

Medium voltage products

# Technical guide

## The MV/LV transformer substations (passive users)



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# 1. Medium voltage/low voltage (MV/LV) transformer substations

## 1.1 Introduction

The subject of this Technical Guide is MV/LV substations; in accordance with the reference standard, the discussion will be limited to substations with installed power limited to 2000 kVA or two 1000 kVA MV/LV transformers.

The purpose of this guide is to give an overview of the guidelines and requirements specified by current regulations for the design and construction of substations in order to guide the designer and the user to the correct system choices.

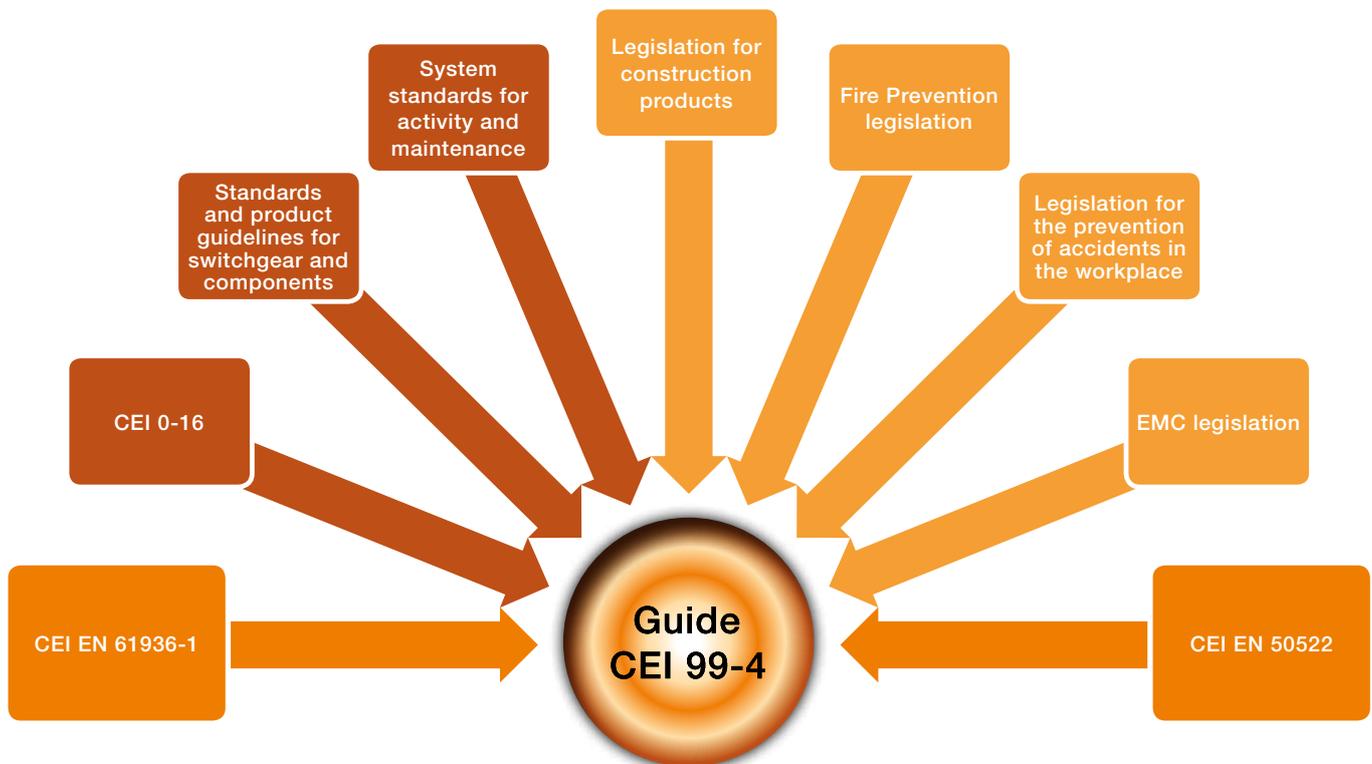
The document will only touch on a few topics such as the sizing of the earthing system and the building aspects, for further details on which you are referred to the specific regulations.

Lastly, the document does not deal with issues related to active Users, in other words those that produce alternating current electricity with parallel operation (even temporary) with the network.

## 1.2 Reference standard and documentation

The general picture providing an overview of the key reference regulations relating to the design and construction of a MV/LV substation is shown in the following figure.

As you can see, the overview is complex, but on the other hand the MV/LV electrical substation is the synthesis of several design activities (electrical, mechanical, construction, installation, etc.) and it is therefore also necessary to consider fire prevention laws on safety and construction materials in order to obtain a workmanlike result.



A non-exhaustive list is provided below of the main Reference Standards used in the drawing up of this Technical Guide.

- CEI TS 62271-210: High-voltage switchgear and controlgear - Part 210: Seismic qualification for metal enclosed and solid-insulation enclosed switchgear and controlgear assemblies for rated voltages above 1 kV and up to and including 52 kV
- CEI 99-4: Customer/End user guide to creating MV/LV electrical substations
- CEI EN 61936-1: CEI classification: 99-2, Power installations exceeding 1 kV a.c. – Part 1: Common rules
- CEI EN 50522: CEI classification:99-3, Earthing of electrical installations with voltage greater than 1 kV AC
- CEI EN 62271-1: High voltage switchgear and controlgear, Part 1: Common specifications
- CEI EN 62271-200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV
- CEI EN 62271-202: High-voltage/low-voltage prefabricated substation
- CEI EN 50532: Compact switchgear assembly for distribution stations
- CEI 11 – 17 and variant V1: Systems for generation, transmission and public distribution of electrical energy. Cable line;
- CEI 64-8: User electrical installations with rated voltage not greater than 1000 V AC and 1500 V DC;
- Guide CEI 11 - 37: Guide for the implementation of earthing systems in user energy systems powered at a voltage greater than 1 kV.
- CEI 64-12, Guide for the implementation of the earthing system in buildings for residential use and in the service sector
- CEI EN 50272-2: Safety requirements for accumulator batteries and their installations, Part 2: Stationary batteries
- DK 5600 ed.IV -March 2004: Criteria for the connection of customers to the MV distribution network

Please note that the Law no.186 of 1 March 1968 and Ministerial Decree no.37 of 22 January 2008, updated by the Decree of 19 July 2010, assigned a legal role to CEI standards. Indeed, Article 2 of the Law and Article 6 of the Decree state that the installations must be constructed in a workmanlike manner, and that this goal can be achieved through compliance with CEI standards.

## 1.3 Traditional definitions and types

An electrical substation is a part of the electrical installation that includes the terminations of the transmission or distribution lines and switchgear, and which may also include transformers. The substation also typically includes all the necessary devices for control and protection. Depending on the function performed, it can be defined as a transforming, conversion, transmission or distribution substation. A MV/LV transformer electrical substation consists, therefore, of the set of devices dedicated to the transformation of the voltage supplied by the distribution network at medium voltage (e.g. 20 kV), into voltage values suitable for the power supply of the low voltage lines (e.g. 400 V).

**Electrical substations can also be divided into public and private substations:**

- **public substations:** these belong to the electricity distribution company and supply private users in single-phase or three-phase alternating current (typical voltage values for the two types of power supply could be 230 V and 400 V). They are in turn divided into urban or rural substations, consisting of a single small power transformer. Urban substations are usually built in brick, whereas rural ones are often installed externally directly on the MV pylon.
- **private substations:** these can often be considered as terminal type substations, i.e. substations where the MV line ends at the installation point of the substation itself. They are owned by the User and can supply both civil users (schools, hospitals, etc.) and industrial users with supply from the public MV grid. The user must make available to the distributing company a special room, accessible to the staff of the company, in which the equipment for which the distribution company is responsible will be installed. There can be various design solutions, although in recent times the use of prefabricated substations is increasingly widespread.

## 2.1 Connection of the substation

The Standard CEI 0-16 suggests three steps for identifying the system for the connection.

**Step 1**, choosing the voltage level and point of the distribution network to which the user can be connected depending on the type, the size and operating requirements of the User installation and on the requirements and characteristics of the portion of the distribution network involved.

These choices are made by the Distributor based on the data listed below.

1. Size of the installation, which must be compatible with the operating criteria of the network. In general terms, the voltage profiles, selectivity of the protections and the use made of the lines and transformers must be evaluated.
2. Location of the surrounding loads in the layout of both the current and the planned network.
3. Characteristics of the neighboring network.
4. Contribution of any generators to the short-circuit power considering all the contributions of the installation (generators, motors, etc.).
5. Levels of interference introduced (rapid variations, harmonics, flicker, asymmetry of voltages) by the loads, both active and passive, that must be such that they do not exceed the levels established by Standard CEI EN 61000-2-12 for the MV network.
6. User requirements regarding continuity of the service.
7. User requirements regarding slow variations, voltage dips, short-circuit power and voltage quality.
8. Possibility of developing the network in order to satisfy the requirements in the above points.

The indicative values of power that can be connected on the different voltage levels of the distribution networks are specified by the standard in the following table.

power MW	Network voltage level
<= 0.1	LV
0.1 - 0.2	LV
	MV
0.2 - 3 Upper limit raised to 6 MW for generating installations	MV
3 - 10 Lower limit raised to 6 MW for generating installations	MV
	HV

**Step 2**, choosing the installation insertion scheme (in-out, antenna, etc.).

To determine the connection scheme the following factors must be taken into account:

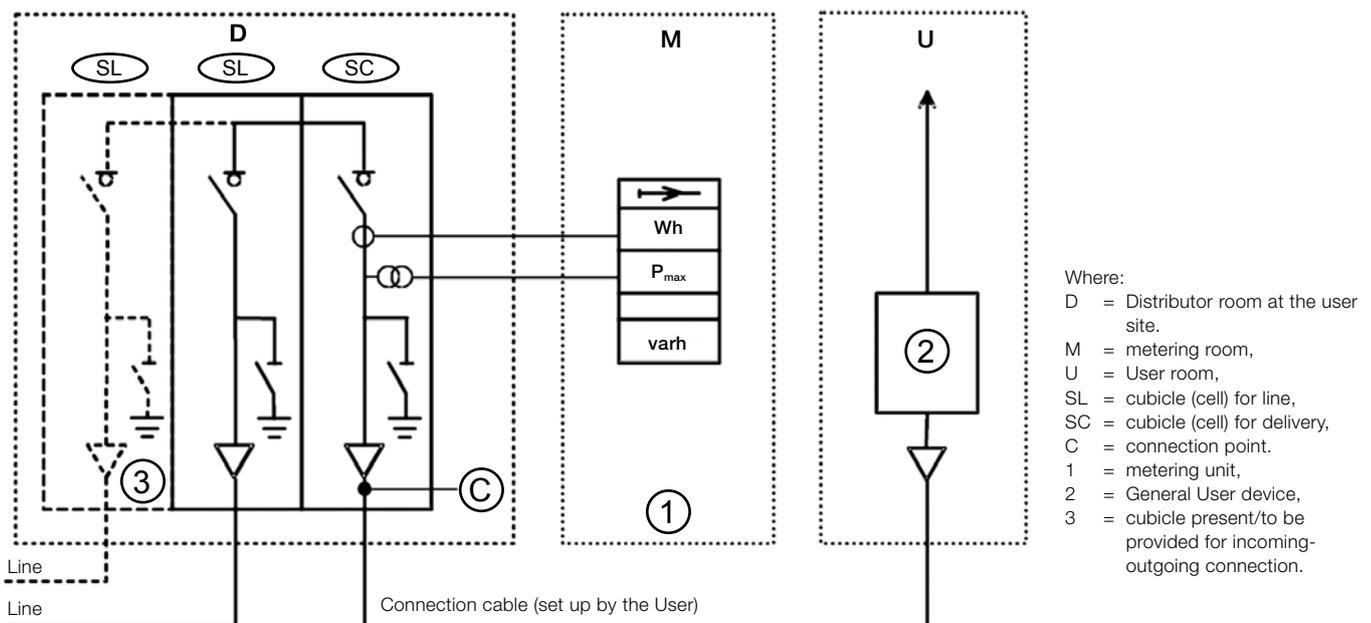
- the size of the installation;
- the position of the installation in relation to the network and the presence, in the area of question, of generating installations, lines and primary and secondary substations;
- operation of the network to which the installation is connected;
- possibility to develop the network;
- protection and automation devices on the Distributor's network;
- User requirements concerning the continuity and quality of service.

**Step 3**, choosing the connection scheme (busbar systems and switching and disconnection parts, in relation to maintenance and the network protection system). Regardless of the connection solution chosen for the network system at the user site, the installation will always be as shown in the following figure.

## 2.2 Structure of the substation

These substations are for the most part located in the in the actual premises of the establishment that they supply and basically consist of three distinct room, of which the first two are available to the Distributor:

- **Distributor room (D)**: where the switching devices of the Distributor are installed. This room must be large enough to allow for possible construction of the incoming-outgoing system that the Distributor is entitled to implement, even at a later stage to satisfy new requirements. The delivery room houses the sampling point that represents the boundary and the connection between the public grid and the user installation.
- **metering room (M)**: where the metering equipment is located. Both of these rooms must be accessible from a public road, to allow maintenance by authorized personnel regardless of whether the User is present.
- **User room (U)**: intended to contain the MV and LV switchgear and protection devices of the User. This room must normally be adjacent to the other two rooms.



Connection diagram between the Distributor's substation at the user site and the User's passive system (CEI 0-16, Figure 7)

## 2. Design and construction specifications of the substation

### 2.3 Construction solutions

With regard to building solutions, the Guide CEI 99-4 distinguishes between the following cases:

- **Open substation** (internal system of the open type according to CEI EN 61936-1): installation in which it not required to use MV components with casing able to provide protection against direct contact and which therefore needs to be completed on site with the security measures designed to protect persons against such risks in accordance with CEI EN 61936-1. The installation is implemented directly on the site by connecting the components appropriately and it is therefore practically impossible to run tests to verify the level of isolation achieved and the ability to withstand the effects of short-circuit currents. The construction solution of a typical internal open substation, which is therefore built in a closed structure sheltered from the elements, generally consist of:
  - one or more cells, equipped with walls or dividing panels, for positioning the MV components;
  - one or more cells, equipped with walls or dividing panels and everything necessary for positioning the transformers;
  - protection barriers such as frames, gratings and wire meshes, fastened rigidly with a minimum degree of protection IPXXB;
  - LV components arranged on open structures or in closed cabinets.

- **Substation built on site or pre-assembled with prefabricated equipment** (internal installation of closed type CEI EN 61936-1): installation whose electrical components are encased in housing capable of ensuring protection against direct contact and which is implemented using prefabricated devices, such as MV and LV switchgear according to product standard CEI EN 62271-200. By substation built on site we mean the structure made from concrete or brick or other material suitable for accommodating electrical equipment tested directly in situ. The typical constructive solution for an internal substation with prefabricated equipment is the following:
  - MV switchgear consisting of a set of functional units according to the project;
  - one or more cells, equipped with walls or dividing panels and everything necessary for arranging transformers housed in prefabricated metal boxes, or else including any necessary protections against direct contacts;
  - LV switchgear consisting of a set of functional units.



- **Prefabricated substation** in accordance with standards CEI EN 62271-202 and CEI EN 50532: the prefabricated substation is considered equipment conforming to the product standard and that has therefore passed all the required tests. The product standard, as well as ratings and test procedures, pays particular attention to the protection of persons, which is guaranteed by the use of components subjected to type tests and by a proper design and construction of the housing. The main components of a prefabricated substation, in addition to the casing, are:
  - power transformers;
  - medium and low voltage switchgear;
  - medium and low voltage interconnections;
  - auxiliary switchgear and circuits.



## 2.4 Main requirements

Regarding the location, the substation can be within the volume of the building to be powered or separate from it. It may also be located on the roof of the building to be served, of course, after a careful study of the static and dynamic loads to which the roof will be subjected. In any case, the location of the substations must be such that it allows authorized personnel to access it as necessary, to perform service operations and maintenance on the components of the substation, even of those of greater size and weight, such as transformers.

In addition, the substation structure must meet the requirements of the standards (CEI 99-4, Sec. 5 and CEI 0-16, para. 8.5.9) as regards:

- a) low frequency magnetic fields
- b) access
- c) walls, floors and ceilings, etc. in accordance with Standard CEI 61936-1
- d) ventilation
- e) infiltration of water or flooding
- f) the expected static and dynamic mechanical loads and internal overpressure caused by arcing
- g) lighting

The substations must be fitted with lockable doors or otherwise require the use of tools to open or remove them so as to prevent access by unauthorized persons. In particular, the room hosting the metering systems must be accessible both by the User and by the Distributor.

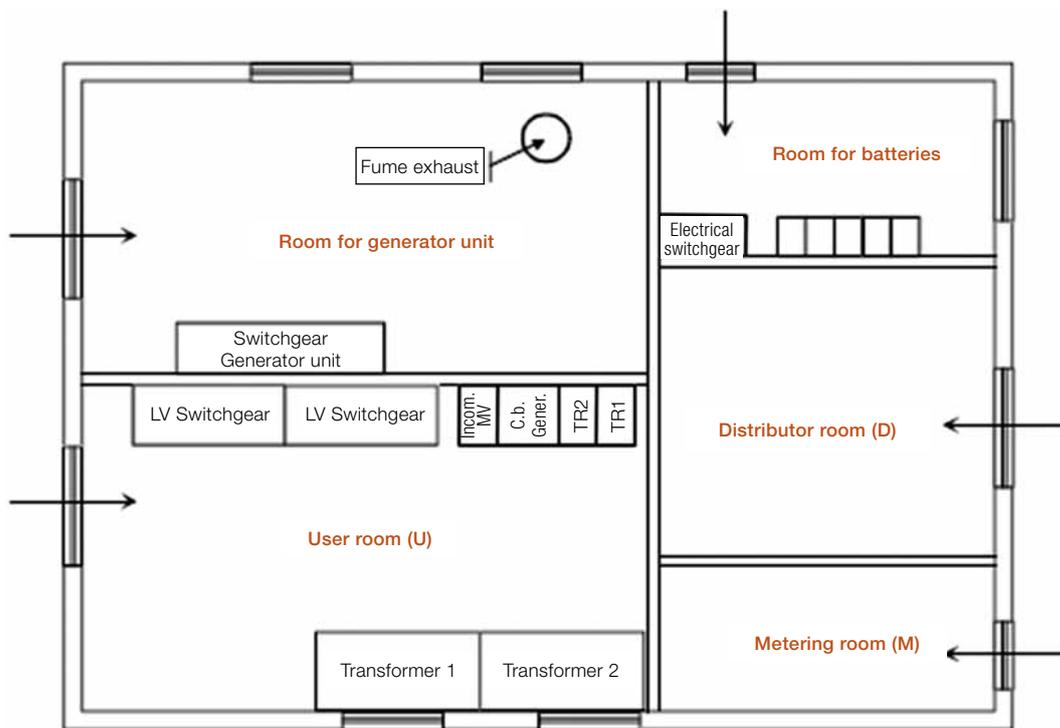
The location of the structures must be such that the MV lines necessary for connection can be built and maintained in compliance with current regulations regarding electrical installations and safety as well as electromagnetic pollution. Separation, in terms of responsibility for the operation, running and maintenance of the various substations, should be easily distinguished on the planimetric diagrams.

Measurement of the energy withdrawn by a User at a sampling point must take place close to the MV connection using voltage and current transformers that are the responsibility of the Distributor. The dimensions of the connection room must necessarily allow the in-out insertion scheme to be adopted, which might be necessary at a later time. As a guideline, the overall surface area occupied by the delivery and metering room should be about 16 m<sup>2</sup>.

The construction details are to be provided in the connection documentation provided by the Distributor; in any case, the design of the room for the network system at the user installation must comply with the regulations issued by the Distributor.

## 2. Design and construction specifications of the substation

Sample solution for substation (non-executive) with equipment against the walls (CEI 99-4, Fig. A.3)



Before positioning equipment inside a substation, you must make sure that the correct distances are observed in the service areas, such as hallways, passages, access and escape routes.

In this regard, CEI 99-4 defines that the width of a maneuvering corridor inside a substation must be sufficient to perform any maneuver or maintenance operation. The width of this corridor must be at least 800 mm.

In particular, make sure that the doors in the open position or the mechanical switching devices protruding from the switchgear and controlgear do not reduce the width of the corridor to less than 500 mm.

The passages for installation or maintenance located behind solid walls (e.g. closed switchgear) should not be less than 500 mm.

In essence, the staff must always have clear and safe access. Even overhead, under the ceiling, coverings or housing, with the sole exception of the cable conduits, a minimum height of 2000 mm is required.

As regards the escape routes, for the purposes of standard CEI EN 61936-1, the exits must be set up so that the length of the escape route within the structure does not exceed 20 m for voltages up to 52 kV. The recommended length for escape routes, however, is no more than 10 m. In addition to this length it is recommended that the passages should be accessible from both sides.

## 2.5 Characteristic of the structure

### Structural specifications

As for the construction of the building and its accessories, you should refer to Italian Ministerial Decree (infrastructure) 14.01.2008 as subsequently amended "Approval of new technical standards for constructions" published in the Official Gazette. no. 29 of 4 February 2008. The decree defines the principles for the design, construction and testing of buildings in relation to the requirements of strength and stability. Consideration should also be given to Regulation (EU) 305/2011, which came into force on 1 July 2013 and which permanently replaces CPD Directive 89/106/EEC. The purpose of this Regulation is to regulate the introduction to the European market of all products (materials, manufactured products, systems, etc.) that are designed to become a permanent part of construction works (buildings and civil engineering works), which should ensure compliance with at least one of the following requirements, the first six of which were already specified by the previous Directive CPD 89/106, to which the last one is added:

- mechanical strength and stability
  - safety in the event of fire
  - hygiene, safety and environment
  - safety during use
  - protection against noise
  - energy savings
  - sustainable use of natural resources for creating the constructions.
- The EU Regulation 305 defines, in particular, the loads and impacts, nominal and/or characteristic, applicable to buildings, and therefore also the housing of a substation, which must therefore have enough mechanical strength to resist them; these are:
- permanent structural and non-structural loads such as the weights of the materials themselves
  - variable loads including loads related to the intended use of the work (persons, vehicles, etc.).
  - seismic action
  - combination of seismic action with the other actions
  - actions of the wind
  - actions of the snow
  - actions of the temperature
  - exceptional actions such as fires, explosions, shocks.

### Specifications for seismic action

Since Italy is a country with high seismic exposure, it is important to consider this type of action in the design of the substation and in the choice of electrical equipment. Once again it is important to rely on qualified builders who have designed and tested their equipment in accordance with the relevant standards. In fact, the strong vibrations caused by an earthquake have a serious impact on the behavior of the electrical switchgear.

This is demonstrated by the fact that CEI Guide 99-4 states in note 1 that when technical specification IEC TS 62271-210 "High-voltage switchgear and controlgear - Part 210: Seismic qualification for metal enclosed and solid-insulation enclosed switchgear and controlgear assemblies for rated voltages above 1 kV and up to and including 52 kV" is published, it will be implemented by the CEI regardless of whether it is transposed by CENELEC.

In the past, the country was classified into zones according to seismic characteristics; each area was assigned a basic risk expressed in terms of maximum acceleration on rigid ground (g).

The current reference source is the web site of the INGV (Istituto Nazionale di Geofisica e Vulcanologia - National Institute of Geophysics and Volcanology) <http://esse1.mi.ingv.it/>. From this site you can obtain the  $a_g$  acceleration values for various probabilities of being exceeded in 50 years, corresponding to different return periods.

The entire national territory has been divided up using a calculation grid (steps of  $0.05^\circ$ , equal to approximately 5.5 km in latitude and longitude) the points of which are identified by code numbers (ID). For each of the 16852 points, ordered from west to east and from north to south, the average values (50th percentile) and those corresponding to the 16th and 84th percentile are given.

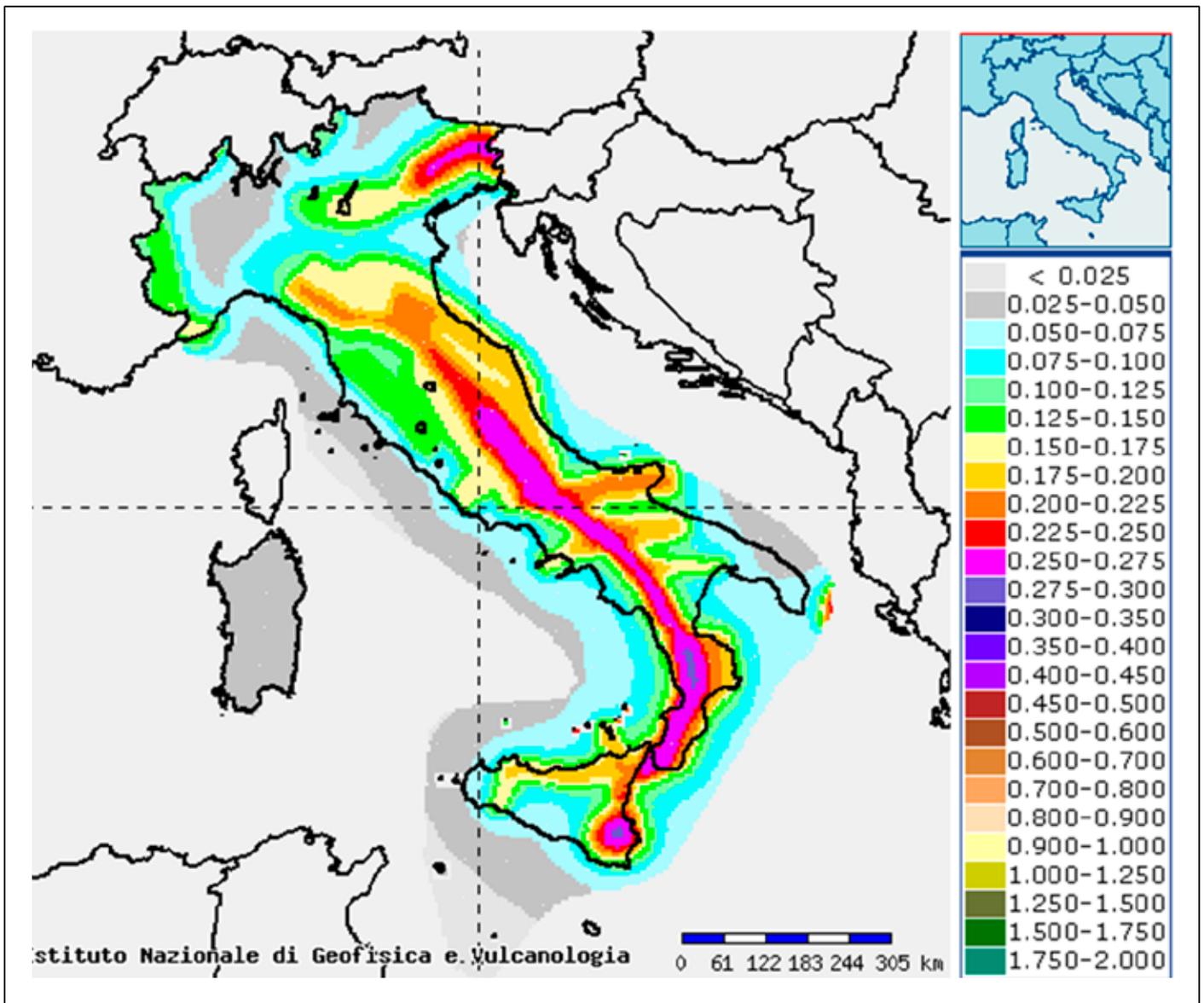
Using the seismic risk interactive map you can easily ascertain the acceleration value  $a_g$  corresponding to the zone where the substation is located and ask the manufacturer of the MV switchgear to provide a suitable product that matches the specifications of Technical Specification IEC/TS 62271-210, in particular as regards the level of severity:

- level 1, recommended for peak ground/floor accelerations up to 0.5 g;
- level 2, recommended for peak ground/floor acceleration up to 1.0 g.

Note that the  $a_g$  values provided by the site require knowledgeable use and should therefore their use is solely the responsibility of the user.

## 2. Design and construction specifications of the substation

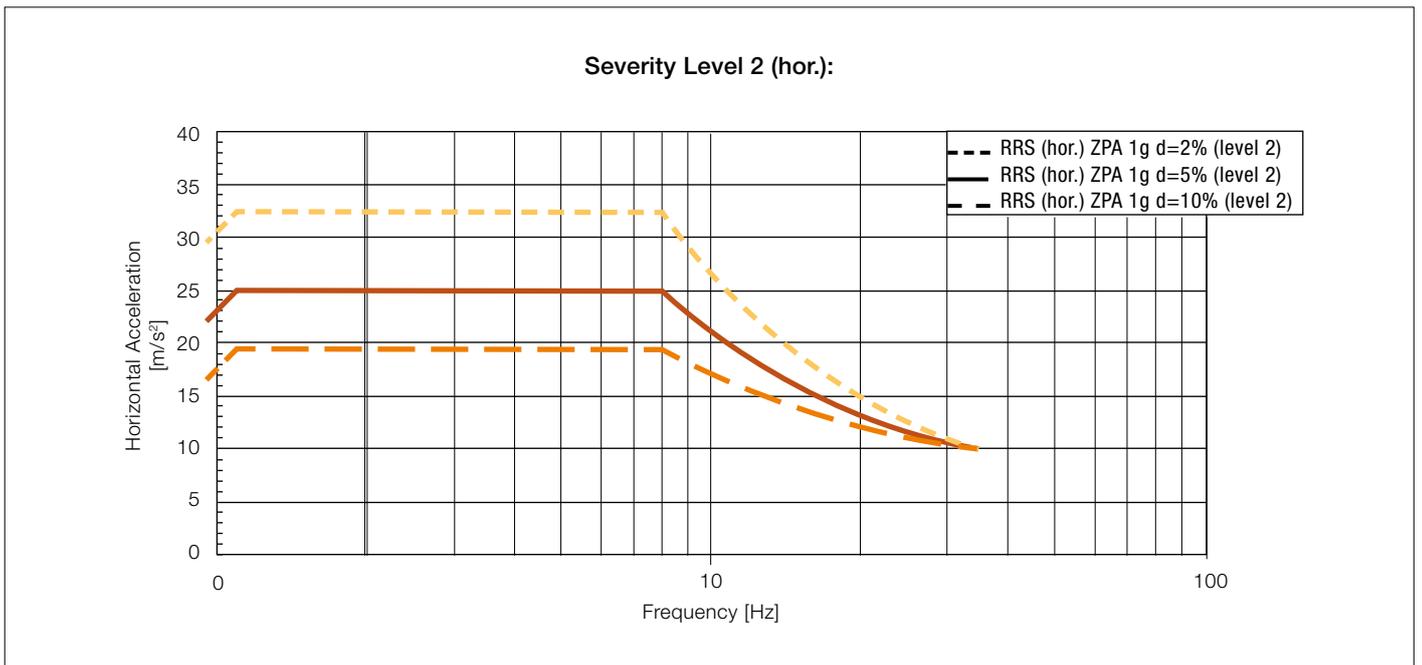
The seismic hazard map available on the website of the National Institute of Geophysics and Volcanology is shown below.



Source: Istituto Nazionale di Geofisica e Vulcanologia (National Institute of Geophysics and Volcanology).

The functional units of the ABB UniSec switchgear have been tested up to level 2, equivalent to Standard IEEE 693 high performance level.  
 The RRS corresponding to severity level 2 indicated in IEC/TS 62271-210 are provided below.

The form of the spectrum (Required Response Spectra, or RRS) can simulate the various conditions related to the intensity, depth and distance from the epicenter of the earthquake, the ground type and the high position of the switchgear located on the upper floors.



**Severity Level 2 (horizontal) – Zero period acceleration (ZPA) = 1 g**

## 2. Design and construction specifications of the substation

The figure indicates the positions of the accelerometers during the seismic test.



Photo 3

**Accelerometer positions**

- AT= Control Positions on base frame
- A1= Structure
- A2= Structure
- A3= busbar
- A4= WBC carriage
- A5= Transformer TA
- A6= Fuse
- A7= Pole base
- A8= Autotransformer




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TEST REPORT
APPROVED B1021565



**Client:** ABB Research & Development

**Address of the client:** Via Friuli 4  
24044 - Dalmine (BG)

**Manufacturer:** ABB Research & Development

**Tested sample/items:** ABB UniSec Switchgear 17.5 kV

**Tests carried out:** SEISMIC TESTS

**Standards/Specifications:** • IEEE Std 693 (2005)

**Tests date:** from 30<sup>th</sup> May 2011 to 6<sup>th</sup> June 2011

The results reported in this document relate only to the tested sample/items.  
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### Specifications for fire action

As regards resistance to fire, the standard requires that the means of classification of fire resistance of construction products and elements of construction works must be identified in accordance with the Decree of the Ministry of Interior of 16/02/2007.

