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MV/LV plants at the service of the industry: design methodology, disciplinary aspects, energy management

TESI DI LAUREA MAGISTRALE IN
ELECTRICAL ENGINEERING
INGEGNERIA ELETTRICA

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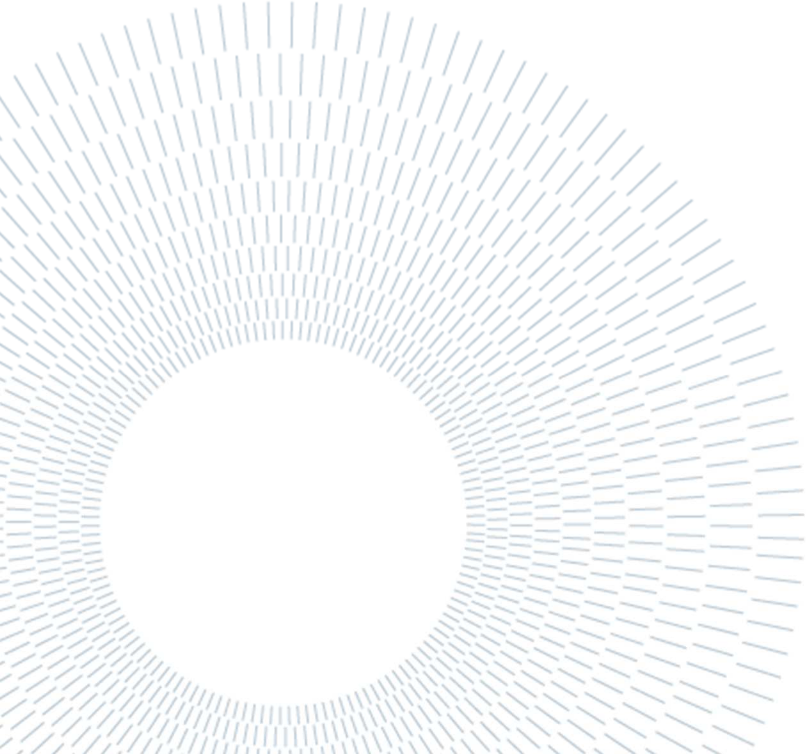


Abstract

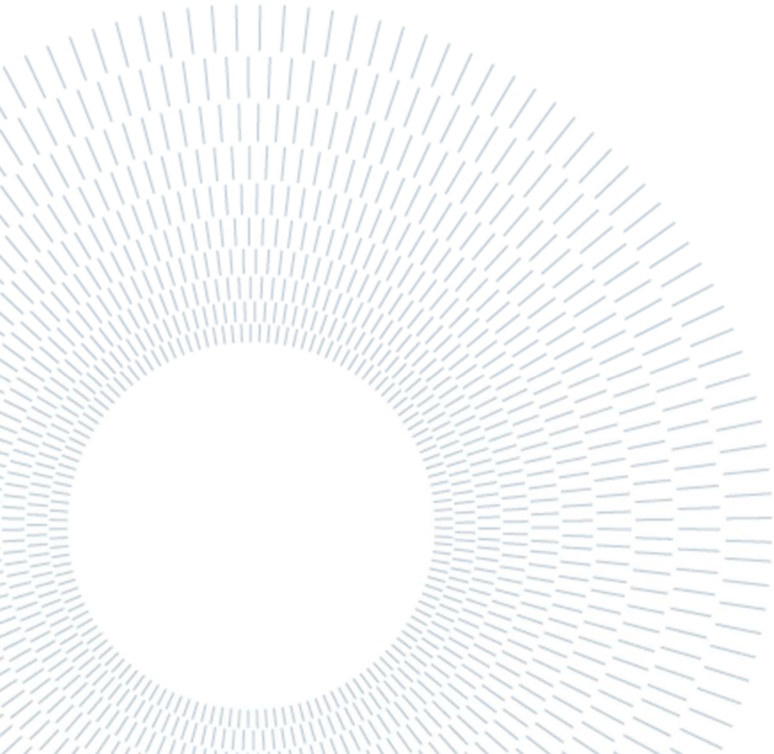
The aim of this thesis is to demonstrate how the electrical system of an industrial plant powered at Medium Voltage (MV) is designed, complying with current regulations. The first part of the work consists of a brief introduction on the structure of the national power grid and some theoretical references regarding electrical systems, illustrating the general structure and function of the plant in question. Then, the evaluation of the configuration of the electrical system to be adopted and the research of the electrical barycentre are discussed, along with the sizing of the main electrical machines. The development of the Low Voltage (LV) network is then presented, integrating the considerations related to the energy and economic aspects of self-production through PV solar panels. A comparison of the data with the results obtained using the DOC software provided by ABB S.p.A. is proposed, which has highlighted the effectiveness of the design and its ability to ensure efficient and economical production, in compliance with safety and environmental regulations. Finally, it is shown how the coordination of protections and the concept of selectivity have been implemented based on the directives provided by the distribution system operator and the CEI standards.

Keywords: MV/LV industrial plants, electrical system design, sizing, protections coordination, selectivity study

Abstract in italiano

L’obiettivo di questa tesi è mostrare come viene effettuato lo studio della progettazione di un impianto elettrico industriale MT/BT alimentato in Media Tensione (MT), nel rispetto delle normative vigenti in materia. La prima parte dell’elaborato consiste di una breve introduzione sulla struttura della rete elettrica nazionale e alcuni richiami teorici riguardanti gli impianti elettrici, illustrando poi la struttura generale e la funzione dello stabilimento in oggetto. Dopodiché, si passa alla valutazione della tipologia impiantistica da adottare e alla ricerca del baricentro elettrico necessario alla costruzione della rete MT, con il conseguente dimensionamento delle principali macchine elettriche. Segue poi lo sviluppo della porzione di rete in Bassa Tensione (BT), integrata dalle considerazioni riguardanti l’aspetto energetico ed economico legato all’autoproduzione mediante pannelli solari. Viene poi proposto un confronto dei dati con i risultati ottenuti mediante l’utilizzo del software di calcolo chiamato DOC di proprietà di ABB S.p.A., il quale ha evidenziato l'efficacia della progettazione e la sua capacità di garantire una produzione efficiente ed economica, nel rispetto delle norme di sicurezza e dell'ambiente. Infine, viene mostrato come il coordinamento delle protezioni e il concetto di selettività sono stati implementati sulla base delle direttive fornite dall’ente distributore e delle norme CEI.

Parole chiave: impianti industriali MT/BT, progettazione impianti elettrici, dimensionamento, coordinamento delle protezioni, studio di selettività



Contents

Introduction

Industrial plants are characterized by a committed power that covers a wide range, which goes from a few hundred kW to a few tens of MW. For contractual powers up to 6MW, users are generally connected to the public grid in Medium Voltage (MV), while for powers above 6MW the supply is generally at High Voltage (HV). Even if MV-fed industries represent by far the majority of industries, not many people deal with the design of their electrical system, especially the MV part of it. The thesis will not only show the "classic" electrical design process in terms of sizing and calculations, but it will insert it in the complete industrial reality, reporting how practical problems coordinated with other disciplines can be overcome. It will be analysed the design of the plant configuration, the evaluation of the electrical barycentre, the search for absorption data as well as the simultaneity and use coefficients as real as possible, in order to avoid the risks of under-sizing components, but, at the same time, without risking to fall into the excessive caution of generalized over-sizing. Moreover, the topic of users safety will be faced and it will be described how the selectivity between protections has been implemented.

1 The structure of an MV industrial electrical system

1.1. Notes about the structure of the national electrical system

For the correct design of user systems and the understanding of regulations governing connections, it is useful to know the structure of the public electrical distribution network. As shown in Figure 1.1, the electrical system is structured in:

- Production;
- Transmission;
- Primary distribution;
- Secondary distribution.

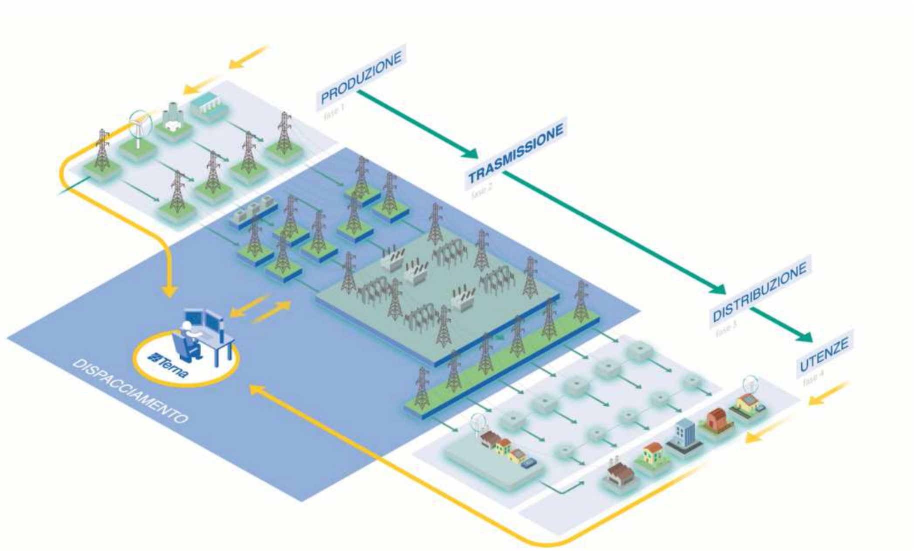


Figure 1.1: Simplified representation of the structure of the national electrical system

The production of electricity takes place in Medium Voltage (MV) at the terminals of the alternators; generally, right outside the power station, the voltage is raised to very high level, typically 220kV or 380kV (EHV). This is fundamental in order to minimize the line losses, which are mainly attributable to the Joule effect and so they are proportional to the square of the current. The transmission lines cover the entire national territory and they are interconnected with the lines of neighbouring states.

Downstream the transmission lines there are primary distribution networks, normally in High Voltage (HV) at 130kV-150kV, while the final part of the network consists of a secondary distribution network at medium voltage (MV) or Low Voltage (LV). The abovementioned sections are connected among themselves by transformer stations (EHV to HV), transformer substations or primary cabins (HV to MV) and finally by MV/LV transformer substations. In addition, stations and substations can also regulate the voltage by means of machines with variable ratio under load. All these systems are built following a three-phase configurations with three conductors, except for the LV secondary distribution (230/400V) where the neutral conductor is also distributed. In the past, the MV public distribution (1kV-35kV) took place with neutral isolated, however in the last 20 years there has been a change in favour of the earthed neutral using the Petersen coil, which has some advantages which are going to be explained in the following dedicated section. For historical reasons, the voltage levels of MV networks are not unified on the national territory; below, in a very qualitative way, the most common levels:

- 15kV: Piedmont, Lombardy (except Milan), Liguria, Emilia-Romagna, Tuscany, Sardinia, Lazio (except Rome)
- 20kV: Rome, Veneto, Trentino-Alto Adige, Puglia, Campania, Sicily
- 23kV: Milan

Nevertheless, in small limited areas, values such as 6kV, 8.9kV, 13.5kV and others can also be used.

1.1.1. The MV User

The average user who will be considered (from now on it will be called "User") has a committed power of a few MW (intended as the maximum value of the moving average based on a 15 minutes window): normally this value is less than 6MW, but there are exceptions in which it goes up to 10MW. Generally, the User is powered by the connection to the public grid located on a peripheral point of the plant area, which is called POD (point of delivery). Except for special cases, the internal User devices have a LV supply (230/400V); therefore, it is necessary to set up at least one transformer cabin downstream of the POD; nevertheless, for Users with a limited extensions, the transformer cabin may correspond with the point of delivery. More frequently, the transformer cabin is located inside the plant, theoretically in the electrical barycentre; in practice, this position is approximated due to the numerous other construction constraints (for a more detailed description, please refer to Chapter 3). The barycentric location of the transformer substations aims to optimize the LV network, both in terms of cable cost and line losses during operation, while the transport of energy from the delivery point to the electrical centres of gravity takes place in MV, so that it has small impacts due to the modest currents involved and absolutely negligible voltage drops (i.e., 6MW at 15kV with a $\cos\varphi = 0.9$, correspond to 230A). The neutral status of the

MV network is decided by the DSO (distribution system operator). As will be seen better in the following, the state of the neutral determines firstly the sizing of the earthing system and secondly the choice of the protections as well as their settings. The MV connection among the POD and the transformer cabins can be realised using a radial or a ring configuration. The ring configuration is generally preferable by virtue of the following advantages:

- Reliability: a fault on one side of the ring can always be isolated with simple manoeuvres and it is not required any plant downtime in order to fix it;
- Flexibility: the network can be easily adapted or modified without having to interrupt the entire network, which means that it is possible to do maintenance on line components or add other cabins inside the ring without shutting down production;
- Improved performance: the ring configuration can increase the load capacity and reduce voltage drop along the network.

However, this configuration has some disadvantages compared to the radial one, such as:

- Installation costs: the ring configuration requires more equipment and cabling than other configurations, which means higher installation costs.
- Complexity: the ring configuration requires proper design and planning to ensure the correct configuration of the network, which can make the system more complex to manage.
- Maintenance: the ring configuration may require higher maintenance and repair costs in case of failures or malfunctions compared to other configurations.

The natural configuration of a MV ring network originates from a double upright connection specifically ruled by the [1]. On the other hand, the radial scheme is simpler and cheaper than the ring configuration, but it has none of the advantages listed above. However, it can be recommended for small plants where significant downtimes due to MV grid failures are acceptable thanks to the lower initial investment.

1.2. The electrical design

The design process of the electrical system of an industrial plant starts from a "creative" phase where a plant structure is outlined and it must:

- Meet the power supply needs of all the users;
- Comply with all the type of constraints, including the technical standards;
- Minimize installation costs, network losses and the occupation of technical spaces;
- Selectively isolate faults;
- Optimize future maintenance.

In this process, the theory of electrical engineering and electrical systems is obviously an indispensable support, although insufficient on its own. The key element in the definition of the plant structure is the preparation and the experience of the engineer who must synthesize a considerable amount of information to reach the operational proposal of a specific plant. Following the creation of the plant structure, calculations and sizing can be developed also automatically through specific software, however the creative process of plant design cannot be done without considering the preparation and professionalism of the designer.

1.3. Energetic aspects, purchase and self-production

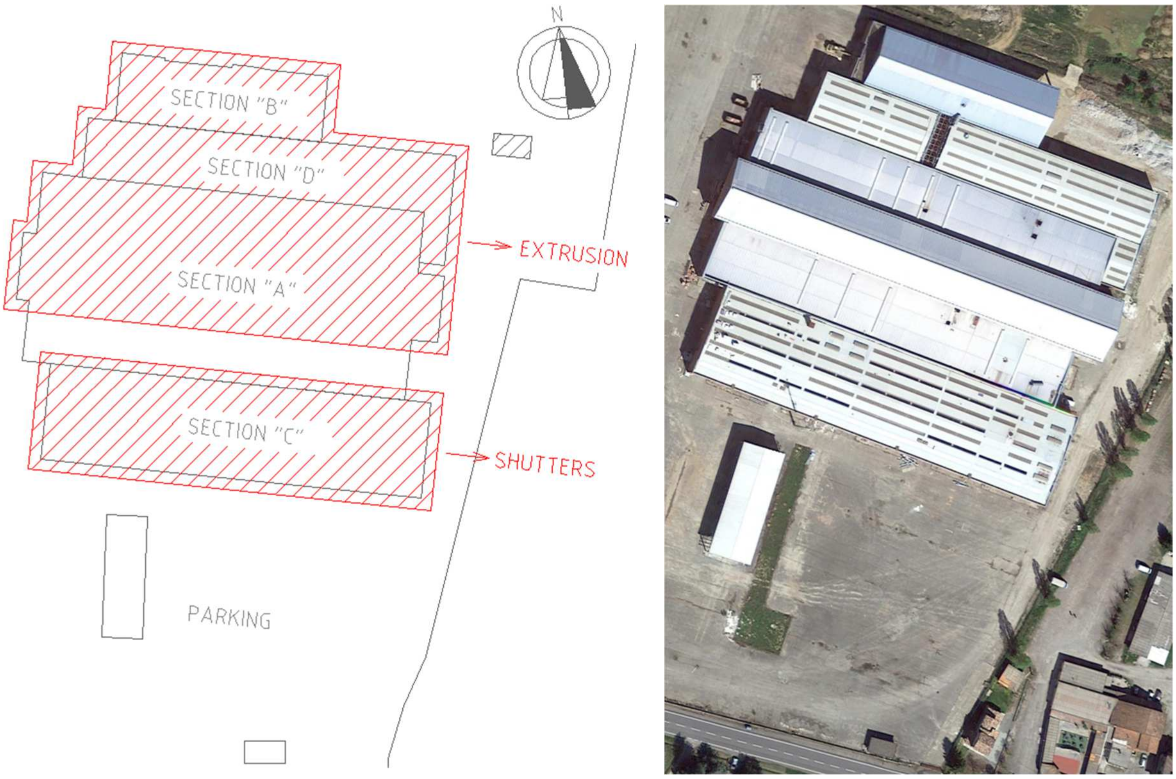
The energetic aspect of an industrial plant should be assessed as a whole by an energy expert in order to:

- Avoid or minimize waste;
- Seize all possible synergies of the site (i.e., recover the heat wasted by the process);
- Evaluate cogeneration opportunities (Electricity and Heat) or trigeneration opportunities (Electricity, Heat, Cold);
- Assessing independent electricity production;
- Choose the form of energy to be used where possible among several alternatives (e.g., gas or electricity)

It will also be seen in the case study that in the evaluation of energy aspects, the electrical part always takes a leading level.

