficient k for the cables (k^2S^2)

Table 6: Values of *k* for protective conductors as a metallic layer of a cable e.g. armour, metallic sheath, concentric conductor, etc.

Conductor insulation	Temperature °C Initial	Final	Material of conductor Copper	Aluminium (Value for k)	Lead	Steel
70 °C PVC	60	200	141	93	26	51
90 °C PVC	80	200	128	85	23	46
90 °C thermosetting	80	200	128	85	23	46
60 °C rubber	55	200	144	95	26	52
85 °C rubber	75	220	140	93	26	51
Mineral PVC covered [a]	70	200	135	-	-	-
Mineral bare sheath	105	250	135	-	-	-

[a] This value shall also be used for bare conductors exposed to touch or in contact with combustible material.

Table 7: Value of *k* for bare conductors where there is no risk of damage to any neighbouring material by the temperature indicated

Conductor insulation	Initial temperature °C	Copper k value	Copper Maximum temperature °C	Aluminium k value	Aluminium Maximum temperature °C	Steel k value	Steel Maximum temperature °C
Visible and in restricted area	30	228	500	125	300	82	500
Normal conditions	30	159	200	105	200	58	200
Fire risk	30	138	150	91	150	50	150

Annex E: Main physical quantities and electrotechnical formulas

The International System of Units (SI)

SI Base Units

Quantity	Symbol	Unit name
Length	m	metre
Mass	kg	kilogram
Time	s	Second
Electric Current	A	ampere
Thermodynamic Temperature	K	kelvin
Amount of Substance	mol	mole
Luminous Intensity	cd	candela

Metric Prefixes for Multiples and Sub-multiples of Units

Decimal power	Prefix	Symbol	Decimal power	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	mikro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	etto	h	10^{-21}	zepto	z
10	deca	da	10^{-24}	yocto	y

Annex E: Main physical quantities and electrotechnical formulas

Main quantities and SI units

Quantity Symbol	Name	SI unit Symbol	Name	Other units Symbol	Name	Conversion
Length, area, volume						
				in	inch	1 in = 25.4 mm
				ft	foot	1 ft = 30.48 cm
l	length	m	metre	fathom	fathom	1 fathom = 6 ft = 1.8288 m
				mile	mile	1 mile = 1609.344 m
				sm	sea mile	1 sm = 1852 m
				yd	yard	1 yd = 91.44 cm
A	area	m^2	square metre	a ha	are hectare	1 a = 10^2 m^2 1 ha = 10^4 m^2
				l	litre	1 l = 1 dm^3 = 10^{-3} m^3
V	volume	m^3	cubic metre	UK pt	pint	1 UK pt = 0.5683 dm^3
				UK gal	gallon	1 UK gal = 4.5461 dm^3
				US gal	gallon	1 US gal = 3.7855 dm^3
Angles						
α, β, γ	plane angle	rad	radian	°	degrees	$1° = \frac{\pi}{180} \cdot \text{rad}$
Ω	solid angle	sr	steradian			
Mass						
m	mass, weight	kg	kilogram	lb	pound	1 lb = 0.45359 kg
ρ	density	kg/m^3	kilogram			
υ	specific volume	m^3/kg	cubic metre for kilogram			
M	moment of inertia	$kg \cdot m^2$	kilogram for square metre			
Time						
t	duration	s	second			
f	frequency	Hz	Hertz			1 Hz = 1/s
ω	angular frequency	1/s	reciprocal second			ω = 2pf
v	speed	m/s	metre per second	km/h	kilometre per hour	1 km/h = 0.2777 m/s
				mile/h	mile per hour	1 mile/h = 0.4470 m/s
				knot	kn	1 kn = 0.5144 m/s
g	acceleration	m/s^2	metre per second squared			
Force, energy, power						
F	force	N	newton	kgf		1 N = 1 $kg \cdot m/s^2$ 1 kgf = 9.80665 N
p	pressure/stress	Pa	pascal	bar	bar	1 Pa = 1 N/m^2 1 bar = 10^5 Pa
W	energy, work	J	joule			1 J = 1 W·s = 1 N·m
P	power	W	watt	Hp	horsepower	1 Hp = 745.7 W
Temperature and heat						
T	temperature	K	kelvin	°C	Celsius	T[K] = 273.15 + T [°C]
				°F	Fahrenheit	T[K] = 273.15 + (5/9)·(T [°F]-32)
Q	quantity of heat	J	joule			
S	entropy	J/K	joule per kelvin			
Photometric quantities						
I	luminous intensity	cd	candela			
L	luminance	cd/m^2	candela per square metre			
Φ	luminous flux	lm	lumen			1 lm = 1 cd·sr
E	illuminance	lux				1 lux = 1 lm/m^2