The aforementioned Ministerial Decree provides the following explanatory table regarding the classification:

Symbols			
<b>R</b>	Bearing capacity	<b>P or Ph</b>	Continuity of current or signaling capacity
<b>E</b>	Resistance	<b>G</b>	Resistance on soot burning
<b>I</b>	Insulation	<b>K</b>	Fire protection capacity
<b>W</b>	Radiation	<b>D</b>	Duration of stability at constant temperature
<b>M</b>	Mechanical action	<b>DH</b>	Duration of stability along the standard time-temperature curve
<b>C</b>	Automatic closing device	<b>F</b>	Functionality of motorized smoke and heat exhaust systems
<b>S</b>	Smoke resistance	<b>B</b>	Functionality of natural smoke and heat exhaust systems

Classifications are typically expressed in minutes, e.g. for floors and roofs, REI 60 indicates the load-bearing capacity, resistance and insulation against fire will be maintained for 60 minutes.

In particular, as regards activities subject to fire prevention control, and in our case substations with fixed electrical machines with presence of combustible insulating liquids in quantities exceeding 1 m<sup>3</sup> and substations inserted in the volume of the buildings subject to fire prevention control, the fire resistance of the structures must be certified in the manner required by Annex II of the Ministerial Decree 07/08/2012 using the forms available from the website [www.vigilfuoco.it](http://www.vigilfuoco.it).

The following table extracted from Standard IEC EN 60695-1-40, Fire Hazard Testing, Part 1-40: Guidelines for Assessing the Fire Hazard of Electrotechnical products - Insulating Liquids, we can find the classification of insulating liquids in relation to the point of combustion and the heat of combustion:

Fire point		Net heat of combustion	
Class O	≤ 300 °C	Class 1	≥ 42 MJ/kg
Class K	> 300 °C	Class 2	< 42 MJ/kg
			≥ 32 MJ/kg
Class L	No measurable fire point	Class 3	< 32 MJ/kg

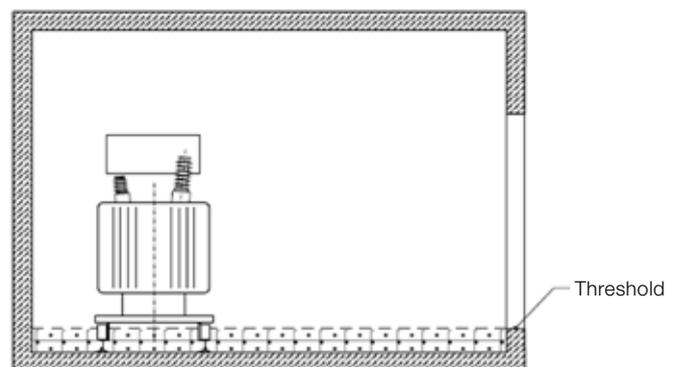
Example Mineral transformer oil (IEC 60296) has a classification of O1.

Finally, we come to Standard CEI EN 61936-1 that prescribes the requirements that the substation structure must possess in the event of a fire involving transformers with different characteristics, namely:

- REI 60 for transformers up to 1000 liters of oil type O
- REI 90 transformers for more than 1000 liters of oil type O
- REI 60 for dry transformers in class F0, while non-combustible walls are enough in the case of dry type transformers in class F1 (CEI EN 60076-11 Power transformers Part 11: Dry-type transformers).

For transformers with oil content greater than 1000 liters you also need to refer to the Ministerial Decree of 15 July 2014: Approval of the Technical Regulation for Fire Prevention for the Design, Installation and Operation of Fixed Electrical Machines with Presence of Combustible Insulating Fluids in a Quantity Exceeding 1 m<sup>3</sup>. Official Journal 5 August 2014, no. 180.

Again in the case of substations containing transformers in oil, in order not to pollute the environment, the Standard CEI EN 61936-1 states that measures must be implemented for the containment of the insulating oil by providing a waterproof floor with the containment thresholds around the area where the transformer is located or by conveying the leaked fluid into a suitable containment area within the building. When defining the containment volume you need to consider the total volume of the insulating liquid in the transformer and the water discharged from the fire fighting system.



The figure shows a section of the transformer room where the hatched area indicates the containment volume. When disposing of the products of combustion in the event of a fire the Fire Prevention Regulations must be taken into account.

# 2. Design and construction specifications of the substation

## 2.6 Thermal sizing and ventilation

While the devices are operating they must not exceed the maximum temperature to avoid degrading the insulating materials or having to resort to downgrading. In the room where the switchgear and controlgear are located the following must be provided:

- in the lower part, one or more air inlets with their bottom edge raised from adequately above the floor of the room (approximately 20 cm);
- at the top, flues or windows, preferably open towards to the fresh air.

Obviously, the vents can not draw from rooms that are at high temperatures or from places that are classified at risk of explosion according to Standard CEI 31-30 and must in any case ensure a degree of protection that will prevent water or snow from penetrating, and animals or objects from getting in that could cause accidents.

Where there is switchgear insulated with SF<sub>6</sub>, please note that this gas complies with CEI 10-7 and is not toxic; however,

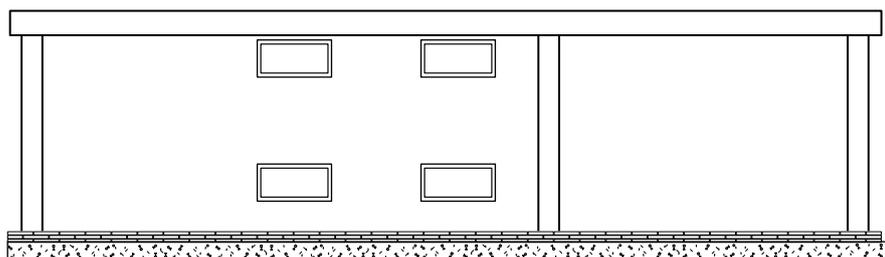
since it can generate oxygen insufficiency (this occurs when the percentage of oxygen in the air falls below 18%) an excessive concentration must be prevented. For this purpose, in structures located above ground level, natural ventilation is sufficient.

In structures below ground level if a harmful concentration is possible, forced ventilation must be provided. This also true for compartments (e.g. conduits) positioned under switchgear in SF<sub>6</sub>. However, forced ventilation may be omitted when the volume of SF<sub>6</sub> gas in a compartment of a bigger size than the switchgear and controlgear, in relation to atmospheric pressure, does not exceed 10% of the volume of the structure.

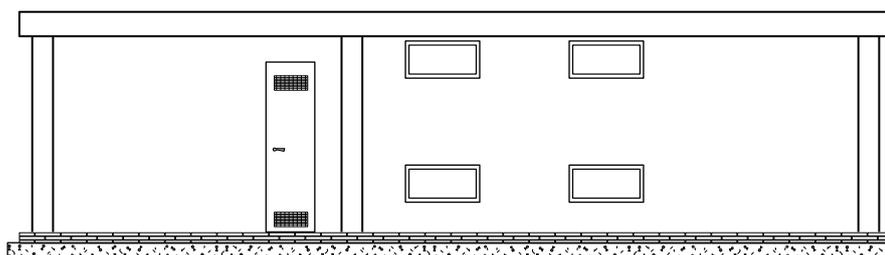
The entire Annex J of Standard CEI 99-4 is dedicated to the thermal sizing and ventilation of the structure.

Speaking of ventilation, Annex B of CEI 99-4 provides a summary of the requirements of standard CEI EN 50272-2 concerning the ventilation of battery rooms and an indicative example. During charging, the batteries develop hydrogen and oxygen as a result of the electrolysis process. The ventilation of battery rooms is necessary to keep the hydrogen concentration in the air volume in question below the danger of explosion, in other words 4%.

**Example views of a substation (non-executive) to highlight the ventilation windows (CEI 99-4, Figure A.5)**



Front view



Rear View

## 2.7 Artificial lighting

To allow the substation to be operated more easily and safely, artificial lighting must guarantee an illuminance level of 200 lx referring, unless otherwise stated, to a uniformity factor of at least 0.7 (UNI EN 12464-1).

For emergency/security lighting, for example, to identify the escape routes and the exits of the substation, the illuminance level must be equal to at least 1 lx that can be obtained using autonomous lighting equipment (for example by equipping operators with a portable lighting device with one hour autonomy).

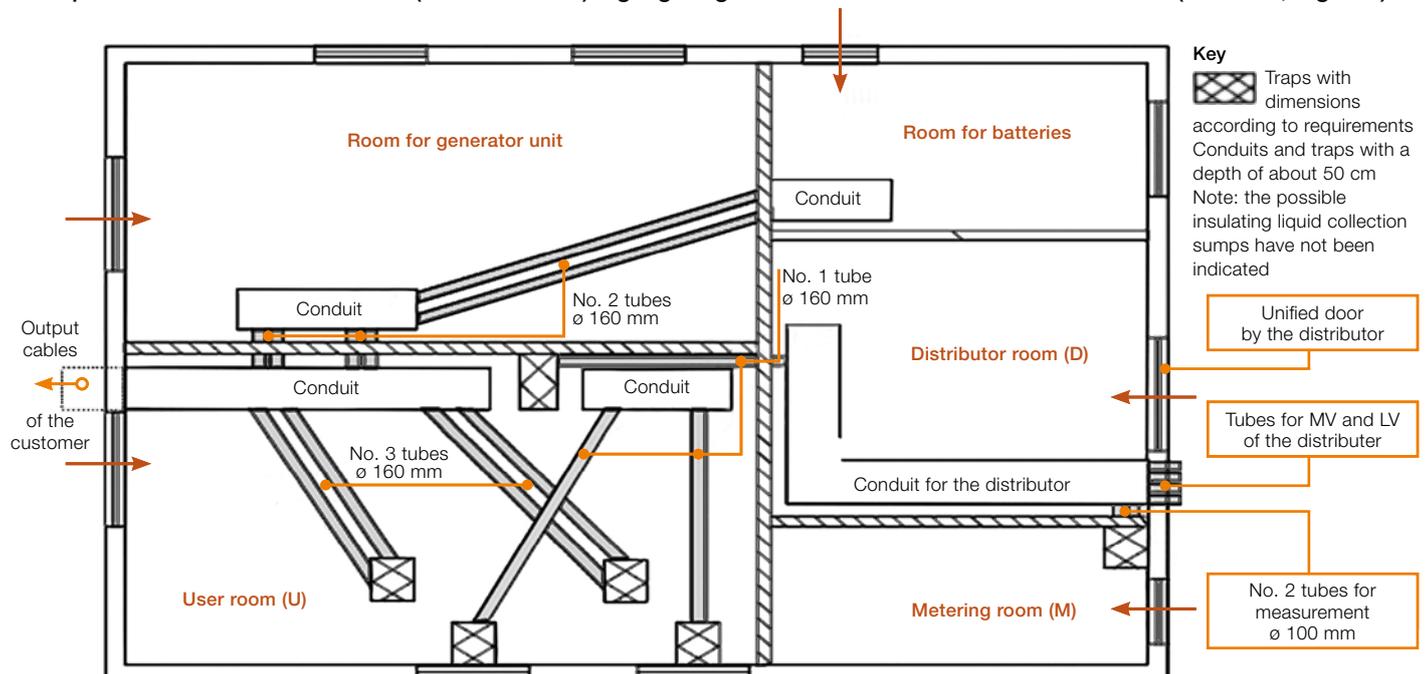
## 2.8 Electrical cables in the substation: position, entry points and separation of the circuits

As regards the cables, in substations we can have the following situations:

- accessible sub-panel compartment, or a walkable basement under the supporting plane of the switchgear, for which a net height of not less than 1.7 m is recommended. This solution is suitable for cases where the cables entering and leaving the substation are many and buried

- floating floor with removable tiles and inspectable space for cables for which we a height of not less than 0.6 m is recommended. This solution is suitable for cases where the number of incoming and outgoing cables is limited while the number of interconnection cables between the switchgear of the same substation is high
- conduits, or a fixed floor and cables contained in conduits prefabricated or built on site
- walkways or equivalent systems (see CEI EN 61936-1); the connections between the various components are mainly implemented by using ceiling cable suspension systems and wall mounted systems made of insulating or metal material
- The Distributor normally indicates how the holes for passing of cables are to be created, between the part of the Distributor's part of the substation structure and the customer's receiver part. In any case, all openings to the outside must be made in accordance with the Standards CEI 11-17 and CEI EN 61936-1 to prevent the entry of animals and water and to prevent the spread of any fires
- we also emphasize compliance with Standard CEI EN 61936-1 and the product standard for the cables for the sizing and positioning of the conduits and protective tubes embedded in the masonry that must ensure compliance with the curvature radii of the cables and allow free expansion
- the armor or metal screen of the cables can be considered as metallic segregation. Therefore the MV cables that are laid on walkways, conduits, piping, etc., can coexist with low voltage cables

Example of an electrical substation (non-executive) highlighting the ducts in the floor and the conduits (CEI 99-4, Fig. A.2)



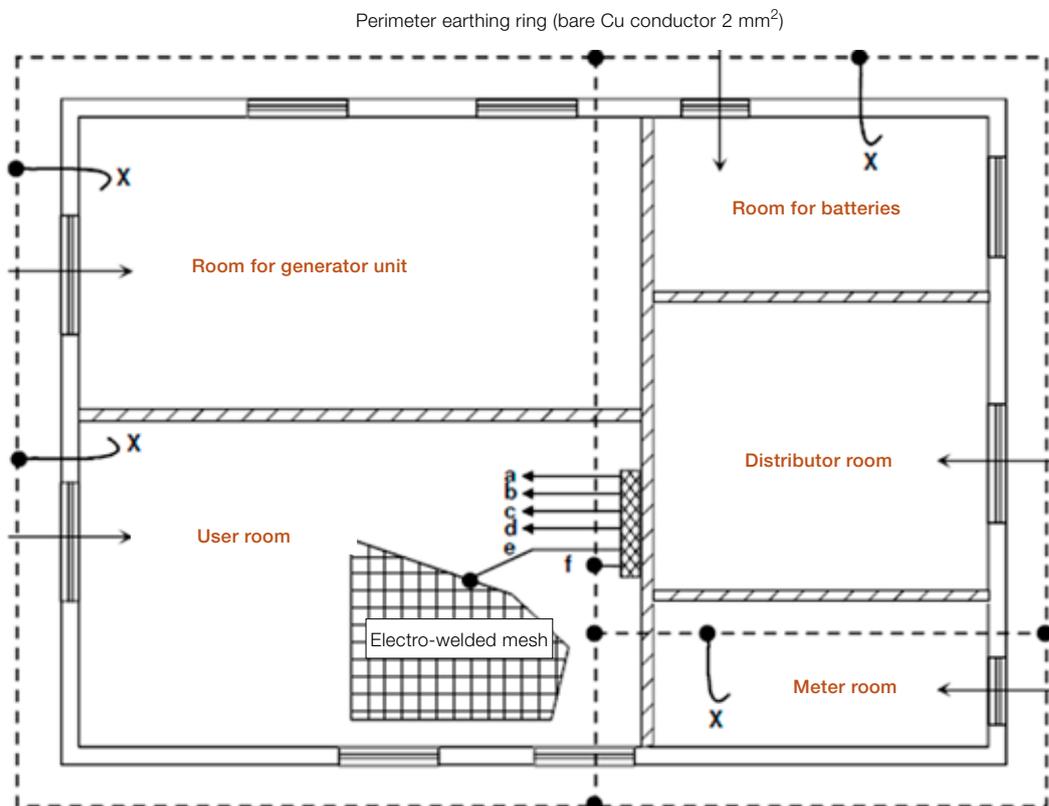
## 2. Design and construction specifications of the substation

### 2.9 Earthing systems

Particular attention should be paid to the design and construction of the substation earthing system. The earthing system is not addressed directly by CEI 99-4 that refers for such details to CEI EN 50522 and for MV systems and to CEI 64-8 only for the relevant LV systems.

The figure below, taken from CEI 99-4, illustrates - merely by way of example - some characteristics of the earthing system in order to draw attention to the elements that make up the earthing system.

Example of substation earthing system (non-executive) and corresponding collector (CEI 99-4, Fig. A.4)



#### Key

- a - Connection between earthing collector and earthing system of structures other than the substation
- b - Connection between transformer 1 star centre and earthing collector
- c - Connection between transformer 2 star centre and earthing collector
- d - Connection to the public distributor in the manner requested
- e - Connection between earthing collector and electro-welded mesh under the foundation
- f - Connection between the peripheral earthing ring and collector
- x - Reinforcement bars of the perimeter earthing ring for connections to the conductive parts

We will look at the main requirements of the earthing system for the three types of substations.

Isolated substation (separated from the building)

- If necessary, insert a perimeter ring earth plate in the foundation excavation, consisting of a conductor buried directly in virgin soil.
- All the reinforcement steel elements of the foundation can be used as an earthing rod.
- Given that the lateral structural elements of the building are connected together for reasons of staticity, if necessary they should be connected to the underfloor electrically welded mesh to obtain better equalization.
- All the elements that contribute to the formation of the earth plate must be connected (individually or in groups) to the collector of the substation.

Substation included within the volume of the building

- The earth plate will be part of the general earth plate of the building (considered as meshed or a ring or equivalent) and will consist of current elements, using the iron bars of the foundations, possibly supplemented by an intentional earthing rod.
- All the elements that contribute to the formation of the earth plate are connected to the main earth collector of the building, which is not necessarily located in the substation structure.
- The collector of the substation is in any case connected to the main collector.
- In particular, the substation and in its immediate vicinity, measures must be taken to achieve equalization of the potential. In addition, the measures to limit the potentials due to earth faults must be evaluated.

Substation in traditional masonry or prefabricated on the roof of a building

- The earth plate will be part of the main earth plate of the building, and must consist of current elements; in particular, for equalization of potential it is recommended that the reinforcing bars of the pillars and the floor slab of the roof should be connected.
- The collector of the substation will be connected to the structure of the building directly on the floor where the substation will be positioned.

Elements of the earth plate

- The earth plate can be implemented as a ring with copper wire or a steel bar according to Standard CEI EN 50522 and CEI Guide 11-37.
- If necessary, the ring may be supplemented with outreaches or with a second outer ring at a greater depth, possibly supplemented, for example, with copper-plated steel pegs 1.50 m in length complete with a collar for fastening the copper rope.
- Due the type and use of current elements, please refer to the Guide CEI 64-12 and CEI 11-37.
- All the necessary measures must be taken to limit the effects of corrosion, with particular attention to combinations of different metals (see UNI standards or the Guides CEI 11-37 and CEI 64-12 within the relevant scope).
- The filling soil around the earth plate must be of vegetation type and must not contain any waste material.

Earthing terminal

- The earth collector (in the form of not necessarily just one drawbar, or a ring) must constitute the point of connection between the elements of the substation earth plate, the earth plate of the building where the substation is inserted (if required), the MV earth conductors, the LV protective conductors LV and the equipotential conductors. The horizontal ducts for implementing these connections are preferably arranged in the floor of the substation.
- The studs of reinforcing rods provided as connection points must be left free from the pouring of the floor.
- To facilitate the maintenance and checking operations the individual conductors arriving at the collector should be signposted.
- The protective, equipotential and earthing conductors, if not exposed, must have a yellow/green sheath.
- The sizing for the sections of the collector and of all the protective conductors is performed by the designer, according to the MV and LV earth fault current.
- The equipotential conductors for the MV installation, if made of copper, must have a minimum cross-section of 16 mm<sup>2</sup>, (see CEI EN 50522). For LV installations, the main equipotential conductors, if made of copper, must have a minimum cross section of 6 mm<sup>2</sup> (see Standard CEI 64-8 for the relevant installations).

## 2. Design and construction specifications of the substation

### 2.10 Earthing devices required by the connection

To carry out work with the equipment de-energized, Standards CEI EN 50110-1 and CEI 11-27 establish that after identifying the corresponding electrical systems, the following five essential requirements must be observed in the order specified:

- 1) isolate the part of the system involved in the work;
- 2) take measures against untimely closing of the disconnecter device;
- 3) make sure that the system is de-energized;
- 4) earth and short-circuit the isolated parts;
- 5) ensure protection against any adjacent live parts.

Regarding point 4), for the construction of the connection, reference must be made to CEI 0-16, para. 8.2.1 where it stresses that earthing and short-circuiting of the HV system (voltage greater than 1 kV) can be implemented in two ways:

- by applying movable devices;
- using, where available, the devices intended for earthing and short-circuiting the relevant part of the installation.

The User can therefore adopt one of the following system solutions:

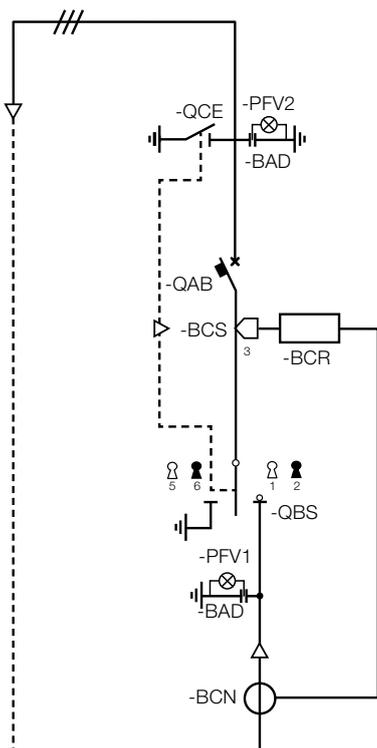
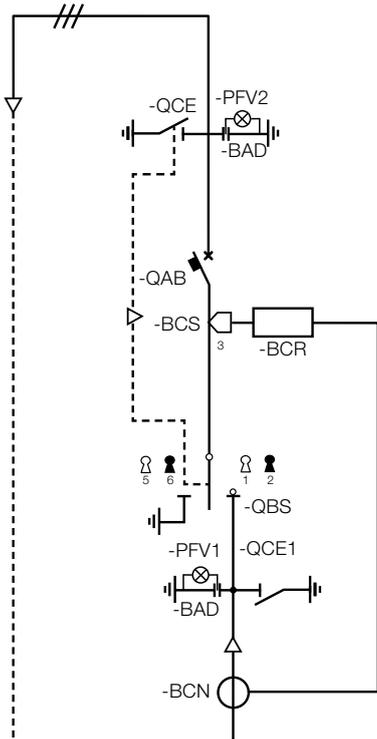
1. Do not use any earthing switch immediately downstream of the terminals of the network connection cable (in the User room, network side); in this case the earthing required by standard CEI 11-27 must be achieved using mobile earthing devices made according to Standard CEI EN 61230: Live works - Portable devices for earthing or for earthing and short-circuiting.

In particular, the User must also make sure that there is no voltage on the cable in question, earth it and short-circuit it using the aforementioned earthing devices. An appropriate notice must be affixed to the panel the removal of which allows access to the terminals of the cable saying "COVER/DOOR REMOVABLE ONLY AFTER ENERGY NETWORK ACTION".



2. Provide an earthing switch immediately downstream of the terminals of the network connection cable (in the User room, network side); in this case the Distributor's personnel must deliver a key - that cannot be copied for the User - that is freed once the earthing switch of the Distributor's delivery cubicle (cell) has been closed and which allows the User's first earthing switch to be closed. An appropriate warning must be affixed on this earthing switch that says "SWITCH TO BE OPERATED ONLY AFTER INTERVENTION BY THE DISTRIBUTOR". Prior to connection, the Distributor must be informed of which solution was chosen. Once the connection exists, the User cannot change the solution unless there is prior written consent from the Distributor.

Two examples of UniSec JTI switchgear are shown below, the first with a keyed earthing switch on the Distributor side that is the responsibility of the Distributor, and the second with provision for earthing via an insulating rod.



## 2.11 Rating plates, warnings and diagrams

Signs must be installed in the MV/LV substation (prohibition, warning and alert) created (pictograms and any tests) according to the provisions of Legislative Decree 81/2008, as amended, Annex XXV and UNI EN ISO 7010:2012.

The signs must be made of materials as far as possible resistant to impacts, weather and damage caused by environmental factors.

Some examples of signs that can be used in an electrical substation are shown later.

The Standard provides examples for correct positioning of notices, rating plates and signs:

- Outside each access door and on every side of any fences:
  - “no entry for unauthorized persons”;
  - “dangerous voltage”;
  - “possible identification of the electrical substation”;
- outside the entrance door to the structure, in addition to the previous three:
  - “do not use water to extinguish fires”;
  - “voltage ... kV”;
- inside the substation:
  - “Instructions for emergency aid to be provided to those injured by electricity” with the sections for the telephone numbers to be contacted case of necessity (the nearest doctors, hospitals, ambulances, etc.) filled in;
  - wiring diagram, which must also indicate, if relevant, also the color coding used for the various voltages;
- near MV switchgear,
  - “voltage ... kV”;
- available to the maintenance personnel,
  - “do not perform switching operations”;
- on any emergency exits:
  - the appropriate sign.

## 2. Design and construction specifications of the substation

It is also necessary to indicate any autonomous energy sources near the circuit disconnection device, the presence of accumulator batteries or capacitors on the doors of the corresponding cells and lastly, for complex electric substations, a single line diagram should be displayed.



Do not alter the state of the circuit-breaker



Sign forbidding access to unauthorized persons



Do not extinguish with water



Sign warning of the danger of hazardous electrical voltage



Sign warning of the hazard of flammable material or high temperature



Sign warning of danger due to an autonomous energy source

Note that the standardized pictograms can be combined and supplemented by explicit wording to make them more complete and understandable.



Warning sign with explicit reference to the deactivation of the electrical system before starting work on it



Combined sign with prohibitions and warning that can be supplemented by explicit wording under one or more of the combined elements



Combined sign with prohibition and warning and with a clear indication of the prohibitions or obligations



Sign for identification of the circuits with different colors for the different voltage levels and for the earthing conductors



Sign for identification of the voltage of an electrical substation (switchgear)



Sign for identification the accumulator battery room

The sign for first emergency first aid is shown below; the standard recommends filling in the necessary data at the bottom of the sign to ensure the prompt arrival of help.

# ACT IMMEDIATELY - DELAYING IS FATAL...

## EMERGENCY FIRST AID TO BE GIVEN TO THOSE SUFFERING ELECTRIC SHOCKS

### IMMEDIATE ACTION

It is critical when the shock affects breathing and cardiac activity; if the victim is not given aid within 3 or 4 minutes he/she can suffer irreparable consequences. Ensure first of all that the victim is out of contact with live parts and then immediately start giving artificial respiration. DO NOT DELAY AID, NOT EVEN TO CALL THE DOCTOR, unless there are at least two aid givers, or if the sole aid giver can call the attention of others without abandoning the victim.

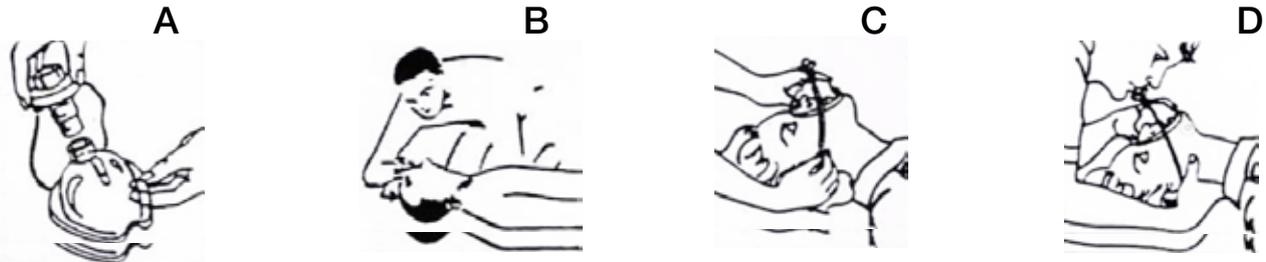
### DO NOT TOUCH

the victim, if you are not sure that he/she is no longer in contact with, or immediately adjacent to live parts. If this not so, disconnect the power. If the circuit cannot be promptly disconnected, insulation your person by means of insulating gloves, dry clothes, by standing on dry wooden planks etc. and remove the victim, preferably grabbing him/her by his/her clothes if they are dry. Alternatively, with a single swift and decisive movement, distance the live part from the victim using insulating rods, pieces of dry wood or other objects made of insulating material. Do not touch any other objects yourself, especially if they are metal. IF THE ORONASAL MASK IS NOT AVAILABLE, THE MOUTH TO MOUTH OR MOUTH TO NOSE TECHNIQUE MAY BE USED, POSSIBLY INTERPOSITION PLACING A HANDKERCHIEF OR GAUZE BETWEEN.

### ARTIFICIAL RESPIRATION

with an oronasal mask:

1. Lay the victim on his/her back and position yourself by the side of his/her head. 2. Equip yourself with an appropriate oronasal mask and position the valve unit correctly in the neck of the mask (see fig. A). 3. Tilt the victim's head back slightly (to open the air passage) placing one hand behind his/her head while the other acts as a lever on the forehead (see fig. B). 4. Apply the mask, covering the nose and mouth of the victim, making sure that it stays in the position shown in Fig. B (see fig. C). 5. Give two slow, deep breaths and observe the rising of the victim's chest. When the chest returns to its natural position, perform a regular cycle of 12-15 insufflations per minute (see fig. D).



IMPORTANT: if the person vomits, remove the mask, turn the head to one side and clean the mouth. Before reusing the mask, blow into the mask to clean it.

### CARDIAC MASSAGE

If not only the breathing stops but there is no heartbeat (to look for this sign, using two fingers press the victim's neck to either side of the Adam's apple), you must perform an external heart massage by pressing rhythmically on the chest. To do this: 1. Apply both hands superimposed with the palms facing down on the lower part of the sternum (see the figure at the side). 2. Apply rhythmic vertical pressure actions using your bodyweight and taking your hands away from the thorax each time to allow it to expand by elasticity. 3. Continue at a rate of 50-60 pressure actions per minute. Cardiac massage must always be preceded by artificial respiration with oral insufflation. Therefore, while the first aid giver is giving artificial respiration using the oronasal mask, a second will simultaneously perform CPR. If the aid giver is alone, he/she should behave as follows: start with 5 heart massage - perform oral insufflation - continue with another 5 massages - perform an insufflation, and so on. Suspend insufflation actions only when the victim has resumed breathing on his/her own and the pupils start to shrink again: however, check for some time to make sure that spontaneous breathing is maintained. If this is not the case, continue also during transport to the hospital and until specialized health personnel can take over.



After recovery, the victim must not be removed until he/she can breathe normally without assistance. He/she should be examined by a doctor before being allowed to walk. He/she must not be given any stimulant, unless directed by the doctor. Remember also that **TIMELINESS IS CRITICAL**.

### IN THE PRESENCE OF BURNS

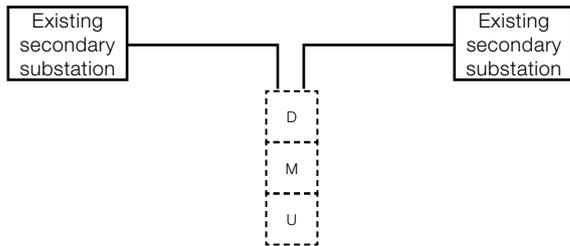
1. First of all, start artificial respiration and possibly cardiac massage if the victim is not breathing and has no cardiac activity. 2. Do not remove burned clothes and do not break any blisters. 3. Do not apply lotions or ointments. 4. Cover the burn with sterile, dry gauze. Also treat any burns (checking to see if there are any) at the exit points of the current. 5. If the victim has lost consciousness and is able to swallow, you can give him/her 300 g. water (a bowl) by mouth in which the baking soda and salt contained in the bags provided has been dissolved. If the victim vomits stop administering the liquid immediately. 6. Transfer the victim to hospital without delay.

NEAREST DOCTORS ..... tel. ....  
..... tel. ....  
NEAREST HOSPITAL ..... tel. ....  
NEAREST AMBULANCE ..... tel. ....

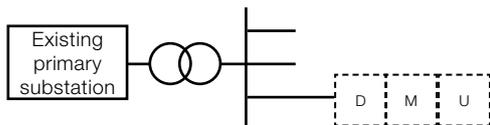
**MAKE SURE, HOWEVER THAT THE VICTIM IS NOT STILL TOUCHING ANY LIVE PARTS**

# 3. Schematic diagrams for the connection

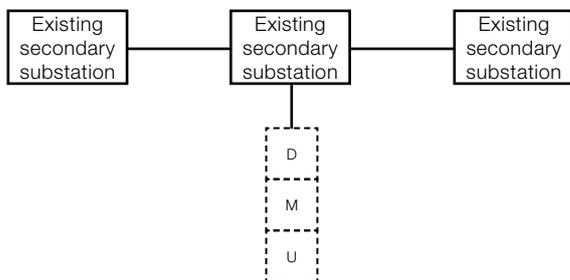
The schematic diagrams regarding insertion of the User's installation on the Distributor's network for connection systems are shown in the following figures:



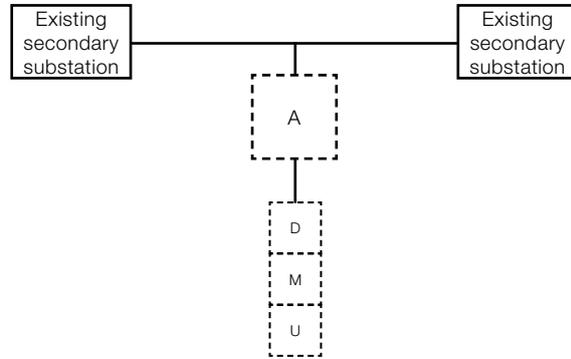
**Scheme A:** Insertion in-and-out mode for connection in the vicinity of an existing line, so as to generate only two line sections belonging to two distinct secondary substations. Under this scheme, the User can be powered again providing better continuity of service.