2 Layout and production cycle

The case study concerns the restoration of an old industrial structure previously used for the production of bricks and other masonry items. The plant is mainly composed of four sections with a total area of about 20,000m^2, within which two main processes take place. The structure is divided into two departments: one is called Shutters department or "S", while the other is called Extrusion department or "E". Both represent the vast majority of the power consumption required by the overall system and are distributed within the building as seen in Figure 2.1.



(a) Simplified layout showing the departments division inside the facility

(b) Satellite image of the facility

Figure 2.1: Overview both of the inside and the outside of the facility to be studied

The Shutters department has a reduced size compared to the Extrusion department and it also has much less impact on the total energy demand of the plant. Moreover, the section concerning the extrusion of aluminium is more interesting for the purposes of the study, since that is the site of the main process carried out in the structure.

2.1. Aluminium extrusion

The production cycle starts with the arrival of "logs," which are 7-meter-long aluminium bars with an 8-inch diameter. The log is loaded onto a rail and pushed into the first oven. Inside the oven, the log is heated to different temperatures along its length: it reaches 230°C in the first part and 450°C at the end, so that it becomes pasty and easier to work with. Once heated, a portion of the aluminium bar up to 1280mm long is made to come out of the oven and cut using a saw; this type of cut prevents the material from deforming, thus preserving its mechanical properties. It is crucial that this step occurs as quickly as possible for two reasons: the first concerns the speed of the production cycle, while the second is related to energy consumption. During the cutting phase, the oven remains open, releasing heat and lowering the internal temperature. This results in an increase in gas consumption needed to maintain the oven at an adequate temperature for processing. The cut piece is transported on a platform called a "manipulator," where it is positioned correctly to continue the cycle by entering the press (from now on, the aluminium piece is called a billet). The billet is inserted into a container to preserve its temperature as much as possible, and a piston pushes it against the die to obtain the desired shape. Moreover, this process is carried out in such a way that impurities present in the material are concentrated in the final part of the billet, which will then be cut before continuing the processing cycle. After exiting the die, the billet has a very high temperature (about 550°C), so there is a risk of material deterioration or geometric deformation. To counter this problem, fluids (water or nitrogen) are used to keep the temperature under control. After passing through the press, the billet is pulled by a machine called a "puller," which pulls the aluminium to elongate it to the desired size (up to 63 meters) on a roller cooled by air and water. During this phase, it is essential that the cooling is carried out as quickly as possible because it fixes the mechanical properties of the aluminium. However, due to the thermal shock, the aluminium profile ends up being wavy and irregular in shape; therefore, it is subjected to a stretching process that must be carried out very delicately to avoid changing its thickness, otherwise it would be compromised. Then, the profile is cut into shorter segments, which are placed in baskets and left for 8-10 hours to fix the acquired mechanical properties during the process. After the rest period, the pieces are placed inside a single-basket oven at 185°C, where they remain waiting to be packaged and stocked.

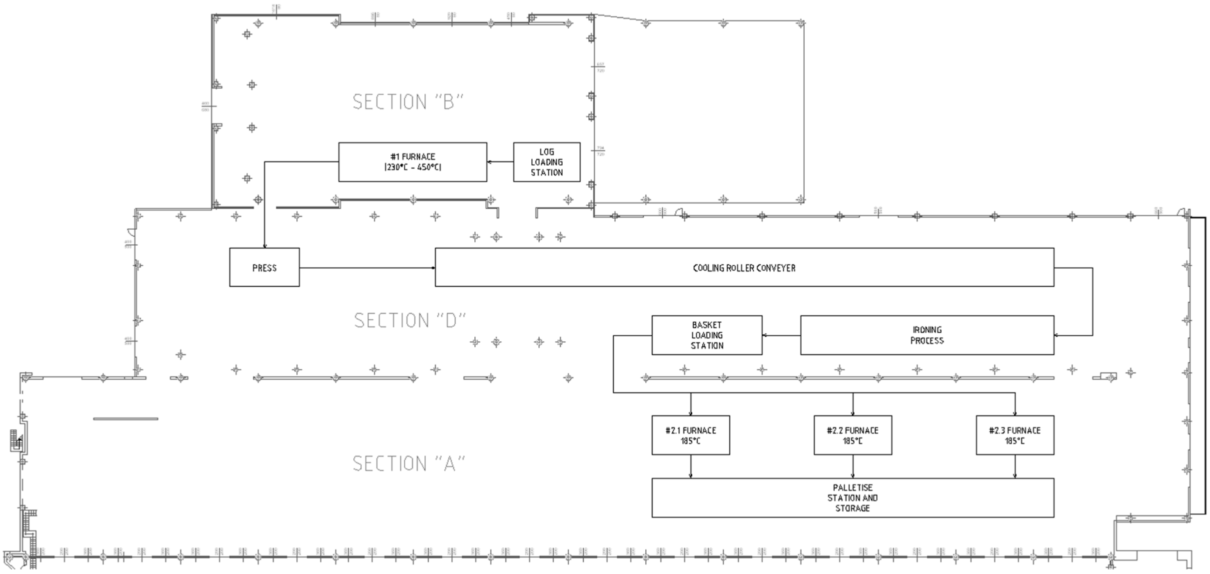


Figure 2.2: Block diagram reporting the aluminium extrusion process

3 Electric loads, electric barycentre and substations

At first glance, the calculation of electrical requirements in the production departments shows a power demand of about 3MW. The client, who manages a similar plant in another production site abroad, estimates by analogy a lower power, of the order of 2.5MW. In the following, a calculation of the power required for the correct request to the distributor (DSO) will be performed considering that the range in which the plant is located is that of a MV User, in this case 15kV. In the case study, the total electrical load is not equally divided between the two departments mentioned in the previous chapter: this is not only because of the different sizes of the rooms that contain them, but mainly because of the different power consumption of the machinery installed. In fact, for example, to carry out the extrusion process, machineries of much larger dimensions are required than those required by the other unit. Nevertheless, due to the important energy demand of both departments, two transformer substations were designed, called "C10" for the "S" department and "C20" for the "E" department. Therefore, the position of these cabins is not random, but it was determined using the electric barycentre method that defines the most strategic position in terms of costs in which to locate them. In fact, considering only the aspect related to the electrical sizing of the circuits, the substations must be positioned preferably in the centre of the system, defined as the point or region where most of the heavy loads are concentrated. In this way, it is possible to save money, considering that the lengths of the circuits are reduced, consequently reducing the voltage drops and possibly, the cross section of the conductors. Also, this will lead to a minimization of the power losses due to the Joule effect on the installed conductors. Thus, the electric barycentre of an electrical installation containing a number of loads equal to “N” is identified by X and Y coordinates, calculated from equations (3.1) and (3.2), which take into account the position and the power consumed by each significant load in the system.

$$X = \frac{\sum_{i=1}^{N} X_i * P_i}{\sum_{i=1}^{n} P_i} \tag{3.1}$$

$$Y = \frac{\sum_{i=1}^{N} Y_i * P_i}{\sum_{i=1}^{n} P_i} \tag{3.2}$$

However, the location of substations must also meet other criteria such as ease of access, functionality and security, which should be considered as a whole in order to obtain the best solution. In fact, in this case due to the positioning of the substations which is going to be showed next, one of the most concerning aspects was to guarantee the protection of the workers from exposure to electric and magnetic fields generated by electrical lines and substations at the grid frequency (50Hz). The art. 3 and art. 4 of [2], in accordance with the 2^{nd} paragraph of art. 4 of the [3], establishes that:

- the effective value of the limit of exposure to electric fields is 5kV/m, while for magnetic fields it is equal to 100μT, in order to guarantee protection against possible short-term effects;
- in children's playgrounds, living environments, school environments and in places used for stays of not less than 4 hours per day, the attention value of the magnetic field, to be intended as the median in 24 hours under normal operating conditions, is 10μT, while the quality objective is equal to 3μT, in order to ensure protection from possible long-term effects related to exposure.

That said, in order to calculate the electric barycentre, the coordinates of the loads were measured as shown in Figure 3.1.

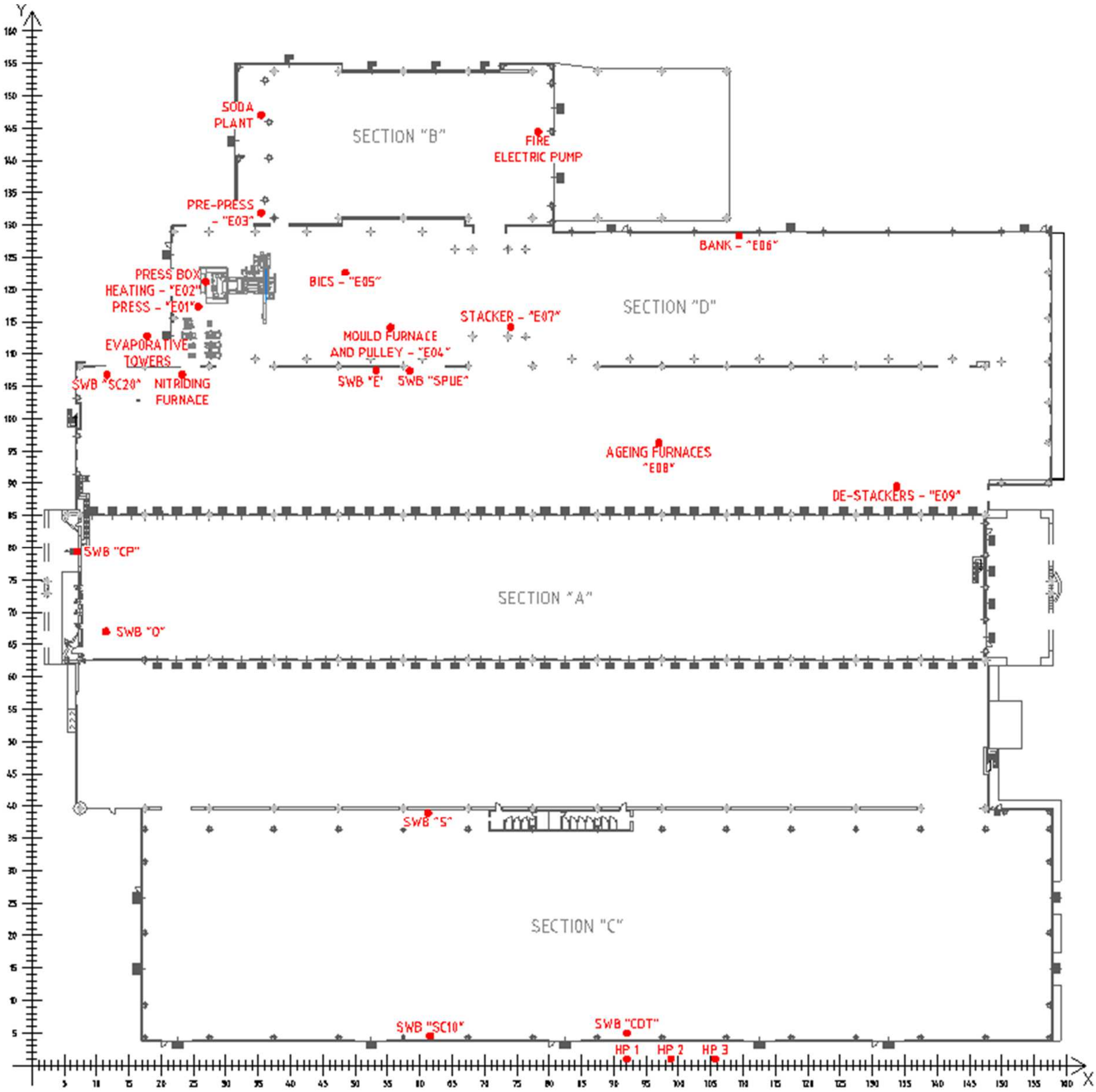


Figure 3.1: Position of the main loads inside the plant. Only the main loads were considered because the contribute of the smaller loads was deemed negligible

3.1. Shutters department – "S"

The project concerning this department provides for the transfer of it in the dedicated section of the new plant, as it already exists in another location. It is also planned to expand it in the near future, reaching an electrical power demand equal to twice the current one. Therefore, the main loads of the department are shown in Figure 3.2 and they are reported more specifically in Table 3.2, where those whose power consumption is negligible have been neglected.

Table 3.1: Coordinates and power demand of the main electrical loads in the "S" department

Description	**X**	**Y**	**Power [kW]**
Heat pump 1 – "HP 1"	92	1	80.5 kW
Heat pump 2 – "HP 2"	99	1	80.5 kW
Heat pump 3 – "HP 3"	106	1	80.5 kW
Electric panel department "S"	61	39	180 kW
Electric panel air-conditioning "CDT"	92	4,5	180 kW
Electric panel offices "O"	11.5	67	30 kW
Electric panel compressors "CP"	7	79.5	30 kW
Electric panel C10 services "SC10"	62	4.5	20 kW
		Total	681.5 kW

So, using equations (3.1) and (3.2) described previously, the optimal position of C10 substation was calculated:

Table 3.2: Theoretical optimal position of the C10 substation

	X	**Y**
Barycentre	78	18.5

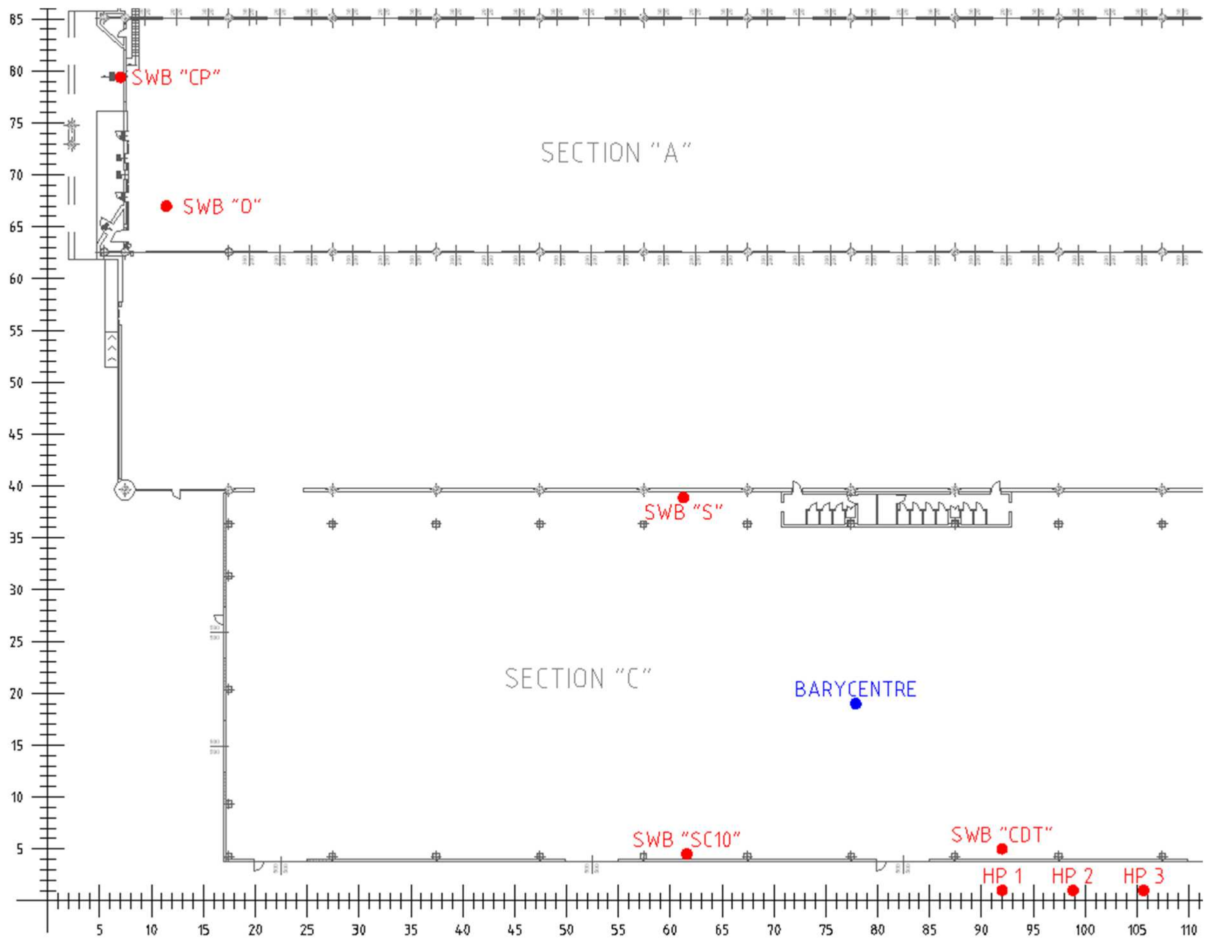


Figure 3.2: Theoretical optimal position of the C10 substation

Therefore, C10 substation should be in the theoretical coordinates given in Table 3.2, but due to the factors that cannot be considered in mathematical calculations mentioned in the previous paragraph, its position was slightly decentralised without adversely affecting the economic and energetic aspects of the projected electrical grid. In addition, the repositioning was studied in order to be in favour of the PV solar panels that will be placed in the underlying area (see Figure 2.1).