Annex E: Main physical quantities and electrotechnical formulas

Main electrical and magnetic quantities and SI units

Quantity Symbol	Name	SI unit Symbol	Name	Other units Symbol	Name	Conversion
I	current	A	ampere			
V	voltage	V	volt			
R	resistance	Ω	ohm			
G	conductance	S	siemens			G = 1/R
X	reactance	Ω	ohm			$X_L = \omega L$ $X_C = -1/\omega C$
B	susceptance	S	siemens			$B_L = -1/\omega L$ $B_C = \omega C$
Z	impedance	Ω	ohm			
Y	admittance	S	siemens			
P	active power	W	watt			
Q	reactive power	var	reactive volt ampere			
S	apparent power	VA	volt ampere			
Q	electric charge	C	coulomb	Ah	ampere/hour	1 C = 1 A·s 1 Ah = 3600 A·s
E	electric field strength	V/m	volt per metre			
C	electric capacitance	F	farad			1 F = 1 C/V
H	magnetic field	A/m	ampere per metre			
B	magnetic induction	T	tesla	G	gauss	$1\ T = 1\ V\cdot s/m^2$ $1\ G = 10^{-4}\ T$
L	inductance	H	henry			1 H = 1 Ω·s

Resistivity values, conductivity and temperature coefficient at 20 °C of the main electrical materials

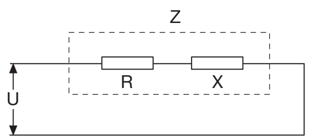
conductor	conductivity resistivity ρ_{20} [$mm^2\Omega/m$]	$\chi_{20}=1/\rho_{20}$ [$m/mm^2\Omega$]	temperature coefficient α_{20} [K^{-1}]
Aluminium	0.0287	34.84	$3.8\cdot10^{-3}$
Brass, CuZn 40	≤ 0.067	≥ 15	$2\cdot10^{-3}$
Constantan	0.50	2	$-3\cdot10^{-4}$
Copper	0.0175	57.14	$3.95\cdot10^{-3}$
Gold	0.023	43.5	$3.8\cdot10^{-3}$
Iron wire	0.1 to 0,15	10 to 6.7	$4.5\cdot10^{-3}$
Lead	0.208	4.81	$3.9\cdot10^{-3}$
Magnesium	0.043	23.26	$4.1\cdot10^{-3}$
Manganin	0.43	2.33	$4\cdot10^{-6}$
Mercury	0.941	1.06	$9.2\cdot10^{-4}$
Ni Cr 8020	1	1	$2.5\cdot10^{-4}$
Nickeline	0.43	2.33	$2.3\cdot10^{-4}$
Silver	0.016	62.5	$3.8\cdot10^{-3}$
Zinc	0.06	16.7	$4.2\cdot10^{-3}$

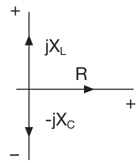
Annex E: Main physical quantities and electrotechnical formulas