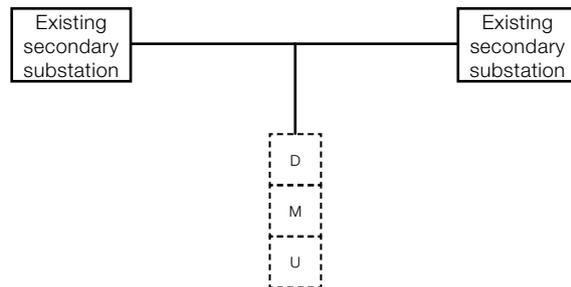
**Scheme B1:** Insertion in antenna mode from a HV/MV station; in this case, it involves the construction of a line powered directly from a primary HV/MV substation. This type of insertion can be adopted when insertion along an existing line is not technically possible. In any case, the room dedicated to the network system at the user site must be able to accommodate the equipment for possible future adoption of in-out insertion.



**Scheme B2:** Insertion in antenna mode from a HV/MV substation for connection via a line section connected to the MV busbars of an existing distribution substation. The room dedicated to the network system at the user site must be able to accommodate the equipment for possible future adoption of in-out insertion.



**Scheme C:** Insertion in antenna mode with actuating means (optionally in an additional substation A) along an existing line. From the actuating means, there must be a line dedicated to powering a user. The room possibly dedicated to the actuating means must be able to accommodate the equipment for possible future adoption of in-out insertion.



**Scheme E:** Inserting a section of line with a rigid T shunt on an existing MV line only with the circuit-breaker at the network connection system. This scheme is the simplest and least expensive, but reduces the reliability of the networks; it also provides inferior continuity of service. This connection is to be understood as exceptional.

In conclusion, of the connection solution chosen for the network system at the user site, the installation will always be as shown in the figure on page 5. Starting from the MV cable downstream of the connection point, the figure indicates the layout of a passive User's system for connection. With reference to the above figure, the Distributor's substation at the user site is the substation created to connect the User's system.

# 4. Sizing and choice of equipment and components

The choice of the wiring diagram of the substation, and therefore of the related equipment, depends on several factors such as:

- the number of power lines
- the number of transformers
- the requirements of the service, etc.

While it is true that the equipment and components of the substations must be chosen based on the rated characteristics and environmental conditions of the installation location, it is also important, on the basis of what we saw in the previous chapters, to adopt the necessary precautions, during the substation design phase, so that the operating temperatures do not exceed the maximum values allowed by the product standards for the equipment, so as not to impair their electrical lifetime and safety.

With particular reference to the Standard CEI 0-16, the general device (or DG) and the protection system associated with the General Device (or General Protection System, abbreviated as SPG below) are essential elements for connection of the Distributor's network.

The SPG consists of:

- current, phase and earthing transformers/transducers (and possibly voltage transformers/transducers) with the associated connections to the protection relay
- protection relay with its power supply
- opening circuits of the circuit-breaker.

The main technical characteristics and the choice of these devices are described below.

## 4.1 Disconnectors, switch-disconnectors, multifunction devices

MV systems must include an isolating device upstream of each switch disconnector that does not comply with the standards for disconnectors, for example, a non-withdrawable circuit breaker, and also on the power lines or with possible return power supply.

MV fuses must, in particular, be associated to a switching or disconnection device that allows them to be replaced safely, such as a switch-disconnector.

Conversely, prefabricated withdrawable circuit-breakers with metal enclosures addressed by the CEI EN 62271-200 also perform the disconnection function.

Since the disconnectors are not equipped with closing and interruption power, they must be operated in the absence of current and are typically interlocked with the associated switching equipment so as to prevent them from opening or closing under load.

In addition, each disconnection device should be associated to an earthing switch interlocked with its open or disconnected position.

For these reasons it is often preferable to have a multifunction device; these devices, since they are coordinated, in fact allow all the problems related to interlocks to be resolved with factory-tested mechanical solutions.

# 4. Sizing and choice of equipment and components

There are basically two types of multifunction devices:

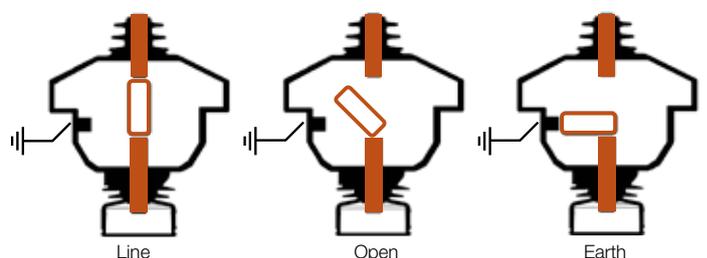
- line switch-disconnector/earthing switch
- circuit-breaker/feeder disconnector/earthing switch

The ABB GSEC switch-disconnector/earthing switch is based precisely on this design philosophy. The enclosure consists two half-shells; the upper one in insulating epoxy resin makes it possible to minimize the distances to the walls of the switchgear, and therefore to achieve particularly compact solutions. The lower half-shell, on the other hand, is made of stainless steel and allows the metallic segregation between the busbar compartment and the compartment adjacent to the switchgear, allowing the earthing of the two compartments and therefore allowing personnel to operate safely. With this solution it is possible to design electrical switchgear classified as PM (Metal Partition).

In accordance with Standard CEI EN 62271-1, the device is classified as a "sealed pressure system" since no interventions related to the gas will be required during its operational life, in this case 30 years. In addition, the high number of mechanical operations (class M2=5000 operations with a single spring operating mechanism and class M1=1000 operations with a double spring mechanism) and electrical operations (class E3 on line contacts with 5 closures on short-circuit currents and 100 interruptions on the rated current) help to make it a virtually maintenance-free device. Its compactness is further improved also by the integration of the capacitive sockets and cable connections directly on the lower insulators. The switchgear can then mount a Voltage Presence Indicating System (VPIS) system, which signals the presence of voltage on the cables connected to the switchgear in accordance with the Standard IEC 61958. Upon completion of the safety measures we find a mechanical indication of the position of the switchgear, a signal connected directly to the operating shaft of the switchgear (as per Annex A of IEC 62271-102).



- |   |                                       |
|---|---------------------------------------|
| 1. Opening and closing push-buttons         | 5. Top insulators                     |
| 2. Connection for the line operating lever  | 6. Enclosure (power part)             |
| 3. Connection for the earth operating lever | 7. Housing of the operating mechanism |
| 4. Voltage signalling lamps (if applicable) | 8. Bottom insulators                  |
|   | 9. Mimic diagram                      |

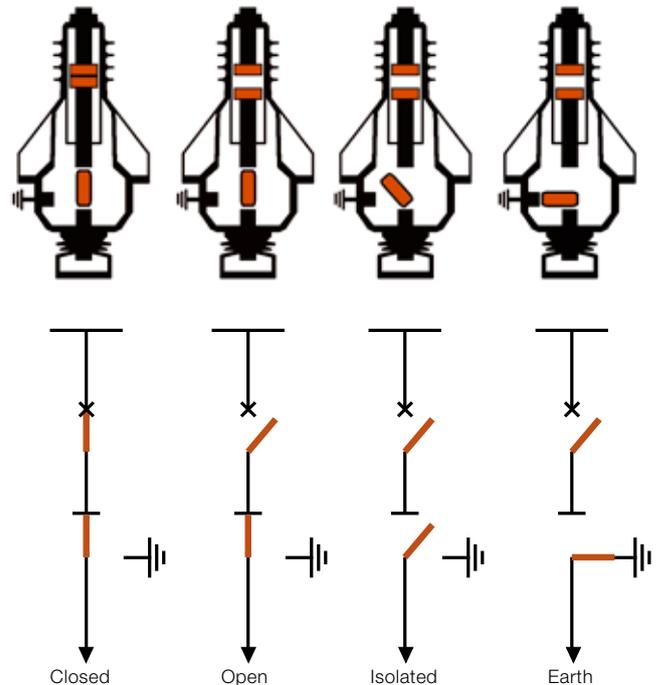


A further development of this concept is the ABB HySec multifunction device, an integrated and highly compact solution that combines the functions of three different devices: circuit-breaker, line disconnector and earthing switch; as in the case of the GSsec, the bottom stainless steel part allows metal segregation between the cable compartment and the busbar compartment, guaranteeing maximum operator safety during installation or maintenance of the switchgear but, at the same time, ensuring continuity of service. In this case too, it has to be considered that the interlocks between the various functions are part of the appliance itself and are therefore factory tested. The integrated solution is therefore particularly interesting for use in medium voltage switchgear for secondary distribution.

The circuit-breaker function is integrated in the upper part and for this purpose a vacuum circuit breaker is housed in the in the upper half-shell. The lower half-shell houses a line switch-disconnector (to isolate the cables from the busbars) and earthing switch (to earth the actual cables).

The use of vacuum interrupters to interrupt short-circuit currents provides a brilliant way to isolate the arc chamber of the circuit-breaker from the rest of the environment, filled with SF<sub>6</sub>, which is therefore aimed at the isolation and operation of the disconnector. The vacuum interruption also ensures high electrical performance.

The appliance is very flexible in that it can be used both as an input and output unit. In addition, the very limited number of components that characterize this integrated solution and the fact that it is tested as a single device makes it intrinsically very reliable. In accordance with Standard CEI EN 62271-1, the device is classified as a “sealed pressure system” since no interventions related to the gas will be required during its operational life, in this case 30 years. Its compactness is further improved also by the integration of the capacitive sockets and cable connections directly on the lower insulators.



1. Operating mechanism of the the interrupting part
2. Resin housing of the interrupting part
3. Mechanical interlock between feeder disconnector and earthing switch
4. Lower part in stainless steel
5. Operating mechanism of the line disconnector and the earthing switch
6. Lower isolators with integrated capacitive sockets

# 4. Sizing and choice of equipment and components

## 4.2 Circuit-breakers

It is important to underline that as a general device DG it is recommended to use a circuit-breaker, because the standard requires all MV Users to be protected against earth faults. The choice of general device may therefore fall either on the multifunction device that we have already seen or, if a more traditional solution is required and with higher performance electrical characteristics in terms of rated current and breaking capacity, on circuit-breakers. Obviously the Standard CEI 99-4 emphasizes that in MV systems the circuit-breakers must have adequate breaking and closing capacity for the short-circuit current calculated at the point of installation. It also suggests including an alarm that will immediately signal a power outage on the operating mechanism so that immediate action can be taken to restore its power supply (see also Standard CEI 0-16).

ABB circuit-breakers of the VD4/R and HD4/R series with lateral operating mechanisms have been designed specifically for use in secondary distribution switchgear and are used in MV/LV transformer substations in the industrial sector in general and in the service sector. The use of vacuum circuit-breakers provides particular advantages in power systems where required frequent operations are required with normal operating currents. VD4/R vacuum circuit-breakers provide high operating reliability and a long life. The HD4/R medium voltage gas circuit-breaker uses SF<sub>6</sub> gas to extinguish the electric arc and as the insulating medium. This circuit-breaker too, like the previous one, is built using the separate pole technique. Its construction is compact, sturdy and lightweight and is a lifetime sealed pressure system (IEC 62271-1).



Gas circuit-breakers HD4/R-Sec  
(with REF601 relay and current sensors)



Vacuum circuit-breakers VD4/R-Sec  
(with REF601 relay and current sensors)

## 4.3 Measuring and protection transformers

The CTs (current or amperometric transformers) and VTs (voltage or voltmetric transformers) are required in the installations to reduce the current and voltage values of the installation to values that can be read by measuring and protection devices; another important function is to make secondary measuring and protection circuits galvanically independent from the primary power circuit, thus ensuring greater safety for operators.

For clearer understanding we have adopted the abbreviations defined by Standard CEI 0-16:

- TA-I: Current transformers/transducers of the inductive type
- TA-NI: Non-inductive current transformers/transducers
- TA-T: Current transformers/transducers of the inductive type without primary winding (of the toroidal type)
- TO: Residual current transformer/transducer of the inductive type without primary winding (of the toroidal type)
- TV-I: Voltage transformers/transducers of the inductive type
- TV-NI: Non-inductive voltage transformers/transducers for use in MV networks

### Inductive transformers (TA-I, TA-T, TO, TV-I)

The main regulatory references for CTs and VTs, also of the inductive type (with iron plates) in medium voltage networks are:

CEI EN 61869-1: Measuring transformers, Part 1: General requirements

CEI EN 61869-2: Measuring transformers, Part 2: Additional requirements for current transformers

CEI EN 61869-3: Measuring transformers, Part 3: Additional requirements for inductive voltage transformers



These Standards specify the construction characteristics and the definition of the precision classes. One should bear in mind that the precision class for measuring CTs and VTs and for protection VTs depends on the load that is connected to the secondary: the precision is only guaranteed when the secondary load is greater than 25% of the rated performance of the transformer. Considering the present low consumption levels of the switchgear connected to the secondary, it is therefore essential for the performance of the VTs (measuring and protection) as well as the measuring CT to be limited in order to ensure that the transducer operates within the precision class for which it was designed.

### Current transformers (TA-I, TA-T, TO) of the inductive type

One important point should be made about the CTs regarding the type of construction and the measuring method. This refers especially to toroidal CTs, which are CTs to all effects and as such must be classified. The CT may be of the following types:

- wound type TA-I (as the CTs normally are inside medium voltage switchgear) with two terminal blocks of the primary circuit and the terminal blocks of the secondary circuit exposed to the outside. The primary circuit can in this case even have a number of turns other than 1;
- TA-T passing bar type in which there is a busbar part (generally copper) already embedded in the resin. In this case the terminals of the primary winding are the ends of the bar, while the ends of the secondary winding are connected to external terminals. The number of primary turns in this case is always equal to 1;
- toroidal type TO where the primary is not required and it will consist of the MV cables that pass through the central hole of the CT; the ends of the secondary winding are connected to the external terminals. The number of primary turns in this case is still generally equal to 1, unless the conductor is not passed several times in the CT. These CTs can also be constructed as openable types for easy installation in existing systems.



# 4. Sizing and choice of equipment and components

For all types of CT, the precision classes are similar and defined according to the standard.

Depending on how the CT is inserted in the network it can perform measurements with varying significance. In particular: a CT that is inserted on a single phase (for example, toroidal CT that embraces only one phase) measures line currents (phase);

a CT that is placed on the three phases (for example toroidal CT that encloses the conductors of the three phases) measures the vector sum of the currents (in reality the sum of the flows) and therefore the homopolar current.

The information provided above indicates that regardless of the form of construction, the measurement that is obtained on the secondary of CTs depends on how it is inserted into the network.

The purpose of the CTs is to translate currents from the power circuit to the measuring circuit. The standard classifies them into two types:

- measuring CTs to which measuring instruments such as ammeters, power meters, converters, etc. are connected;
- protection CTs to whose secondary the protection relays are connected This classification is based on independent measuring and protection systems. With today's digital devices (REF Units) protection and measurement are carried out by the same device and separate inputs with different characteristics (size, protection) are not provided by the CT. Consequently, to implement proper use of digital relays, the CTs should be chosen with double precision class, such as:

## 100/1 - 4 VA - Cl. 0.5 + 5P10

The two precision classes are defined for the different areas of operation of the CT and can thus coexist.

As described for CTs, the same reasoning can be applied to VTs. Therefore when using digital relays of the RE\_ family, a VT with a dual precision class should be chosen, for example: 6000:  $\sqrt{3}$ / 100:  $\sqrt{3}$  - 10 VA - Cl. 0.5 + 3P

## Metering CT

An essential factor in choosing the characteristics of measuring CTs is that the precision class is guaranteed for secondary loads 25% higher than the rated performance. When the instrumentation was electromechanical it was therefore logical to purchase CTs with high performance, but today, with digital instruments, CTs with truly limited performance (typically 5, maximum 10 VA) can be purchased. An essential feature of measuring CTs is saturation for currents slightly above the nominal primary current, to guarantee protection of the instruments (typically able to withstand a maximum of 20 In for 0.5 seconds) in the event of a short circuit. For measuring CTs, according to the standard, a safety factor (Fs) must therefore be defined such that, for currents higher than Fs x In, the CT is safely saturated (consequently protecting the secondary circuit).

In reality, the CT is not loaded on the secondary up to its rated performance but to a lower load. The real safety factor (F's) is therefore greater than the rated factor and a check is essential to ensure that the instrumentation connected to the secondary circuit is adequately protected.

The real safety limit factor can be calculated with the following relationship:

$$F'_s = F_s \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{TRUE}}$$

- F'\_s = real safety factor on the real secondary load;
- F\_s = rated safety factor of the CT;
- S\_N = rated performance of the CT;
- S\_TA = internal consumption of the CT = R\_TA x I\_2N^2;
- I\_2N = rated secondary current of the CT;
- R\_TA = secondary resistance of the CT at 75°C;
- S\_TRUE = true load on the secondary of the CT = I\_2N^2 x (R\_INSTRUMENTS + R\_C);
- R\_C = resistance of the wiring circuit;
- R\_INSTRUMENTS = load (internal consumption) of the instrumentation connected to the CT secondary.

Two examples may be of help in selecting the characteristics of the measuring CTs and in highlighting the errors that can be made in the case of oversizing.

Consider a CT with a 100/1 ratio and with a secondary load consisting of an ammeter (internal consumption 0.5 VA) and a multifunction converter (internal consumption 0.5 VA). Resistance of the secondary circuit between the terminals of the CT and the instrumentation 0.1 ohms.

Example 1

CT 100/1 - Cl. 0.5 - 4 VA -  $F_s = 5$  -  $R_{TA} = 0.8$  ohm

The real secondary load is 1.1 VA or 27.5% of the rated performance, and therefore the precision class is guaranteed.

The value of the real safety factor is:

$$F'_s = F_s \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{TRUE}} = 5 \cdot \frac{0.8 + 4}{0.8 + 1.1} = 12.6$$

The CT saturates for currents below the withstand of the instruments connected to the secondary and is therefore adequately sized.

Example 2

CT 100/1 - Cl. 0.5 - 10 VA -  $F_s = 10$  -  $R_{TA} = 0.8$  ohm

The real secondary load is 1.1 VA or 11.5% of the rated performance, and therefore the precision class is not guaranteed. The value of the real safety factor is:

$$F'_s = F_s \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{TRUE}} = 10 \cdot \frac{0.8 + 10}{0.8 + 1.1} = 57$$

The CT saturates for currents higher than the withstand of the instruments connected to the secondary, and therefore in the event of a short-circuit on the network the instruments could be destroyed and the secondary circuit could be opened as a result with serious risk to the safety of personnel (overvoltages). It is therefore evident that all the secondaries of the measuring CTs should be carefully sized in order to avoid serious damage to the system in the case of a fault and to obtain measurements in the required precision class.

### Protection CT

The CTs that are associated with the protections have the peculiarity of not saturating until the tripping of the protection is guaranteed for the maximum short-circuit current. The parameter in protection CTs that defines the value within which the response is linear is the precision limit factor (FL), usually equal to 10-15-20 or even greater.

In choosing the characteristics of the protection CT (performance and precision limit factor) the following conditions must be met:

- the performance of the CT must be greater than the secondary load (relay and wiring);
  - the CTs to be associated with overcurrent protections should not saturate until their safe operation is guaranteed. Generally for ABB relays it can be assumed that the saturation should be at least twice the set value with a minimum of 20 In, but precise values can be found in the catalogues for the various types of relays;
  - the CTs to be associated with special protections such as differential relays, distance measuring relays, etc. must have a safety factor defined on a case by case basis and provided in the catalogues for the relays;
  - the CTs must saturate for appropriate current values in order to read overcurrents correctly and at the same time to preserve the relays and the secondary circuits in the event of a short circuit. Overcurrent relays typically have a tolerability of 100 In for 1 second and peak 250 In, but more precise values can be found in the catalogues for the various relays.
- The last condition is not generally given much consideration and can result in serious damage to components if not checked.

As for the safety limit factor for measuring CTs, also for protection CTs the real precision limit factor must be calculated according to the load actually connected to the secondary, and can be calculated using the following relationship:

$$F'_L = F_L \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{TRUE}}$$

- $F'_L$  = real precision limit factor for the real secondary load;
- $F_L$  = rated precision limit factor of the CT;
- $S_N$  = Rated performance of the CT;
- $S_{TA}$  = internal consumption of the CT =  $R_{TA} \times I_{2N}^2$ ;
- $I_{2N}$  = rated secondary current of the CT;
- $R_{TA}$  = secondary resistance of the CT at 75°C;
- $S_{TRUE}$  = true load on the secondary of the CT =  $I_{2N}^2 \times (R_{RELAY} + R_C)$ ;
- $R_C$  = resistance of the wiring circuit;
- $R_{RELAY}$  = load (internal consumption) of the relays connected to the CT.

# 4. Sizing and choice of equipment and components

As is the case for measuring CTs, two examples can be significant for checking the characteristics of protection CTs. Consider a CT with a 100/1 ratio with a secondary load consisting of an overcurrent relay (internal consumption 0.05 VA). Resistance of the secondary circuit between the terminals of the CT and relay 0.1 ohm, therefore the real secondary load is 0.15 VA.

Example 1

CT 100/1 – 4 VA – 5P10 -  $R_{TA} = 0.8$  ohm

The value of the real precision limit factor is:

$$F'_L = F_L \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{TRUE}} = 10 \cdot \frac{0.8 + 4}{0.8 + 0.15} = 50.5$$

The CT saturates for a sufficiently high current for overcurrent protection (maximum relay adjustment generally not more than 20 In). The relay and the entire secondary circuit (terminals and wiring) are adequately protected against very high short-circuit currents.

Example 2

CT 100/1 – 10 VA – 5P20 -  $R_{TA} = 0.8$  ohm

The value of the real precision limit factor is:

$$F'_L = F_L \cdot \frac{S_{TA} + S_N}{S_{TA} + S_{TRUE}} = 20 \cdot \frac{0.8 + 10}{0.8 + 0.15} = 227$$

If the CT is inserted in a circuit in which the short circuit current is high (for example, 31.5 kA switchgear), in the event of a short circuit instead of the protection to control the opening of the switch tripping, the relay will probably be destroyed, with the consequences that one can imagine. It is therefore evident that, as also for protection CTs, every secondary should be carefully calculated to avoid serious damage in the installation in the event of a fault and to guarantee safe protection of the underlying portion of the network.

## Inductive voltage transformers (TV-I)

For voltage transformers, for both measuring instruments and protection relays, the same rule as for measuring CTs applies in relation to the range within which the precision class is guaranteed: the precision class is guaranteed only

if the secondary load is greater than 25 % of the rated performance. It is not easy to ensure that a VT will operate in precision class when instrumentation (relay or measuring instruments) with internal consumption in the order of fractions of VA is connected to the secondary.

The use of ballast loads (resistance) to be inserted in the secondary of VTs when these have been chosen with performance that is too high in order to ensure the precision class has two drawbacks:

- an element is added to the circuit (which may also be a protection circuit) that can fail and that therefore reduces the overall reliability of the system;
- a heating element is added in the measuring cell of the switchgear with obvious issues of heat extraction.

The selection of VTs must also take account of any ferroresonance. The phenomenon of ferroresonance is a typical aspect of VTs inserted on networks in a cable with isolated neutral or not effectively earthed. The capacity of the cable, together with the inductance of the VTs, constitutes an oscillating circuit (RLC). Conditions can therefore arise on the circuit as a result of which the circuit itself resonates (capacitive reactance=saturated inductive reactance of the VT) and, even though the cause that provoked the saturation ceases (for example an earth fault), a transient oscillation (at a frequency that is a several times that of the network) of reactive energy persists caused by the components of the oscillating circuit. Because of the frequency of this oscillation, a permanent and high circulation of current is produced in the primary winding only. Since this is only a magnetizing current, the secondary winding is barely affected, resulting in high heating on the primary but negligible on the secondary. The abnormal heating of the windings always produces a strong internal pressure resulting in breakage of the outer housing. The precautions to be taken to avoid ferroresonance phenomena are primarily:

- increase the magnetization impedance of the VT;
- use VTs that work with induction lower than that recommended;
- use VTs with highly permeable plates;
- insert damping resistances (or in any case devices with nonlinear resistance) in series with the secondary windings connected in an open delta (the voltage relay must be connected in parallel to the anti-ferroresonance resistance).
- use the ABB VT Guard Pro device connected to the open delta, which increases resistance as the voltage increases.

In the past, for measurement of homopolar voltages (necessary for identifying earth faults) a secondary set of VTs connected in an open delta was used. In modern digital switchgear it is no longer necessary to provide this secondary of the VTs because the homopolar voltage (vector sum of the three phase voltages) is calculated inside the actual relay (the signal coming from an open delta secondary often has lower precision).

#### Non-inductive current and voltage sensors (TA-NI, TV-NI)

Since the power absorbed by the devices that are connected on the secondary circuit is extremely reduced it is no longer necessary to have magnetic circuits for the coupling between primary and secondary circuits. Therefore current sensors or air CTs (Rogowsky coil) and voltage sensors (voltage dividers) were developed that eliminate the negative aspects of inductive transformers (hysteresis loop). Reference is made in particular to:

- saturation: with current sensors the phenomenon of saturation does not exist (there is no iron) and there the definition of the precision limit factor is no longer a problem;
- performance: we have seen in the examples above that it is difficult to reconcile the performance of measuring transformers with loads connected to the secondary. In fact, the need to have at least 25% of load to ensure precision is no longer a problem;
- primary rated currents and voltages: the linearity of response allows 95% of applications to be covered with only two or three types of transducer, with considerable advantages for the standardization of the cells of the switchgear and the possibility of their rapid conversion;
- it is no longer necessary to have a measuring CT or VT and/or protection CT or VT because the precision is constant and there is no longer the problem of saturation.

The Reference standards (currently being revised) for current and voltage sensors are:

- CEI EN 60044-8: Measuring transformers, Part 8: Electronic current transformers
- CEI EN 60044-7: Measuring transformers, Part 7: Electronic voltage transformers

For current sensors or air CTs, the main feature is that they are transformers in which the magnetic circuit is replaced by air. A particular characteristic of these types of CTs is that the secondary signal is not proportional to the primary quantity, but to its derivative (which, if properly integrated in the devices connected to the secondary, allows current measurement to be obtained). As already noted, there are no saturation phenomena but, as a negative aspect, there is in general the precision class that at the current design stage does not attain the characteristics that can be achieved for inductive measuring CTs.

For voltage sensors the main feature is the absence of the ferroresonance phenomenon (obviously, since there iron is not present anymore). This is a significant advantage where networks operated with isolated neutral are still used. As for the air CTs, also for the voltage dividers (VTs), at the current state of the technology, the precision class has not yet reached that of inductive VTs.

ABB circuit-breakers of the VD4/R and HD4/R series can be equipped with two or three current sensors; three current sensors are required to perform the functions of protection against homopolar instantaneous overcurrent and homopolar inverse time overcurrent for the vector sum of the phase currents; if these functions are performed with an external toroidal current transformer, only two current sensors can be installed; the external toroidal transformer is available on request.

The current sensors are the air type previously (Rogowsky coils) encapsulated in epoxy resin.



# 5. Protection relay

The Standard CEI 99-4 reiterates that each circuit equipped with a circuit-breaker must be equipped with overcurrent protection devices that act on the opening command of the circuit-breaker. Protective devices may be:

- direct relays mounted on board the circuit-breaker and powered directly from the primary current (not used in medium voltage)
- indirect relays without auxiliary power
- indirect relays with auxiliary power

The overcurrent relays must be selected taking into account the characteristics of the circuit to be protected and the selective coordination of the protections; if the Distributor requires a protection with instantaneous tripping, it may be impossible to achieve selective coordination of the protections as part of the internal MV distribution network (if present) due to instantaneous tripping of the main circuit-breaker. In this case, however, it is possible to limit disruption resulting from a fault in the internal network by adopting, for instance, a suitable distribution scheme (e.g. double radial, open ring) and appropriate devices to identify the faulty section or to implement current selectivity with the LV network.

The Standard CEI 0-16 introduced general rules for protection of the connection between Users and Distributors.

The standard also defines the corresponding features and settings in detail. The protections provided on the connection point between Users and Distributors are not intended to protect the equipment and systems, but are only used to define the contractual values above which the User must disconnect from the Distributor's network.

Therefore the installation of a protection device on the delivery point is not a guarantee of adequate protection of the network downstream.

In general, the protection system must provide at least the following functions:

- phase overcurrent protection phase with three thresholds:
  - first threshold with a characteristic of very inverse time trip for overload protection ( $I>$ );
  - second threshold to identify minor multi-phase short-circuit faults in the User network ( $I>>$ );
  - second threshold to identify multi-phase short-circuit faults in the User network ( $I>>>$ );
- homopolar overcurrent (or earth) protection: this protection can be implemented in two different ways depending on the capacitive contribution of the User network to the Distributor. In particular, if the contribution of the User network to the Distributor is less than 80% of the value required by the Distributor, the protection may be of the non-directional type, otherwise must necessarily be directional (with activation direction for currents flowing from the Distributor to the User network).
- For networks with capacitive contribution less than or equal to 80% of the imposed setting, two maximum homopolar current thresholds are required with the following characteristics:
  - first threshold with characteristic of defined time tripping to identify single-phase earth faults in the User network user ( $I_{o>}$ );
  - second threshold with characteristic of defined time tripping to identify double single-phase earth faults in the User network user ( $I_{o>>}$ );
- For networks with capacitive contribution greater than 80% of the imposed setting, three maximum homopolar current thresholds are required with the following characteristics:
  - first threshold of directional type with characteristic of defined time tripping to identify single-phase earth faults in the User network with a compensated neutral system ( $I_{o->}$  the Standard calls it 67N.S1);
  - second threshold of directional type with characteristic of defined time tripping to identify single-phase earth faults in the User network with an isolated neutral system ( $I_{o->}$  the Standard calls it 67N.S2);
  - third threshold of non-directional type with characteristic of defined time tripping to identify double single-phase earth faults in the User network user ( $I_{o>>}$ );

In order to understand when the 67N is necessary you can proceed as indicated below.

In the case of systems with isolated neutral, it is possible to determine the value (in Amperes) of the single-phase earth fault conventionally, according to the following empirical formula:

$$I_F = U (0,003 L_1 + 0.2 L_2)$$

Where:

U is the rated voltage between the phases of the network in kV:

$L_1$  is the sum of the lengths in km of the overhead lines and

$L_2$  is the sum of the lengths in km of the cable lines, under normal conditions, connected with each other metalically during operation of the network.

The above formula is approximate; more precise values can be calculated according to the Standard CEI EN 60909 (CEI 11-25).

In the case of a system with neutral earthed through impedance, the value of the single-phase earth fault current is independent of the size of the MV network and is conventionally defined by the Distributor.

In any case, as an example, since the required calibration of the protection is usually 2A, we apply the formula using this value, and therefore 80% of 2 A gives 1.6A ( $I_0$ ). Furthermore, in small to medium industrial and service sector installations there are no overhead lines, and therefore the formula can be further simplified:

in other words,  $I_F = 0.2 U L$ .

Therefore, we have:

$L = I_F / (0.2 U)$  and lastly replacing  $I_0$  for  $I_F$ :  $L = 1.6 / (0.2 U)$

By applying the formula we find out we will have to adopt the 67N protection:

- with mains voltage of 20 kV for MV cable > 400m
- with mains voltage of 15 kV for MV cable lines > 533m

For other mains voltage values the maximum length can again be calculated using the formula above.

The standard also specifies some typical settings for the protections on the basis of which a number of considerations can be made.