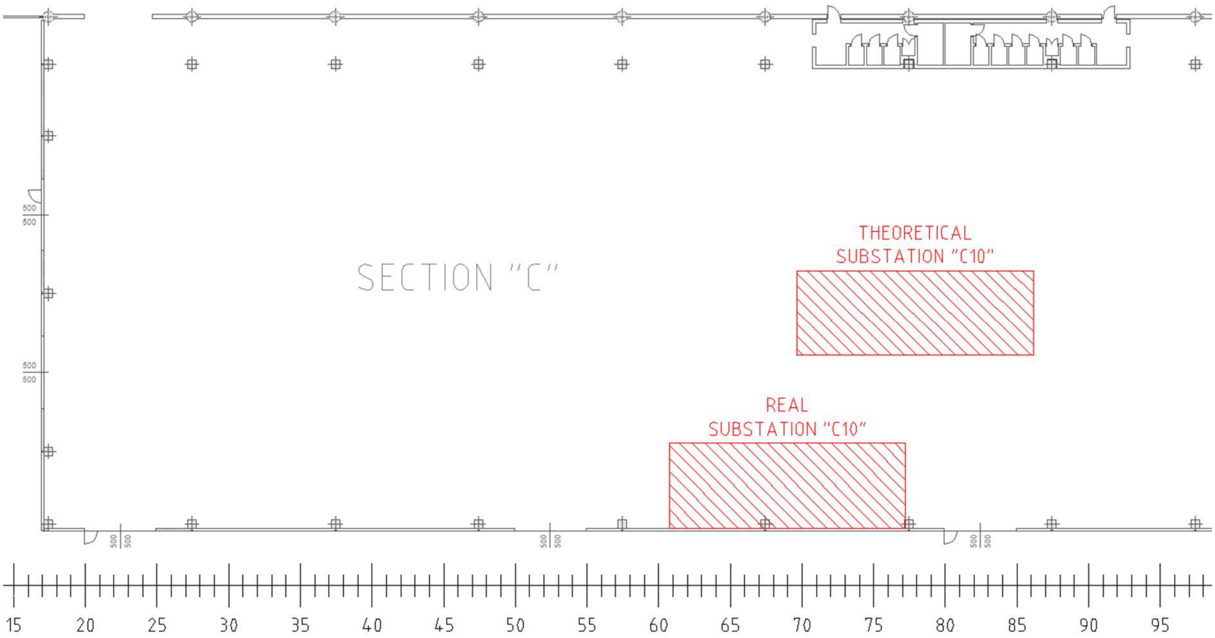


Figure 3.3: Actual position of C10 substation

This substation contains the step-down transformers and the LV switchboard called "PW10", which all the loads described previously are connected to, as well as the PV system. All these components are going to be described in their dedicated section of this thesis.

3.2. Extrusion department – “E"

In this case, the power consumption is greater than in the previous paragraph. Despite this, the process used in the design stage is the same. Hence, Table 3.3 shows the loads that will be handled by the C20 substation, so as to determine the optimal coordinates of its location.

Table 3.3: Coordinates and power demand of the main electrical loads in the “E” department

Description	X	Y	Power [kW]
Press – “E01”	26	114.5	800 kW
Press box heating – “E02”	27	121	80 kW
Pre-press – “E03”	35.5	132	110 kW
Mould furnace and pulley – “E04”	52.5	114	120 kW
Bics – “E05”	48.5	123	260 kW
Bank – “E06”	109.5	128.5	150 kW
Stacker – “E07”	74	114	100 kW
Ageing furnaces – “E08”	97	96	280 kW
De-stackers – “E09”	134	89.5	80 kW
Nitriding furnace	23	107	85 kW
Evaporative towers	18	113	66 kW
Fire electric pump	78.5	144.5	30 kW
Soda plant	35.5	147	35 kW
Electric panel department “E”	53	107.5	70 kW
Electric panel single-phase utilities “SPUE”	58.5	107.5	55 kW
Electric panel C20 services “SC20”	12	107	20 kW
		Total	2341 kW

As before, by applying equations (3.1) and (3.2), the best theoretical position of C20 substation was found.

Table 3.4: Theoretical optimal position of the substation “C20”

	X	Y
Barycentre	52	114.5

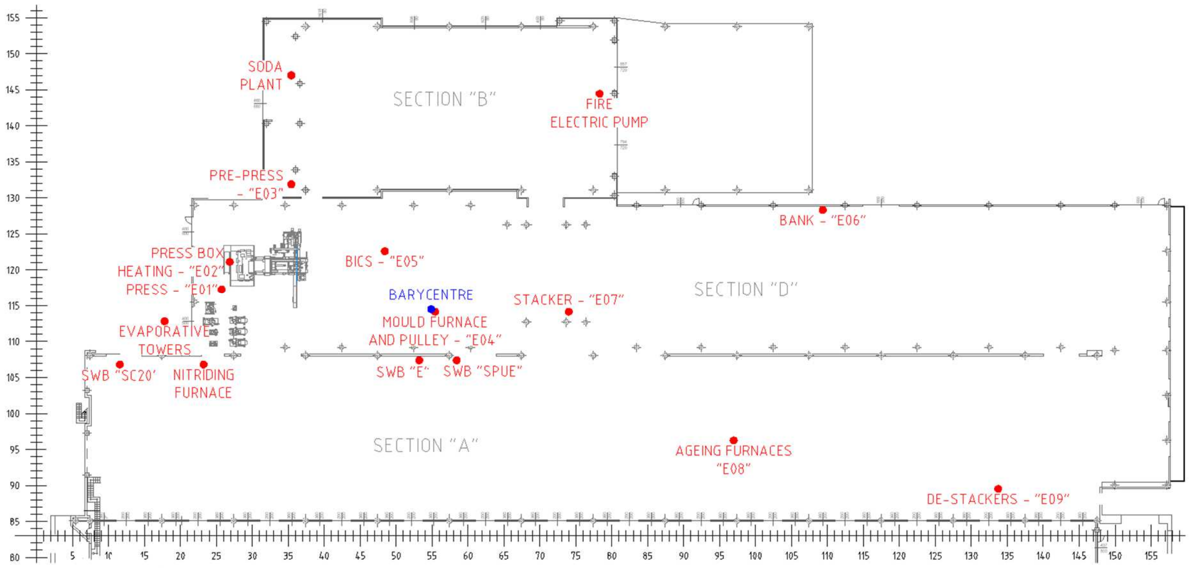


Figure 3.4: Theoretical optimal position of the C20 substation

Therefore, C20 substation should be located in the theoretical coordinates indicated in Table 3.4, but similarly to the previous case, its position does not exactly correspond to the calculated one. In fact, even in this case, the repositioning of the substation was analysed and was done in favour of the PV panels that are going to be installed in the yard next to the building, subject to spatial constraints. Despite this, even on this occasion, it did not weigh negatively on the economic and energetic aspects of the project.

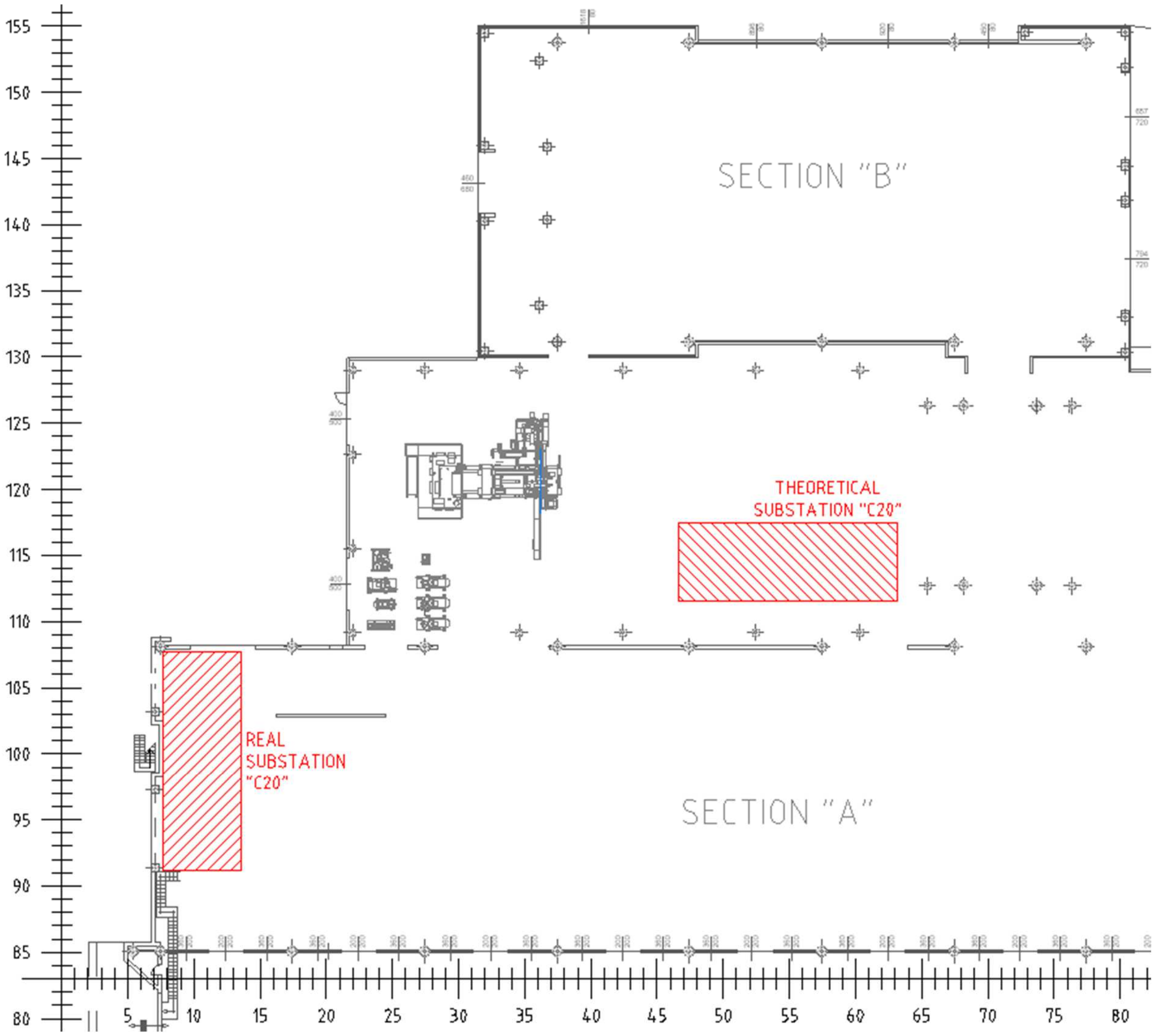


Figure 3.5: Actual position of C20 substation

This substation contains the step-down transformers and the LV switchboard called "PW20", which all the loads described previously are connected to as well as the related PV system. All these components are going to be described in their dedicated section of this thesis.

4 The Medium Voltage network

4.1. Topology and circuit diagram

In the previous chapter the location of substations C10 and C20 was reported, but there is the need of an interface cabin that connects the public grid at 15kV with the private MV network: this is the POD (Point Of Delivery) electrical room and it is called “C00”. Its position is determined according to the DSO, that gives guidelines depending on the topology of the public grid. Usually, the point of delivery is located on a perimetral point owned by the User that it is also accessible using a public path. In the case study, the position of C00 cabin is reported in Figure 4.1 and it is in line with the directives stated above.

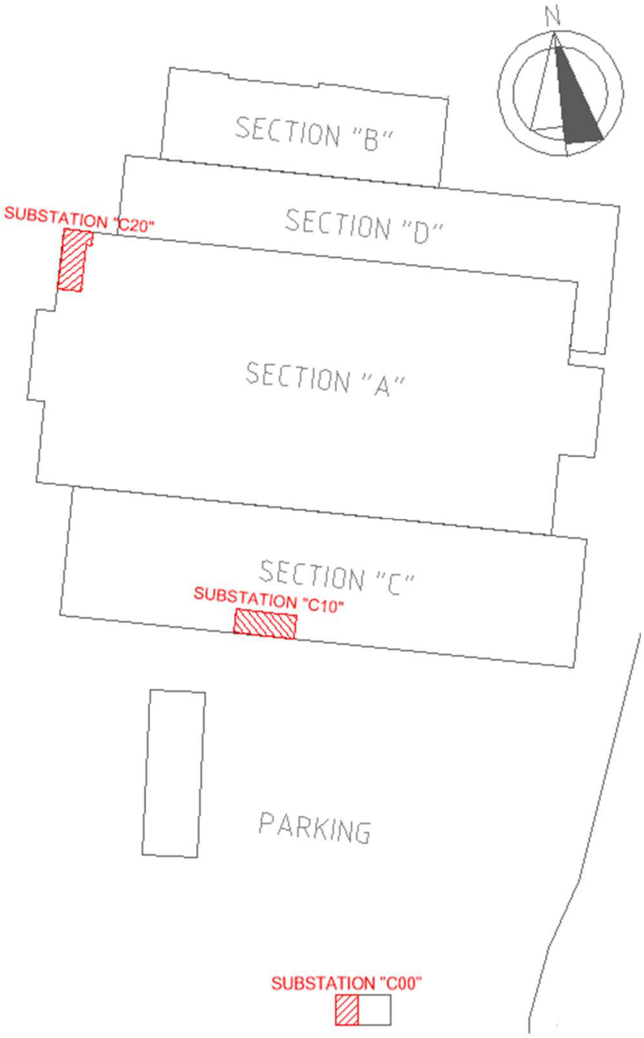


Figure 4.1: Position of all the three substations on a simplified layout. The C00 cabin is on the perimetral of the plant and it also has an access from a public path

Once that the position of the substations was decided, they were interconnected among themselves to create the MV network that will feed the plant. The MV network was designed following a ring configuration: this includes the use of a double column configuration in the MT00 switchboard (see Section 4.1.1). In this way it is possible to omit the General Device (DG), attributing its functions to the circuit breakers connected to the User busbar, which are called general line devices.

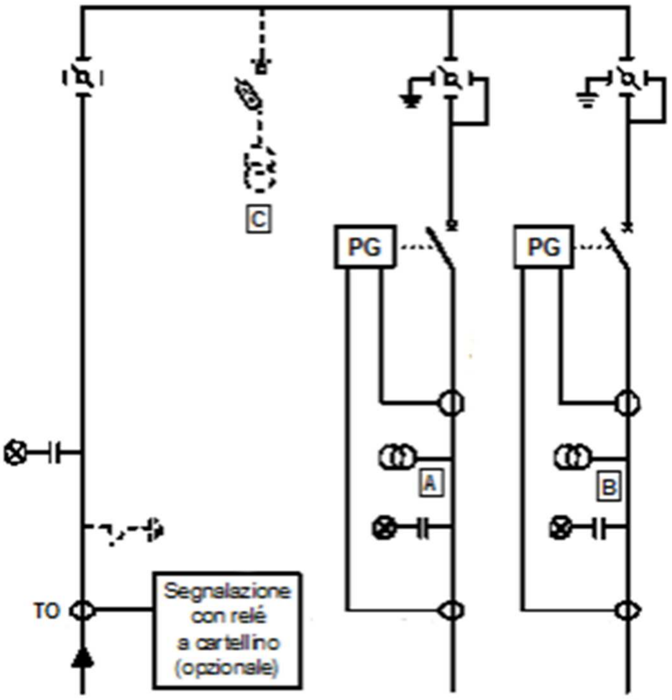


Figure 4.2: Double column configuration scheme

The main disconnector is optional, but if present it must be interlocked with the open position of both column circuit breakers. In this way the cost is reduced and the selectivity of the User system is improved, since a fault on a column does not imply the disconnection of the whole plant.