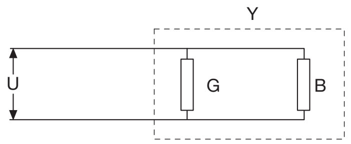
Main electrotechnical formulas

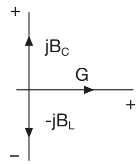
Impedance

resistance of a conductor at temperature ϑ	$R_\vartheta = \rho_\vartheta \cdot \frac{\ell}{S}$
conductance of a conductor at temperature ϑ	$G_\vartheta = \frac{1}{R_\vartheta} = \chi_\vartheta \cdot \frac{S}{\ell}$
resistivity of a conductor at temperature ϑ	$\rho_\vartheta = \rho_{20}[1 + \alpha_{20}(\vartheta - 20)]$
capacitive reactance	$X_C = \frac{-1}{\omega \cdot C} = -\frac{1}{2 \cdot \pi \cdot f \cdot C}$
inductive reactance	$X_L = \omega \cdot L = 2 \cdot \pi \cdot f \cdot L$
impedance	$Z = R + jX$
module impedance	$Z = \sqrt{R^2 + X^2}$
phase impedance	$\varphi = \arctan \frac{R}{X}$
conductance	$G = \frac{1}{R}$
capacitive susceptance	$B_C = \frac{-1}{X_C} = \omega \cdot C = 2 \cdot \pi \cdot f \cdot C$
inductive susceptance	$B_L = \frac{-1}{X_L} = -\frac{1}{\omega \cdot L} = -\frac{1}{2 \cdot \pi \cdot f \cdot L}$
admittance	$Y = G - jB$
module admittance	$Y = \sqrt{G^2 + B^2}$
phase admittance	$\varphi = \arctan \frac{B}{G}$





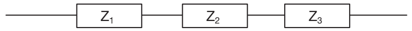




Annex E: Main physical quantities and electrotechnical formulas

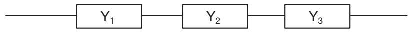
Impedances in series

$$Z = Z_1 + Z_2 + Z_3 + \dots$$



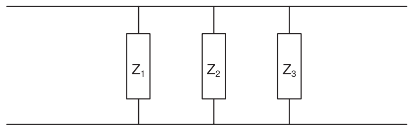
Admittances in series

$$Y = \frac{1}{\frac{1}{Y_1} + \frac{1}{Y_2} + \frac{1}{Y_3} + \dots}$$



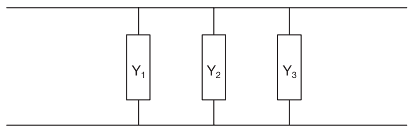
Impedances in parallel

$$Z = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \dots}$$

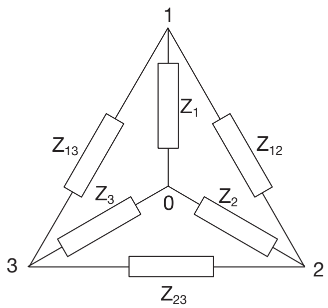


Admittances in parallel

$$Y = Y_1 + Y_2 + Y_3 + \dots$$



Delta-star and star-delta transformations



Y→Δ	Δ→Y
$Z_{12} = Z_1 + Z_2 + \frac{Z_1 \cdot Z_2}{Z_3}$	$Z_1 = \frac{Z_{12} \cdot Z_{13}}{Z_{12} + Z_{13} + Z_{23}}$
$Z_{23} = Z_2 + Z_3 + \frac{Z_2 \cdot Z_3}{Z_1}$	$Z_2 = \frac{Z_{12} \cdot Z_{23}}{Z_{12} + Z_{13} + Z_{23}}$
$Z_{13} = Z_3 + Z_1 + \frac{Z_3 \cdot Z_1}{Z_2}$	$Z_3 = \frac{Z_{23} \cdot Z_{13}}{Z_{12} + Z_{13} + Z_{23}}$

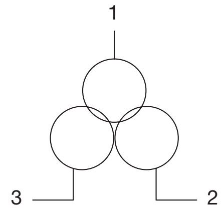
Annex E: Main physical quantities and electrotechnical formulas