The minimum indicated settings are:

<b>I&gt;</b>	<b>Phase overcurrent protection:</b> first threshold (optional activation)	To be agreed with the Distributer
<b>I&gt;&gt;</b>	<b>Phase overcurrent protection:</b> second threshold	≤ 250 A, overcurrent extinction time ≤ 500 ms
<b>I&gt;&gt;&gt;</b>	<b>Phase overcurrent protection:</b> third threshold	≤ 600 A, overcurrent extinction time ≤ 120 ms
<b>I0&gt;</b>	<b>Homopolar overcurrent protection</b> first threshold (used only in the absence of the 67N) For networks with isolated neutral	≤ 2 A, fault extinction time ≤ 170 ms
	For networks with compensated neutral	≤ 2 A, fault extinction time ≤ 450 ms
<b>I0&gt;&gt;</b>	<b>Homopolar overcurrent protection</b> For networks with isolated neutral (used only with 67N present). S2)	value 140% of the single-phase earth fault specified by the Distributer; fault extinction time: ≤ 170 ms
	For networks with compensated neutral (always present also with 67N)	value 140% of the single-phase earth fault specified by the Distributer (typically, 70 A for networks at 20 kV and 56 A for networks at 15 kV); fault extinction time: ≤ 170 ms
<b>I0-&gt; S1</b>	<b>Directional earth protection</b> threshold 67N.S1 (earth fault selection in a compensated neutral system)	$I_0$ : 2 A, $U_0$ : 5 V; tripping sector (delay of $I_0$ compared to $U_0$ ): $60^\circ \div 250^\circ$ ; fault extinction time: ≤ 450 ms;
<b>I0-&gt; S2</b>	<b>Directional earth protection</b> threshold 67N.S2 (earth fault selection in an isolated neutral system)	$I_0$ : 2 A, $U_0$ : 2 V; tripping sector (delay of $I_0$ compared to $U_0$ ): $60^\circ \div 120^\circ$ ; fault extinction time: 170 ms;

# 5. Protection relay

As an alternative to the settings described above, for Users of compensated neutral systems that do not require 67N.S1 and 67N.S2 protections, the threshold  $I_{o>}$  can simply be used, with the following settings: value 2 A; fault extinction time: 170 ms.

Please note: by overcurrent extinction time (fault extinction time), we mean the sum of the tripping time of the protection, the opening time of the circuit-breaker until complete extinction of the current. So in calculating the protection settings the opening time of the circuit-breaker (typically 60-70 ms) must be subtracted.

The settings shown, which must however be agreed on a case by case basis, show that it is in general possible to achieve good and selective protection only for earth faults in a compensated neutral system, while for earth faults in an isolated neutral system or in the case of multi-phase short circuits (two-phase, earthed or otherwise, and three-phase) the selectivity between MV protections within the User network is practically impossible (given the operation time of the circuit-breakers).

The rule provides that in special cases logical selectivity can also be used, but this has to be agreed between User and Distributor.

Another protection function required by CEI 0-16 that must be provided in some installations is minimum voltage, which has, however, an application of automatism rather than a true protective application. Where the total power of transformers that can be remagnetized simultaneously following a power failure (if the circuit-breakers remain closed) is greater than the value specified in the standard, a disconnection must be performed, followed by reinsertion in steps to prevent inrush currents that are too high causing the overcurrent protections not equipped with the 'magnetization lock' function to trip. Given the critical nature in the coupling between the current transformers and relays, the adoption of integrated relay/CT solutions as in the case of ABB circuit-breakers of the VD4/R and HD4/R series can eliminate the risks of making a wrong choice. Not surprisingly, the standard recommends paying particular attention to the coordination between current transformers and relays.

Where indirect relays are used with auxiliary power supply there must be an independent source (usually an accumulator battery) available that will guarantee power supply even in the event of a failure. Furthermore, the lack of auxiliary source must be properly signalled.



In transformer substations for the connection of MV Passive Users to the Distributor's network, ABB offers the REF 601, CEI version (protections and trip curves complying with CEI 0-16, with thresholds that can be set in accordance with ENEL specification DK 5600). The available protection functions are:

- overcurrent protection (ANSI code 50 - 51), two-phase or three-phase depending on whether two or three current sensors are connected
- homopolar earth fault protection (ANSI code 50N - 51N) by means of the internal vector sum of the three phase sensors or by means of the external earth fault toroid and two or three current sensors
- detection of the magnetizing current of a three-phase transformer to prevent untimely tripping on switch-in (ANSI code 68).

The device can operate with up to 3 inputs from TA-NI current sensors of the Rogowsky coil type.

The current sensors are available in an integrated version with KEVCR24 OC2 circuit-breakers. If a homopolar sensor is required in the CEI 0-16 kit, the TO11S3 or TO21S3 models (110 mm or 210 mm hole) are provided.

The protections installed are:

- Protection against overload  $I >$  (51)
- Protection with delay against the multi-phase short circuit  $I >>$  (51)
- Instantaneous protection against the multi-phase short circuit  $I >>>$  (50)
- Protection against single-phase earth fault  $I_0 >$  (51N)
- Protection against single-phase double earth fault  $I_0 >>$  (50N)

Other important features of the REF 601, are:

- pushbuttons for the circuit-breaker's local switching operations (opening and closing pushbutton. The lateral operation mechanism is always supplied with a shunt opening release. Application of the shunt closing release must obviously be requested to operate the closing command via REF 601).
- 5 separate indicators: "relay operating", "relay at tripping threshold", "relay tripped", "relay tripped due to phase overcurrent", "relay tripped due to earth fault overcurrent"
- HMI consisting of an LCD display and "arrow", "enter" and "esc" keys for user-friendly browsing amongst the "measuring", "date recording", "event recording", "settings", "configuration" and "test" menus
- three User levels with different operations allowed and two passwords
- continuous display of the current in the most loaded phase and the earth current
- recording of the values of the currents that caused the device to trip
- storage of the number of openings caused by the device
- event recording (storage of the previously described parameters in the last 5 tripping actions of the device) in a non-volatile memory
- circuit-breaker opening by means of the undervoltage release (CEI 0-16 version)
- multi-voltage 24...240 V AC/DC power supply.

The REF601 can also be installed on board the switchgear. In this case the following kit of components is required:

- REF601
- TA-NI CEI 0-16 toroidal sensors to be mounted on a cable (KECA 250 B1)
- homopolar sensor TO CEI 0-16 TO11S3 or TO21S3
- power failure release.

If a more sophisticated general protection is required, the REF 542plus can be used. This device is extremely versatile and can be used for the protection of any type of load (line, transformer, motor, ...), it can perform functions of automation and control at the level of functional unit and the switchgear, and provides a graphical interface for viewing the state and commanding the circuit-breaker.

In the CEI 0-16 base version the device consists of:

- 1 110 V DC fixed voltage power supply
- 1 main board module
- 1 binary input output module (14 inputs, 8 outputs, 1 watchdog)
- 1 analog input module for 3 current sensors, 3 voltage sensors, 1 homopolar current sensor
- 1 HMI interface unit and cable for connection to the base unit
- 1 connection kit for wiring the unit inside the panel.



# 5. Protection relay

Given the great versatility, several additional configurations are available on request to meet every need.

The software configurations that can be downloaded to the device are of two types:

**Configuration A**, without directional earth protections. This configuration is suitable for simple installations, characterized by the absence of overhead lines, the limited extent of the cable lines and installation of all the MV/LV transformers in a single User room.

The protections installed are:

- Protection against overload  $I >$  (51)
- Protection with delay against the multi-phase short circuit  $I >>$  (51)
- Instantaneous protection against the multi-phase short circuit  $I >>>$  (50)
- Protection against single-phase earth fault  $I o >$  (51N)
- Protection against single-phase double earth fault  $I o >>$  (50N)
- Optionally, the undervoltage protection 27 for the disconnection of additional transformers.

Since directional protections are not required, voltage measurements are not necessary.

In this case, the KIT consists of the following:

- REF542plus unit
- 3 current sensors of the type KECA for measurement of the phase 1 currents
- 1 homopolar earth sensor of the type TO11S3 or TO21S3 for measuring the earth current.

**Configuration B**, with directional earth protections used in the other cases, again for Passive Users.

The protections installed are:

- Protection against overload  $I >$  (51)
- Protection with delay against the multi-phase short circuit  $I >>$  (51)
- Instantaneous protection against the multi-phase short circuit  $I >>>$  (50)
- Protection against single-phase earth fault  $I o >>$  (50N)
- Directional protection against earth faults for compensated neutral 67N NC
- Directional protection against earth faults for isolated neutral 67N NI
- Optionally, the undervoltage protection 27 for the disconnection of additional transformers.

The directional earth protections require measurement of the voltages for calculation of the residual voltage; in this case, therefore, combined voltage and current sensors (combisensors) are used in the kit. The KIT consists of the following:

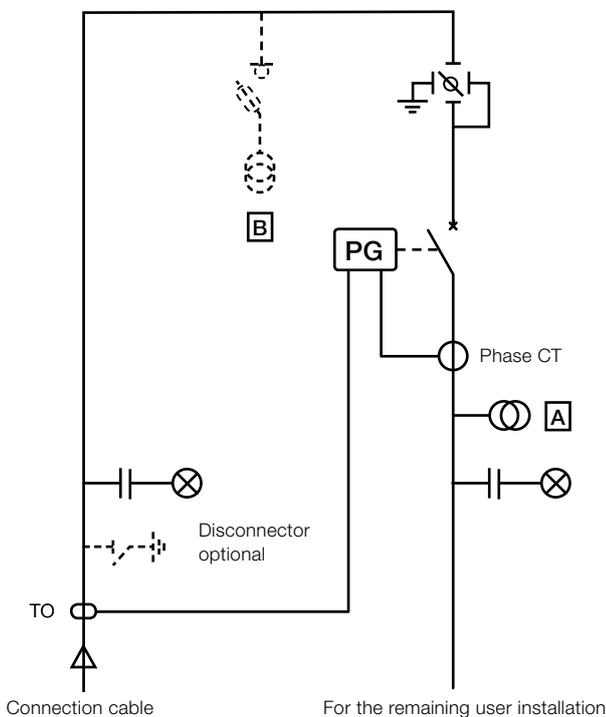
- REF542plus unit
- 3 combisensors of the type KEVCD 24 AE3 for the measurement of the phase currents and phase voltages.
- 1 homopolar earth sensor of the type TO11S3 or TO21S3 for measuring the earth current.

# 6. Diagram of user system for connection and MV switchgear

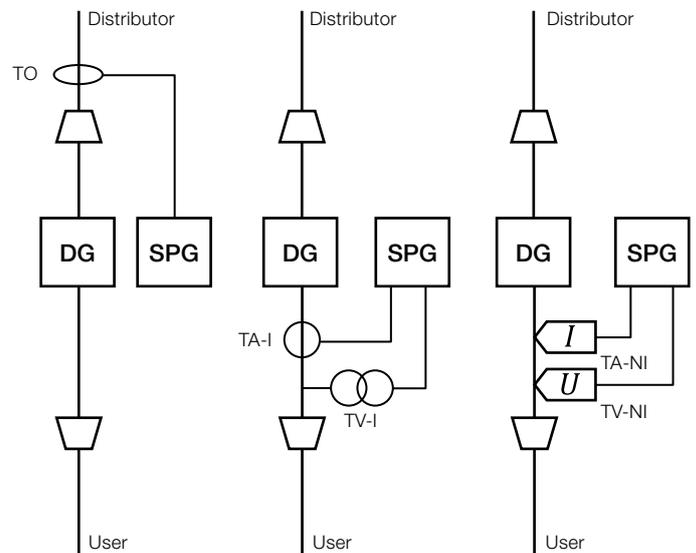
The MV switchgear must contain the previously described devices safely according to the product standard CEI EN 62271-200. The switchgear must be located in the User room of the electrical substation and is therefore one of the most important elements for the physical sizing of the structure. The configuration of the MV switchgear, in addition to containing the input of the connection cable and the DG, depends on the wiring diagram of the User installation.

## 6.1 Diagram of the user installation

The scheme to be adopted in general for the users for the MV switchgear immediately downstream of the connecting cable is shown in the following figure. Depending on the protections requirements, the scheme must be completed with a set of transformers/transducers that may be of the type TV-I or TV-NI.



The dashed VT branched on the busbar, indicated by B, is an alternative to the recommended solution indicated by A. As you can tell from the previous figure, the ideal positioning of the homopolar toroid TO is upstream of the DG; the ideal solution both for the inductive CTs and VTs and for the non-inductive transducers is to position them immediately downstream of the DG.

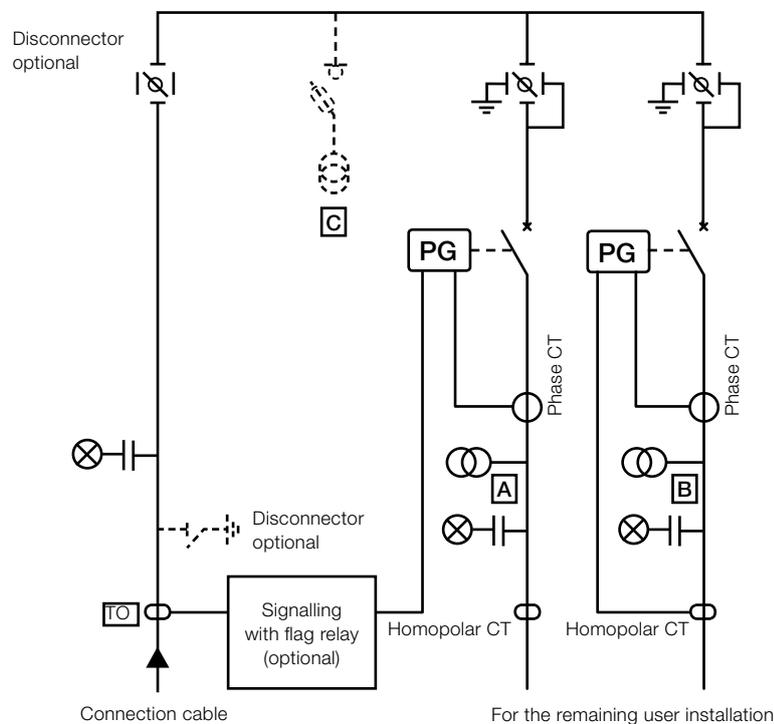


DG = General Device  
SPG = General Protection System

It is also allowed to position the TV-I upstream of the circuit-breaker or of the phase CTs, but in this case they must be protected, on the MV side, with an IMS combined with fuses ( $I_n \leq 6.3 \text{ A}$ ) to protect the primary of the TV-Is. It must be highlighted that the tripping of any primary fuses and/or protections of the secondary circuit must in any case cause the DG to open, or switching of the function of protection 67N (directional protection for earth faults) to 51N (homopolar overcurrent protection), keeping the same set values relating to homopolar current tripping thresholds, and restoring the 67N protection in the shortest possible time so as to avoid accidental tripping in the event of single-phase earth fault external to the User network. If instead the VTs are branched downstream of a DG and phase CT, there are no constraints on the primary protection of the actual VTs. Lastly, the TV-NIs do not require protection on the MV side.

# 6. Diagram of user system for connection and MV switchgear

The standard provides for a second case: in an MV installation with only two MV risers, it is possible to omit the General Device (DG) where the functions normally attributed to the DG are accomplished by the circuit-breakers joined to the User busbar (general line devices). As regards the connection cable, in such a configuration this cable is meant to terminate on the terminals of upstream of the first disconnector as shown in the following figure:



The dashed VT branched on the busbar, indicated by C, is an alternative to the solution indicated by A and B.

For this type of installation, the following conditions must be met:

- single MV switchgear (excluding open structures);
- no additional equipment apart from the two MV risers with circuit-breaker indicated.

In this case what was said about the first scheme about the position of the TV-Is also applies where necessary for the operation of the 67N protection.

In this second type, regarding the security function one must consider that the protections  $I>$ ,  $I>>$  of the User installation are implemented with the relays that equip all the riser devices, but requiring the sum of the thresholds for each

relay to respect the constraints imposed by the Distributor or summing the secondary signals of the phase CTs of the two risers.

The main disconnector (if installed) must be interlocked with the "open" position of both circuit breakers downstream, or otherwise must be a switch-disconnector.

The short-circuit protection ( $I >>>$ ) is instead normally set on the short-circuit fault current of each riser.

Caution! Where this solution is used with the two transformers in parallel on the LV side, in order to avoid having voltage on the MV side of a transformer due to the parallel connection on the LV, appropriate interlocks will be required between the MV and LV circuit-breakers of each transformer .



# 6. Diagram of user system for connection and MV switchgear

## 6.2 MV switchgear solutions



Now let's look at a real-world solution; in the first case examined in the previous paragraph, that is, incoming from the Distributor and a single transformer in the substation, we can see the ABB solution (Figure a) with UniSec switchgear consisting of:

- 1 HBC unit with HySec multifunction device + # 1 RLC cable entry unit to the left
- Voltage present on the busbar side and on the cable side
- HySec p230 multifunction device comprising:
  - Vacuum circuit-breaker with or without motorization
  - Disconnecter in SF<sub>6</sub>

- REF 601 protection relay without communication (51, I>; 51, I>>; 50, I>>>; 51N, I<>; 50N, I<>>,68) with 3 current sensors and toroid for earth fault, conforming to the Standard CEI 0-16
- Setup for earthing by means of insulating rod on the busbar side.

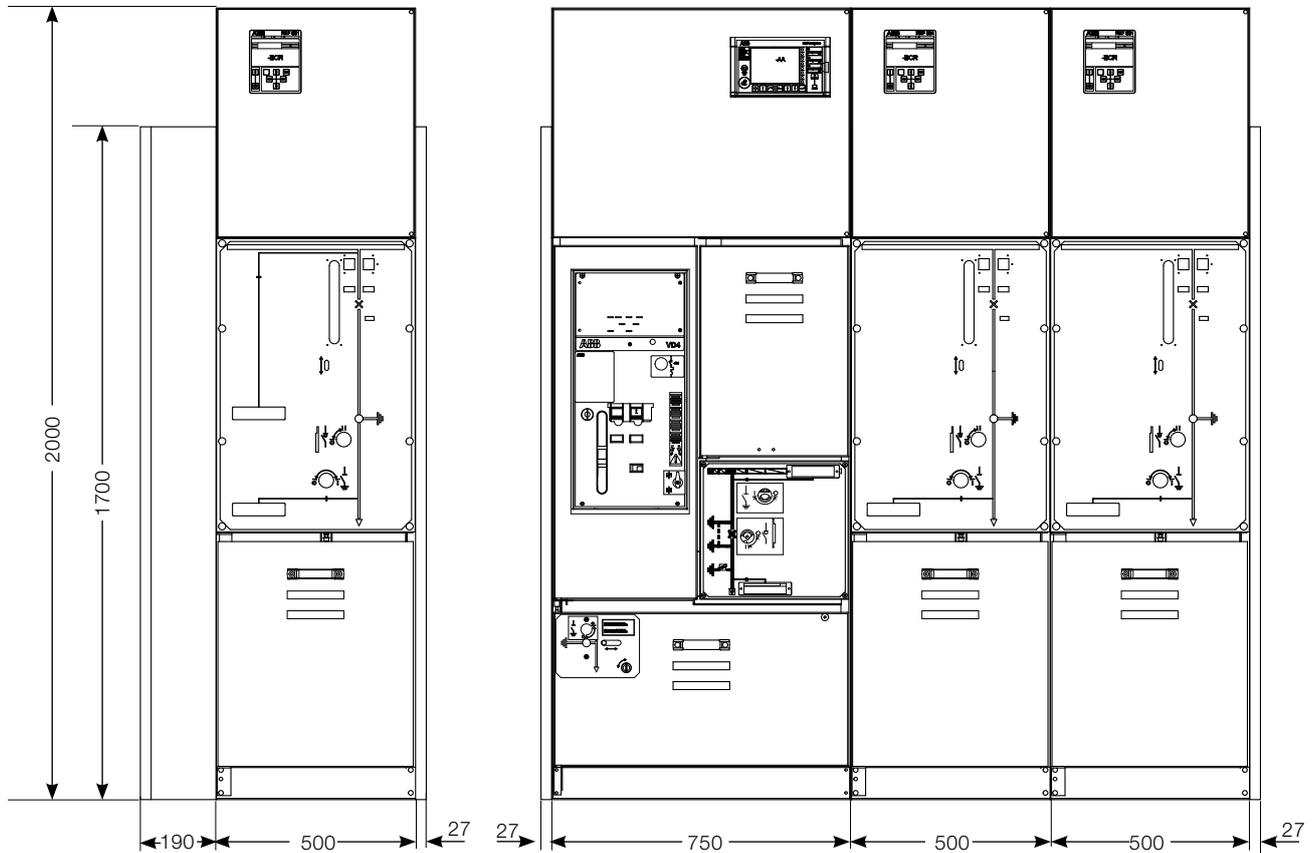


Figure a

Figure b

As regards the second case indicated by the standard, in the following example we consider UniSec switchgear (Figure b) comprising:

- 1 incoming line with SBR Unit (Incoming unit CEI 0-16)
- Voltage present on the busbar side and on the cable side
- VD4/R-Sec p230 circuit-breaker with or without motorization
- REF542plus protection and control unit (51, I>; 51, I>>; 50, I>>>; 51N, Io>; 50N, Io>>; 67NI; 67NC) with Data Logger and 3 ABB current/voltage sensors of the KEVCD type mounted inside the busbar compartment and toroid for earth faults conforming to Standard CEI 0-16
- GSEC disconnector
- Earthing switch with key on the Distributor side that is the responsibility of the Distributor, according to Standard CEI 0-16

2 Transformer protections with HBC Unit

- Presence of voltage on the cable side.
- HySec p230 multifunction switchgear consisting of:
  - Vacuum circuit-breaker with or without motorization
  - Disconnector in SF<sub>6</sub>
- REF 601 protection relay without communication (51, I>; 51, I>>; 50, I>>>; 51N, Io>; 50N, Io>>,68) with 3 current sensors and toroid for earth fault, conforming to the Standard.

# 7. Power transformers

## 7.1 Main characteristics

The transformer is the most important part of the transformer substation. The choice of transformer affects the design of the substation and is made on the basis of several factors, primarily:

- Characteristics of the User installation
- Level of continuity of service required
- Location of the electrical substation

Some important characteristics must therefore be considered and defined according to the product standard CEI EN 60076:

- Type of transformer, for example with  $n$  separate windings or autotransformer, etc.
- Single-phase or three-phase
- Frequency
- Dry or in insulating liquid, and in the latter case what kind of liquid (oil, natural or synthetic liquid, etc.)
- For internal or external

- Rated power for each winding
- Nominal voltage for each winding (and therefore the transformation ratio)
- Type of cooling
- Presence of load or no-load tap-changer
- Earthing connections and method for each winding

Other data will have to be defined or clarified with the manufacturer:

- short circuit voltage percentage  $U_{cc}\%$
- no-load current percentage  $I_0\%$
- losses in the copper at rated current  $P_{cu}$  and losses in the iron at nominal voltage  $P_{fe}$
- no-load current
- CEI connection assembly, conventionally indicated by a number that, when multiplied by 30, gives the value of the phase voltage delay angle on the LV side compared with the MV side.



Depending on the type of cooling the transformers are identified as follows:

- AN** cooling with natural air circulation;
- AF** cooling with forced air circulation;
- ONAN** cooling with natural circulation of oil and air;
- ONAF** cooling natural circulation of oil and forced circulation of air;
- OFAF** cooling with forced circulation of oil and air.

The most frequently chosen types are AN and ONAN because since the substations are never manned, it is not recommended to use machines that use fans or oil circulators.

On the other hand, the Distributor, when requesting connection, must specify the limit for the maximum power of a single transformer or several transformers in parallel on the same LV busbar referring to the typical short-circuit voltages specified in Standard CEI EN 60076-5 (UDC = 6% for transformers with rated power greater than 630 kVA), that the User can install in his own system in order to avoid the tripping of the overcurrent protection installed on the MV line that powers it in the event of a short circuit on the LV transformer busbars.

This limit on maximum power (specified by the Distributor) is normally 2000 kVA (20 kV networks) and 1600 kVA (15 kV networks).

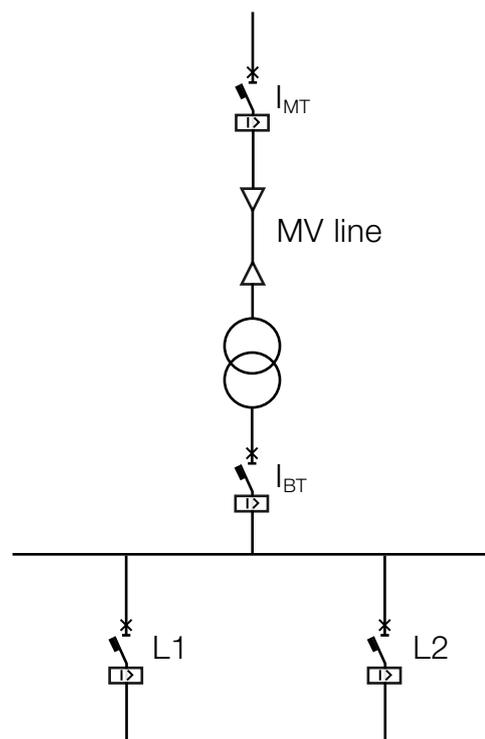
It is normally required that the customer should use MV/LV transformers with:

- **delta primary, ( $\Delta$ )** since with this type of connection the third harmonics of the magnetizing current (distorted by the non-linearity of the magnetic circuit) and any homopolar load currents are free to circulate in the sides in the triangle without flowing into the network; the magnetic flows remain sinusoidal and consequently also the EMFs induced on the secondary. Furthermore, if there are unbalanced loads on the secondary, the reaction current retrieved on the primary will circulate only in the corresponding winding without affecting the other two; if this happened, as in a star connection, the currents in these windings would be magnetizing and would cause asymmetry in the phase voltages. Only when special applications (welding machines, actuators, etc.) are supported, the connection might not be triangular, agreeing on the choice with the Distributor.
- **earthed star secondary, ( $Y_{\text{TE}}$ )** to make phase-to-phase voltages and phase voltages easily available, but above all for reasons of safety, since in the event of a fault between the medium and low voltage, the voltage delivered to the secondary will remain close to the phase value, thus guaranteeing greater safety for persons and preserving insulation.

The transformer is connected to the sampling point of the delivery room through the MV switchgear and the copper connection cable, which must have a minimum cross section of 95mm<sup>2</sup> regardless of the power supplied. This cable is the property of the User and must be as short as possible (maximum 20 m including terminations). If the delivery and User rooms are not adjacent or actually in separate structures, it is allowed to derogate from this requirement as long as a single-length cable is used with additional mechanical protection (see Standard CEI 11-17) but with the prior consent of the Distributor.

In general, the choice of the number of transformers to be installed depends on installation considerations on the reliability and flexibility required in using electrical energy. It can be stated that for the request of small power installations (indicatively up to 630kVA - 800kVA), a single transformer can be installed, whereas for higher power (indicatively up to 1000kVA - 2000kVA) it is convenient to split the power over multiple units in parallel.

From an installation point of view, the simplest substation will have only one MV/LV transformer; this solution is simple and economic, but not flexible because the downtime or maintenance on a component requires disconnection of the entire system.



# 7. Power transformers

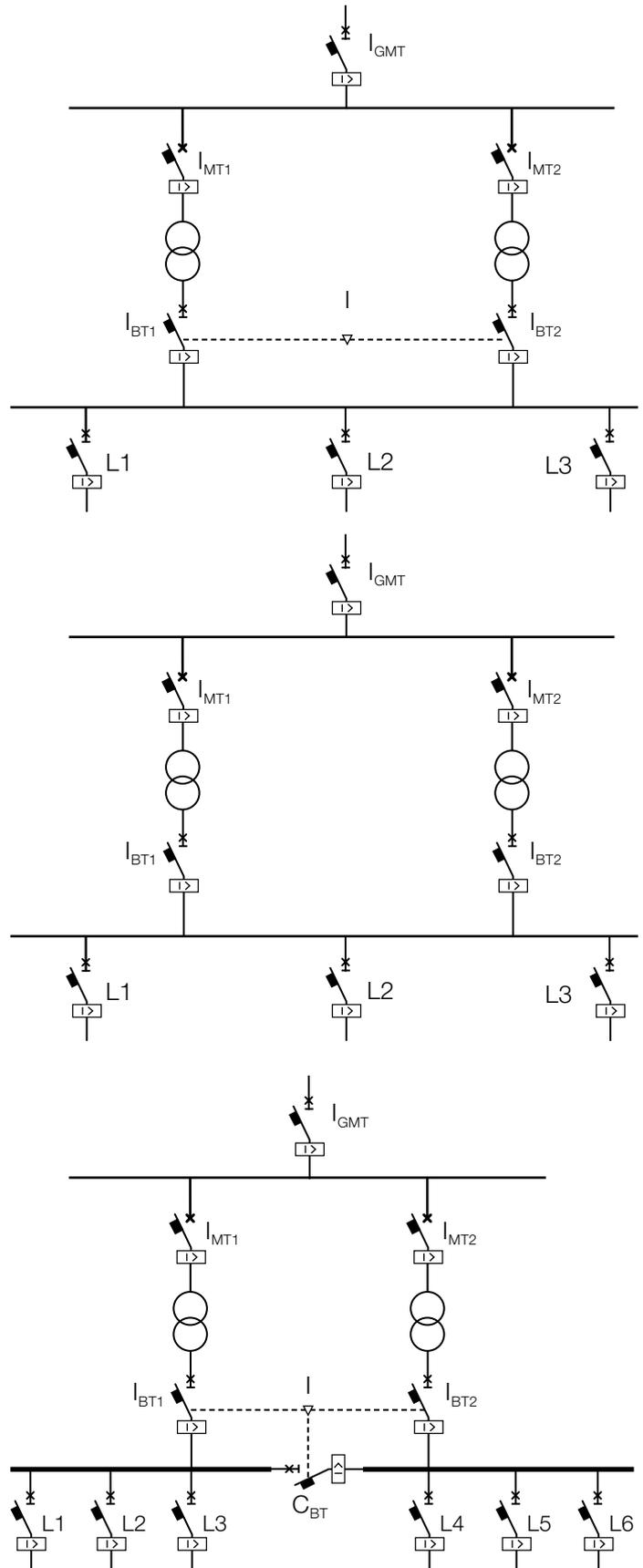
If the continuity of service required justifies it, a more expensive but more flexible solution consists in having a second transformer as a backup to the first one.

In this case the two LV circuit-breakers are interlocked to prevent operation in parallel. Obviously, in addition to the switching and disconnect device on the incoming MV line it is convenient to also provide a switching, disconnection and protection device on the individual MV risers of the two transformers ( $I_{MT1}$  e  $I_{MT2}$ ).

In this way when the device upstream and downstream of a transformer is opened it is possible to guarantee isolation and to access the machine without putting the entire substation out of service.

A further possibility, again where the aggregate power of 2000 kVA at 20kV and 1600 kVA at 15 kV is not exceeded, it is that of managing the two transformers in parallel. The parallel operation of the transformers generates greater problems in network management. In fact, the outage of a machine might require a certain flexibility in load management, ensuring that power is supplied to those considered a priority through appropriate automation. This solution is simple, relatively cheap and flexible.

Finally, the last feasible configuration is also the one that offers the most flexibility. Its primary use is in installations that require high continuity of service. Maintenance of the transformer risers and portions of the installation is possible while continuing to operate the remaining portion. From a cost perspective, in addition to the second transformer a coupler has to be inserted in the LV switchgear for parallel management. If the system is to operate with the coupler closed, the limits imposed by the Distributor must be respected; conversely, an appropriate interlock must be introduced that will prevent the coupler from being closed when both incoming circuit-breakers from the transformer are closed in order to avoid the parallel operation in question. This mode of management, for the same power of the installed transformers, makes it possible to have a lower value for the short-circuit current on the busbar. In other words, each transformer establishes the short-circuit level for its corresponding busbar without having to consider



the contribution of other machines. Again in this case, with a transformer out of service, with the possible closure of the coupler, it changes over to a system with a single busbar powered only by the healthy transformer, and load management logic must be provided with disconnection of non-priority loads.

In the case of several transformers in parallel, we must consider the limits imposed by the Standard CEI 0-16 and deal with in CEI Guide 99-4 on simultaneous energization of the transformers installed.

To meet this requirement, the User may not install transformers with a total capacity of more than three times the power limits previously indicated for each voltage level, even with separate LV busbars. Where the installed power is higher than the specified limit, appropriate devices must be provided in the User's installation in order to avoid the simultaneous energization of those transformers that would result in the above limitations being exceeded. These devices must trip in the case of a power outage exceeding 5 s and re-energize the transformers according to the overall quantities not exceeding the limits determined above, with re-entry times at an interval of at least 1 s.

CEI Guide 99-4, Annex F, provides guidelines for evaluation of the peak value of the inrush current of transformers in oil and the minimum delay time necessary to prevent unwanted tripping of protection:

In practice, the table gives the ratio  $K_i$  between the rated current of the transformer ( $i_{oi}$ ) and the maximum peak value of the inrush current ( $I_{Tn}$ ) based on the power of the transformer and the time constant  $T_i$  of the inrush current. In the graph, however, we find the setting of the MV overcurrent relay on the primary of the transformer in order to avoid it tripping on power-up; the curve separates the field of possible tripping of the relay (on the left of the curve) from that certain non-tripping (on the right of the curve), where:

$t_r$  = delay time setting

$I'_r$  = setting of the threshold in current (primary value).