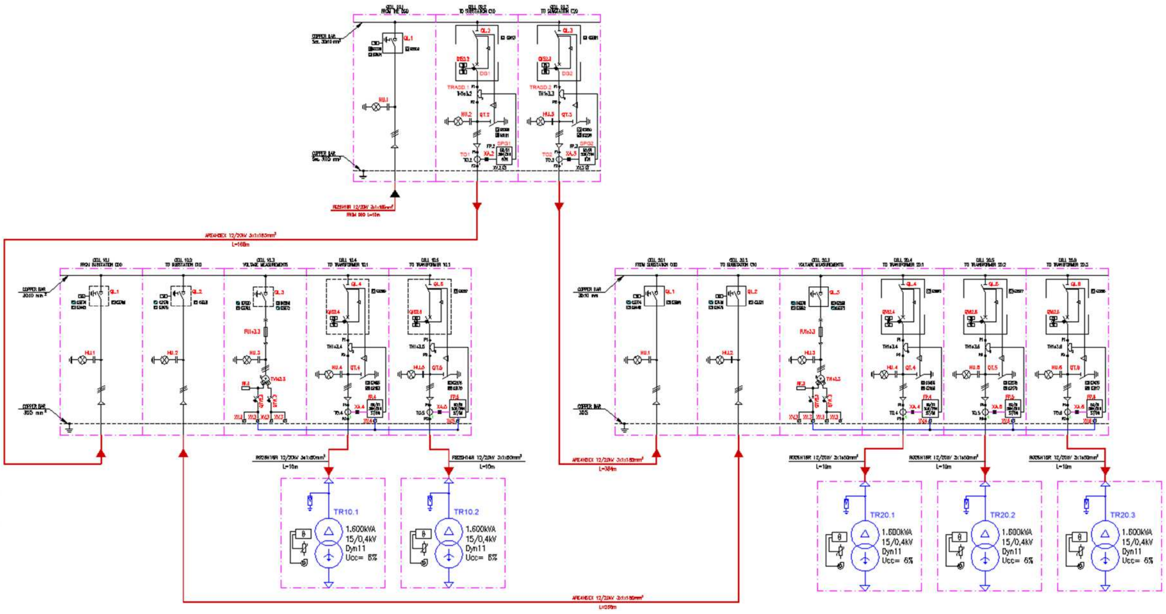


Figure 4.3: Ring configuration of the MV section of the electrical system

Following the [1], each column must be protected with a circuit breaker equipped with protections (50), (51), (51N) and, if necessary, (67N). The necessity of the (67N) protection depends on the value of the earth-fault capacitive current of the User's MV grid, which can be translated in terms of length of the User's MV grid. The [1] establishes the maximum extension of the aforementioned grid which does not imply the necessity to install a (67N) protection.

$$L_{max} = \frac{1,6}{0,2 \cdot U}\ [km] \tag{4.1}$$

where:
U indicates the rated voltage expressed in kV.

Using Equation (4.1), the value of the maximum length can be retrieved and it is:

- 400m for grids powered at 20kV;
- 533m for grids powered at 15kV;

The case study is part of this category, so that a (67N) protection was installed.

4.1.1. MT00 switchboard

This switchboard is installed in C00 cabin. However, before speaking about the switchboard, it is notable to underline some important aspects of this electrical cabin; in fact, it is the site where the connection between the DSO and the User takes place and it is divided in two areas of competence as shown in Figure 4.4:

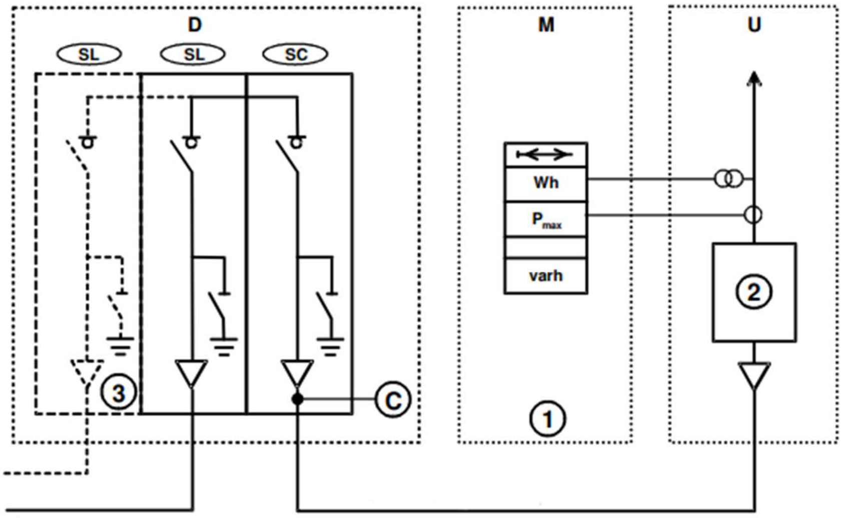


Figure 4.4: Layout of the energy point of delivery electrical cabin

The part indicated with "D" is under the responsibility of the DSO, while the part indicated with "U" is the User section. This latter section is very important and it must fulfil some criteria that are listed in the [1] and in the case that they are not satisfied, the DSO is allowed to negate the connection to the public grid. There are two possible configurations that the User can realise:

- Choose to not install an earth disconnector directly at the end of the connection cables; in this case, when the User requests the intervention of the DSO to put the connection cable out of voltage, the grounding required by the [4] must be achieved through the use of mobile earthing devices according to the [5] and its variants. In particular, the User, after having dissected, grounded and short-circuited the parts of his system to avoid any other possible power supply, must also ascertain the absence of voltage on the cable in question, connect it to the ground and short-circuit it with the aforementioned grounding devices.
- Choose to install an earth disconnector directly at the end of the connection cables; in this case, when the User asks the intervention of the DSO to put the connection cable out of voltage, the DSO representatives must hand over a key - absolutely non-duplicable for the User - which is released once the earth disconnector of the compartment (cell) of the DSO is closed (indicated with SC in Figure 4.4), and which allows the closure of the first User's ground disconnector. The User must also ascertain the absence of voltage on the cable in question before operating the grounding of the disconnector itself.

In this case the first option was chosen and now it will be described the configuration of the switchboard installed in this cabin. The switchboard in question is called "MT00" and it is composed of 3 cells, named cell "00.1", cell "00.2", cell "00.3". The switchboard has a double column configuration as mentioned above (cf. Figure 4.5), that is compliant with art. 8.4.2. of [1].

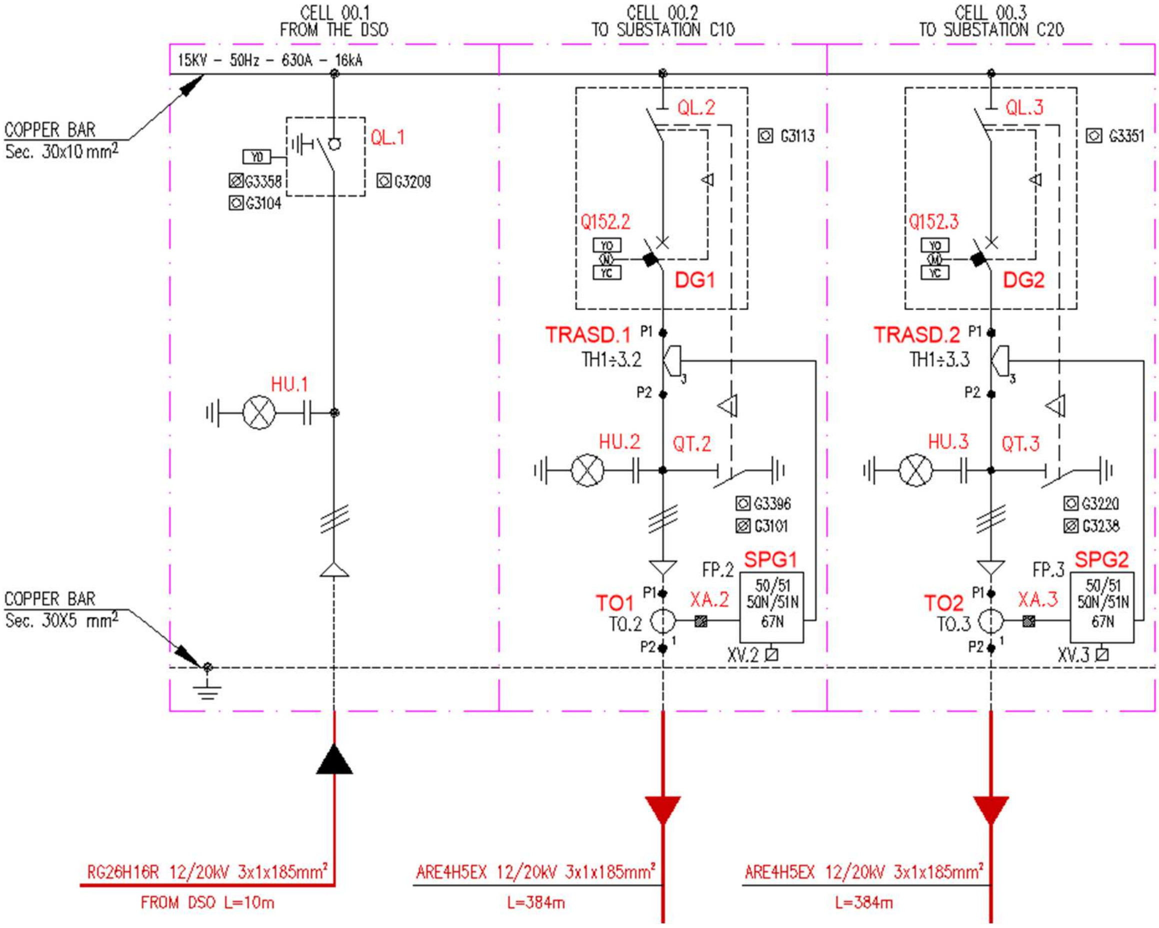


Figure 4.5: MT00 switchboard configuration

Cell 00.1 is the cell where the point of delivery is located, while cells 00.2 and 00.3 are responsible for protecting the columns, where each column feeds one side of the ring. In cell 00.1, starting from the bottom, can be seen the lights which warns that the line is powered (HU.1) and the load break switch with the earth disconnector (QL.1). These devices are essential and they are equipped with the keys that are interlocked among themselves: more precisely, to be compliant with [6], the earth disconnector cannot be maneuvered until the load break switch is opened successfully. Instead, in the cell 00.2, starting from the top, there is the disconnector (QL.2) which is interlocked with the earth disconnector (QT.2) and then there is the circuit breaker (DG1) which is interlocked with the disconnector. Even in this case, the devices cannot be maneuvered freely, but there is a precise sequence that unlocks the keys necessary to do so. In fact, if it is necessary to open the door, first the circuit breaker must be open, then the disconnector can be opened and the earth disconnector can be closed. This procedure must be done backwards in order to close the door and restore the network. The structure of the cell 00.3 is the same of the one next to it. Moreover, in the last two cells, according to the [1], (50), (51), (51N), (67N) protections were implemented (SPG) and so, a zero-sequence transformer (TO1 – TO2) was installed. The protection communicates with the circuit breaker by means of a transducer (TRASD.1) that interconnects them. In addition, each relay was programmed with a double setup (see

Section 8.3.1). To be more precise, the protection of column #1 (cell 00.2) takes the circuit breaker and the disconnector states of column #2 (cell 00.3) as input, which determines the switching between the two different setups. Symmetrically, the protection of column #2 receives as input the circuit breaker and the disconnector state of column #1, which determines the switch between the two programmed options. In addition, both relays were set up with at least two other configurations to be activated depending on the status of the MV network, which will be communicated through the other protections present in the switchboards of the C10 and C20 cabins.

4.1.2. MT10 switchboard

This switchboard is installed in the substation C10 and it is composed of 5 cells.

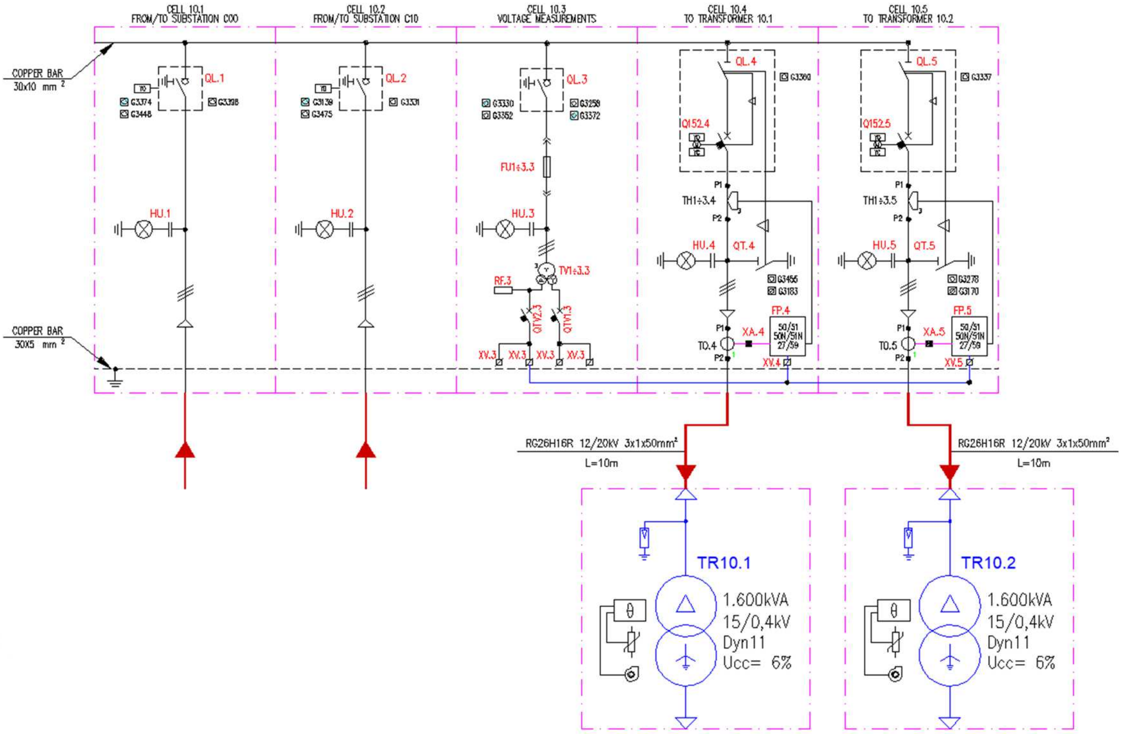


Figure 4.6: MT10 switchboard configuration

Cell 10.1 and cell 10.2 are the responsible for the connection of the substation into the ring configuration. They both have the same electric scheme which is identical to the one of the cell 00.1, so the description is deferred to Section 4.1.1. Next to them, there is cell 10.3 that is used as a measurement compartment. Starting from the top, there is the load break switch and the earth disconnector (QL.3) like in the previous cells, then there is a fuse (FU.1-3.3) and a voltmetric transformer with a double secondary winding (TV.1-3.3). The latter is in compliance with [1] and it is needed to eventually trigger protection (27) and (59Vo), that were not present in the previous cells; although, for the PV system the voltmetric transformer is needed for the triggering of the protection (59Vo) only. Protection (27) is very important to disconnect the transformers in case of a network outage and then gradually re-energize them with differentiated delays (2s) in order to limit the transformer insertion current to that of a single machine. Due to the size of the transformers (cf. Section 4.2.1), it is also necessary to comply with paragraph 8.5.14 of [1], which states:

"The User may not install transformers for a total power exceeding 3 times the limit of 1600kVA for grid at 15kV and 2000kVA for grid at 20kV, even if they have separate LV busbars. In the case of installation of transformers with a total power exceeding the aforementioned limits, it must be provided appropriate devices in the system in order to avoid the simultaneous energization of those transformers that determine the overcoming of the aforementioned limitations. These devices must trigger in the event of a voltage failure of more than 5s and provide for the re-energization of the transformers, according to the total quantities not higher than the limits determined above, with re-entry times interspersed with at least 1s".