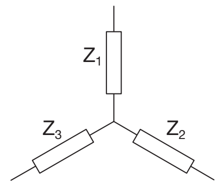
Transformers

Two-winding transformer

rated current	$I_r = \frac{S_r}{\sqrt{3} \cdot U_r}$
short-circuit power	$S_k = \frac{S_r}{u_k\%} \cdot 100$
short-circuit current	$I_k = \frac{S_k}{\sqrt{3} \cdot U_r} = \frac{I_r}{u_k\%} \cdot 100$
longitudinal impedance	$Z_T = \frac{u_k\%}{100} \cdot \frac{U_r^2}{S_r} = \frac{u_k\%}{100} \cdot \frac{S_r}{3 \cdot I_r^2}$
longitudinal resistance	$R_T = \frac{p_k\%}{100} \cdot \frac{U_r^2}{S_r} = \frac{p_k\%}{100} \cdot \frac{S_r}{3 \cdot I_r^2}$
longitudinal reactance	$X_T = \sqrt{Z_T^2 - R_T^2}$

Three-winding transformer





$Z_{12} = \frac{u_{12}}{100} \cdot \frac{U_r^2}{S_{r12}}$	$Z_1 = \frac{1}{2}(Z_{12} + Z_{13} - Z_{23})$
$Z_{13} = \frac{u_{13}}{100} \cdot \frac{U_r^2}{S_{r13}}$	$Z_2 = \frac{1}{2}(Z_{12} + Z_{23} - Z_{13})$
$Z_{23} = \frac{u_{23}}{100} \cdot \frac{U_r^2}{S_{r23}}$	$Z_3 = \frac{1}{2}(Z_{13} + Z_{23} - Z_{12})$

Annex E: Main physical quantities and electrotechnical formulas

Voltage drop and power

	single-phase	three-phase	direct current
voltage drop	$\Delta U = 2 \cdot I \cdot \ell \cdot (r \cos\varphi + x \sin\varphi)$	$\Delta U = \sqrt{3} \cdot I \cdot \ell \cdot (r \cos\varphi + x \sin\varphi)$	$\Delta U = 2 \cdot I \cdot \ell \cdot r$
percentage voltage drop	$\Delta u = \frac{\Delta U}{U_r} \cdot 100$	$\Delta u = \frac{\Delta U}{U_r} \cdot 100$	$\Delta u = \frac{\Delta U}{U_r} \cdot 100$
active power	$P = U \cdot I \cdot \cos\varphi$	$P = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi$	$P = U \cdot I$
reactive power	$Q = U \cdot I \cdot \sin\varphi$	$Q = \sqrt{3} \cdot U \cdot I \cdot \sin\varphi$	–
apparent power	$S = U \cdot I = \sqrt{P^2 + Q^2}$	$S = \sqrt{3} \cdot U \cdot I = \sqrt{P^2 + Q^2}$	–
power factor	$\cos\varphi = \frac{P}{S}$	$\cos\varphi = \frac{P}{S}$	–
power loss	$\Delta P = 2 \cdot \ell \cdot r \cdot I^2$	$\Delta P = 3 \cdot \ell \cdot r \cdot I^2$	$\Delta P = 2 \cdot \ell \cdot r \cdot I^2$

Caption

ρ_{20} resistivity at 20 °C
ℓ total length of conductor
S cross section of conductor
α_{20} temperature coefficient of conductor at 20 °C
θ temperature of conductor
$\rho\theta$ resistivity against the conductor temperature
ω angular frequency
f frequency
r resistance of conductor per length unit
x reactance of conductor per length unit
$u_k\%$ short-circuit percentage voltage of the transformer
S_r rated apparent power of the transformer
U_r rated voltage of the transformer
$p_k\%$ percentage impedance losses of the transformer under short-circuit conditions

Due to possible developments of standards as well as of materials, the characteristics and dimensions specified in this document may only be considered binding after confirmation by ABB SACE.

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