To understand how to use the table and the graph, we also provide the following example:

Transformer data: 800 kVA; 15 kV;  $I_{Tn} = 30.8$  A

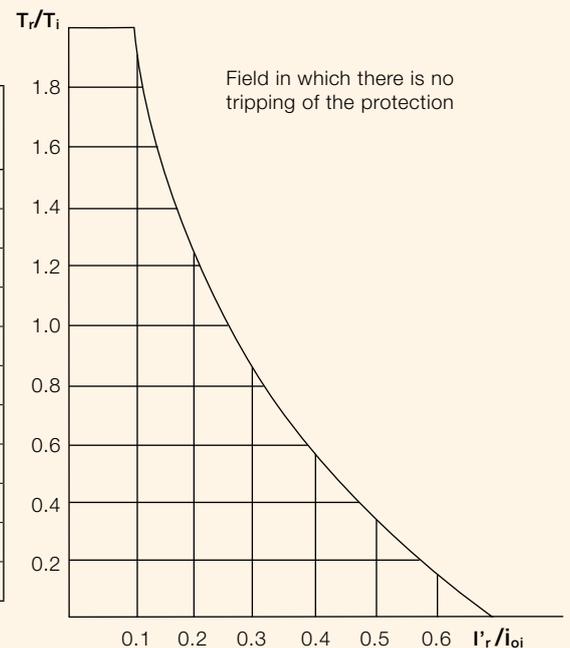
In the table we find:

$K_i = 10$ ;  $i_{oi} = 10 * 30.8 = 308$  A;  $T_i = 0.3$  s.

Assuming  $I'_r = 50$  A we get  $I'_r/i_{oi} = 50 / 308 = 0.16$

Finally, at this value on the curve we find  $t_r/T_i = 1.45$ , in other words  $t_r = 1.45 * 0.3 = 0.44$  s, which is the minimum delay time to avoid unwanted tripping.

Transformer power rating $S_r$ (kVA)	Primary rated current $i_r$ (A)		$K_i$	Time constant $T_i$ (s)
	15 kV	20 kV		
50	1.9	1.4	15	0.10
100	3.8	2.9	14	0.15
160	6.2	4.6	12	0.20
250	9.6	7.2	12	0.22
400	15.4	11.5	12	0.25
630	24.2	18.2	11	0.30
800	30.8	23.1	10	0.30
1000	38.5	28.9	10	0.35
1250	48.1	36.1	9	0.35
1600	61.6	46.2	9	0.40
2000	77.0	57.7	8	0.45



# 7. Power transformers

## 7.2 Selection of transformers on the basis of losses and energy efficiency

The requirements of the EU MEPS (European Minimum Energy Performance Standards, i.e. the minimum European requirements for energy efficiency) establish the minimum compulsory efficiency level for all transformers placed on the European market. They were introduced in accordance with Directive 2009/125 /EC of the European Parliament and the Commission, also known as the EcoDesign Directive, which establishing a reference framework for the producing specifications for the eco-compatible design of energy-related products (ERP). As part of ERPs, transformers have been identified as one of the priority product groups because of their considerable potential in terms of energy savings. Total annual losses produced by the currently installed transformers within the 28 EU member states amount in fact to about 100 TWh, equivalent to 40 million tonnes (Mt) of CO<sub>2</sub> emissions.

To implement the Directive in the area of transformers, the European Commission adopted, as a legal reference framework, regulation no. 548/2014 that sets the minimum efficiency requirements applicable to transformers. The purpose of the regulation is to prevent inefficient products from being introduced to the European market. The regulation is binding in its entirety and directly applicable in all 28 Member States of the EU. EU MEPS requirements apply to distribution transformers, of both the dry type and those immersed in a liquid, as well as power transformers with a minimum rated power of at least 1 kVA, used in networks for the transport and distribution of electricity or for industrial applications. As of 1 July 2015, transformers that do not comply with the regulation can no longer be marketed in Europe. It is the responsibility, above all of the manufacturer, to make sure that the transformers conform to the regulations. The manufacture or importation into the European market of non-compliant transformers has been illegal since 1 July 2015. However, especially during the transition period, it may be advisable to refer to the regulation as regards the minimum level of efficiency required.

The European Commission has also provided that from 1 July 2021 all transformers must comply with the efficiency requirements specified the “Phase 2” level of the regulation, which are more stringent. The Commission also plans to undertake, at the latest in the 2017, an “interim” assessment of the regulation during which levels the the requirements established for “Phase 2” will be reviewed and may be changed.

## 7.3 Efficiency requirements and classes for transformers

The maximum permitted levels of losses for transformers with maximum rated power not exceeding 3150 kVA are based on the classification of the Standards CEI EN 50464-1:2007 and subsequent variant /A1:2012 and CEI EN 50541-1:2011. It should be emphasized that the above EN standards are undergoing unification and revision in order to support the regulation more directly. Efficiency classes lower than those specified in the EU MEPS regulation will disappear completely. For medium/low voltage transformers in oil, the Standard CEI EN 50464-1 provides 4 loss class due to the load and 5 no-load loss classes.

The two following tables show the values prescribed for losses due to the load  $P_k$  and the no-load losses  $P_0$  for transformers with rated voltages up to 24 kV.

Losses due to the load ( $P_k$ )

Power rating voltage	$C_k$	$B_k$	$A_k$	Short-circuit impedance
KVA	W	W	W	%
50	1100	875	750	4
100	1750	1475	1250	
160	2350	2000	1700	
250	3250	2750	2350	
315	3900	3250	2800	
400	4600	3850	3250	
500	5500	4600	3900	
630	6500	5400	4600	6
630	6750	5600	4800	
800	8400	7000	6000	
1000	10500	9000	7600	
1250	13500	11000	9500	
1600	17000	14000	12000	
2000	21000	18000	15000	
2500	26500	22000	18500	

No-load losses ( $P_o$ )

Power rating voltage	$D_o$		$C_o$		$B_o$		$A_o$		Short-circuit impedance
	$P_o$ W	$L_{WA}$ dB(A)	$P_o$ W	$L_{WA}$ dB(A)	$P_o$ W	$L_{WA}$ dB(A)	$P_o$ W	$L_{WA}$ dB(A)	
kVA									%
50	145	50	125	47	110	42	90	39	4
100	260	54	210	49	180	44	145	41	
160	375	57	300	52	260	47	210	44	
250	530	60	425	55	360	50	300	47	
315	630	61	520	57	440	52	360	49	
400	750	63	610	58	520	53	430	50	
500	880	64	720	59	610	54	510	51	
630	1 030	65	860	60	730	55	600	52	
630	940	65	800	60	680	55	560	52	
800	1150	66	930	61	800	56	650	53	
1000	1400	68	1100	63	940	58	770	55	6
1250	1750	69	1350	64	1150	59	950	56	
1600	2200	71	1700	66	1450	61	1200	58	
2000	2700	73	2100	68	1800	63	1450	60	
2500	3200	76	2500	71	2150	66	1750	63	

In the Standard CEI EN 50541-1 instead, we find a similar table for dry-type transformers with rates voltages of 17.5 and 24 kV and short-circuit impedance of 6%:

$U_m$	$S_r$	$P_k$	$P_k$	$P_o$	$L_{WA}$	$P_o$	$L_{WA}$	$P_o$	$L_{WA}$
		$A_k$	$B_k$	$A_o$	dB (A)	$B_o$	dB (A)	$C_o$	dB (A)
kV	kVA	W	W	W	dB (A)	W	dB (A)	W	dB (A)
17.5 and 24	100	1800	2050	280	51	340	51	460	59
	160	2600	2900	400	54	480	54	650	62
	250	3400	3800	520	57	650	57	880	65
	400	4500	5500	750	60	940	60	1200	68
	630	7100	7600	1100	62	1250	62	1650	70
	800	8000	9400	1300	64	1500	64	2000	72
	1000	9000	11000	1550	65	1800	65	2300	73
	1250	11000	13000	1800	67	2100	67	2800	75
	1600	13000	16000	2200	68	2400	68	3100	76
	2000	16000	18000	2600	70	3000	70	4000	78
	2500	19000	23000	3100	71	3600	71	5000	81
3150	22000	28000	3800	74	4300	74	6000	83	

# 7. Power transformers

Returning to the EU MEPS requirements, the classes indicated for distribution transformers immersed in liquid with  $U_m \leq 24$  kV are as follows according to the specifications for the two phases:

	Phase 1	Phase 2
25–1000 kVA	C <sub>k</sub> , A <sub>0</sub>	A <sub>k</sub> , A <sub>0</sub> -10%
1001–3150 kVA	B <sub>k</sub> , A <sub>0</sub>	A <sub>k</sub> , A <sub>0</sub> -10%

On the other hand, for dry type transformers, again with  $U_m \leq 24$  kV, we have:

	Phase 1	Phase 2
25–630 kVA	B <sub>k</sub> , A <sub>0</sub>	A <sub>k</sub> , A <sub>0</sub> -10%
631–3150 kVA	A <sub>k</sub> , A <sub>0</sub>	A <sub>k</sub> , A <sub>0</sub> -10%

From 1 July 2015, the operating data plate for transformers that are within the scope of the regulation must necessarily include the following information on the product, in addition to those required under the standard EN 60076-1:

- Values and name of the load loss and no-load loss classes for transformers  $\leq 3150$  kVA
- information on the weight of all the main components of a transformer (including at least the conductor, its type and the base material)

Type		TNOSCT-100/11PNS UNI	
No.	1LPL525913	Year of manufacture	2014
Rated power	100 kV-A	No. of phases	3
TRANSFORMER to specification EN (IEC) 60076-1			
Rated voltage [V]	Current [A]	Insulation level	
HV 11000 ± 2x2.5%	5.25	LI75 AC28	
LV 415	139.10	AC3	
Tap no.	HV voltage [V]	Connection symbol	Dyn11
1	11550	Cooling	ONAN
2	11275	Rated frequency	50 Hz
3	11000	Short-circuit imp.	3.88 %
4	10725	Load losses	1750 W
5	10450	No-load losses	145 W
Ambient temp. 40°C		Total mass	463 kg
*Temperature rise of.		Mass of active part	279 kg
Windings	60K	Mass of oil	100 kg
Oil	55K	Type of oil	Mineral Nyro Taurus
		Oil to	IEC 60296
Windings material HV/LV: Al/Al		Core material: grain-oriented electrical steel	
Mass of windings: 53kg		Mass of core: 169kg	

As can be deduced from the values shown in the tables of losses, values obviously resulting from different construction characteristics, the oil transformers have lower no-load losses than the dry type transformers and comparable load losses. It follows that, in choosing the transformer, one must take into account the type of operation for which it is intended: if the prevalent use is with low loads or even no load, an oil transformer is preferable; otherwise, you can use a dry transformer with reduced losses.

## 7.4 Selection criteria for transformers based on capitalization of the losses

Both CEI 99-4 and CEI EN 50464-1 deal with the choice of transformers based on capitalization of losses, an indication of how important this parameter is in the selection process. This method, in fact, allows an economic valuation of the cost of the machines basing it on the losses and therefore considering real-world operation; the formula used is of the type:

$$C_c = C_T + A P_0 + B P_k$$

Where:

$C_c$  cost capitalized;

$C_T$  price at offer;

A monetary value by W no-load losses;

$P_0$  no-load losses guaranteed in W;

B monetary value by W of load losses;

$P_k$  losses due to the load in W.

In assessing the purchase of the transformer, it is worthwhile considering not only the initial cost but also the cost capitalized over a given number of years of operation, in order to take account of losses.

The result of the analysis may in fact show that it is more economical to purchase a transformer with reduced losses even if it is more expensive than one with higher losses but cheaper.

## 7.5 Example of a transformer for a transformer substation

The location of the substation can be a deciding factor in the choice of the transformer; in electrical substations located in public buildings or with high presence of persons such as shopping centers, hospitals or sports facilities, it may be necessary to minimize the risk of fire and therefore to recommend the installation of dry type transformers in class F1 with minimum flammability and smoke emission.

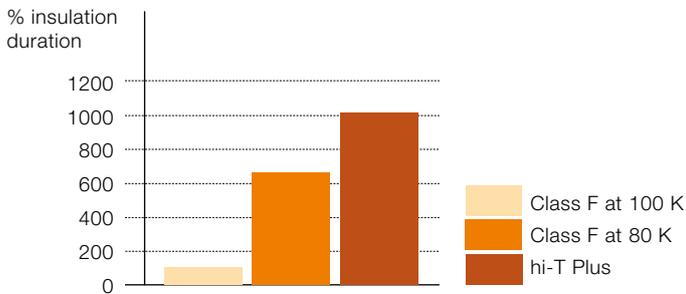
An excellent solution for the the above-mentioned electrical substations might be the ABB hi-T Plus dry transformers encased in resin. These transformers are in class H (the highest with reference to IEC 60076-11) but instead of reaching the maximum temperature of the hottest point allowed by the standard of 180 °C, they are designed to reach a lower temperature, a maximum of 155 °C.

This leads to enormous advantages in terms of duration of insulation and/or possibility of overload (according to IEC 60076-12). In fact, thanks to these 25 K of difference in ABB hi-T Plus transformers the expected average life of the insulation is more than ten times higher than that of a standard class F transformer working at the same temperature of the hottest point, and is almost double that of larger, more expensive class F transformers with an overtemperature limited to 80 K.



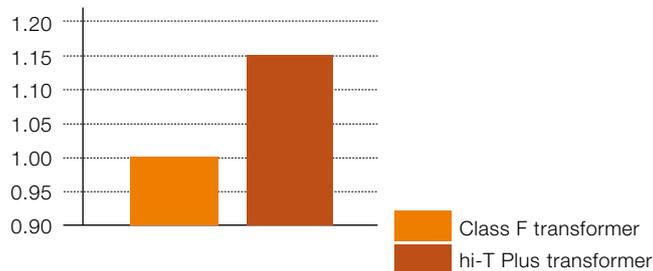
# 7. Power transformers

Expected duration of the insulation, assuming that  $F_{100K} = 100\%$



Alternatively, these transformers can be permanently overloaded up to 115% of the rated load, without this having any negative impact on duration. During this overload the maximum temperature of the hot spot would reach 180 °C in accordance with the Standard IEC EN 60076-12.

Overload



Such superior insulation performance makes ABB hi-T Plus transformers the ideal solution for networks with a high level of harmonic distortion, load peaks, sudden overloads and high ambient temperatures.

The hi-T Plus transformers also combine extremely reduced loss values  $A_0A_k$ , and therefore lower losses according to the Standard CEI EN 50464-1 and in full accordance with the MEPS European Regulation, which allow the cost of losses to be reduced.

To understand the benefits of a hi-T Plus transformer and a normal dry transformer, we apply the loss capitalization method already discussed and proposed by the Standard CEI 99-4.

We hypothesize that with a load of 1100 kVA, thanks to the overload capacity, it is possible to choose a 100 kVA hi-T Plus transformer instead of a normal 1250 kVA transformer:

- Hi-T Plus transformer with reduced losses with  $P_0 = 1550$  W ( $A_0$ ) and  $P_k = 9000$  W ( $A_k$ )
- Dry transformer with normal losses with  $P_0 = 2800$  W ( $C_0$ ) and  $P_k = 13000$  W ( $B_k$ )

The following calculations can be made.

Assuming that the transformer has a load of 60% power for 16 hours a day for 230 working days and 10% in the remaining 8 hours, while during the 135 non-working days it is 10% for all 24 hours, with the reduced loss transformer we will have the following annual losses:

$$P_0 = 365 \times 24 \times 1.55 = 13578 \text{ kWh};$$

$$P_k = 230 \times 16 \times 0.6 \times 0.6 \times 9.0 = 11923 \text{ kWh};$$

$$P_k = 230 \times 8 \times 0.1 \times 0.1 \times 9.0 = 165 \text{ kWh};$$

$$P_k = 135 \times 24 \times 0.1 \times 0.1 \times 9.0 = 292 \text{ kWh}.$$

In total there will be about 25958 kWh of losses.

On the other hand, with the dry transformer with normal losses annual losses will be as follows:

$$P_0 = 365 \times 24 \times 2.80 = 24528 \text{ kWh};$$

$$P_k = 230 \times 16 \times 0.6 \times 0.6 \times 13.0 = 17222 \text{ kWh};$$

$$P_k = 230 \times 8 \times 0.1 \times 0.1 \times 13.0 = 239 \text{ kWh};$$

$$P_k = 135 \times 24 \times 0.1 \times 0.1 \times 13.0 = 421 \text{ kWh}.$$

In total there will be about 42410 kWh of losses.

Then if we want to evaluate the cost of the losses over a period of use of 10 years, and assuming that the average cost of energy per time slot are:

$$A = 0.098 \text{ €/kWh and } B = 0.13 \text{ €/kWh},$$

the following values are obtained:

Hi-T Plus transformed with reduced losses:

$$A \times P_0 = 13578 \times 0.098 \times 10 = 13306 \text{ €}$$

$$B \times P_k = 12380 \times 0.13 \times 10 = 16094 \text{ €}$$

Total cost of losses equal to approximately 29400 €.

Dry transformer with normal losses:

$$A \times P_0 = 24528 \times 0.098 \times 10 = 24037 \text{ €}$$

$$B \times P_k = 17882 \times 0.13 \times 10 = 23247 \text{ €}$$

Total cost of losses equal to approximately 47285 €.

The saving calculated is therefore 17884 € in 10 years.

The low-loss transformer has a higher purchase cost, but this saving the payback time would be very short, probably less than 2 years.

## 7.6 Level of noise in the transformers

In the choice of equipment and components one must take account of the noise transmitted into the environment inside and outside the substation. The Standard CEI 99-4 recommends that the noise level should be compatible with the characteristics of the installation environment and with the applicable regulations.

In transformer substations the main source of noise is the transformers themselves. The limits of the sound power level (dB) emitted are set by the Standards CEI EN 50464-1:2007 and CEI EN 50541-1:2011. The same tables used for the load and no-load losses also specify the sound power levels  $L_{WA}$  expressed in dB.

## 7.7 Losses in the substation

To determine the necessary air flow and the section of the openings for ventilation, one must know the total amount of overall heat produced by losses in the substation.

As long as the heat produced is not equal to the heat dispersed outside through the ventilation system (thermal regime) the internal temperature will increase. The component that produces the greatest losses is the transformer; we can therefore use some simplified methods, adding an estimate of the losses of the other components to the losses of the transformer.

Standard CEI 99-4 suggests three:

- consider additional losses as equal to about 10% to 15% of the total losses of the transformer
- consider for the additional losses values per  $m^2$  of the surface of the substation (typical values around  $100 \text{ W/m}^2 \div 200 \text{ W/m}^2$ )
- consider the losses of the components provided by the manufacturers and estimate a value for the cable losses.

# 8. LV Switchgear and Systems

## 8.1 Connection of the transformer and the LV switchgear

Normally the connection between the MV/LV transformer and the LV switchgear in the substation is made in the busbar duct. The busbar duct is a viable alternative to a cable connection as it is very compact at high currents compared to the cable solution and connects naturally both to the LV terminals of the (see the figure) on one side, and to the busbars of the LV switchgear on the other end. In addition, busbar ducts have the advantage of having electrical and mechanical characteristics that are already defined and factory tested by the manufacturer and of reducing the risk of fire compared to the use of cables. Not least, busbar ducts are cheaper than cables for high currents.



## 8.2 LV switchgear

Low voltage switchgear, installed downstream of the MV/LV power transformers, are equipped with the main incoming circuit-breaker (open or moulded case) and with a number of circuit-breakers for startups with electrical characteristics (rated voltage, rated current, breaking capacity), in a number and configuration that depend on the electrical installation to be powered.

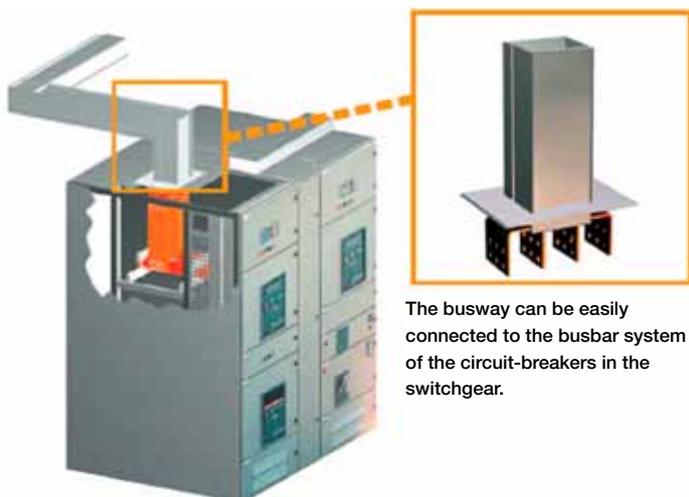
Therefore we will not go into the details of this key component of the substation.

The reference standard for LV switchgear is CEI 61439-1, which is the base standard, followed by all the sub-standards of the 61439 family (6 in total):

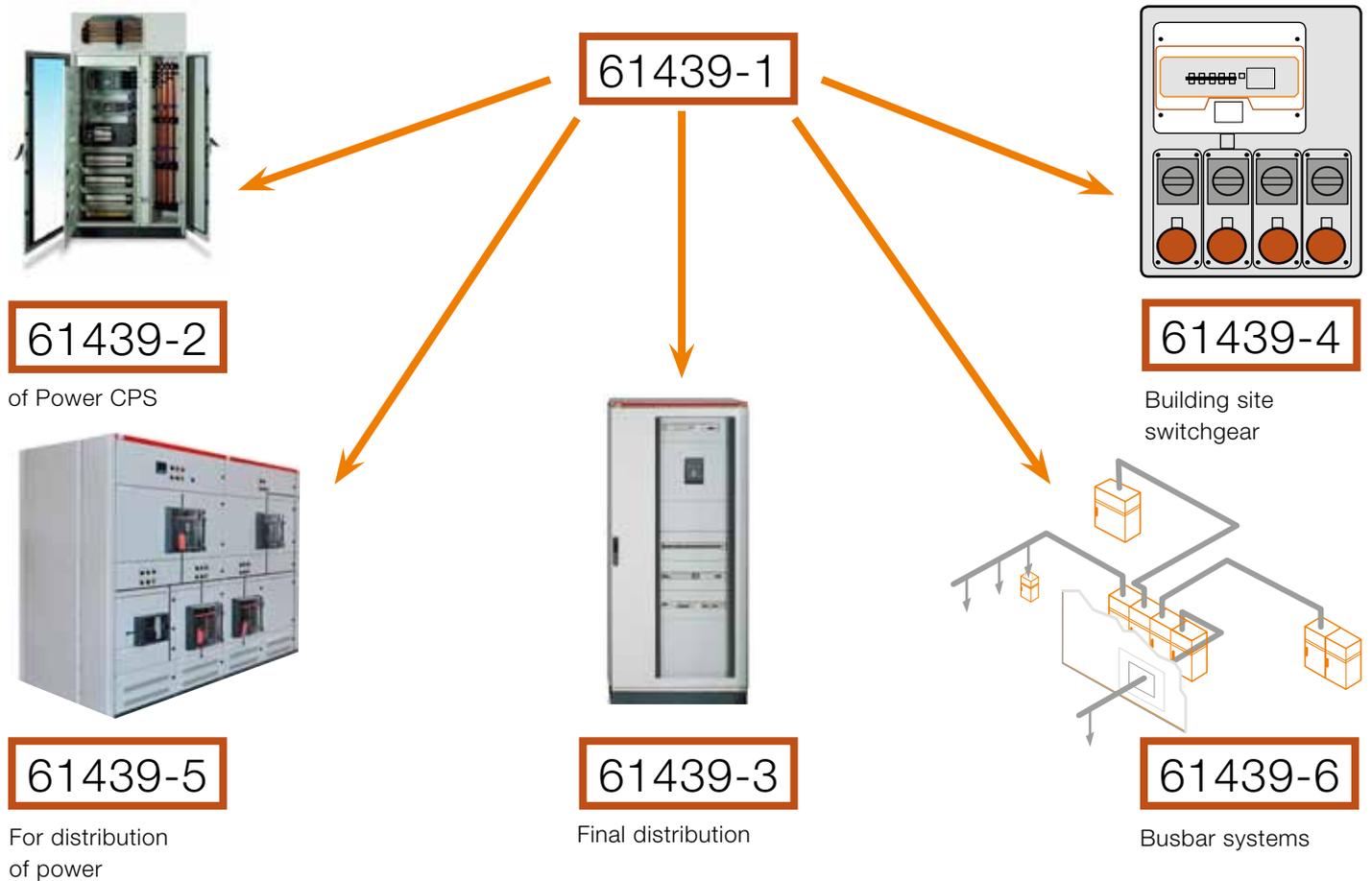
- 1) CEI 61439-1: "Assembled protection and switching equipment for low voltage (LV switchgear ) Part 1: "General rules"
- 2) CEI EN 61439-2: "Power switchgear"
- 3) CEI EN 61439-3: "Distribution switchgear"
- 4) CEI EN 61439-4: "Switchgear for building sites"
- 5) CEI EN 61439-5: "Switchgear for power distribution"
- 6) CEI EN 61439-6: "Busbar duct systems"

The base standard establishes the requirements for the construction, safety and maintenance of electrical switchgear by identifying the rated characteristics, environmental conditions of service, mechanical and electrical requirements and requirements regarding performance

In addition, for protections against direct contact and indirect contact, the requirements of Standard CEI 64-8 apply.



The busway can be easily connected to the busbar system of the circuit-breakers in the switchgear.



The following figure shows examples of Power Centers implemented with ABB switchgear of the ArTù K type and ABB circuit-breakers (System Pro M modular circuit-breakers, Tmax moulded case circuit-breakers T series T and XT series,

and Emax air circuit-breakers) with an optimal and certified level of integration. Key elements to consider in the design of the substation are the dimensions of the switchgear for sizing the User room and dissipation for the calculation of natural or forced ventilation.



# 9. Prefabricated substations

The reference standard for these products is the Standard CEI EN 62271-202. Prefabricated substations contain all the electrical equipment necessary for the operation of the substation: the transformer, the MV and LV switchgear, the connections and all the auxiliaries. Since these substations are often located in areas accessible to the public, the law prescribes specific tests to ensure the protection of persons against an internal arc. In particular, three classes are specified for the internal arc according to accessibility: class IAC-A for substations that guarantee protection to operating personnel inside or outside the substation; class IAC-B for substations that guarantee protection to the public on all sides; lastly, class IAC-AB for substations that guarantee protection to both, operators and the public. In versions accessible inside, in combination with the UniSec switchgear for secondary distribution, ABB CSS (Compact Secondary Substations) prefabricated substations can guarantee class IAC-AB up to 20 kA for 1 s and therefore, in addition to internal safety for authorised operators, also external safety for operators and the public, according to both CEI EN 62271-202 and to CEI EN 62271-200 regarding the switchgear.

Regarding the operating conditions, the standard requires the class of the structure to be defined based on the rated maximum power of the prefabricated substation. There is, in fact, an increase in the temperature of the transformer, greater than the overtemperature in free air, which depends on the characteristics of the structure as well as on the conditions of service. The class then defines the overtemperature  $\Delta t$  that occurs on the transformer during operation in the substation in K:

Class 5:  $\Delta t \leq 5$  K, Class 10:  $\Delta t \leq 10$  K, Class 15:  $\Delta t \leq 15$  K, Class 20:  $\Delta t \leq 20$  K, Class 25:  $\Delta t \leq 25$  K, Class 30:  $\Delta t \leq 30$  K.

Take, for example, the hi-T Plus transformer in insulation class H and therefore with a maximum temperature that can be reached equal to 180 °C. The Standard CEI EN 62271-202 provides the following chart to determine the load factor of the transformer as a function of the nominal class of the substation and of the average ambient temperature in a given period of time. We will assume the following environmental conditions:

Average ambient temperature during the year of 10 °C, in particular the average ambient temperature during the winter is 0 °C and the average ambient temperature during the summer is 20 °C.



Consider a 630 kVA transformer with average load during the year of 600 kVA.

Using figure DD.7 of the Standard, for a temperature of 10 °C and with a load factor of 0.95, we find that we must ask the manufacturer for class 25.

Considering the worst situation, however, namely the summer average temperature of 20 °C and with the same load factor, you will need to request class 15.

The metal reinforcement with which the substation is equipped implements a homogeneous equipotential earthing mesh throughout the structure, which subsequently connected to the earthing system protects the internal equipment against atmospheric overvoltages and limits the effects of step and contact voltages to negligible values. The whole structure is entirely assembled and tested with electrical equipment in the factory and is ready to be located at the site for subsequent commissioning. Installation activities are therefore limited to the cable connections between the various substations and distribution switchgear.

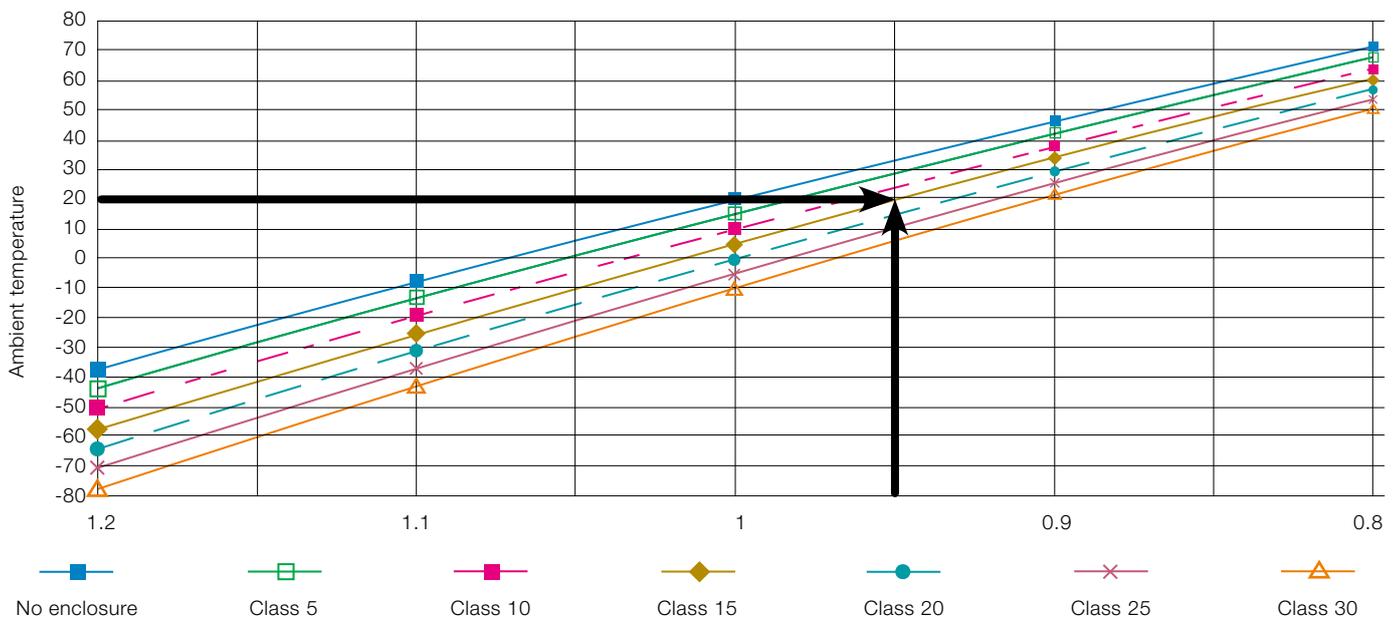
The transportation of the substation does not require the use of exceptional transport, and should it be necessary to move the substation to another location the operation is simple and takes a short time. The substations have a base with the same characteristics as the casing footprint of which has the same dimensions as the substation.

The substations are available in three different materials: steel, concrete and GRP (Glass-Fiber Reinforced Polyester), the latter with interesting characteristics of lightness, strength and thermal capacity, and transparency to electromagnetic waves, useful where communication systems are used for the management of the networks (e.g. smart grids).

Therefore the main advantages offered by prefabricated substations are:

- easy to transport
- immediate on-site installation after laying the base
- product build in full compliance with CEI EN 62271-202
- product tested in the factory with all the various components and therefore immediately usable.

Figure DD.7 – Insulation class 180 °C (H) dry-type transformers load factor in an enclosure



# 10. Other requirements of the substation electrical system

It is important not to overlook the design of the electrical system of the substation, certain requirements mentioned in the standard CEI EN 61936-1 concerning overvoltages, harmonics and electric and magnetic fields, very important for the impact that they can have on the health of persons and the life of the electrical equipment.

## 10.1 Overvoltages

As regards the overvoltages, the standard requires that the switchgear be protected against overvoltages caused by opening or closing operations and by atmospheric discharges. The standard also requires an analysis to be carried out to check for the presence of such overvoltages during operation so as not to exceed the withstand values of the switchgear. If such limits are exceeded the designer must provide suitable protections.

It is emphasized that the choice of such protection devices depends on the neutral earthing system and the sizing of the earthing system.

CEI 0-16 merely indicates that any impulse overvoltages may damage both control and power electronic components as well as motors, cables and electrical equipment in general, damaging the circuits and perforating insulation.

Network models are often very complicated and require technicians who are expert in simulations, but they obtain the result of highlighting the most hazardous transient phenomena for the installation.