Following the standard, it would be possible to energize two transformers at a time; however, it was decided to re-energize only one transformer at a time in order to reduce the high inrush currents and standardized the protections of the transformers, even in the case of future upgrades. Finally, there are cells 10.4 and 10.5 that are connected to the step-down transformers from which the LV network starts from. Bear in mind that only one transformer is operative, while the other is a spare transformer used to guarantee the continuity of service of the system even in case of failure or maintenance of the other one (see Section 4.2.1). Furthermore, the configuration of these cells is identical to the one of cells 00.2 and 00.3 of C00 cabin (see Section 4.1.1) except for the protections installed (FP.4, FP.5). In addition, there is a cable connection between the protections installed in cells 10.4, 10.5 and the load break switches in cells 10.1, 10.2 respectively. In particular, the protections installed in cell 10.4 receive the states of the load break switch placed in cell 10.1 as input. After that, it communicates with the protections placed in the MT00 switchboard (see SPG1 and SPG2 in Figure 4.5) using a IEC61850 protocol via a dedicated optical fibre network, so as to adapt the setup programmed on the latter. Symmetrically, the same process is implemented in the protection installed in cell 10.5, that takes the state of the load break switch placed in cell 10.2 as input. This is essential to implement a logical selectivity and make it possible to set different network configurations without re-calibrate protections.

4.1.3. MT20 switchboard

The MT20 switchboard has a configuration very similar to the MT10, with the only difference that in this case there is an additional cell as there are three transformers.

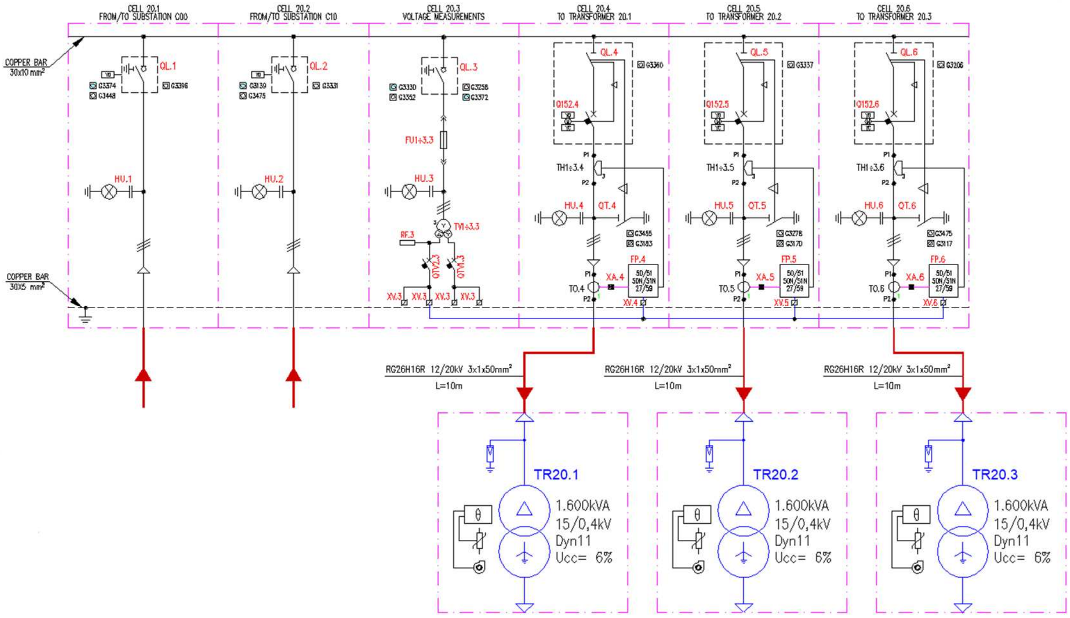


Figure 4.7: MT20 switchboard configuration

In this case, the active transformers are TR20.1 and TR20.3, while TR20.2 is a spare transformer with the role of ensuring the continuity of service of the system even in case of failure or maintenance of one of the other two. Even in this switchboard, it has been implemented a cable connection between the protections of the operating transformers and the load break switches placed in cells 20.1 and 20.2; the protections communicate with the ones that are in MT00 switchboard as well. For a more in-depth description of the switchboard please refer to Section 4.1.2.

4.2. Transformers sizing and purpose

The LV side is realised following a radial scheme where every transformer is connected to its own LV busbar (this issue will be described more deeply in the next chapter).

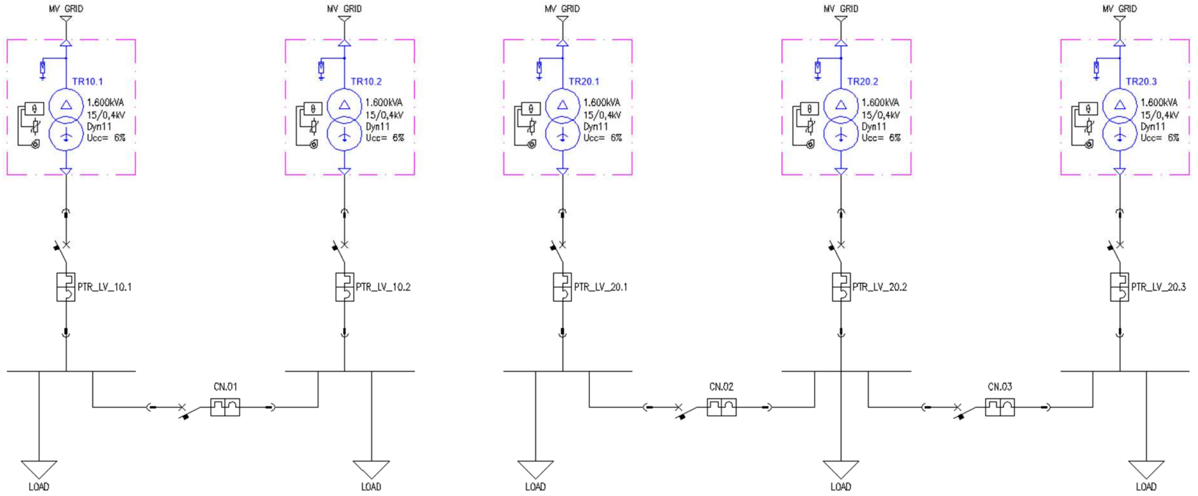


Figure 4.8: Simplified scheme representing the radial configuration used for the LV section of the electrical system

In both substation C10 and C20 it was foreseen to install an additional transformer to be used as a spare. In this way, the reliability of the plant is increased and maintenance work can be carried out without having interruption in the production process. In addition, this choice guarantees continuity of service even in the event of a failure of one of the transformers. To do so, between the transformers installed in the same substation it is placed a bus-tie, which is open in the rated working conditions (for a more specific description, please refer to Section 5.1.2). Furthermore, the paragraph 8.5.13 of [1] states:

"The limit of the nominal power of a single transformer or more transformers connected in parallel on the same LV busbar is equal to 1600kVA for grids at 15kV and 2000kVA for grids at 20kV"

So, in both the substations, an interlock system was implemented which avoids the parallel connection of one or more transformers. This is required due to the size of the transformers chosen, which is going to be discussed in the following. This threshold is used to limit the short-circuit current on the MV side caused by a fault on the LV side of the grid. In fact, it must be avoided that a fault on the LV side of the circuit, which is under the responsibility of the User, causes a trigger of a protection installed in the portion of the MV side under the responsibility of the DSO. The backup transformer may be used in two configurations: as a cold reserve in which it is normally turned off and used only in case of fault or maintenance of another one, or as a hot reserve where it is always turned on and used to power part of the load. The first case is characterized by low no-load losses and high load losses, while the second option has the opposite features; in the following there are reported the evaluations made in order to choose the best configuration.

4.2.1. C10 substation transformers

In Table 4.1 it is reported the load split made on the basis of the transformer that energise them, in the case that all the transformers are operative. The partition of the load was studied as to make the load as balanced as possible between the transformers.

Table 4.1: Characteristics of LV main loads managed by C10 substation

TR	ID	Description	P_n [kW]	S.U.F.	P_e [kW]	$\cos\varphi$	I_n [A]	I_e [A]
10.1	HP 1	Heat Pump 1	80.5	0.90	72.5	0.90	129.1	116.2
	HP 2	Heat Pump 2	80.5	0.90	72.5	0.90	129.1	116.2
	HP 3	Heat Pump 3	80.5	0.90	72.5	0.90	129.1	116.2
	S	"S" department switchboard	180.0	0.90	162.0	0.90	288.7	259.8
	CDT	Air – conditioning switchboard	180.0	0.90	162.0	0.90	288.7	259.8
10.2	O	Offices switchboard	30.0	0.90	27.0	0.90	48.1	43.3
	CP	Compressors switchboard	30.0	0.90	27.0	0.90	48.1	43.3
	SC10	C10 cabin services switchboard	20.0	0.90	18.0	0.90	32.1	28.9

where the following equations were used:

$$P_e = P_n \cdot S.U.F. \tag{4.2}$$

$$I_n = \frac{P_n}{\sqrt{3}V_n \cos\varphi} \tag{4.3}$$

$$I_e = \frac{P_e}{\sqrt{3}V_n \cos\varphi} \tag{4.4}$$

where:

S.U.F. indicates the Simultaneous Use Factor;

P_n indicates the rated power;

P_e indicates the effective power;

I_n indicates the rated current;

I_e indicates the effective current;

From the evaluation of the table above it emerges that two size of transformers can be used: 1250kVA or 1600kVA.

Table 4.2: Data required to evaluate the losses of 1250 kVA and 1600 kVA transformers. This data were retrieved from the rating plates of the transformers

1250 kVA transformer	
P_{cu} **[kW]**	9.10 kW
P_0 **[kW]**	1.55 kW
h_{op} **[h/day]**	16 h/day
I_{2n} **[A]**	1804.3 A

1600 kVA transformer	
P_{cu} **[kW]**	11.65 kW
P_0 **[kW]**	1.98 kW
h_{op} **[h/day]**	16 h/day
I_{2n} **[A]**	2309.4 A

Then, the daily losses of transformers were calculated, considering them as the sum of iron losses (P_0) and copper losses (P_{cu}).

- iron losses are always present and they are independent of the load, so they were considered for 24 hours (indicated with t_0);
- copper losses have a strong dependence on the load, so they were taken into account only for the operating hours of the machine, which in this case was assumed to be equal to 16 hours (indicated with h_{op}).

Equation (4.5) shows how the calculation described above were performed:

$$Losses = P_0 \cdot t_0 + P_{cu} \left(\frac{I_{phase}}{I_{2n}} \right)^2 \cdot h_{op} \tag{4.5}$$

where:

I_{phase} indicates the current flowing in the considered conductor;
I_{2n} indicates the rated current at the secondary winding of the transformer.

Thus, the results are reported in the following tables:

Table 4.3: Losses evaluation in the case of 1250kVA transformers installed in C10 substation as a hot reserve (left) or as a cold reserve (right)

ID	2 lines distribution	Losses/day
TR 10.1	964.66 A	78.75 kWh
TR 10.2	128.30 A	37.86 kWh
	Total	116.61 kWh

ID	1 line distribution	Losses/day
TR 10.1	1092.96 A	90.55 kWh
TR 10.2	-	-
	Total	90.55 kWh

Table 4.4: Losses evaluation in the case of 1600kVA transformers installed in C10 substation as a hot reserve (left) or as a cold reserve (right)

ID	2 lines distribution	Losses/day
TR 10.1	964.66 A	80.04 kWh
TR 10.2	128.30 A	48.10 kWh
	Total	128.14 kWh

ID	1 line distribution	Losses/day
TR 10.1	1092.96 A	89.27 kWh
TR 10.2	-	-
	Total	89.27 kWh

In Table 4.3 and Table 4.4 the results obtained for the C10 substation are reported. In this case, the cold reserve configuration is better, since it leads to lower losses and allows an economic saving. Then, comparing the two possible sizes, it results that the 1600kVA option is the better one because the losses associated to it are the lowest. However, the difference is really small and it does not completely justify the choice to buy those transformers which are more expensive than the 1250kVA ones. In fact, there is another important reason that explains this choice and it is related to the size adopted for the transformers installed in C20 substation. In fact, as will be described below, it was decided to install 1600kVA transformers in C20 substation as well. Having all the transformers of the same size is a big advantage since in case of failure of one of them, the damaged machinery can be replaced by using one of the other transformers instead of stop the production and wait for the arrival of a new one that could require a very long time.

4.2.2. C20 substation transformers

The same process was done with the C20 substation transformers, so in Table 4.5 there are reported the loads split with the same logic as in the previous section.

Table 4.5: Characteristics of LV main loads managed by C20 substation

TR	ID	Description	P_n [kW]	S.U.F.	P_e [kW]	$\cos\varphi$	I_n [A]	I_e [A]
20.1	E02	Press box heating	80.0	1.00	80.0	0.90	128.3	128.3
	E03	Pre - press	110.0	0.95	104.5	0.90	176.4	167.6
	E04	Mould furnace and pulley	120.0	1.00	120.0	0.90	192.5	192.5
	E05	BICS	260.0	0.90	234.0	0.90	416.9	375.3
	E06	Bank	150.0	0.90	135.0	0.90	240.6	216.5
	E07	Stacker	100.0	0.90	90.0	0.90	160.4	144.3
	NF	Nitriding furnace	85.0	0.90	76.5	0.90	136.3	122.7
	ET	Evaporative towers	66.0	1.00	66.0	0.90	105.9	105.9
	FP	Fire electric pump	30.0	0.80	24.0	0.90	48.1	38.5
20.2	E08	Ageing furnaces	280.0	0.90	252.0	0.90	449.1	404.2
	E09	De - stacker	80.0	0.85	68.0	0.90	128.3	109.1
20.3	E01	Press	800.0	1.00	800.0	1.00	1.154.7	1.154.7
	SP	Soda plant	35.0	0.95	33.3	0.90	56.1	53.3
	E	"E" department switchboard	70.0	0.90	63.0	0.90	112.3	101.0
	SPUE	Single-phase utilities switchboard	55.0	0.90	49.5	0.90	88.2	79.4
	SC20	C20 cabin services switchboard	20.0	0.90	18.0	0.90	32.1	28.9

The same calculations as before were performed, resulting in the values reported below:

Table 4.6: Losses evaluation in the case of 1250kVA transformers installed in C20 substation as a hot reserve (left) or as a cold reserve (right)

ID	3 lines distribution	Losses/day
TR 20.1	1605.35 A	152.39 kWh
TR 20.2	577.35 A	52.03 kWh
TR 20.3	1443.38 A	130.31 kWh
	Total	334.73 kWh

ID	2 lines distribution	Losses/day
TR 20.1	1733.65 A	171.55 kWh
TR 20.2	-	-
TR 20.3	1892.43 A	197.30 kWh
	Total	368.86 kWh

Table 4.7: Losses evaluation in the case of 1600kVA transformers installed in C20 substation as a hot reserve (left) or as a cold reserve (right)

ID	3 lines distribution	Losses/day
TR 20.1	1605.35 A	137.59 kWh
TR 20.2	577.35 A	59.17 kWh
TR 20.3	1443.38 A	120.33 kWh
	Total	317.09 kWh

ID	2 lines distribution	Losses/day
TR 20.1	1733.65 A	152.56 kWh
TR 20.2	-	-
TR 20.3	1892.43 A	172.68 kWh
	Total	325.24 kWh

In Table 4.6 and Table 4.7, it is noted that in both cases the hot reserve configuration is associated with a lower loss value than the equivalent of the cold reserve configuration. Moreover, it is a better way of use of the spare transformer since it was chosen to install resin transformers. In fact, if a resin transformer remains unused for a long time (cold reserve configuration), there may be some consequences. In particular:

- Dust deposits: if the transformer is left unused for a long time, it is likely that a certain amount of dust will accumulate on the surface of the resin. These dust deposits can reduce the efficiency of the electrical transformer, as they create an insulating layer between the transformer and the surrounding environment, preventing proper heat dissipation.
- Degradation of insulation: if the transformer remains unused for a long time, the internal insulation of the transformer may deteriorate. This can cause a

reduction in the transformer's performance and increase the risk of failures when it is reactivated.

Despite the lower costs with respect to the others, 1250kVA transformers are not adequate in this case, because if during normal operation it is necessary to disconnect one of them, the resulting current circulating in the other two would be too high and would exceed the rated current value. This problem might be overcome by inserting a ventilation system in the transformer boxes that allows operating conditions with higher current values. Nevertheless, for reliability reasons, it was still decided to install transformers with a rated power of 1600kVA. After all the considerations and the calculations made in the paragraphs above, it was decided to install the following transformers:

Table 4.8: Shred of the most useful data of the installed transformers rating plate

Transformers rating plate	
Model	TESAR TRZ 1600
Type	Dyn11
Apparent power $\boldsymbol{A}$ **[kVA]**	1600 kVA
Primary winding rated voltage $\boldsymbol{V_{1n}}$ **[kV]**	15 kV
Secondary winding rated voltage $\boldsymbol{V_{2n}}$ **[kV]**	0.4 kV
Primary winding rated current $\boldsymbol{I_{1n}}$ **[A]**	61.6 A
Secondary winding rated current $\boldsymbol{I_{2n}}$ **[A]**	2309.4 A
$\boldsymbol{v_{cc\%}}$ **[%]**	6%

5 The Low Voltage network

5.1. Topology and circuit diagram

The LV grid follows a radial distribution scheme: this means that every load has its own power supply line. Precisely, in this case scenario, the LV network has the aspect reported below.

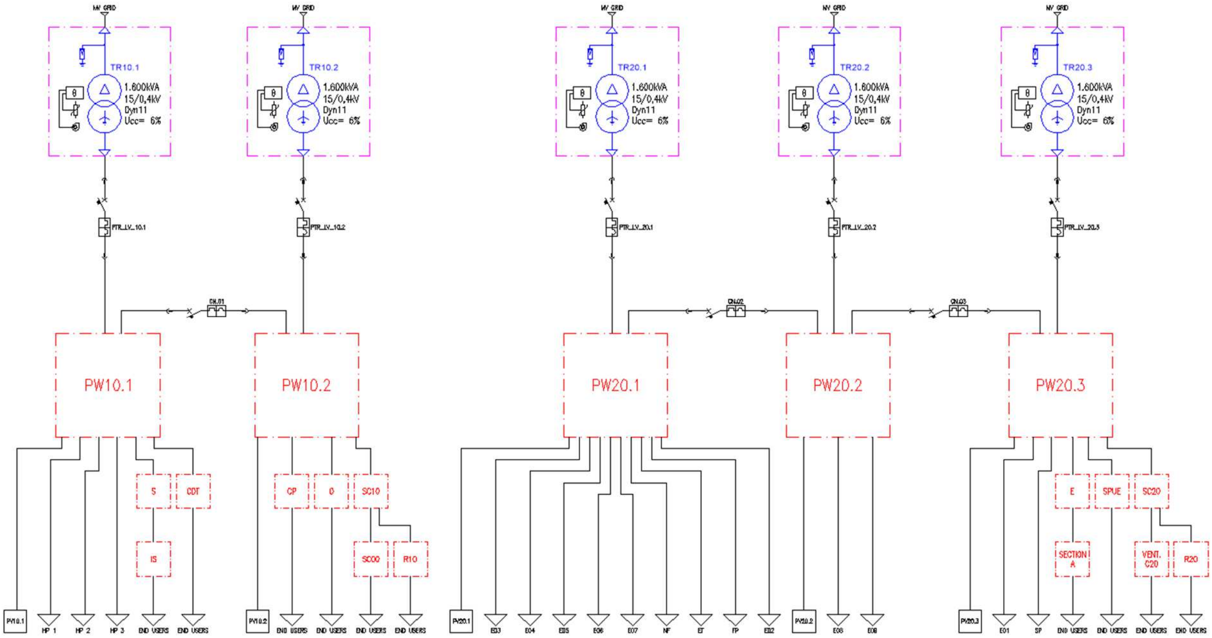


Figure 5.1: Radial configuration of the LV side of the designed network

This configuration has the following advantages:

- Ensure a better continuity of service, since, in case of a fault it affects only the line where it is located;
- Ease in the operating current (I_b) calculations because they are determined by the power demand of every distinct load;
- Ease in the fault area detection;
- More precise set-up of protections;

and disadvantages:

- High number of conductors and longer than in other configurations;
- High number of switching and protection devices;
- Increase of the complexity of the circuit;
- Increase of the cost of the plant.

The main issue with this configuration is that if there is a failure on the transformer, the entire LV grid downstream does not receive any power; however, in the case study, this problem is solved by installing more than one transformer upstream (see Section 4.2).

5.1.1. PW10 and PW20 power centres

As shown in Figure 5.1, there are two main switchboards, named “PW10” and “PW20”, downstream the transformers. They are the most important LV switchboards because they feed all the other loads in the factory. In particular, the PW10 switchboard is mainly responsible for the energization of the shutters department, while the PW20 switchboard is responsible for the energization of the extrusion department. The bigger loads are directly connected to them, while the other loads are grouped and powered by other smaller switchboards, which are in turn connected to the power centres.

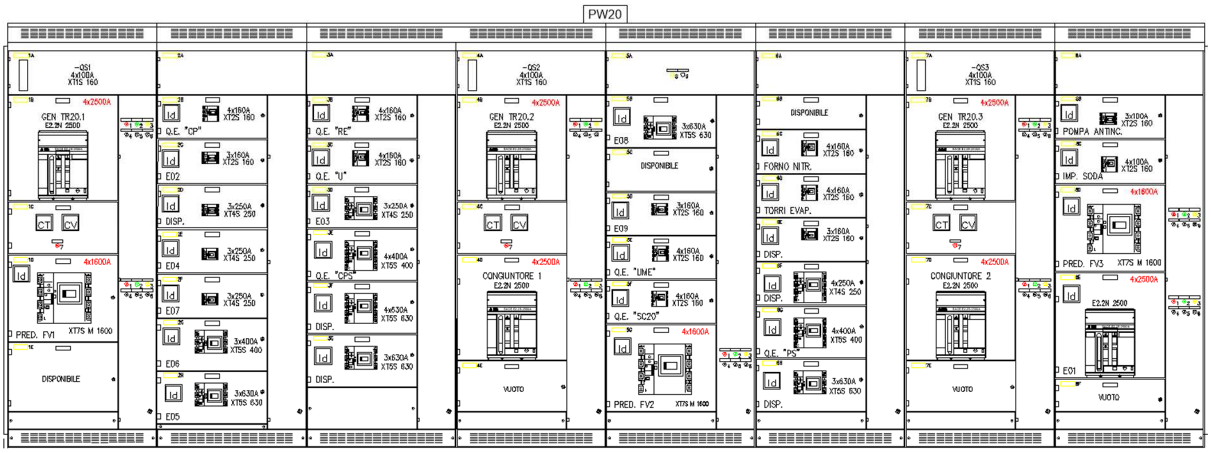


Figure 5.2: PW20 switchboard front view. The respective of the PW10 is made along the same lines as the PW20 one

The power centres must have a short-circuit current breaking capacity of at least 36.6kA, since they are connected to the LV busbars (see Section 6.2). Thus, it was rounded up to the next available value resulting in a short-circuit breaking capacity of 40kA. In addition to the loads mentioned in the previous sections, it was planned to install a PV system which is connected to the power centres and it will be described in Section 5.2.

5.1.2. Bus-tie purpose

Between the LV busbars it was installed a bus-tie. This device is crucial because it is needed to enhance the spare transformer installed in both the substations: in case of failure or maintenance of a transformer, the bus-tie connects the busbar left without power supply to another busbar which is still powered. In this way, the LV network configuration can be changed depending on the necessities in order to guarantee the power supply to all the electrical loads. The bus-tie could have been realised using a load break switch; however, it is important to note that it was decided to install extractable circuit breakers as to protect the LV busbars (see Figure 5.1). Even if it is a more expensive solution, it was decided to realise the bus-tie using circuit breakers identical to the ones installed on the LV busbars. This choice leads to a big advantage:

- In case of failure of a LV busbar circuit breaker, it can be extracted and replaced by the circuit breaker used as the bus-tie. This operation allows to keep the connection between the load and its power source up, which would not be possible in any other way due to the radial configuration adopted for the LV network. In addition, this choice drastically reduces the waiting time that would have been waited if it would have been necessary to order a new circuit breaker.

5.2. Photovoltaic (PV) generation

In order to minimize energy consumption, a photovoltaic system was designed for the production site, which was derived from an old brick and masonry products factory. The large outdoor areas available on the site were suitable for installing the PV modules, while the building roof was not due to both structural and fire safety reasons.

- Structural issues - the existing structure does not allow to install any further load on the roof;
- Fire prevention - the material with which the roof is made does not fulfil the fire prevention specifications in case of installation of PV panels.

The available surfaces have allowed for the design of a PV system with a capacity of approximately 3.1MW. This capacity is in line with the available budget, the estimated power of the system, and the maximum electrical power that the DSO allows to be fed into the grid. The PV system consists of two main sections: one is located in the external area in the south direction, while the other is placed in the courtyard next to the extrusion department (see Figure 5.3).

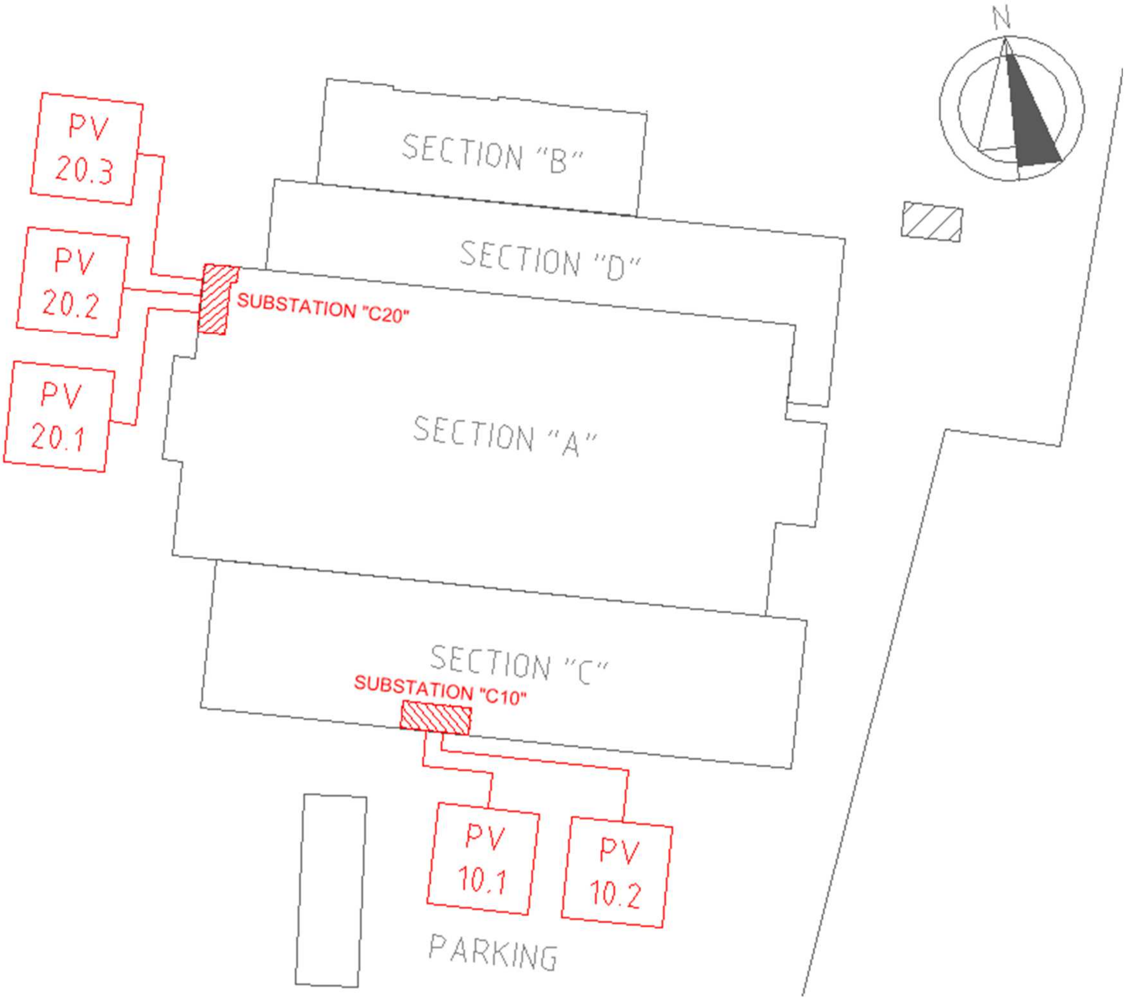


Figure 5.3: Simplified layout that shows the position of the two groups of PV panels

Using the PVGIS online tool (European Commission's Tool) which is based on historical solar radiation data from previous years, the optimized values of the slope (β) and the azimuth (or orientation γ) were chosen. The slope indicates the angle of the PV modules from the horizontal plane and it is equal to 38°, while the azimuth indicates the angle of the PV modules relative to the direction due South (-90° is East, 0° is South and 90° is West) and it is equal to 1°. Moreover, the southern PV section is composed of two groups of panels, each of them with an installed power of 500kW, while the other section is made of three groups with an installed power of 700kW each. The different size is determined by the substation to which they are connected with.

Figure 5.4: Graphic example of the slope (β) and azimuth (γ)

Based on calculations performed using the aforementioned software, it has appeared that for every 100kWp installed the expected annual energy production is 131MWh/year, for a total of 4,061MWh/year. In absolute terms, this represents approximately 40% of the total energy consumption estimated in the factory's business plan (approximately 10,000MWh/year). It goes without saying that, due to the different temporal profiles of production and consumption, this energy can only be partially used directly within the production site. In order to improve the percentage of self-produced photovoltaic energy used, two different energy storage systems were hypothesized:

- Battery storage - the energy stored in the batteries could be reused in the absence of sufficient solar radiation.
- Hydrogen production – the hydrogen produced through water electrolysis could be reused both in the log heating furnaces and in the aging furnaces.

However, both of these hypotheses were excluded since preliminary studies showed that there is currently no economic return on investment (see Section 5.2.1). On the other hand, from a global perspective beyond the interest of the individual site, the optimal energy solution for primary energy consumption is to feed any excess production back into the public grid and to use this energy without it experiencing any degradation or loss, except for transport losses. It is not excluded that in the future energy storage systems could become economically viable from a global perspective, which could happen when national electricity production will be based completely or nearly on renewable sources.

5.2.1. Economic analysis on the storage of extra auto-produced energy

In the previous section, two methods of extra auto produced energy management were proposed. Considering the battery storage system solution, in order to do the economic analysis the following market prices were considered:

Table 5.1: Market price of energy updated to 23/02/2023

Price range of energy		
F1 [€/MWh]	**F2 [€/MWh]**	**F3 [€/MWh]**
227.1	96.3	96.3

Transport cost [€/MWh]	39
Tax [€/MWh]	22.7
Selling price [€/MWh]	50

Equation (5.1) shows the formula that calculates the total cost of energy:

$$TC = PoE + T + Tax \tag{5.1}$$

where:
TC indicates the total cost of energy purchasing;
PoE indicates the market price of energy;
T indicates the cost of transport of the energy;

All the following calculations were made on the assumption that energy is purchased in F2 and F3 price range since they represent the more convenient time to do it. Considering the cost of energy and the selling price of it, the economic advantage was calculated using Equation (5.2):

$$EA = TC - SP \tag{5.2}$$

where:
EA indicates the economic advantage;
SP indicates the total selling price of energy;

In Table 5.2, all the results of the abovementioned calculations are reported:

Table 5.2: Results of the total cost of energy assuming that it is purchased during F2 or F3 price range and the economic advantage that is generated by producing energy using the PV system

Total cost of energy [€/MWh]	**Economic advantage [€/MWh]**
158 €/MWh	108 €/MWh

The cost of a battery storage system with a capacity of 1MWh is equal to 250,000€ and it can be used at the 80% of its maximum capacity. Then, it was supposed that the PV system would produce energy for 240 day/year. Assuming to fully charge the battery during the day and discharge it during the night, the economic revenue per year was calculated using Equation (5.3):

$$R = BC \cdot PV \cdot EA \tag{5.3}$$

where:
R indicates the economic revenue;
BC indicates the effective battery storage system capacity;
PV indicates the operational days of the PV system per year;

Table 5.3: Economic revenue per year assuming that the PV works for 240 day/year in which it is able to fully charge the battery storage system

Rated storage system capacity [MWh]	**Effective storage system capacity [MWh]**	**PV system working days [day/year]**	**Economic revenue [€/year]**
1 MWh	0,8 MWh	240 day/year	20736 €/year

The revenue must be compared with the cost of the storage system in order to calculate what is the time necessary to cover its cost, which is reported in Table 5.4:

Table 5.4: Necessary years in order to cover the cost of installing a battery storage system

Recovery time [years]
12 years

Table 5.4 shows that it is not convenient to invest in a battery storage system since its expected life is about 5/10 years. The second possibility mentioned in the previous paragraph is even more disadvantageous since the cost of the gas is lower than the electric energy (70.4€/MWh). Moreover, the conversion of electric energy into gas has an efficiency of the 60%. Thus, the best solution is to feed any excess production back into the public grid.