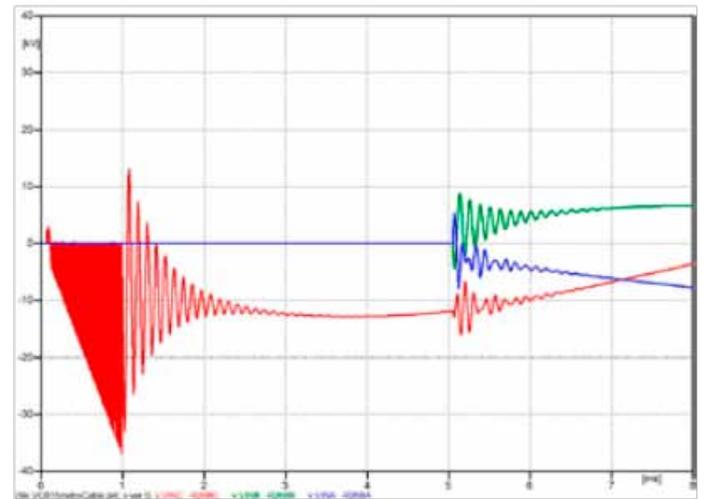
On the basis of its experience as a manufacturer of electrical equipment, ABB is able to support those who are designing complex systems with appropriate studies aimed at:

- calculation of transient overcurrents caused by the insertion of capacitor banks.
- calculation of transient overcurrents caused by the insertion of filtering banks
- calculation of insertion transients of power transformers
- calculations of ferroresonance
- calculation and analysis of Transient Recovery Voltage
- calculation of switching overvoltages and their suppression
- calculation of starting currents of critical motors
- analysis of the network in order to analyze in general the abnormal conditions which may occur in the installation, identifying the critical points to be checked

## 10.2 Harmonics and electrical and magnetic fields

### Harmonics

The maximum disturbances, including harmonics, which can be introduced into the network are indicated by the Distributor, taking into account the margins available in the network zone involved. The same user appliances may be sensitive to harmonics; the Standard CEI 0-16 provides a list of them with the possible related consequences.



Harmonics	Capacitors	Overheating and condensation damage
	Protection relays	Accidental tripping of protection relays
	Low power level connections	Malfunction of control systems and data transmission
	Motors and rotating machines	Increase in losses of motors, transformers and cables and consequent overheating
	Transformers	
	Electrical Cables	

In industrial plants, some appliances contribute to the generation of harmonics and must, therefore, be checked; these are:

- Industrial furnaces (induction, HF, UHF, arc)
- Motors (asynchronous, variable speed)
- Converters (AC/DC, AC/AC and cyclo-converters)
- Equipment for electrical discharge machining
- Discharge lamps
- Televisions
- Equipment for radiology

A mention should be made regarding the power factor correction capacitors (low and medium voltage); they are to be installed in such a way as to present no danger of initiation or propagation of fire to adjacent material, and in such a way as not to amplify the harmonic currents present in the plant and thus without worsening the level of low frequency electromagnetic pollution (see IEC/TR 61000-3-6).

### **Electromagnetic fields**

Annex I of CEI 99-4 deals with the problem of possible measures to reduce the electromagnetic field (EMF) that can be associated with MV/LV substations.

From the legislative point of view, for exposure to electric, magnetic and electromagnetic fields at industrial frequency, the reference is the Law no.36 of 22 February 2001 “Framework law on protection against exposure to electric, magnetic and electromagnetic fields” and the Decree of the President of the Council of Ministers of 8 July 2003 “Establishment of exposure limits, attention values and quality objectives for the protection of the population from exposure to electric and magnetic fields at mains frequency (50 Hz) generated by power lines”.

In addition, regarding the positioning of the substation at the user site with consideration to the surrounding environment, consideration must be given to the requirements of the Ministerial Decree of 29 May 2008 “Approval of the calculation methodology for determining the distance restrictions for power lines”, in relation to the first approximation distance (DPA) regarding exposure to electromagnetic fields and the Ministerial Decree of 29 May 2008 on “Approval of the

procedures for measuring and assessing magnetic induction”. Finally, as regards the methods for mitigation of the magnetic fields generated by MV/LV substations, the Standard CEI 99-4 refers to the information in CEI Guide 106-12 “Practical Guide to the methods and criteria for the reduction of the magnetic fields produced by MV/LV substations”.

Based on the provisions of the above-mentioned legislative framework, in designing new substations located in the vicinity of play areas for children, residential areas, school environments and places where persons spend more than four hours per day, account must be taken as regards magnetic induction of the quality objective of 3  $\mu\text{T}$  defined in the Decree of the President of the Council of Ministers of 8 July 2003. Within the restricted areas around substations, defined as the surrounding space that includes all the points characterized by magnetic induction of an intensity greater than or equal to the quality objective, there must be no allocated use involving presence greater than 4 hours.

Note that the owner or operator, together with the design data must also provide the competent authority, as part of the authorization procedure, with the first approximation distances, defined as the distance from all sides of the the substation box that guarantees that every point, the projection of which to the ground is further than the DPA from the projection of the center, is outside the restricted zones. For DPAs of transformer substations (MV/LV) you can refer to Ministerial Decree 29/05/2008, paragraph 5.2.1.

# 10. Other requirements of the substation electrical system

To determine the DPA the owner/operator of the substation must:

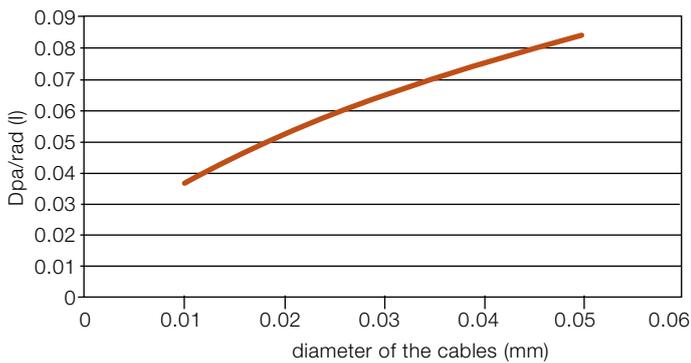
1. Use the curve illustrated in the chart below to calculate the value of DPA/root of the current for the type of output cables from the MV/LV transformer
2. Multiply this value by the root of the current round up to the next half meter

Equation of the curve: 
$$\frac{Dpa}{\sqrt{I}} = 0.40942 * x^{0.5241}$$

Dpa = First approximation distance (m);

I = rated current (A);

x = diameter of the cables (m)



By way of example, the following table shows the DPAs for 3  $\mu$ T zones calculated in some real-world cases.

Diameter of the cables (m)	Type of transformer (kVA)	Current (A)	Dpa (m)
0.010	250	361	1
	400	578	1
	630	909	1.5
0.012	250	361	1
	400	578	1.5
	630	909	1.5
0.014	250	361	1
	400	578	1.5
	630	909	1.5
0.018	250	361	1.5
	400	578	1.5
	630	909	2
0.022	250	361	1.5
	400	578	1.5
	630	909	2
0.027	250	361	1.5
	400	578	2
	630	909	2.5
0.035	250	361	1.5
	400	578	2
	630	909	2.5

As an indication, therefore, for standard secondary substations the DPA varies from 1.0 m to 2.5 m.

# 11. Request for connection

Before completing the connection, the User must provide a declaration for the substation (both those included in buildings and those constituting a building in their own right) stating that the performance of the structures comply with the requirements and accompanied by:

- an original copy of the certificate of viability and building registration
- an original copy of all licenses and various permits
- the test certificate for reinforced concrete works (Law 1086)
- certificates of conformity for the technological systems of the building
- final drawings “as built” both building electromechanical
- final drawings for HV and MV overhead and cable lines
- copy of deeds and easements
- use and maintenance manuals including the construction drawings of the equipment
- project report
- check and test sheets countersigned by the technician carrying out the work and the manufacturer certifying conformity of the rooms to the Standard CEI 99-2 (in the case of a substation built on site or inside civil buildings) or the compliance of the rooms and their plant with the same standard CEI 17-103 (in the case of a low substation in a prefabricated box)
- protection calibration tables
- pre-stressing tables
- earthing system report

Finally, with regard to the surrounding environment, the positioning of the structures must meet the requirements of the Ministerial Decree of 29 May 2008 “Approval of the calculation methodology for determining the restricted zones for power lines”, in relation to the first approximation distance (DPA) regarding exposure to electromagnetic fields.

Once the check on all the documentation listed above has been completed favourably, the Distributor will draw up the “Report on testing and final acceptance of network works for connection”.

# 12. Inspections and tests in situ prior to putting into service

Prior to commissioning, inspections and tests must be carried out to verify the compliance of the installation of the electrical components with the applicable technical specifications that must be subject to agreement between supplier and user.

The Standard CEI 99-4 includes in turn the provisions of standard CEI EN 61936-1.

This verification can be performed in the following ways:

- visual inspection
- functional tests
- measurements.

In fact, the inspections and tests on parts of the electrical installations can be performed after delivery and even after completion of the installation.

Typically the following checks are performed:

- verification of the characteristics of the electrical components for the intended operating conditions;
- verification of the minimum isolation distances between live parts, and between live parts and earth
- test on voltages for cables
- verification of the minimum heights and distances between the barriers
- visual inspections and/or functional tests on electrical components and parts of the installation
- functional tests and/or measurements on protection, monitoring, measurement and command devices
- inspection of rating plates, safety signs and safety devices
- check on the earthing system as specified by the Standard CEI EN 61936-1.

# 13. Maintenance of the electrical substation

In Italian Legislative Decree 81/08 “Electrical installations and equipment” Article 80 “Obligations of the employer” it states that the employer must, among other things, develop procedures for use and maintenance that can guarantee that the safety level reached with the adoption of the measures taken will be maintained over time. Poor maintenance, in fact, over time generates those risk conditions that technical standards and the manufacturers seek to limit by introducing rules and innovations at the design and construction stages. There is a specific standard, CEI 78-17 2015: Maintenance of MV/MV and MV/LV electrical substations of customers/end users (revision of the previous edition CEI 0-15 2006) the purpose of which is to propose a maintenance method based on the identification of all the components of the substation that are to be maintained.

In addition, with the Resolution of 29 December 2011, ARG/elt 198/11, in point 39.2 of Annex A -, the AEEG (Authority for Electricity, Gas and the Water System) requires MV Users, with power available for withdrawal less than or equal to 400 kW, who meet the simplified requirements, to carry out maintenance pursuant to Standard CEI 0-15 (now CEI 78-17) recording it in a special register, as a condition for access to compensation if the specific level of service continuity as specified by the Distributor is not respected.

The standard provides the technical instructions for carrying out the necessary maintenance work safely for the proper operation of electrical substations and associated connected systems with reference also to the Standard CEI 0-16.

Therefore it refers to:

- all the MV and LV electrical components of the reception substation and of any MV/MV distribution substations of the end user (e.g. circuit-breakers, disconnectors, switchgear, transformers, converters, batteries, capacitors, earthing systems, etc.. )
- all the components powered by the MV network of the end customer (e.g. circuit-breakers, switchgear, motors, etc.).
- all the MV cables
- all safety systems dedicated to the protection of the persons operating on the systems and/or in their vicinity (in accordance with the Standards CEI 11-27 and CEI 11-15) and of the actual electrical installations (e.g. buildings, fences, safety exits, fire extinguishers and sprinkler systems, equipment for emergency lighting, signs, locks, interlocks, protection relays, etc.).

The provisions also cover the components used for the generation of both MV and LV, even if located in different rooms, which are not, however, the subject of this publication.

Remember that maintenance may be corrective or preventive:

- corrective maintenance involves the renovation or replacement of components affected by a fault so as to return the system to operating conditions
- preventive maintenance, on the other hand, is designed to limit degradation of the components due their use. A particular case of preventive maintenance is predictive maintenance, which consists in checking the state of preservation of the components and, therefore, to anticipate their decay using methods to determine the residual lifetime of the components, reporting the need for maintenance or replacement, also with new generation components.

In the latter case, ABB offers the MyRemoteCare and MySiteCare products.

MyRemoteCare provides the ability to store diagnostic information on the individual devices and use this to generate reports and alarm signals. In addition, the analysis of historical data and trends makes it possible to determine deviations of the components from standard behavior over time. In this way the ABB service technicians can analyze the diagnostic data of the circuit-breakers remotely, but also low, medium and high voltage devices and transformers, signalling any possible problems, verifying the causes and undertaking where appropriate the necessary short or long-term maintenance. The maintenance managers can check the activities planned and carried out by ABB experts by consulting the MyRemoteCare portal.

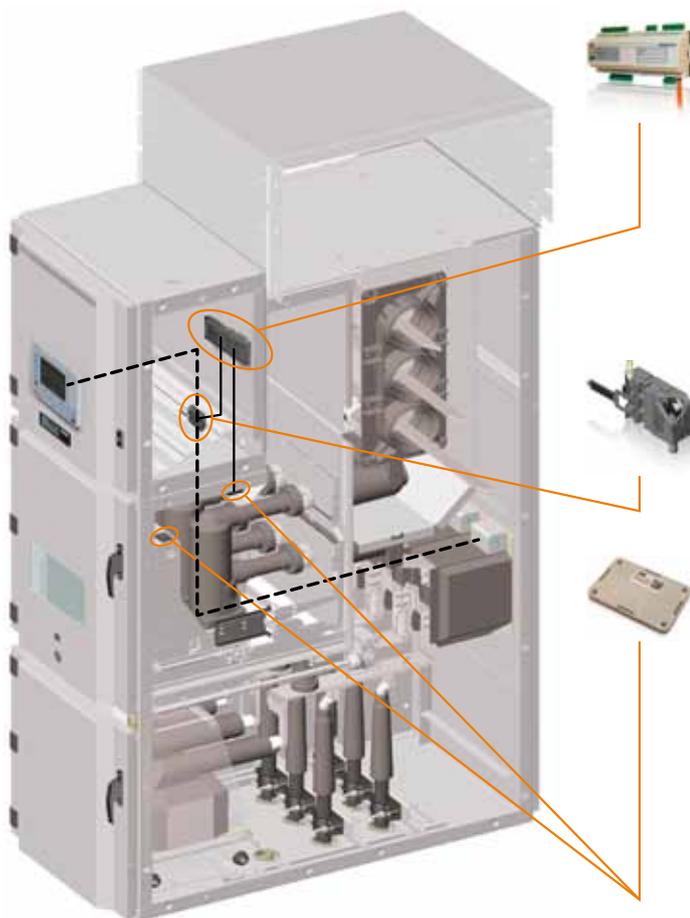
The system collects diagnostic information mainly through MySiteCare or a universal diagnostic device for circuit-breakers.

The MySiteCare monitoring and diagnostic device acquires the typical data of the circuit-breakers and transforms them into diagnostic data so as to determine the operating conditions and allow maintenance to be scheduled. The device can gather the following information:

- mechanical data: opening and closing times, loading time of the springs of the operating mechanism, failed attempts to load the spring, number of operations, downtime;
- environmental data, such as the temperatures in the compartments of the functional unit;
- real diagnostic data such as the estimated residual life and wear of the contacts.

On the basis of these data the device runs predictive diagnostic algorithms, providing information on the mechanical, electrical and functional conditions of the circuit-breaker.

# 13. Maintenance of the electrical substation



No change is required to the switchgear, the circuit-breaker or the protection relay. The components to be installed are the central unit, the current sensor and the wireless identification device (RDIF) that stores the data of the circuit-breaker in a unique manner and transmits them to the central unit. The predictive algorithms are configured by ABB technicians during installation.

The information processed by each MySiteCare is transmitted through a concentrator and telephone network to the ABB Data Centre.

In the absence of significant events that are reported immediately, the status of the system is updated every 24 hours. The ABB specialized technicians can access the portal via the Internet to consult the diagnostic data and provide the necessary support.

Finally, as a further solution to the problem of maintenance, we also consider the upgrading and retrofitting equipment in order to adapt it to the state of the art in terms of technology and safety.

After an appropriate analysis of the state of the equipment, complete replacement may in fact turn out to be more convenient than the usual ordinary maintenance. For example, it is possible to upgrade old circuit-breakers that have become obsolete in terms of technology, such as air or reduced oil circuit-breakers with modern switches in SF<sub>6</sub> or vacuum circuit-breakers where all the solutions for increasing safety of personnel are implemented.

The solution proposed by ABB in this case is called OneFit: the new circuit-breaker is adapted mechanically and electrically by means of a check carried out on site on the existing switchgear by qualified and experienced personnel. The result is an improvement not only in the typical performance of a new device, but also and above all in safety.

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After an appropriate analysis of the state of the equipment, complete replacement may in fact turn out to be more convenient than the usual ordinary maintenance. For example, it is possible to upgrade old circuit-breakers that have become obsolete in terms of technology, such as air or reduced oil circuit-breakers with modern switches in SF<sub>6</sub> or vacuum circuit-breakers where all the solutions for increasing safety of personnel are implemented.

The solution proposed by ABB in this case is called OneFit: the new circuit-breaker is adapted mechanically and electrically by means of a check carried out on site on the existing switchgear by qualified and experienced personnel. The result is an improvement not only in the typical performance of a new device, but also and above all in safety, through solutions such as interlocks between the circuit-breaker and the door, remote control, insertion/extraction with the door closed and everything else that is made possible by modern technology in terms of protection and monitoring.

Addressing the issue of contracting and carrying out maintenance work, remember that the Employer/principal of the company who owns the substation and facilities, if such activity is outsourced in part or in whole to an outside company, has full responsibility both for the choice of the contracting company for checking the suitability of their personnel as required by Article 26 of Legislative Decree 81/08 and subsequent amendments.

All work must be carried out in compliance with the applicable laws and technical standards.

The documentation relating to specific maintenance operations may consist of a "maintenance log", which can also be computerized and which must in any case be available at the installation, that contains the wiring diagrams and technical specifications.

The maintenance sheets, the preparation of which is the responsibility of the owner of the electrical installation, are based on the technical and maintenance manuals of the manufacturers of components and services, and must contain at least the following:

- identification of the substation
- code or progressive number of the sheet
- name of the circuit and/or element in question
- summary description of the checks or service operations
- maximum time interval between actions
- particular work carried out and, if not carried out, the reason
- date carried out and initials of the maintenance worker
- outcome of the maintenance work
- signatures of maintenance staff and any notes

Annex B of Standard CEI 78-17 provides examples of maintenance sheets complete with all the necessary information in order to provide a method for preparing and completing them. The sheets must obviously be adapted to the actual system. An example of a sheet is shown below that is included in the standard to which you are referred for the necessary complete information.

# 13. Maintenance of the electrical substation

– Identifier MV/MV or MV/LV SUBSTATION xx xxx - QMT-A/CFE1-MV - SHEET NO. 1 -

## Circuit-breaker in SF<sub>6</sub> for General Protection of the installation (PG)

NOTE: Consult the manufacturers' specifications, if they exist or are available - Interventions are carried out following a visual and/or instrumental inspection		Max Period	Result	Initials	Date	Notes												
1	PGISF <sub>6</sub> - General and installation check	1 year																
2	PGISF <sub>6</sub> - Check on integrity of insulating parts and cleaning	1 year																
3	PGISF <sub>6</sub> - Check and clean of the main coupling and connection contacts	1 year																
4	PGISF <sub>6</sub> - Check electrical operation	1 year																
5	PGISF <sub>6</sub> - Check auxiliary voltages	1 year																
6	PGISF <sub>6</sub> - Control gas pressure in the poles and refill if necessary	1 year																
7	PGISF <sub>6</sub> - Run O-CO operating cycle	1 year																
8	PGISF <sub>6</sub> - Check insertion - test - extracted	1 year																
9	PGISF <sub>6</sub> - Replace components of the mechanical control that are subject to wear	5 years																
10	PGISF <sub>6</sub> - Adjustment of the mechanism control	5 years																
11	PGISF <sub>6</sub> - Measure opening and closing times and compare with rated data	2 years																
12	PGISF <sub>6</sub> - Check wear on arc contacts, if possible	5 years																
13	PGISF <sub>6</sub> - Check features relay of protection supplemented by test switchgear	2 years																
14	PGISF <sub>6</sub> - Clean and lubricate operating mechanisms	2 years																
15	PGISF <sub>6</sub> - Replacement of the mechanical operating mechanism only on reaching the operation limit specified by the manufacturer																	
16	PGISF <sub>6</sub> - Replacement of the poles only on reaching of the limit of current interruptions specified by the manufacturer																	
17	-																	
Overall outcome of periodic servicing																		

In the "Outcome" columns write "P" if the maintenance job is positive - or - "PI" if the check is positive following a maintenance job - or - "NA" when the maintenance job is postponed to subsequent sessions - or - "NP" if the component is not present - or - "VN" acronym for SEE NOTE ("VEDERE NOTA" in Italian) (to be inserted in the NOTES column to the side) - or - "B" if the maintenance work will be carried out by the manufacturer/service centre - or - "C" if the necessary partial or total replacements will be carried out by the manufacturer/service centre according to the indications to be entered in the NOTES column at the side. In the "Initials" column enter the initials that identify the maintenance worker and in the "Date" column write the date on which the maintenance was carried out.

Signatures of Maintenance Staff

1	
2	
3	
4	
5	

# 14. Example of substation design - electrical part

## 14.1 Estimate of the power supplied to a small industrial factory

We will take a small industrial plant as an example. Production involves a stabilized thermal cycle in the furnace for which reason a total black-out is not possible. The plant is also located in a densely populated area.

The starting point for the design is the estimation of the consumption of the various users.

If in assessing the required power you were to consider the sum of the rated power of all equipment and users you would

get a value that is certainly excessive, for two reasons:

- some equipment might not be used at its full power
- the equipment will not all be work at the same time

This is taken into account with two coefficients: the utilization factor  $K_u$  and the contemporaneity factor  $K_c$ . The ideal would be to have the actual data, as in the case of renovation of an existing installation for which the load diagrams are available; however, in the case of new projects, the load diagram is not available, and therefore one has to estimate the actual load by using factors derived statistically on homogeneous categories of installations as proposed by CEI Guide 99-4, Annex E, attached here.

Type of system	Contemporaneity factors				
	Type of environment				
	Individual housing units	Civil buildings for housing	Offices, shops, warehouses, departments	Hotels, hospitals	Medium and high power industrial plants
Lighting	66% of the installed power	75% of the installed power	90% of the installed power	75% of the installed power	90% of the installed power
Heating (see also 3 or 6)	100% of the power of the equipment up to 10A + 50% of the remainder	100% of the biggest user + 50% of the remainder	100% of the biggest user + 75% of the remainder	100% of the biggest user + 80% of the second + 60% of the remainder	100% of the biggest user + 75% of the remainder
Kitchens	100% of the power of the equipment up to 10A + 30% of the equipment over 10A permanently connected	100% of the biggest user + 80% of the second + 60% of the remainder	–	100% of the biggest user + 80% of the second + 60% of the remainder	–
Motors (with the exclusion of lifts, elevators, cranes, etc.).	–	–	100% of the biggest motor + 80% of the second motor + 60% of the remainder	100% of the biggest motor + 80% of the second motor + 60% of the remainder	To be considered on a case by case basis
Water heaters	No contemporaneity is allowed				
Socket outlets	100% of the biggest user + 25% of the remainder	100% of the biggest user + 25% of the remainder	100% of the biggest user + 40% of the remainder	100% of the biggest user + 75% of the rooms + 25% of the remainder	25% of the user installed

Alternatively you can use table 101 of the Standard CEI EN 61439-2:

**Table 101 - Values of assumed loading**

Type of load	Assumed loading factor
Distribution - 2 and 3 circuits	0.9
Distribution - 4 and 5 circuits	0.8
Distribution - 6 and 9 circuits	0.7
Distribution - 10 or more circuits	0.5
Electric actuator	0.2
Motors ≤ 100 KW	0.8
Motors > 100 KW	1.0

# 14. Example of substation design - electrical part

In the example provided, the power used on the main LV switchgear is 732 kVA.

Considering the values of the rated power of the transformers available commercially, it can be assumed that two transformers 400 kVA transformers will be installed, which although resulting in a more expensive solution than that with only one 800 kVA transformer, can nevertheless be justified by the need to have a greater continuity of service in case of failures or maintenance.

In this situation the two transformers are loaded at 92% ( $732/800=0.92$ ) of their rated power, and in the case of an outage of one of the two, it will still be possible to provide 55% of the required power.

The other features of the substation are:

- the substation is powered by a buried cable
- The transformers are closed in parallel on the secondary so as to guarantee the power supply of the LV installation by both of them
- The size of the internal MV network is less than 400 m

	User	S rated KVA	Ku	S used KVA	Kc	S used KVA	S used KVA	S used KVA
Department A	motors (3)	150	0.8	120	0.8	96	134	732
	various socket outlets	80	1	80	0.25	20		
	lighting	20	1	20	0.9	18		
Department B	compressors (2)	130	0.8	104	0.8	83.2	140.45	732
	various socket outlets	85	1	85	0.25	21.25		
	lighting	40	1	40	0.9	36		
Department C	motors (2)	50	0.8	40	0.8	32	131.25	732
	furnaces (1)	70	1	70	1	70		
	various socket outlets	45	1	45	0.25	11.25		
	lighting	20	1	20	0.9	18		
Department D	various socket outlets	155	1	155	0.25	38.75	92.75	732
	lighting	60	1	60	0.9	54		
Department E	motors (3)	125	0.8	100	0.8	80	141	732
	various socket outlets	100	1	100	0.25	25		
	lighting	40	1	40	0.9	36		
Department F	various socket outlets	155	1	155	0.25	38.75	92.75	732
	lighting	60	1	60	0.9	54		
	Sub-switchgear							
	Department switchgear							
	Main LV switchgear							

## 14.2 Calculation of short circuit and coordination of protections

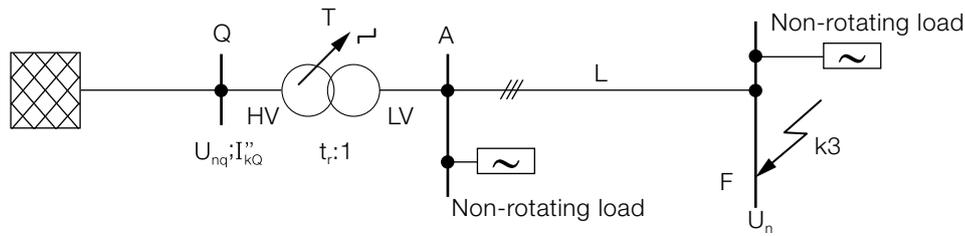
### Theory behind calculation of the short-circuit current

To deal with the theory of calculation of short-circuit currents we will refer to the Standard IEC 60909-0 "Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents". With reference to the electrical network schematised in figure 1, a short-circuit is assumed on the load terminals. The network can be studied and represented by using the resistance and reactance parameters of each electrical component.

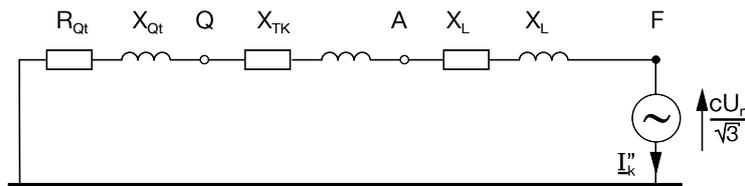
The resistance and reactance values of must be all related to the same voltage value assumed as a reference for calculating the short-circuit current.

The change from impedance values  $Z_1$  referring to a higher voltage ( $U_1$ ) to the values  $Z_2$ , referring to a lower voltage ( $U_2$ ), takes place using the transformation ratio  $K = U_1/U_2$  according to the following relationship:

$$Z_2 = Z_1/K^2$$



The structure of the electrical network in question can be represented through elements in series; in this way an equivalent circuit is obtained like that shown in the following figure which makes it possible to calculate the equivalent impedance seen from the fault point.



# 14. Example of substation design - electrical part

An equivalent voltage source ( $U_{eq}$ ) is positioned at the point of the short circuit with the value:

$$U_{eq} = c U_n / \sqrt{3}$$

The factor “c” depends on the system voltage and takes into account the influence of the loads and of the variation in mains voltage. The following is the table taken from Standard IEC 60909-0.

Nominal voltage $U_n$	Voltage factor c for the calculation of	
	maximum short-circuit currents $C_{max}^1$	minimum short-circuit currents $C_{min}$
<b>Low voltage</b> 100 V to 1000V (IEC 60038, table I)	1.05 <sup>3)</sup> 1.10 <sup>4)</sup>	0.95
<b>Medium voltage</b> > 1kV to 35 kV (IEC 60038, table III)	1.10 AM	1.00
<b>High voltage</b> <sup>2)</sup> > 35 kV (IEC 60038, table IV)		

- <sup>1)</sup>  $C_{max} U_n$  should not exceed the highest voltage  $U_m$  for equipment of power systems.  
<sup>2)</sup> If no nominal voltage is defined  $C_{max} U_n = U_m$  or  $C_{min} U_n = 0.90 \times U_m$  should be applied  
<sup>3)</sup> For low-voltage systems with a tolerance of + 6%, for example systems renamed from 380 V to 400 V  
<sup>4)</sup> For low-voltage systems with a tolerance of + 10%.

## Power supply network

In most cases, the installation will be supplied by a medium voltage distribution network, for which it is quite easy to obtain the value of the supply voltage  $U_{nQ}$  and the initial short-circuit current  $I''_{kQ}$ .

On the basis of these data and of a correction coefficient for the change in voltage caused by the short-circuit it is possible to determine the short-circuit direct impedance of the network with the following formula:

$$Z_Q = c U_{nQ} / (\sqrt{3} I''_{kQ})$$

For the calculation of the network resistance and reactance parameters, if a precise value for value for  $R_Q$  is not available, the following approximate formulas can be used:

$$X_Q = 0.995 Z_Q$$

$$R_Q = 0.1 X_Q$$

## Transformer

The impedance of the machine can be calculated using the rated parameters of the machine itself (rated voltage  $U_{rT}$ ; apparent power  $S_{rT}$ ; short circuit voltage at the rated current in percent  $u_{kr}$ ) using the following formula:

$$Z_T = (u_{kr} / 100\%) (U_{rT}^2 / S_{rT})$$

The resistive component can be determined by knowing the value of the total losses

$P_{krT}$  referring to the rated current according to the following relationship:

$$R_T = P_{krT} / (3 I_{rT}^2)$$

The reactive component can be determined with the classic relationship

$$X_T = \sqrt{(Z_T^2 - R_T^2)}$$

## Cables

The impedance value of these connection elements depends on various factors (technical, constructive, temperature, etc.) that condition the linear resistance  $R'_L$  and the linear reactance  $X'_L$ . These two parameters expressed per unit of length are provided by the manufacturer of the cable; alternatively, reference values can be found in IEC 60909-2. In general, the resistance values are based on a reference temperature of 20 °C; for different operating temperatures  $\theta$  the following formula makes it possible to relate the resistance value to the operating temperature.

$$R'_{L\theta} = [1 + \alpha (\theta - 20)] R'_{L20}$$

where:

$\alpha$  is the temperature coefficient that depends on the type of material (for copper, aluminum and aluminum alloys  $4 \times 10^{-3}$  holds true with good approximation).

Therefore, in very simple terms we have:

$$R_L = L R'_L \text{ and } X_L = L X'_L$$

with L the length of the cable line.

### Calculation of the short-circuit current

The definition of the short-circuit resistance and reactance values of the main elements forming a circuit allow the short circuit currents in the installation to be calculated.

With reference to Figure 2, with the method of reducing elements in series the following values are determined:

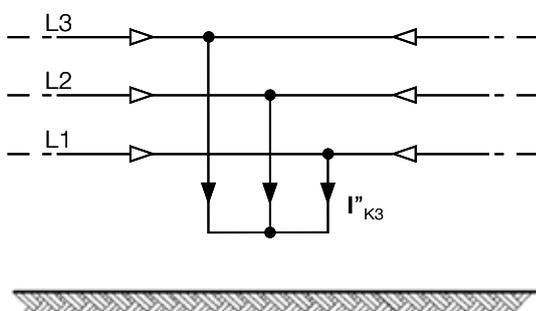
- the total short-circuit resistance value  $R = \sum R_i$
- the total short-circuit reactance value  $X = \sum X_i$

Once the two preceding parameters are known, it is possible to determine the total short-circuit direct impedance  $Z$

$$Z = \sqrt{R^2 + X^2}$$

Once the equivalent impedance seen from the fault point has been determined, one can proceed with the calculation of the symmetrical three-phase initial short-circuit current:

$$I''_{k3} = c U_n / \sqrt{3} Z$$



The three-phase short circuit is generally considered as the fault which causes the highest currents (except in particular conditions). In the absence of rotary machines, or when their action is diminished, it also represents the permanent short-circuit current and is the value taken as a reference to determine the breaking capacity of the protection device.