6 Sizing of the electrical devices

In the previous sections, the transformers were sized and the power required from the grid in order to run the plant was estimated. In fact, during the design session of the electrical system this order of events was followed:

- Size all the machines, generators and the power demand of the plant;
- Size all the switchboards and cables that compound the electrical system.

In order to complete the second point, it is necessary to follow some criteria regulated by the CEI standards and perform some calculations which are both going to be described in this chapter. Furthermore, the industrial electrical plant engineering does not require calculations made with very high precision since it is based on approximate and uncertain data, as it will be seen better in Section 6.1.1.

6.1. CEI standards criteria

The CEI standards imposes the main criteria listed below in order to ensure the safety of people and the reliability of the system.

- Operating current evaluation;
- Maximum load capability;
- Protection against overcurrents;
- Protection against short circuit;
- Limitation of the voltage drop.

In order to size the devices and verify that they are compliant with these constraints, it is necessary to perform network calculations (cf. Section 6.2).

6.1.1. Ampacity (I_z)

The current carrying capacity of a conductor, or ampacity, (I_z) represents the maximum current value that a conductor is able to carry continuously without exceed its limit temperature.

$$I_z = \pi \sqrt{\frac{2hr^3}{\rho}(\theta_s - \theta_r)} \tag{6.1}$$

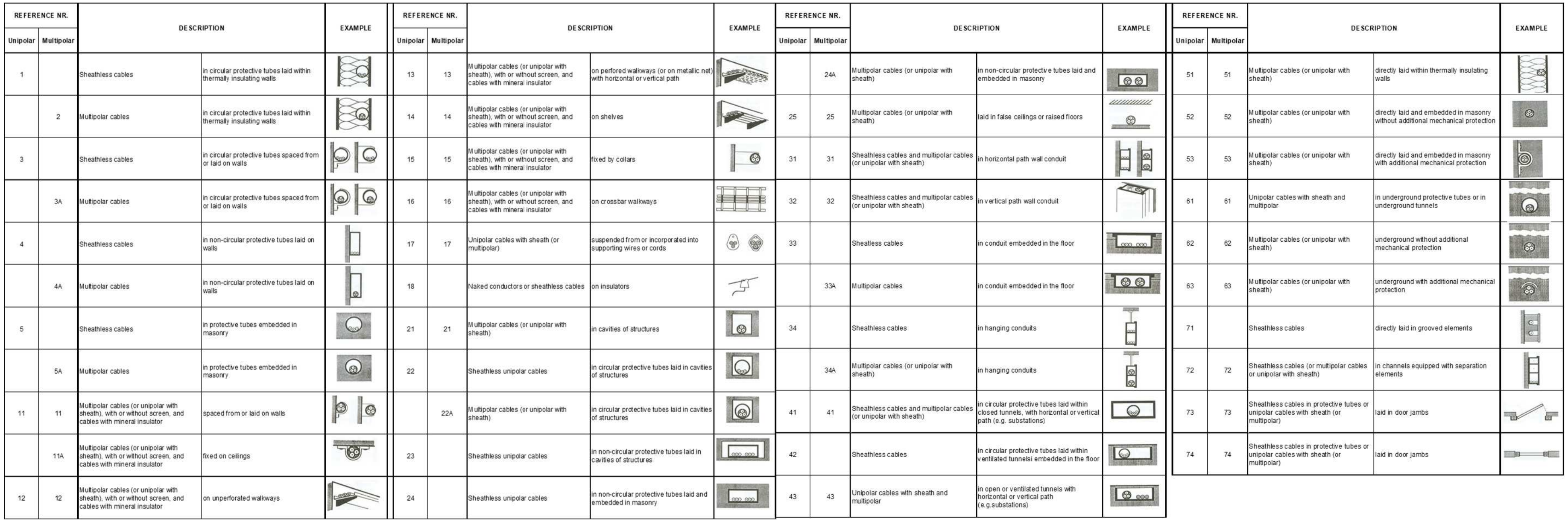
where:

h indicates the thermal conductivity coefficient between the conductor and the environment;
r indicates the radius of the cross section of the conductor;
ρ indicates the resistivity of the conductor;
θ_s indicates the limit temperature after which the cable would suffer damages and would not guarantee its electrical and mechanical properties;
θ_r indicates the room temperature;

The latter equation does not have a very practical use, but it is useful to evaluate which factors affect the current carrying capacity of a conductor and shows that it does not linearly depend on the cross section of the conductor. Also, the ampacity varies with the type of laying of the conductors. As mentioned before, the main issue with the current carrying capacity calculations is that the available data are uncertain and approximate. Usually, it is necessary to:

- Assume the current absorbed by every single electrical load as well as their simultaneous use factor;
- Define the arrangement of the cables within the single overlayed cable trays and assume the room temperature;
- In the case of underground laying: assume the arrangement of the cables in every layer, the number of layers and the depth of laying, as well as the thermal resistivity of the ground and its temperature.

Hence, it is useless to consider the very little theoretical differences between LV and MV cables or armoured and non-armoured cables, because it will only entail many difficulties. As a solution, the [7] introduces Tab.52 which standardizes all the method of laying of the electric conductors, in order to create a universal reference.



REFERENCE NR.		DESCRIPTION		EXAMPLE
Unipolar	Multipolar			
1		Sheathless cables	in circular protective tubes laid within thermally insulating walls	
	2	Multipolar cables	in circular protective tubes laid within thermally insulating walls	
3		Sheathless cables	in circular protective tubes spaced from or laid on walls	
	3A	Multipolar cables	in circular protective tubes spaced from or laid on walls	
4		Sheathless cables	in non-circular protective tubes laid on walls	
	4A	Multipolar cables	in non-circular protective tubes laid on walls	
5		Sheathless cables	in protective tubes embedded in masonry	
	5A	Multipolar cables	in protective tubes embedded in masonry	
11	11	Multipolar cables (or unipolar with sheath), with or without screen, and cables with mineral insulator	spaced from or laid on walls	
	11A	Multipolar cables (or unipolar with sheath), with or without screen, and cables with mineral insulator	fixed on ceilings	
12	12	Multipolar cables (or unipolar with sheath), with or without screen, and cables with mineral insulator	on unperforated walkways	
13	13	Multipolar cables (or unipolar with sheath), with or without screen, and cables with mineral insulator	on perfored walkways (or on metallic net) with horizontal or vertical path	
14	14	Multipolar cables (or unipolar with sheath), with or without screen, and cables with mineral insulator	on shelves	
15	15	Multipolar cables (or unipolar with sheath), with or without screen, and cables with mineral insulator	fixed by collars	
16	16	Multipolar cables (or unipolar with sheath), with or without screen, and cables with mineral insulator	on crossbar walkways	
17	17	Unipolar cables with sheath (or multipolar)	suspended from or incorporated into supporting wires or cords	
18		Naked conductors or sheathless cables	on insulators	
21	21	Multipolar cables (or unipolar with sheath)	in cavities of structures	
22		Sheathless unipolar cables	in circular protective tubes laid in cavities of structures	
	22A	Multipolar cables (or unipolar with sheath)	in circular protective tubes laid in cavities of structures	
23		Sheathless unipolar cables	in non-circular protective tubes laid in cavities of structures	
24		Sheathless unipolar cables	in non-circular protective tubes laid and embedded in masonry	
	24A	Multipolar cables (or unipolar with sheath)	in non-circular protective tubes laid and embedded in masonry	
25	25	Multipolar cables (or unipolar with sheath)	laid in false ceilings or raised floors	
31	31	Sheathless cables and multipolar cables (or unipolar with sheath)	in horizontal path wall conduit	
32	32	Sheathless cables and multipolar cables (or unipolar with sheath)	in vertical path wall conduit	
33		Sheatless cables	in conduit embedded in the floor	
	33A	Multipolar cables	in conduit embedded in the floor	
34		Sheathless cables	in hanging conduits	
	34A	Multipolar cables (or unipolar with sheath)	in hanging conduits	
41	41	Sheathless cables and multipolar cables (or unipolar with sheath)	in circular protective tubes laid within closed tunnels, with horizontal or vertical path (e.g. substations)	
42		Sheathless cables	in circular protective tubes laid within ventilated tunnelsi embedded in the floor	
43	43	Unipolar cables with sheath and multipolar	in open or ventilated tunnels with horizontal or vertical path (e.g.substations)	
51	51	Multipolar cables (or unipolar with sheath)	directly laid within thermally insulating walls	
52	52	Multipolar cables (or unipolar with sheath)	directly laid and embedded in masonry without additional mechanical protection	
53	53	Multipolar cables (or unipolar with sheath)	directly laid and embedded in masonry with additional mechanical protection	
61	61	Unipolar cables with sheath and multipolar	in underground protective tubes or in underground tunnels	
62	62	Multipolar cables (or unipolar with sheath)	underground without additional mechanical protection	
63	63	Multipolar cables (or unipolar with sheath)	underground with additional mechanical protection	
71		Sheathless cables	directly laid in grooved elements	
72	72	Sheathless cables (or multipolar cables or unipolar with sheath)	in channels equipped with separation elements	
73	73	Sheathless cables in protective tubes or unipolar cables with sheath (or multipolar)	laid in door jambs	
74	74	Sheathless cables in protective tubes or unipolar cables with sheath (or multipolar)	laid in door jambs	

Figure 6.1: : Table 52 of the CEI 64-8 standard reporting the method of laying of cables

Thus, the tables in [8] (for in-air laying) and [9] (for underground laying) summarise all the calculations reported above and give easier guidelines to compute the ampacity of LV cables. So, for the sake of sizing, the ampacity can also be expressed using the following formula:

$$I_z = I_0 \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \tag{6.2}$$

where:
I_0 is the theoretical current carrying capacity of a conductor at 30°C when it is the only active conductor in the passage;
k_1 is a correction factor that considers the room temperature (in case of in-air laying) or the ground temperature (in case of underground laying);
k_2 is a correction factor that in both cases takes into account the number of active circuits in the same passage (neutral is not considered as such);
k_3 is a correction factor that is considered only in underground laying and it considers the depth at which the conductor is installed;
k_4 is a correction factor that is considered only in underground laying and it considers the ground thermal resistivity;
k_5 is a correction factor related to the Arrhenius law (cf. Section 6.1.2).

Of course, the CEI standards have also standardized the coefficients reported in the latter equation based on the type of laying. For the reasons cited above, the same values of current carrying capacity reported in [8] and [9] are valid for MV cables too, even if it in this case is advisable to reduce them by 2 ÷ 3%. Moreover, it is necessary to make an important consideration: the advantages related to the in-air laying with respect to the underground laying. Although the ground thermal resistivity value is crucial because a small change of it corresponds to a big variation of the related correction factor, it is very uncertain and difficult to determine. In addition, there are more correction factors associated to the underground laying and they are also more restrictive than the ones related to the in-air method of laying: this results in the fact that usually the current carrying capacity of the underground laid cables is half of the equivalent laid in air.

6.1.2. Heat and Arrhenius law

An important aspect that need to be considered is the relation between the lifetime of the cables and their operating temperature. The temperature of a conductor in which flows a current (θ_c) is higher than the room temperature (θ_r) due to the dissipation related to the Joule effect and it can be calculated using the following equation:

$$\frac{\rho\, l}{\pi\, r^2}\, I^2 = h(\theta_c - \theta_r)2\pi\, r\, l \tag{6.3}$$

where:
ρ is the resistivity of the conductor;
r is the radius of the cross section of the conductor;
l is the length of the conductor;
h is the thermal conductivity coefficient between the conductor and the environment;
I is the current intensity;

Furthermore, the heat is exchanged with the insulation. The worst case scenario is represented by a short circuit. This phenomenon is very quick, thus the heat exchange process is considered as an adiabatic process, so that the wire insulation coating temperature is equal to the conductor one. It is necessary that this is lower than the limit temperature (θ_s) after which the cable would suffer damages and would not guarantee its electrical and mechanical properties.

$$\theta_c \leq \theta_s \tag{6.4}$$

The limit temperature depends on the type of material with which insulation is made. In fact:

- PVC has a limit temperature of 70°C / 160°C;
- EPR/XLPE has a limit temperature of 90°C / 250°C;

The first temperature value is referred to the normal operating conditions, while the second is referred to the case of a short circuit. Cables that have an insulation made with EPR (Ethylene-Propylene) or XLPE (Cross Linked Propylene) are more expensive, but they guarantee a better behaviour to the heat; consequently, they are much more diffuse. The heat is a really important issue because it has a big influence on the life of the conductor. The temperature values reported above are referred to a lifetime of the conductor of 20 years, nevertheless the relation between the service life of the conductor and its temperature is a logarithmic relation and it is based on the Arrhenius law. This formula is able to calculate the operating temperature based on the theoretically desired lifetime of the conductor.

$$\theta = q - m\log(t) \tag{6.5}$$

where:
θ is the operating temperature;
q is a dimensionless parameter equal to 235.31;
m is a dimensionless parameter equal to 26.81;
t is the lifetime of the conductor.

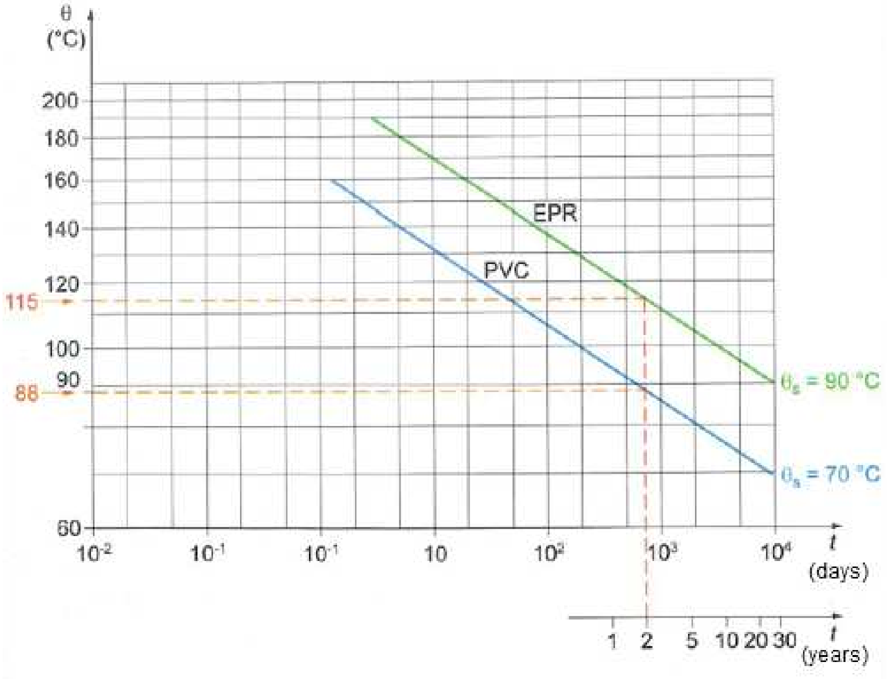


Figure 6.2: Lifetime of a conductor depending on its operating temperature and the material of its insulation

Although it is difficult to apply directly in most cases, the knowledge of the Arrhenius law, allows to better interpret the sizing calculations and to size more accurately cables dedicated to intermittent or emergency services (such as cables for emergency generators in the absence of a power grid), for which, due to short operating periods, higher temperatures can be allowed and therefore more economical sizing can be achieved. This consideration is taken into account by the coefficient k_5.

$$k_5 = \sqrt{\frac{\theta_2 - \theta_r}{\theta_s - \theta_r}} \tag{6.6}$$

where:
θ_2 is the temperature corresponding to a lifetime of the conductor of 2 years.

6.1.3. Protection against overcurrents

In order to choose the cross section of the conductors (S) and the size of the circuit breakers to be coordinated with, it is necessary to know the value of the operating current that flows in them (I_b). Then, since the conductor must be able to carry the I_b continuously without experiencing any negative side effect, a cable with an ampacity (I_z) greater or equal than the operating current must be chosen.

$$I_b \leq I_z \tag{6.7}$$

Furthermore, the switch coordinated with the conductor must withstand the I_b without trigger under rated operating conditions, so:

$$I_b \leq I_n \tag{6.8}$$

Then, the protection device should not allow the flowing of currents with a value higher than the ampacity of the cable, thus:

$$I_b \leq I_n \leq I_z \tag{6.9}$$

What is more, the protection triggers only for currents that are higher than its conventional triggering current (I_f). So, there is a range of currents in between I_n and I_f in which the device does not have a definite behaviour and this could damage the conductor connected to it. To solve this, the CEI standards has imposed a compromise that is the one reported in Equation (6.10).

$$I_f \leq 1{,}45\, I_z \tag{6.10}$$

The standards regulates the value of I_f:

- Open and enclosed industrial switchgear (regulated by [10]):

  $$I_f = 1.30\, I_{th} \text{ or equivalently } I_{th} \leq 1.12\, I_z$$

  where I_{th} is the thermal adjustment current;
- Modular switches (regulated by [11]):

  $$I_f = 1.35\, I_{th} \text{ or equivalently } I_{th} \leq 1.07\, I_z$$

Therefore, they are usually approximate for the sake of reliability to $I_{th} \leq I_z$.