### Calculation of the contribution of motors

In the event of a short circuit, the motor starts to function as a generator and powers the fault for a limited time corresponding to the time required to eliminate the energy that has been stored in the magnetic circuit of the motor. Through an electrical diagram of the motor with its subtransient reactance it is possible to calculate the numerical value of the motor contribution.

In low voltage, the Standard IEC 60909-0 provides the minimum indications for which the phenomenon must be taken into account, it will be

$$\sum I_{rM} \leq 0.01 I''_k$$

where:

$\sum I_{rM}$  represents the sum of the rated currents of the motors connected directly to the network where the short circuit occurs.  $I''_k$  is the initial three-phase short-circuit current determined without contribution of motors.

If it has to be taken into account, the impedance of the motors may be calculated using the formula:

$$Z_M = \frac{1}{I_{LR} / I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3} I_{rM}} = \frac{1}{I_{LR} / I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}}$$

where:

$U_{rM}$  is the rated voltage of the motor

$I_{rM}$  is the rated current of the motor

$S_{rM}$  is the rated apparent power of the motor

( $S_{rM} = P_{rM} / (\eta_{rM} \cos \phi_{rM})$ )

$I_{LR} / I_{rM}$  is the ratio between the locked rotor current and the rated current of the motor.

The current  $I_{LR}$  is often a value that is difficult to obtain and therefore it is common practice to consider this value as a multiple of the rated current of the motor. The typical values of the ratio  $I_{LR} / I_{rM}$  vary from 4 to 6.

Finally, for groups of low voltage motors connected via cables we can, with good approximation, use the relationship  $R_M / X_M = 0.42$  with  $X_M = 0.922 Z_M$ .

# 14. Example of substation design - electrical part

## Calculation of the peak current

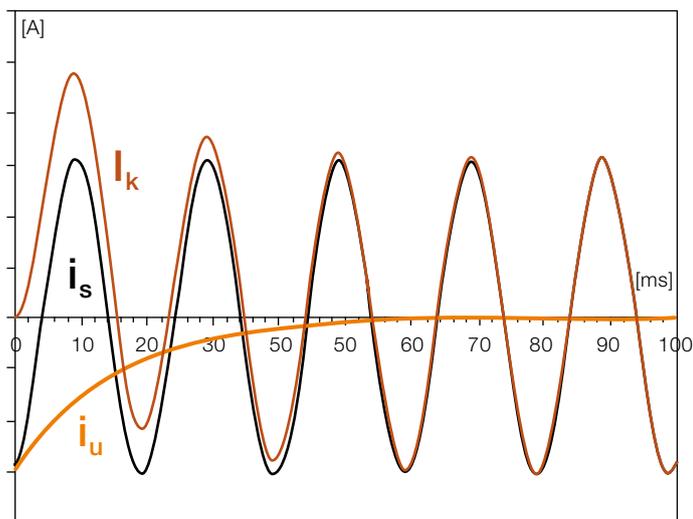
The short circuit current  $I''_k$  can be considered to consist of two components:

- a symmetrical component  $i_s$  with sinusoidal wave form and in fact symmetrical in relation to the horizontal time axis.
- a unidirectional component  $i_u$  with exponential trend due to the presence of an inductive component. This component is characterized by a time constant  $\tau = L/R$  ("R" indicates the resistance and "L" indicates the inductance of the circuit upstream of the failure point) and is extinguished after 3-6 times  $\tau$

During the transitional period, the unidirectional component makes the short-circuit current asymmetric, characterized by a maximum value, referred to as the peak value, which is higher than what it would be with a purely sinusoidal magnitude. In general we can say that, considering the effective value of the symmetrical component of the short-circuit current  $I_k$ , the value of the first peak current may vary from

$$\sqrt{2} I''_k \text{ to } 2\sqrt{2} I''_k.$$

After the transitional period, the short-circuit current becomes practically symmetrical. An example of the current trend is shown in the following figure.



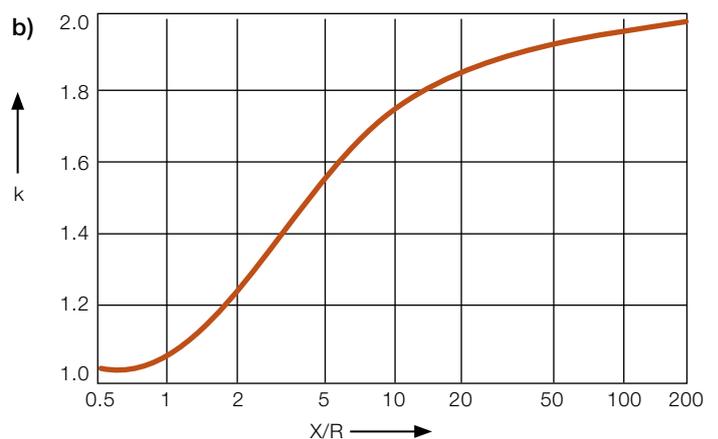
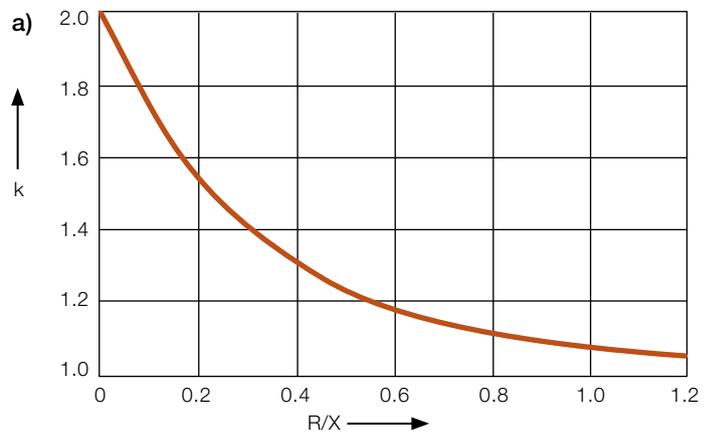
The Standard IEC 60909-0 provides useful indications for calculating the peak current. In particular, it indicates the following relationship:

$$i_p = k\sqrt{2} I''_k$$

where the value of  $k$  can be evaluated with the following approximate formula:

$$k = 1.02 + 0.98 \cdot e^{-\frac{3R}{X}}$$

or through the following charts that show the value of "k" as a function of the parameter "R/X" or "X/R"



## Sizing of the electrical installation and coordination of the protections

Knowledge of certain parameters is fundamental for sizing the installation. For the calculations of the study and protection coordination it has been used and the software-design of ABB.

### Distribution network data

We will start with an example of a letter of information supplied by the Distributor specifying the maximum levels of three-phase short-circuit and earth fault that could affect the installation:

Subject: Information about the Distributors power supply network for sizing of the equipment, calibration of protection devices, the design and verification of the earthing system regarding the supply:

Company: xxxxxxx - Substation xxxxxx - Street xxxxxxx - xxxxx

With reference to your request of xx.xx.xxxx please note that:

- 1) your earthing system is compensated
- 2) the substation in question is powered by the MV line "xxxxx" leaving from the Primary substation "xxxxx";
- 3) it has the following characteristics:
  - Rated voltage: 20 kV  $\pm$  10%
  - Rated frequency: 50 Hz  $\pm$  1% (95% of the year)
  - Three-phase short-circuit current: 12.5 kA
  - State of the neutral: compensated
  - Single-phase earth fault current: 50 A
  - Single-phase earth fault clearance time: 10 s
  - Double earth fault clearance time: < 0.2 s
  - MV power supply characteristics: conforming to standard CEI EN 50160

It is worthwhile highlighting that the value of the single-phase earth fault current and corresponding fault elimination time indicated above are subject to change following future development of the distribution network; therefore, in periodically checking your earthing system, you must take account of the new parameters provided in accordance with Standard CEI 0-16.

In the letter we can then find some important data such as the rated voltage 20 kV and the three-phase short-circuit current 12.5 kA; we know that it is a network with compensated neutral with a single-phase earth fault current of 50 A.

## Development of the proposed example

Now we will develop the example proposed evaluating the main electrical parameters of the network and the choice of circuit-breakers and protections for proper operation of the system, in particular coordinating the protections.

Description of the characteristics of the installation (as specified in the letter from the Distributor).

Distribution network:

- rated voltage  $U_{nQ}=20\text{kV}$
- short circuit current  $I''_{kQ}=12,5\text{kA}$

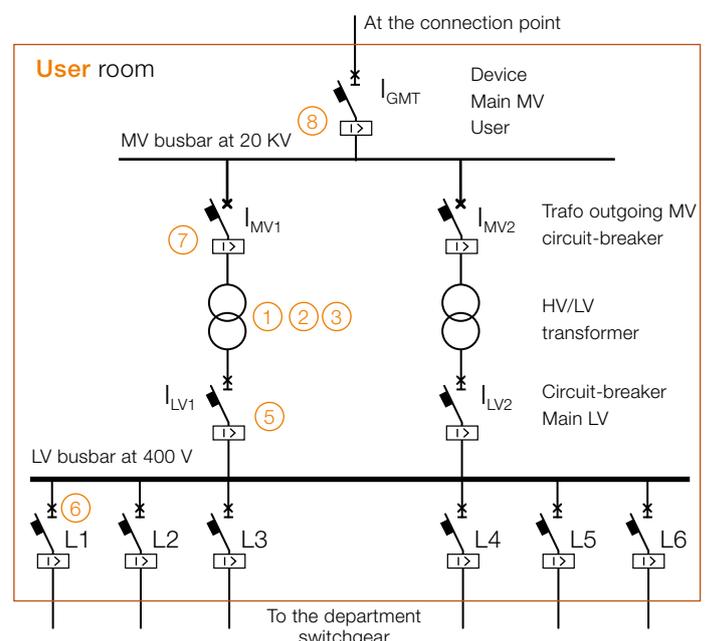
20/0.4 kV substation transformers with the following data:

- rated power:  $S_{rT}=400\text{kVA}$
- short circuit voltage:  $u_{kr}\%=4\%$
- primary rated current:  $I_{rT1} = 11.5 \text{ A}$
- secondary nominal current:  $I_{rT2} = 578.0 \text{ A}$
- plug-in current:  $I_i = 12 I_{rT1} = 138 \text{ A}$
- insertion time constant  $T_i = 0.25 \text{ s}$

Short-circuit current on the LV busbar side:

- Rated voltage:  $U_{rLV} = 400 \text{ V}$
- Short-circuit current downstream of one of the two transformers  $I''_{kLV} = I_{rT2} / u_{kr} = 15 \text{ kA}$ , corresponding to  $I''_{kMV} = 300 \text{ A}$

Department switchgear are connected to the low voltage switchgear using cables of differing lengths. The simplified single line diagram of the installation being analysed is shown here.

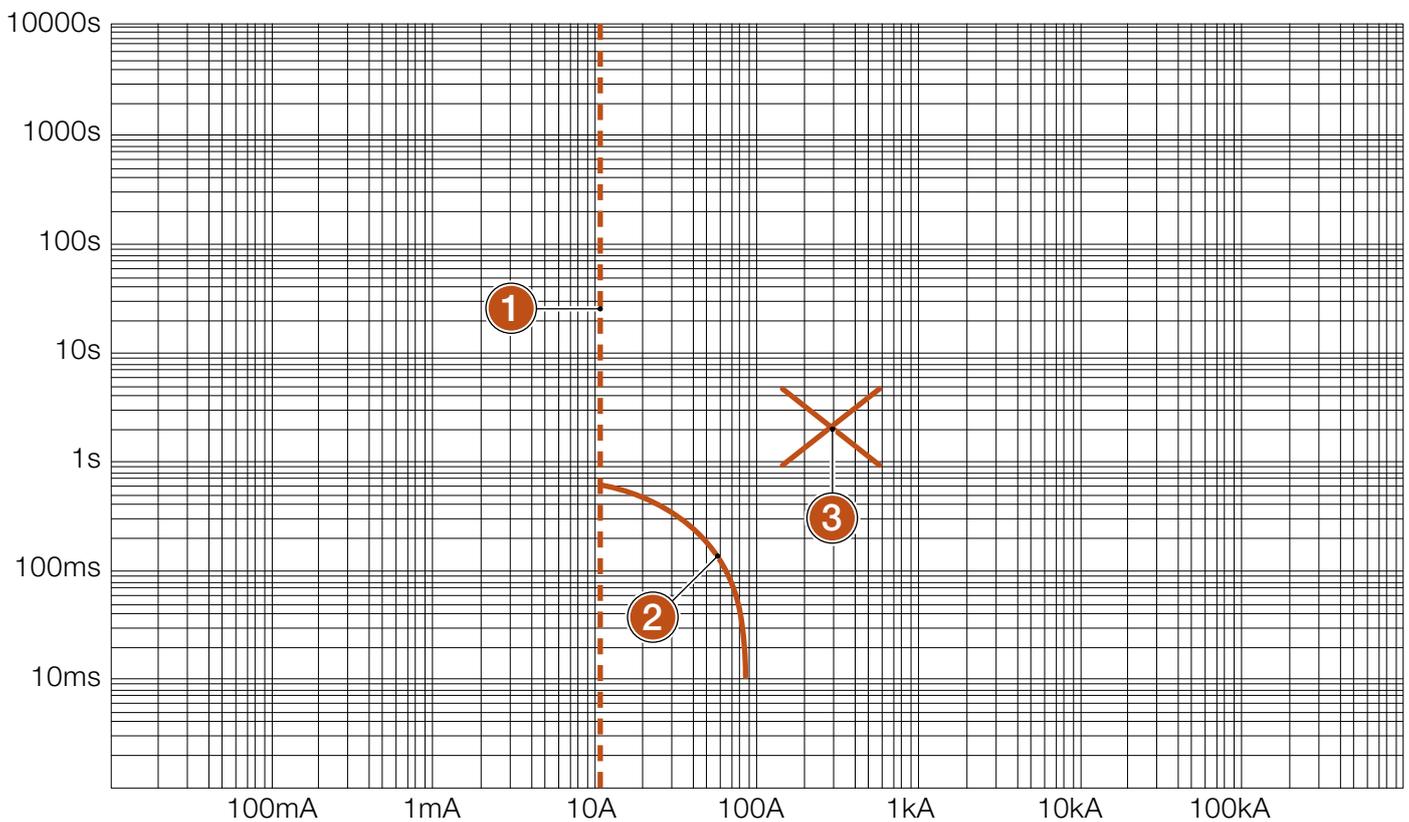


# 14. Example of substation design - electrical part

The installation on the MV side consists of an incoming line with a circuit-breaker unit and two transformer outputs equipped with circuit-breakers. The protections, since protection 67N is not required, are of the type REF601, version CEI 0-16.

In the graph below, in logarithmic scale, we find the following parameters that are required in order to establish the protection of the transformer: the insertion curve of the 400 kVA transformer (1), its rated current (2) and the symmetric short-circuit current on the LV side referring to the primary for 2 s (3) required for the thermal protection of the transformer ( $I''_{kMV} \times 2s$ ).

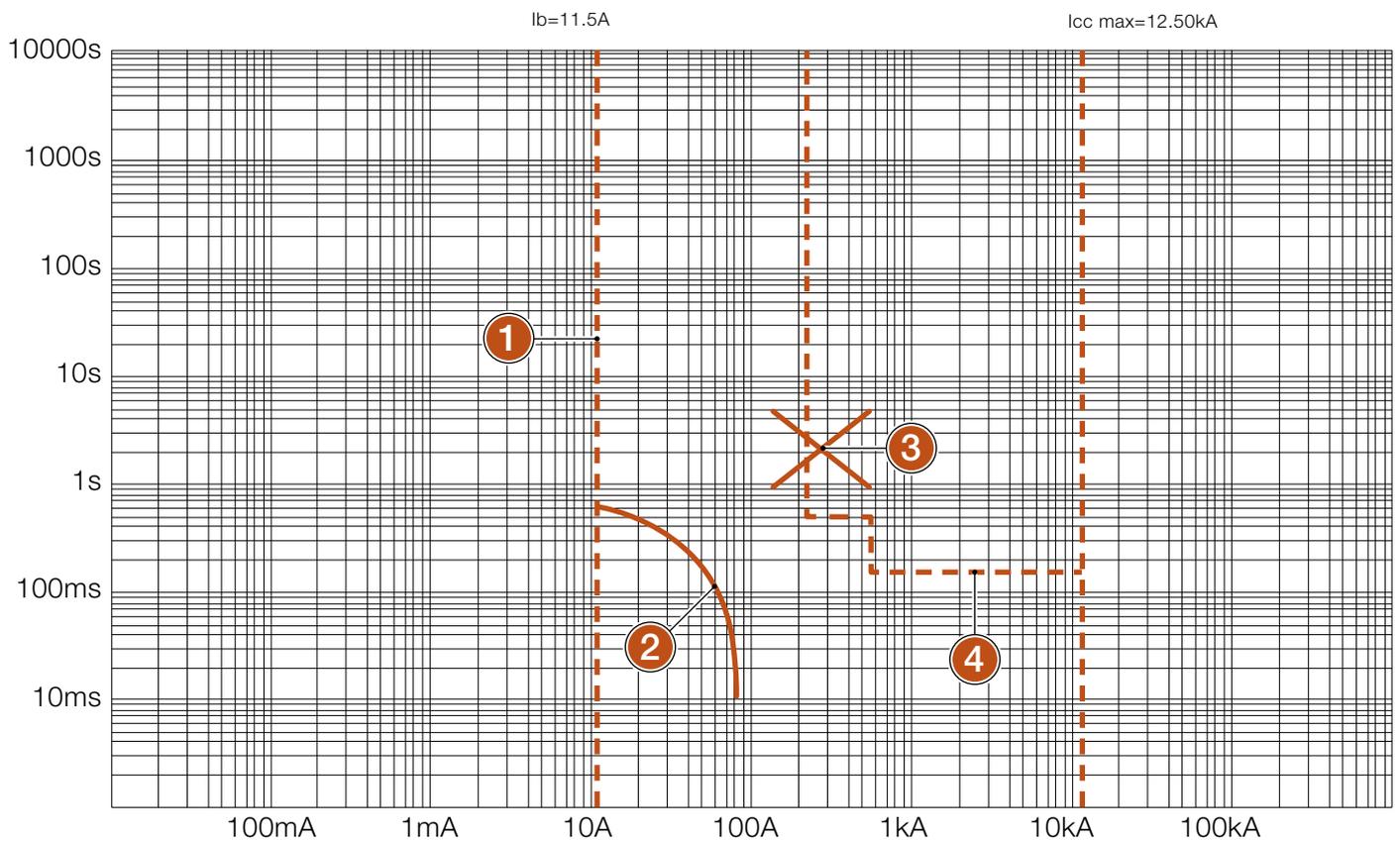
**Time-current curve, Three-phase fault @ 20000V**



Based on what we have already seen in the chapter on protection relays, the limits imposed by the standard apply, in this case:

I>>	Phase overcurrent protection: second threshold	≤ 250 A, overcurrent extinction time ≤ 500 ms	I>>>	Overcurrent protection phase: third threshold	≤ 600 A, overcurrent extinction time ≤ 120 ms
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### Time-current curve, Three-phase fault @ 20000V



Curve 4 refers to the maximum adjustable values on the protection in accordance with Standard CEI 0-16.

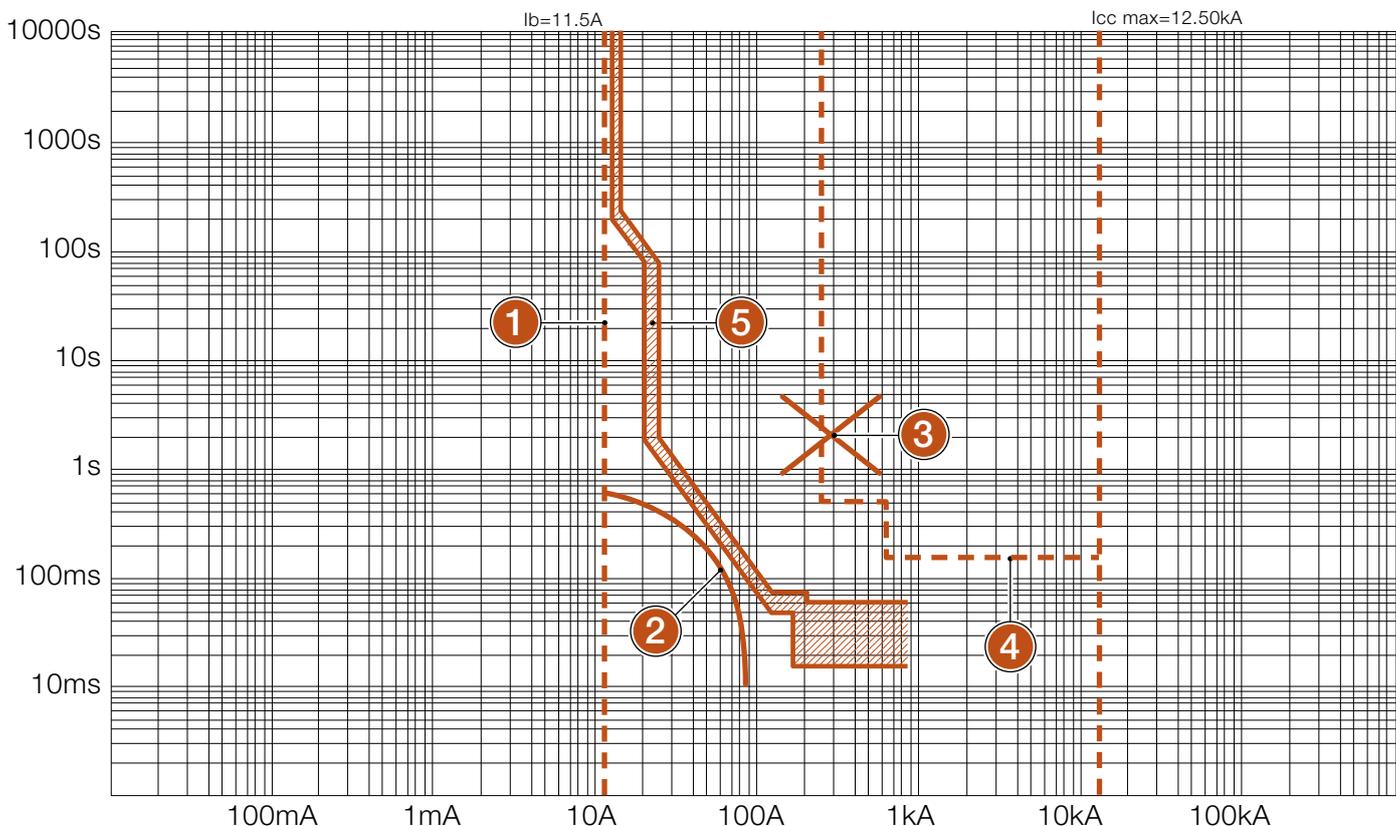
# 14. Example of substation design - electrical part

Now we look at the low voltage; the characteristics of the main LV circuit-breakers must be chosen so that they will be selective with the relays of the switches of the sub-switchgear A, B, C, D, but, at the same time, protect the transformer against overload, recalling that the secondary current  $I_{rT2} = 578 \text{ A}$ .

Taking into account the tolerances specified by Standard CEI 60947-1, we can consider certain tripping at a value greater than 1.2 times the value set (and certain non-tripping at a value less than 1.05 the value set).

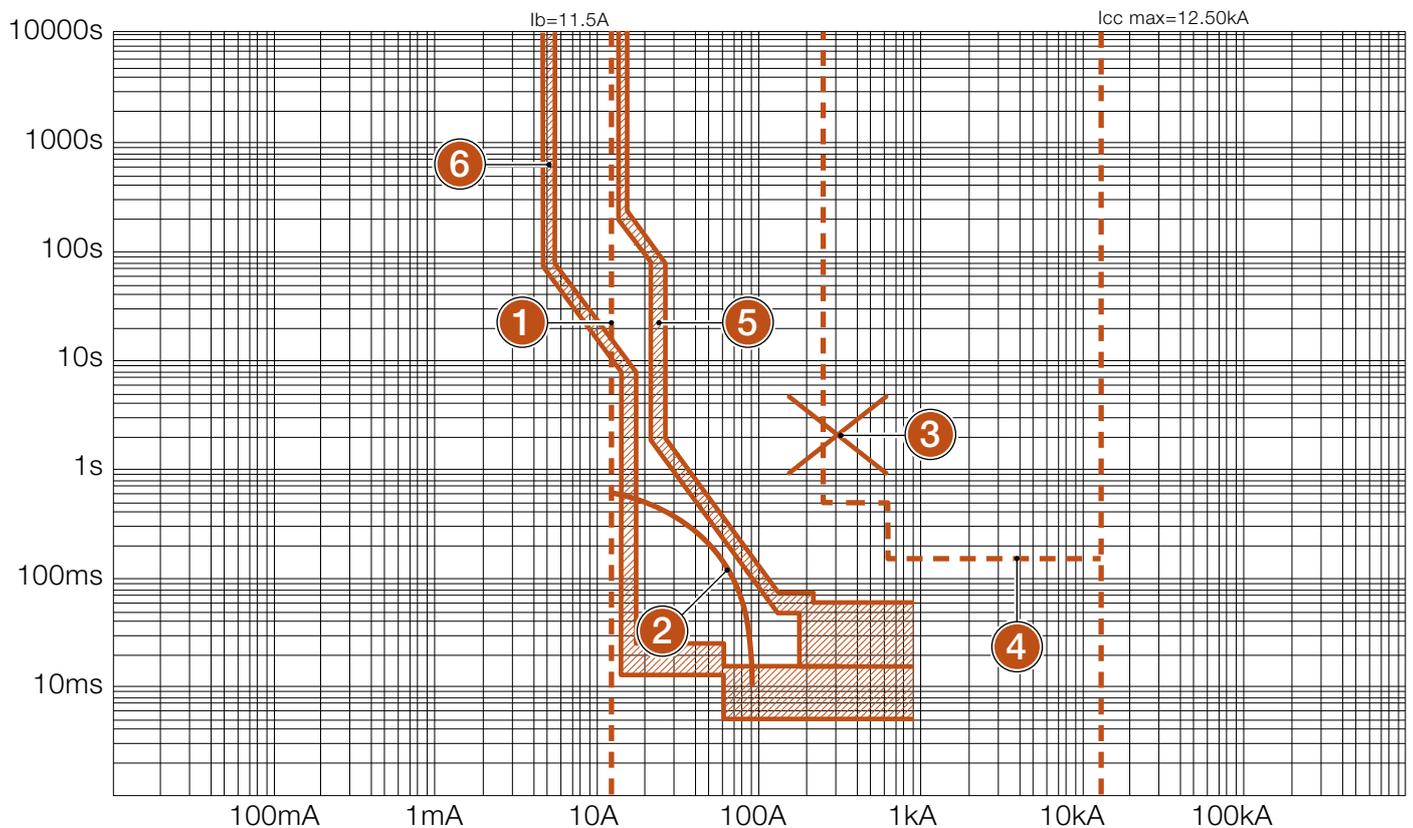
Choosing an Emax new X1B 630 air circuit-breaker as the circuit-breaker, equipped with PR332 LSIG electronic relay,  $I_n = 630 \text{ A}$ , with setting of the curve L to 0.96, we obtain a current setting of 605 A, which related to the primary equals 12.1 A. The tolerance will therefore range from 12.7 A (1.05  $I_n$ ) to 14.5 (1.2  $I_n$ ). Therefore the curve S,  $I^2t = \text{cost}$ , was selected with setting of 1.8  $I_n = 1134 \text{ A}$  equivalent to 23 A and time 0.06 s in order to obtain chronometric selectivity. Finally, the instantaneous trip will occur at 15  $I_n = 9450 \text{ A}$  equivalent on the primary to 189 A with a nominal tripping time of 10 ms. The curve (5) is illustrated below with the respective tolerances.

**Time-current curve, Three-phase fault @ 20000V**



The use of PR221 electronic relays on all the Tmax circuit-breakers of the main LV switchgear in any case guarantees the selectivity of the main LV circuit-breakers with all the outgoing connections to the department switchgear. The following graph shows the curve for the most critical outgoing connection to department A (6).

**Time-current curve, Three-phase fault @ 20000V**



# 14. Example of substation design - electrical part

Now we move on to the setting of the overcurrent relay for the 20 kV startup circuit-breaker to the 400 kVA transformer. The most important condition to be met is the protection of the transformer against short circuits, while the overload protection can be delegated to the low voltage circuit breaker. It must also protect the transformer against faults on the low voltage riser upstream of the circuit breaker, but it must not trip due to the inrush current of the transformer. Finally it must be selective with the main MV circuit breaker, which must in turn meet the requirements of the Distributor and the standard, and with the low voltage circuit breakers.

As we know, the first overcurrent threshold  $I_{>}$  is optional and in this example it is difficult to implement selectivity with the LV circuit breaker. Therefore we will use a protection with two independent time thresholds  $I_{>>}$  and  $I_{>>>}$ . The protection must meet the following requirements:

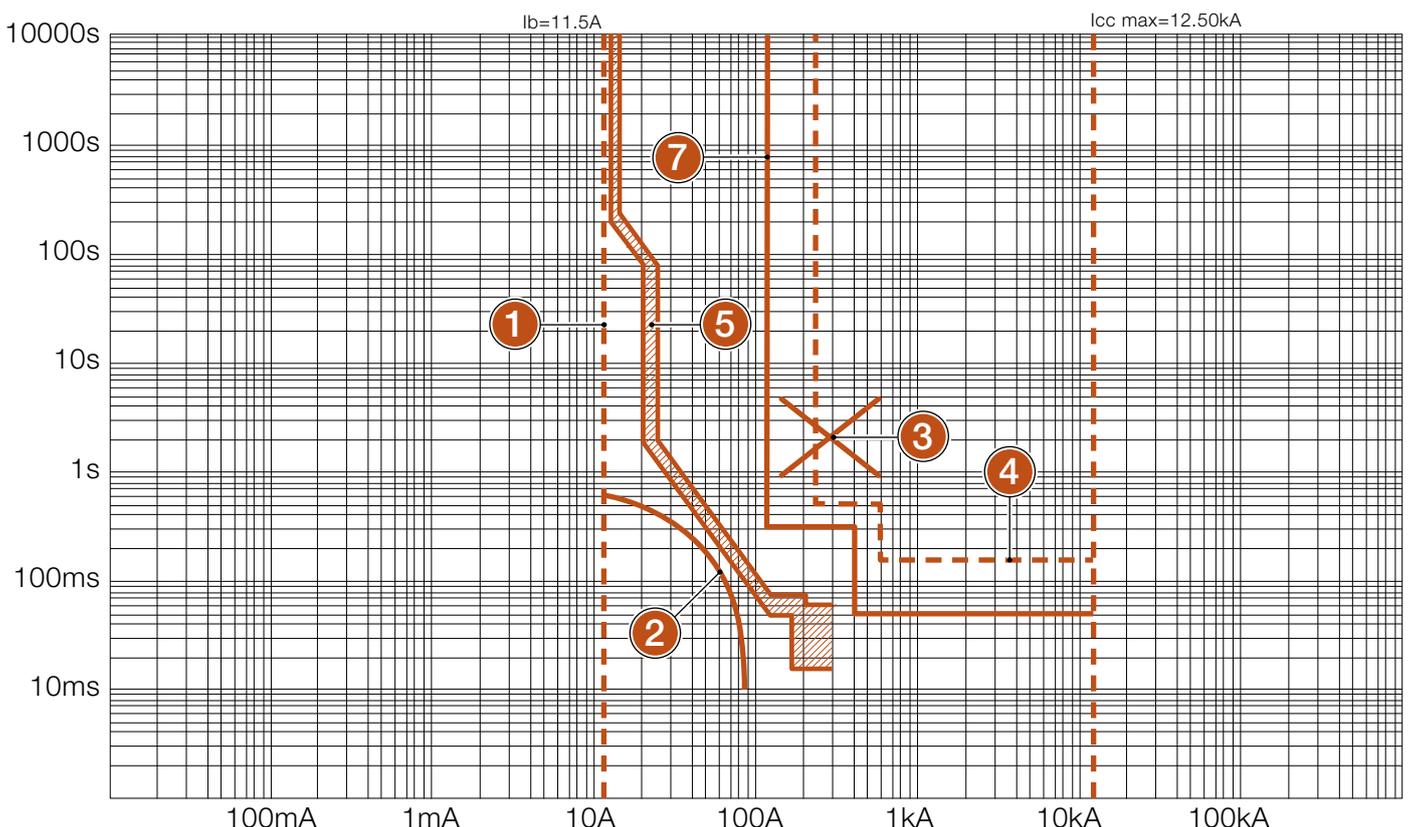
- first threshold disabled
- the setting of the second threshold must be higher than the regulated current of the second threshold S of the LV circuit breaker that in relation to the primary is 23 A. Applying the tolerance we get 27.6 A.
- e selective in general with the LV circuit breakers
- must trip in less than 2 s on the short-circuit current  $I''_{kMV} = 300$  A (held on the short circuit of the transformer)

- the time must in any case be less than the value of 0.5 s set for the second threshold,
- have the setting of the third threshold greater than the short-circuit current due to a fault in LV. In this regard, the standard recommends adopting, for protection devices installed at the two ends of a non-negligible impedance circuit, such as the transformers, a coefficient  $\alpha$  by which to multiply the initial short circuit current in order to obtain selectivity between the two devices upstream and downstream. The coefficient takes into account the asymmetry of the current and varies for the transformers from 1.2 for 50 kVA transformers to 1.6 for 2500 kVA transformers. Therefore we need to set the second threshold to a value greater than  $1.4 I''_{kMV} = 1.4 \cdot 300 = 420$  A.
- and lastly, it must be less than the set value of 600 A and with a time less than 0.12 s.

We therefore obtain the curve (7) where:

- $I_{>}$  disabled
- $I_{>>} = 120$  A,  $t_{>>} = 0.3$  s
- $I_{>>>} = 416$  A,  $t_{>>>} = 0.05$  s

**Time-Current Curve, Three-phase fault @ 20000V**



Only the relay of the general device DG still needs to be set.

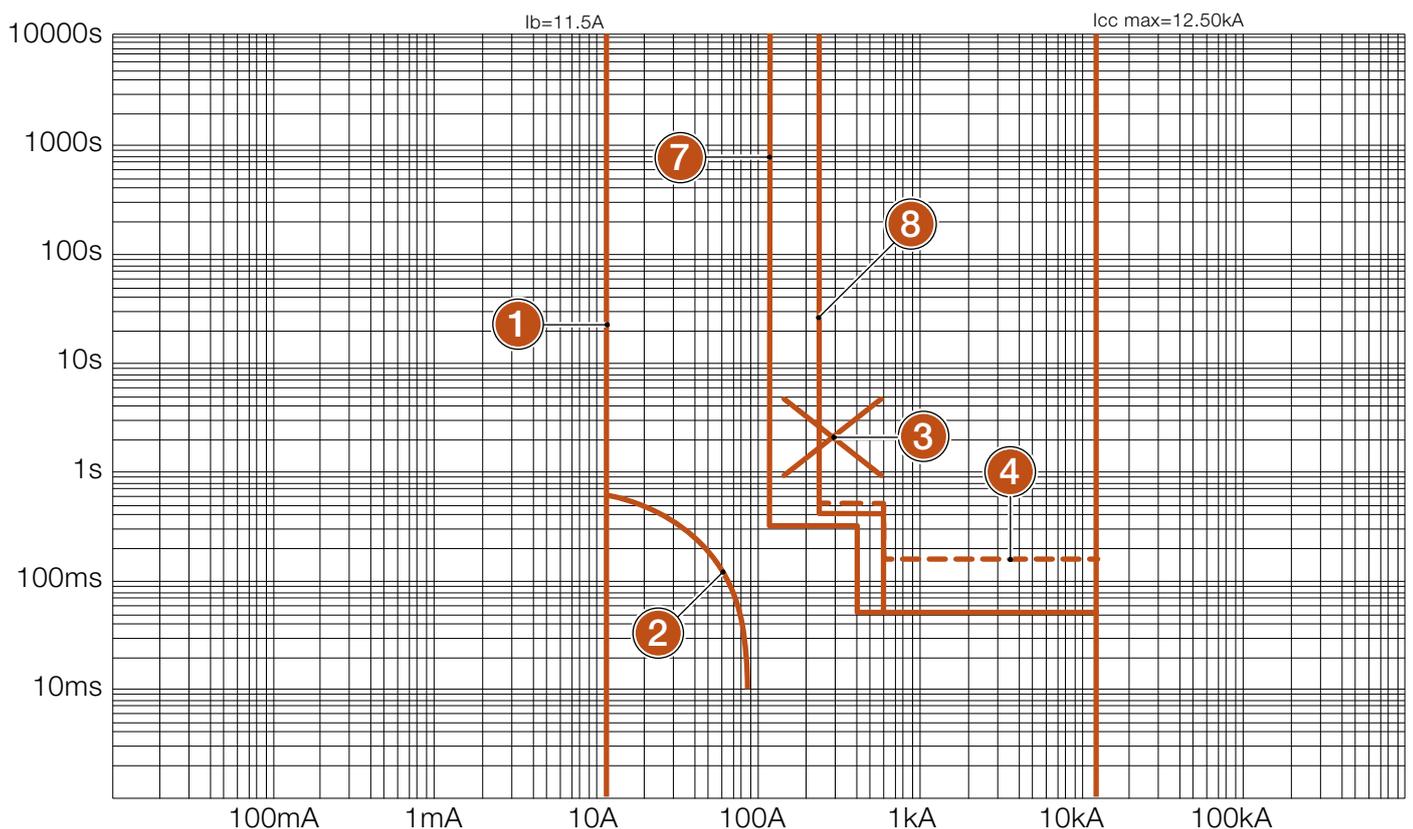
The setting must meet the following requirements:

- comply with the limits set
- be selective with the protections of the two circuit-breakers protecting the transformers
- protect the section between the delivery point and the transformers

Since this is the last step of selectivity required, we get the two current settings to match the specifications of the standard, in other words 250 A for the second threshold and 600 A for the third (the first is always disabled).

As regards timing, we will select 0.4 s for the second threshold and 0.05 s for the third (8).

### Time-Current Curve, Three-phase fault @ 20000V

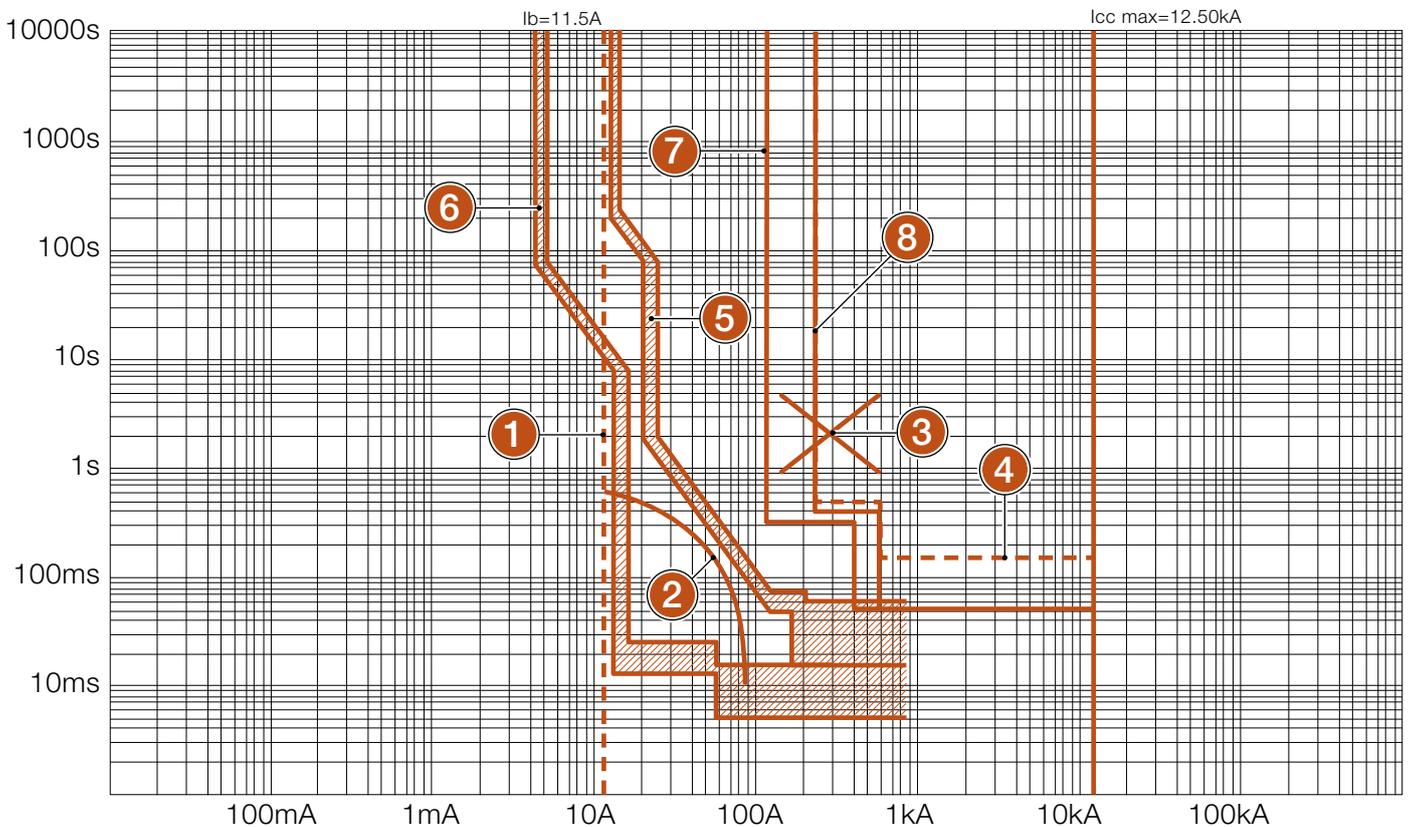


# 14. Example of substation design - electrical part

It can be noted that, having already selected an instantaneous value of 0.05 s as the tripping time for the MV transformer protection (7) for the third threshold, it is not possible to obtain selectivity over the whole range of short-circuit currents. Above 600 A, therefore, both the circuit-breakers of the transformers and the DG will trip. However we can

note that the selectivity covers the entire field of short circuit currents in low voltage (600 A in relation to the primary) and we will still have selectivity for faults in MV up to the third protection threshold of the DG. The chart below provides a general summary of the coordination study:

**Time-Current Curve, Three-phase fault @ 20000V**

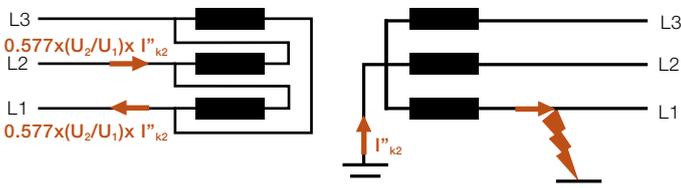


We will now check the coordination of the earth fault protections.

In the case of a transformer with a delta-star connection with earthed neutral, a phase-earth fault on the secondary side gives rise to a line current on the primary side that is equal to  $1/\sqrt{3} = 0.577$  times the three-phase fault ( $I''_{k2}$ ).

Consequently the setting of the first or second current threshold of the relay on the MV side should be  $< 0.577 I''_{k2}$ . In our case, we have  $I''_{kLV} = 15 \text{ kA}$  corresponding to  $I''_{kMV} = 300 \text{ A}$  on the primary and therefore  $300 \times 0.577 = 173 \text{ A}$ . The fault current is therefore higher than the threshold of 120 A set for the MV protection of the transformer (curve 7) which will trip for earth fault currents on the LV side greater than:

$$120 \times (20000/400) / 0.577 = 10397 \text{ A}$$



As regards, instead, the earth fault on the transformer and on the medium voltage riser, the protection will not only have to protect the transformer but also respect the limits imposed by the Distributor and by the standard. In our example, the Information letter from the Distributor said:

- Single-phase earth fault current: 50 A
- Single-phase earth fault clearance time: 10 s
- Double earth fault clearance time: < 0.2 s

In addition, standard CEI 0-16 requires the following for networks with compensated neutral:

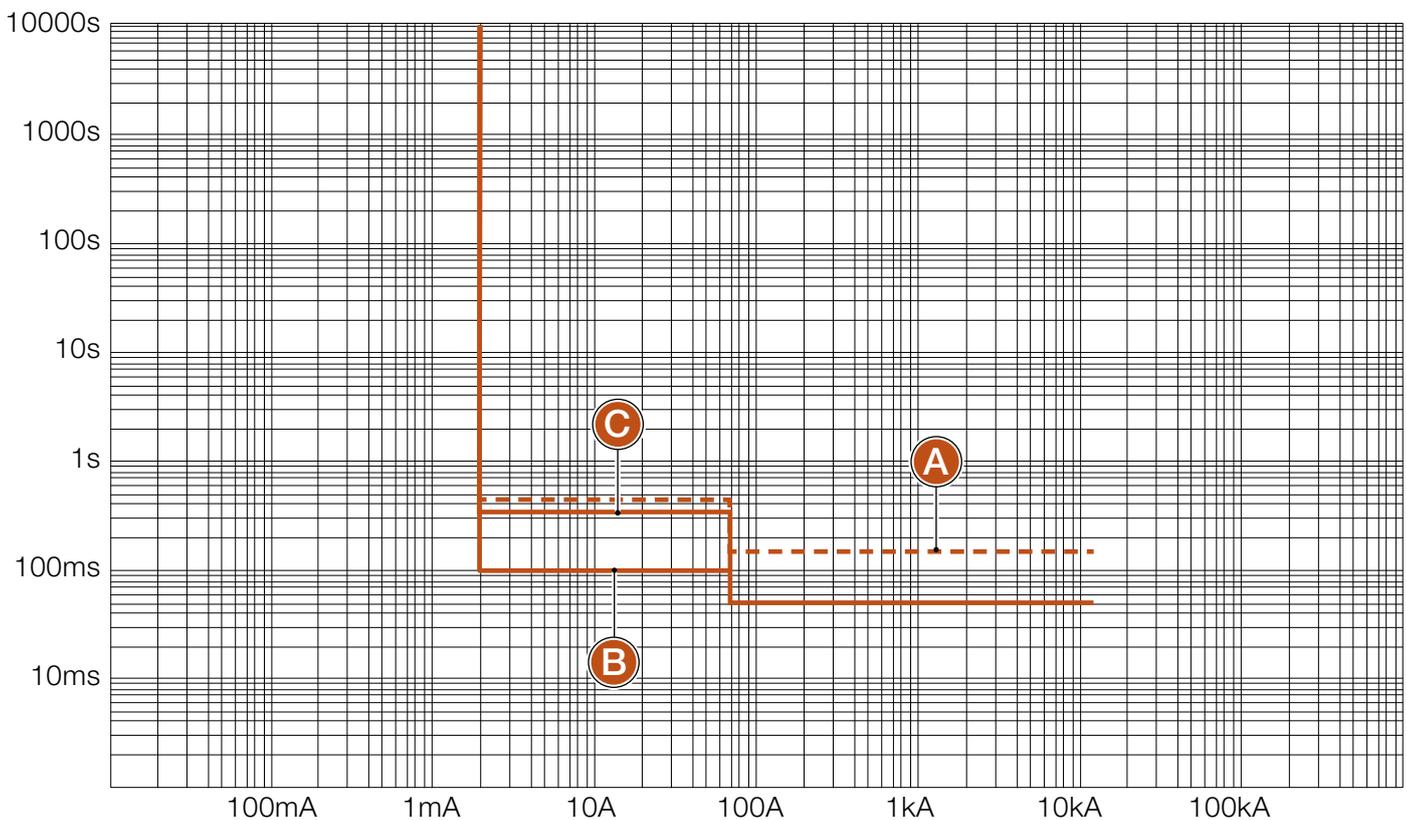
$I_{o>}$	<b>Homopolar overcurrent protection</b> first threshold (for networks with compensated neutral)	$\leq 2$ A, fault extinction time $\leq 450$ ms
$I_{o>>}$	<b>Homopolar overcurrent protection</b> second threshold (for networks with compensated neutral)	$\leq 70$ A (140% of the single-phase earth fault current communicated by the Distributor = 50 A); fault extinction time: $\leq 170$ ms

The limits set are highlighted in curve (A).

Then we set the first threshold  $I_{o>}$  on the required current of 2A with the lowest time allowed by the REF601 protection for the first threshold, in other words 0.1 s. The second threshold  $I_{o>>}$  will once again be set to the limit required by the Standard of 70 A ( $50 \times 1.4$ ) and with an instantaneous set to 0.05 s (curve B).

Finally, we set the protection of the DG so that it is, if possible, selective with that of the transformer. Therefore we leave the two current settings at the values set by the Distributor (2 A and 70 A) and we set the time of the first threshold to the maximum allowed value (0.45 s) less the tripping time of the circuit-breakers, let's say 0.35 s. Lastly we set the second threshold again to the set value of 70 A and with tripping time set again to the instantaneous value of 0.05 s (curve C). Selectivity on the second threshold is not guaranteed, but the protections are in any case selective up to the fault current value provided by the Distributor.

**Time-Current Curve, Phase to earth fault @ 20000V**



# 15. Conclusion of the example and selection of the switchgear: the ABB offer

For the example given, we can summarize the choices made and define the necessary switchgear.

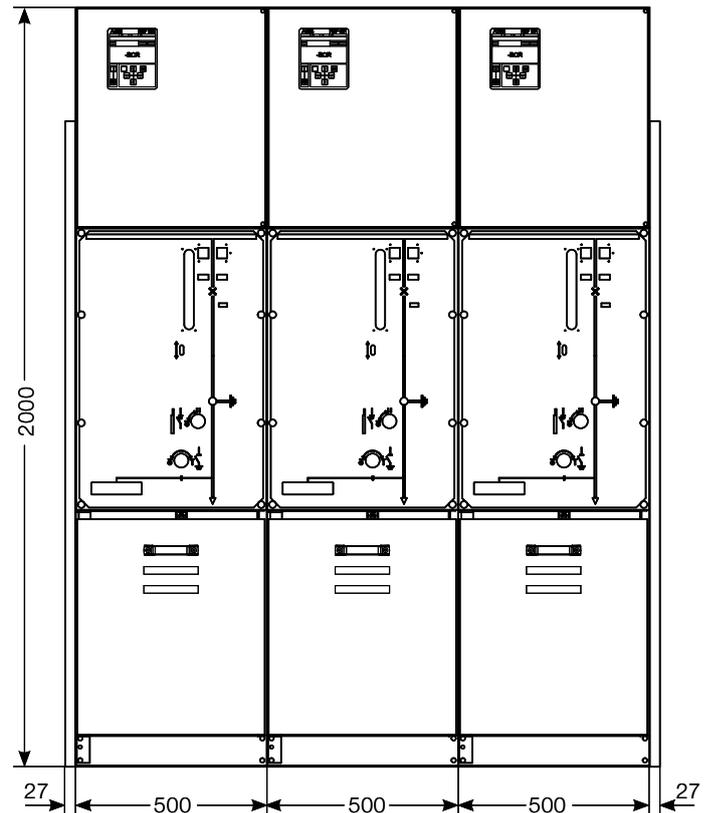
## Medium voltage switchgear:

- The installation on the MV side, downstream of the delivery point, will be implemented using an ABB UniSec switchgear. The switchgear consists of 1 Incoming line with HBC Unit and HySec multifunction device + 2 transformer startups with HBC units equipped with HySec multifunction devices.
- Since the protection 67N is not required, the protections are of the type REF601.
- The DG unit is equipped with KECA 250 B1 approved current sensors and a 100 A toroidal CT TO11S3.
- The transformer starting units are equipped with a 30A CT and 100 A toroidal CT TO11S3.

In particular, we will have the following series of components:

### HBC CEI 0-16 Incoming Unit

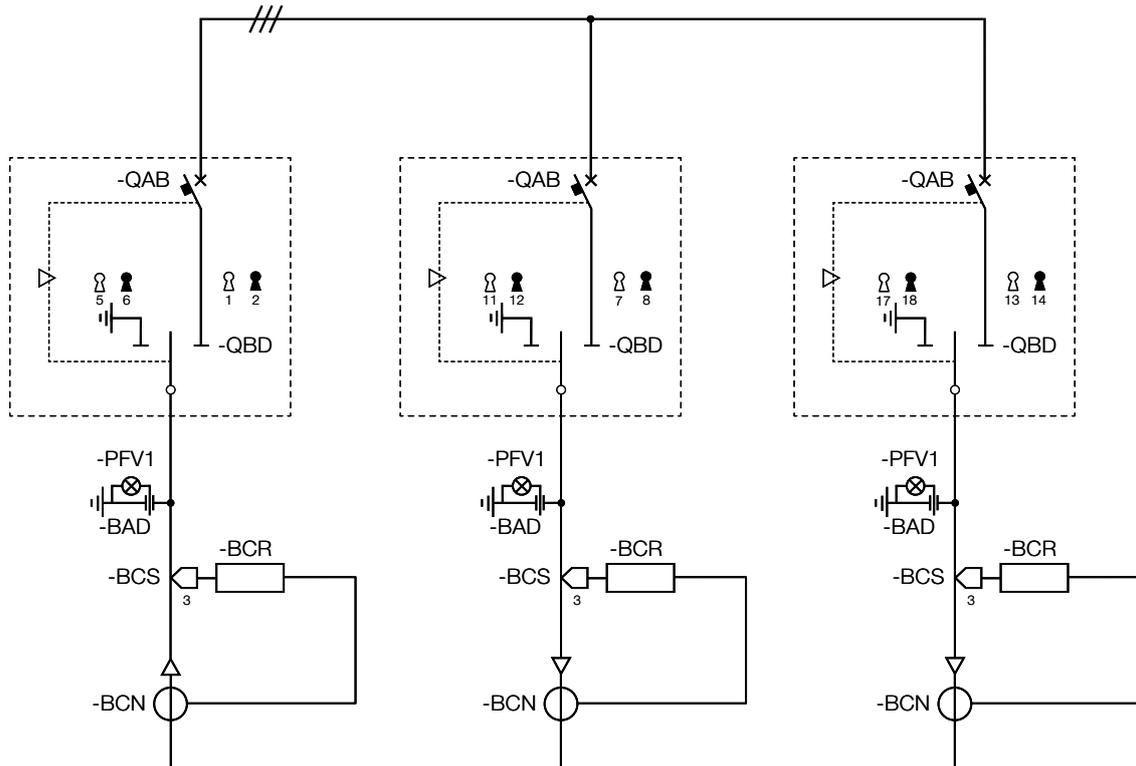
- Presence of voltage on the cable side.
- HySec p230 multifunction switchgear consisting of:
  - Vacuum circuit-breaker without motorization and with opening release, closing release, operation counter, and auxiliary contacts 6NO + 6NC;
  - Disconnecter in SF<sub>6</sub> with:
    - 1 removable key with feeder disconnecter in closed position and 1 removable key in the open position;
    - 1 removable key with earthing switch in closed position and 1 removable key in the open position.
  - Earthing switch on the distributor side with a key that is the responsibility of the distributor, according to the Standard CEI 0-16.
- Protection relay REF 601 with Data Logger, Modbus communication RS 485 serial output (51, I<sub>></sub>; 51, I<sub>>></sub>; 50, I<sub>>>></sub>; 51N, I<sub>o></sub>; 50N, I<sub>o>></sub>, 68) with 3 current sensors and toroid for earth fault, conforming to Standard CEI 0-16.



### Transformer starting unit

- Presence of voltage on the cable side.
- HySec p230 multifunction switchgear consisting of:
  - Vacuum circuit-breaker without motorization and with opening release, closing release, auxiliary contacts 6NO + 6NC and , operation counter;
  - Disconnecter in SF<sub>6</sub> with:
    - 1 removable key with feeder disconnecter in closed position and 1 removable key in the open position;
    - 1 removable key with earthing switch in closed position and 1 removable key in the open position.
- Protection relay REF 601 without communication (51, I<sub>></sub>; 51, I<sub>>></sub>; 50, I<sub>>>></sub>; 51N, I<sub>o></sub>; 50N, I<sub>o>></sub>, 68) current sensors and toroid for earth fault, conforming to the IEC Standard.

Overall dimensions (HxLxP) [mm]: 2000x1554x1248;  
the wiring diagram of the switchgear is shown below.



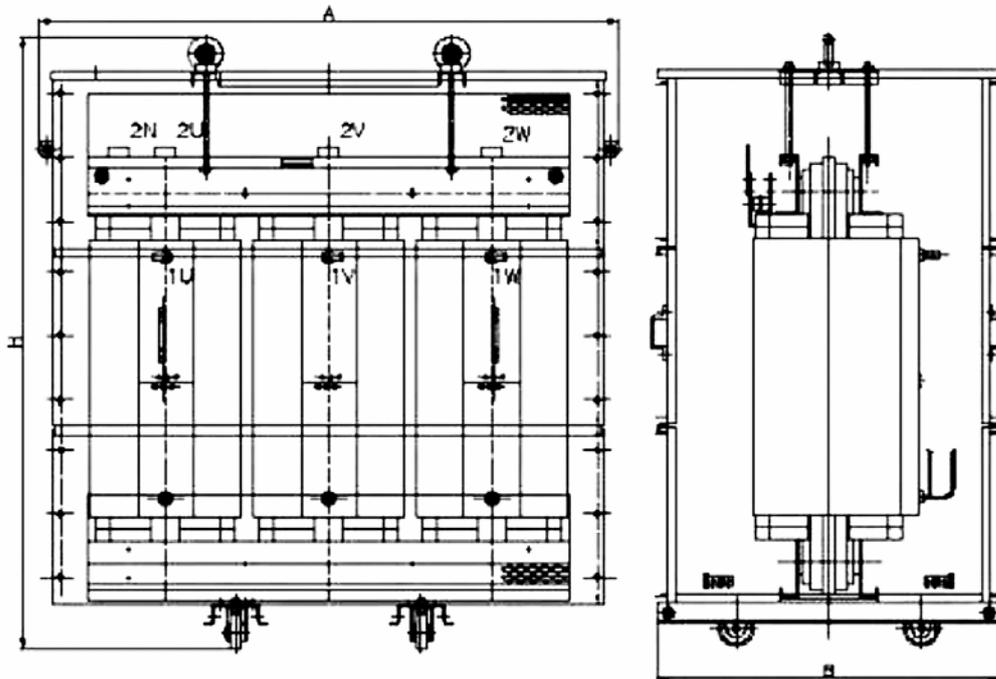
For venting of gases resulting from an internal arc fault, the most technically appropriate solution to prevent the escape of hot gases and the creation of overpressures inside the substation is to require release to the outside of the room. In this case a suitable gas exhaust duct must be provided, paying attention to accessibility by persons to the gas exit zone and protecting the end of the duct so as to prevent water, dust, small animals and foreign bodies from getting in.

A less expensive option is to request the switchgear with units with filters for withstanding the arc. In this case, the gases are conveyed into the filter, which cools them and lowers the pressure before they are released into the room. In the example shown the second solution was selected.

# 15. Conclusion of the example and selection of the switchgear: the ABB offer

## Transformers

Two 400 kVA MV/LV 20/0.4 kV dry transformers with windings encased in resin, type ABB hi-T Plus, primary delta ( $\Delta$ ) winding and secondary earthed star winding ( $\text{Y}_n$ ). Class F1 class in order to reduce the fire risk.



### Guaranteed values

Reference standards	IEC 60076, EN 50541-1 EU Regulation 548/2014 – Eco Design	
No-load losses, $P_o$	[W]	750 (+ 0 Tol.)
No-load losses, $P_k$ at 75 °C	[W]	4840 (+ 0 Tol.)
No-load losses, $P_k$ at 120 °C	[W]	5500 (+ 0 Tol.)
Sound power level $L_{wa}$	[dB]	60

### Preliminary values IP00

Length (Approx.)	[mm]	1546
Width (Approx.)	[mm]	826
Height (Approx.)	[mm]	1565
Wheel base (Approx.)	[mm]	670x670
Diameter of wheels (Approx.)	[mm]	125
Total weight	[kg]	1680

### Low voltage switchgear

ABB low voltage switchgear, type ArTù K, IP65, equipped with the following circuit-breakers:

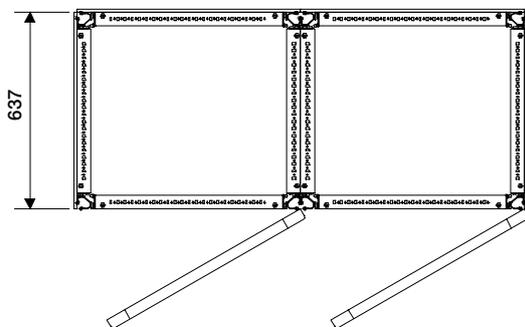
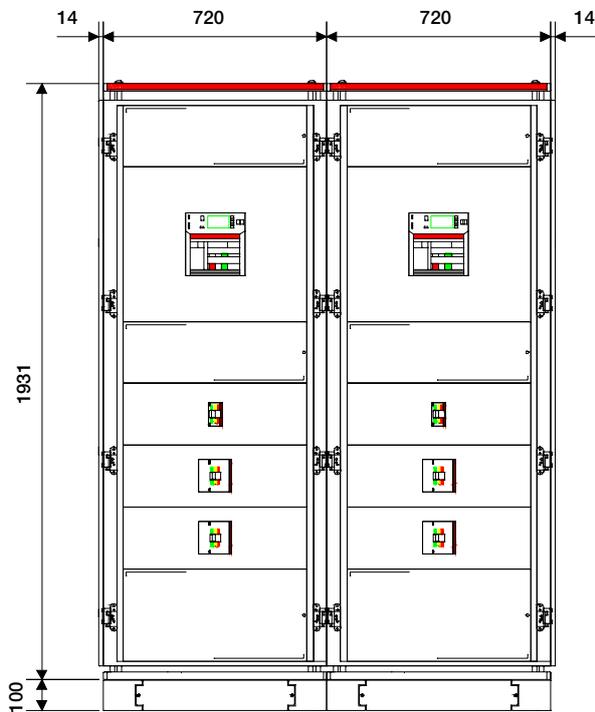
2 air circuit-breakers, Emax new series, type X1B 630 with release PR332/P LSIG In=630 A

4 moulded-case circuit-breakers, Tmax series, type T4N 250 with release PR221DS-LS/I In=250 A

2 moulded-case circuit-breakers, Tmax series, type T2N 160 with release PR221DS-LS In=250 A

Overall dimensions (HxLxP) [mm]: 2031x1468x637

With these switchgear the space required for the User room of the substation is now well defined.



# 15. Conclusion of the example and selection of the switchgear: the ABB offer

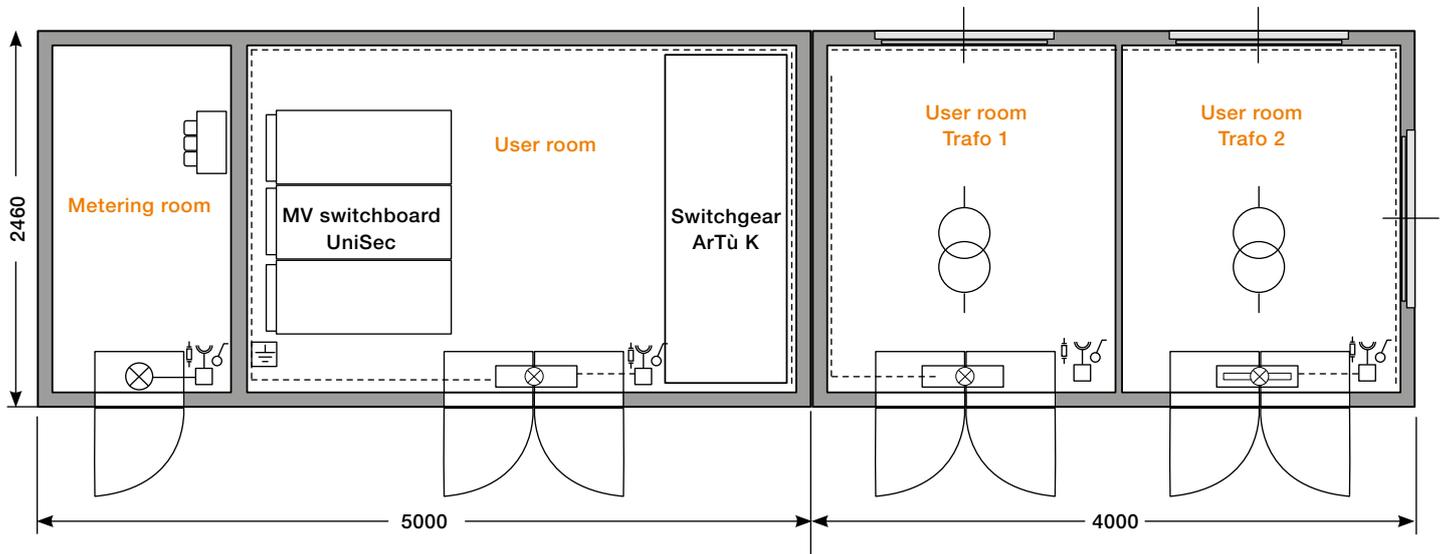
## Prefabricated substation

To conclude the example, to avoid any structural problem or failure to comply with laws and regulations, we will assume that a prefabricated substation is chosen.

This type that will contain the switchgear consists of two modules, one containing the metering room and the User room with the UniSec MV switchgear and the ArTù K LV switchgear. The second module containing the two MV/LV transformers placed in separate room and with independent access, in order to be able to carry out separate maintenance on one without de-energizing the other.

The foundation is also prefabricated in such a way that the interspace created between the bottom of the foundation and the floor of the substation can be used for laying MV/LV cables, avoiding the design and construction of a foundation built on site complete with conduits.

The two modules finally be coupled to a monobloc with the Distributor room that complies with the technical specifications of the Distributor.





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