6.1.4. Protection against short circuit

The protection to be installed must be able to open the circuit even in the case of a short circuit, so it must have a breaking capacity (I_{cu}) greater than the short-circuit current (I_k).

$$I_{cu} \geq I_k \tag{6.11}$$

Nevertheless, this is not sufficient, because the switch must be able to open the circuit fast enough to protect the cable that is connected with and this is determined by the let-through energy of the protection device (I^2t). In fact, during a short circuit, the cable in which flows the short-circuit current is really stressed by a thermal point of view and it is important that it does not reach a temperature higher than its limit. Thus, the following relation, named Joule integral, must be always guaranteed:

$$\int_0^{t_i} i^2 dt \leq K^2 S^2 \tag{6.12}$$

where:
t_i is the breaking time of the protection device;
K is a coefficient that depends on the conductor material and on the insulator.

In particular, the coefficient "K" is equal to:

- 115 for copper conductors PVC insulated;
- 143 for copper conductors EPR/XLPE insulated;
- 74 for aluminium conductors PVC insulated;
- 87 for aluminium conductors EPR/XLPE insulated;

The Joule integral specification may be automatically complied thanks to the art. 435.1 of [7] which prevents to do the latter calculations in some cases. It states that:

"If a protection device against overcurrents is in accordance with the CEI 64-8 standards requirements and it has a breaking capacity not less than the value of the presumed short-circuit current at its point of installation, it also ensures the protection against short-circuit currents of the conductor downstream".

However, this is not valid for all the protection devices, especially for those which does not limit the short-circuit current.

6.1.5. Voltage drop

Cable sizing must also verify voltage drop criteria ($\Delta V\%$). According to the art. 525 of [7], the voltage drop should not exceed the 4% of the rated voltage. This value is calculated using the equations:

1-phase circuit
$$\Delta V\% = 2 \cdot l \cdot I_b (r \cos\varphi + x \sin\varphi) \cdot \frac{100}{V_n} \tag{6.13}$$

3-phase circuit
$$\Delta V\% = \sqrt{3} \cdot l \cdot I_b (r \cos\varphi + x \sin\varphi) \cdot \frac{100}{V_n} \tag{6.14}$$

where:
I_b is the operating current of the conductor;
r is the resistance per kilometre of the conductor;
x is the reactance per kilometre of the conductor;
φ is the phase displacement between voltage and current.

In the context of the internal extension of an industrial plant (on the order of a hundred meters), voltage drops on the MV network are usually negligible.

6.2. Network calculations

To determine the minimum and maximum short-circuit currents for sizing cables and equipment and determining the protection settings, appropriate network calculations were carried out. In the case under consideration, the ABB DOC software version 3.7.25.0000 was used; however, in order to further validate the output of the software, a preliminary sizing was carried out through simple calculations based on the short-circuit power.

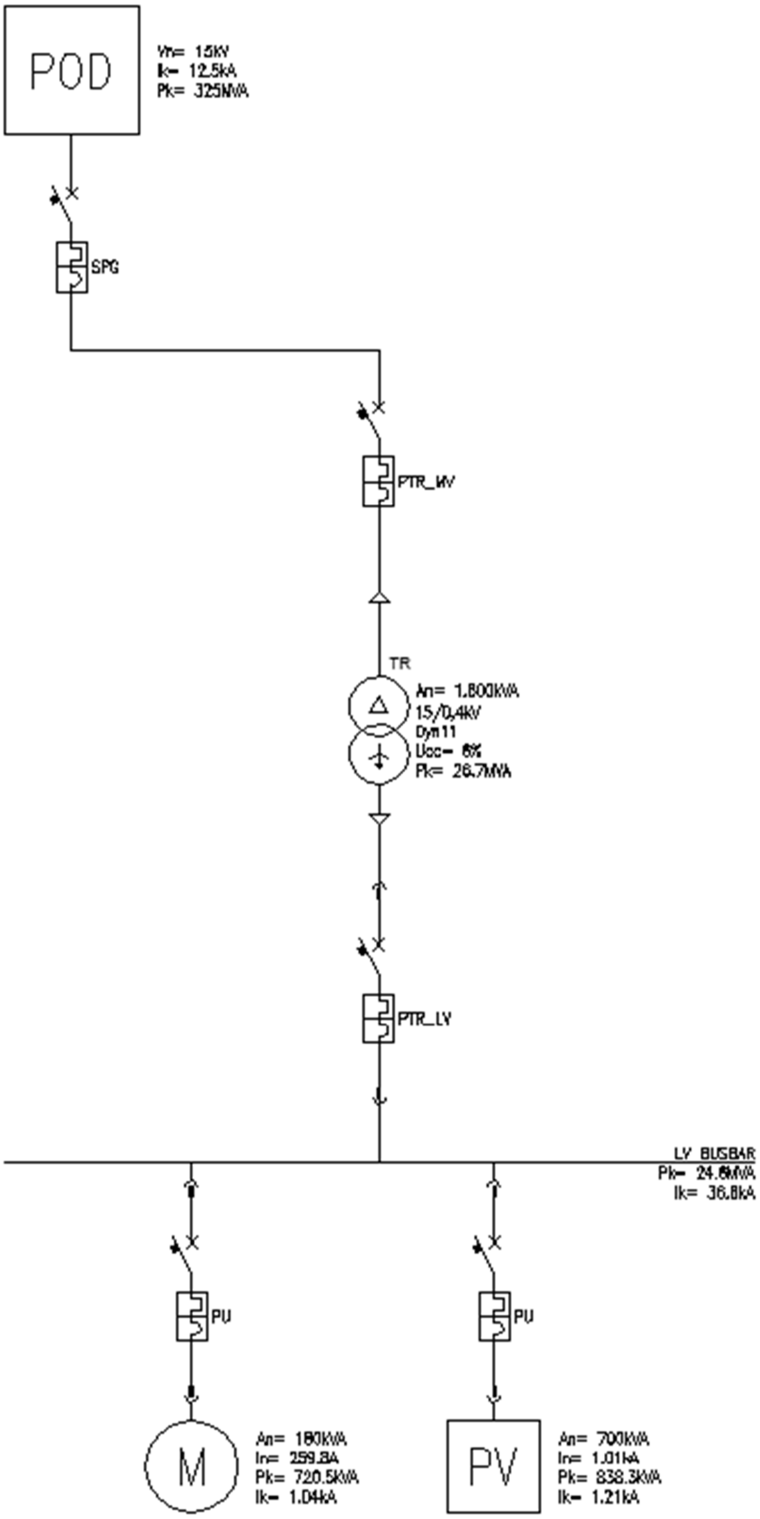


Figure 6.3: Simplified representation of the network layout showing the short-circuit power and the short-circuit current values of the more interesting points. Since the transformers have all the same size, for the sake of simplicity it has been represented only one transformer connected to its busbar

Considering the point of delivery, it is necessary to determine two values of the short-circuit power:

- The maximum short-circuit power which is considered in the case that all the energy sources are turned on at their maximum capacity. This value is associated to the maximum short-circuit current which corresponds to the three-phase fault current calculated in the same conditions.
- The minimum short-circuit power which is obtained from the latter by considering one or more energy sources turned off for any reason (fault, maintenance, reduced availability of primary energy, etc.). This value is associated to the minimum short-circuit current which corresponds to the line-to-line fault current calculated in the same conditions.

This values are provided by the DSO, but unfortunately usually it only communicates the first value neglecting the impact of the minimum short-circuit current on the sizing of electrical systems. The maximum value must be calculated considering the internal contributes of the machines and generators and it is crucial to size the cables and the principal devices, such as switchboards, circuit breakers, busbars, etc. Moreover, it has a big impact on the cost of the electrical system and the design engineer must keep this value as low as possible. On the other hand, the minimum value must be calculated without considering the internal contributes of the system; it affects the voltage drop at the starting of big motors and the distortion of the voltage waveform due to non-linear loads (rectifiers, inverters, etc.). The short-circuit power (P_k) can be calculated using the following equation:

$$P_k = \sqrt{3}\, U\, I_k \tag{6.15}$$

where:
I_k indicates the short-circuit current;
U indicates the rated voltage of the system.

In a distribution grid the ratio between X and R up to the busbars can be considered equal to 7. Hence, the resistance value weighs less than that of the reactance in the total impedance value as demonstrated in Equation (6.16):

$$Z = \sqrt{R^2 + X^2} = \sqrt{\frac{X^2}{49} + X^2} = 1.01\, X \tag{6.16}$$

Hence, considering the hypothesis described above, the short-circuit power can be also calculated as follows:

$$P_k = \frac{U^2}{X} \tag{6.17}$$

The short-circuit power of a system composed of n elements in series, each one with its respective reactance is given by the next formula:

$$P_k = \frac{U^2}{X_1 + X_2 + \cdots + X_n} \tag{6.18}$$

or considering the relation between X and P reported in Equation (6.17):

$$P_k = \frac{1}{\frac{1}{P_1} + \frac{1}{P_2} + \cdots + \frac{1}{P_n}} \tag{6.19}$$

6.2.1. POD and MV lines short-circuit power

Starting from the POD, the DSO has communicated a short-circuit current at the point of delivery equal to 12.5kA, which corresponds to a P_k of 325MVA at a rated voltage of 15kV (cf. Equation (6.15)).

Table 6.1: Overview table reporting the short-circuit current and the short-circuit power values at the point of delivery

POD short-circuit data		
U [kV]	**I_k [kA]**	**P_k [MVA]**
15 kV	12.5 kA	325 MVA

Then, the short circuit power of the MV lines that connect the POD with the transformers installed in the two substations C10 and C20 should be calculated. Nevertheless, in the case of MV lines with a length of a few hundreds of meters, it can be neglected because the reactance value is not significant.

6.2.2. Transformers short-circuit power

Following the scheme, (see Figure 6.3) the next elements to be considered are the step-down transformers; since they have all the same size, below there the calculations and the considerations made just for one transformer are reported but they are valid for all of them. The short-circuit power of a transformer is given by the following equation:

$$P_k = \frac{A_n}{v_{k\%}} \tag{6.20}$$

where:

A_n indicates the rated apparent power of the transformer;

$v_{k\%}$ indicates the percentage short-circuit voltage.

So, referring to Table 4.8, the short circuit parameters at the secondary windings terminals of the transformers were evaluated:

Table 6.2: Overview table reporting the short-circuit current and the short-circuit power values of the installed transformers

Transformers short-circuit data		
U **[kV]**	I_k **[kA]**	P_k **[MVA]**
0.4 kV	38.5 kA	26.7 MVA

Finally, in order to know the value of the short-circuit current and the short-circuit power at the LV busbars, it is necessary to combine the transformers short-circuit values with the POD ones.

6.2.3. LV busbars short-circuit power

Considering the data obtained in Table 6.1 and Table 6.2 and combining them as shown in Equation (6.19), the values of the short-circuit current and short-circuit power at the LV busbars were calculated.

Table 6.3: Overview table reporting the short-circuit current and the short-circuit power values at the LV busbars

LV busbars short-circuit data		
U **[kV]**	I_k **[kA]**	P_k **[MVA]**
0.4 kV	35.6 kA	24.7 MVA

Nevertheless, this value may not be correct since the contribution of the motors and the contribution of the PV systems have not been considered yet.

6.2.4. Contribution of the electrical motors to the short-circuit power

The [12] regulates the contribution of the electrical motors to the short-circuit current calculation. MV and LV motors contribute to the initial symmetrical short-circuit current ($I_k^{"}$), to the peak short-circuit current (i_p), to the symmetrical short-circuit breaking current (I_b) and, for unbalanced short circuits, also to the steady-state short-circuit current (I_k).

- I_k'' is the rms value of the a.c. symmetrical component of a prospective (available) short-circuit current, applicable at the instant of short circuit if the impedance remains at its zero-time value;
- i_p is the maximum possible instantaneous value of the prospective (available) short-circuit current;
- I_b is the rms value of an integral cycle of the symmetrical a.c. component of the prospective short-circuit current at the instant of contact separation of the first pole to open of a switching device;
- I_k is rms value of the short-circuit current which remains after the decay of the transient phenomena.

Reversible static converter-fed drives are considered for three-phase short circuits only, if the rotational masses of the motors and the static equipment provide reverse transfer of energy for deceleration at the time of short circuit. Then, they contribute only to the initial symmetrical short-circuit current (I_k'') and to the peak short-circuit current (i_p). They do not contribute to the symmetrical short-circuit breaking current (I_b) and the steady-state short-circuit current (I_k). As a result, reversible static converter-fed drives are treated for the calculation of the short-circuit currents in a similar way as asynchronous motors. Instead, all the other static converters are disregarded for the short-circuit current calculation according to [12]. Furthermore, the evaluation of the contribution of the motors to the short-circuit current calculation is very complicate and may take into account many parameters; this is simplified by considering it equal to:

- 4 times the value of the rated current in the case of LV motors (sub-transient reactance of 25%);
- 5 times the value of the rated current of the motor in the case of MV motors (sub-transient reactance of 20%).

In the case study, all the motors belonging to the categories listed above were considered as single motors, each one connected to the respective busbar. For the sake of reliability, the worst case was considered, so that it was taken into account a motor with a power of 180kVA, which corresponds to a short-circuit current of 1.04kA.

Table 6.4: Overview table reporting the motors contribution to the short-circuit current calculation

Motors short-circuit current		
U [kV]	**I_n [A]**	**I_k [kA]**
0.4 kV	259.8 A	1.04 kA

Referring to [12], the short-circuit current reported in Table 6.4 must be added to the short-circuit current evaluated before, which is reported in Table 6.3. This leads to a short-circuit current on the LV busbars equal to 36.6kA.

Table 6.5: Overview table reporting the short-circuit current and the short-circuit power values at the LV busbars considering the contribution of the motors

LV busbars short-circuit data		
U **[kV]**	$\boldsymbol{I_k}$ **[kA]**	$\boldsymbol{P_k}$ **[MVA]**
0.4 kV	36.6 kA	25.4 MVA

6.2.5. Contribution of the PV systems to the short-circuit power

According to [12], power stations units with full size converter, e.g. wind power station units (WF) and photovoltaic station units (PV), are modelled in the positive-sequence system by a current source. The source current depends on the type of short circuit and has to be provided by the manufacturer. The positive-sequence shunt impedance (Z_{PF}) is assumed to be infinite. In case of unbalanced short circuits the negative-sequence impedances ($Z_{(2)PF}$) depend on the design and control strategies, the values are given by the manufacturer. The zero-sequence impedance ($Z_{(0)PF}$) is infinite. Power station units with full size converter may be neglected if their contributions are not higher than 5% of the initial short-circuit current evaluated without these power station units. Also in this case, the worst situation was considered for the sake of reliability and corresponds to the PV systems connected to the C20 substation, which each of them have a power of 0.7MW; for the PV systems, it has been considered a $\cos\varphi = 1$, so the active power (P) corresponds to the apparent power (A). The manufacturer of the inverters connected to the PV panels has declared a short-circuit current of 1.2 times their rated current. Thus, it results in a rated current of 1.01kA, which means consequently that the short-circuit current value is 1.21kA.

Table 6.6: Overview table reporting the PV systems contribution to the short-circuit current calculation

PV systems short-circuit current		
U **[kV]**	$\boldsymbol{I_n}$ **[kA]**	$\boldsymbol{I_k}$ **[kA]**
0.4 kV	1.01 kA	1.21 kA

6.2.6. Software simulation

All the calculations reported in the previous sections were also implemented in a calculation software called DOC, provided by ABB S.p.A., where the same network as the one supposed in the design phase was recreated in order to compare the results and eventually highlight any criticism. In Table 6.7, the data related to the POD are reported:

Table 6.7: The POD related data are identical both for the manual calculations and the DOC simulation since they are communicated by the DSO and they do not depend on any calculation

POD short-circuit data			
Manual		**Software**	
I_k [kA]	**P_k [MVA]**	**I_k [kA]**	**P_k [MVA]**
12.5 kA	325 MVA	12.5 kA	325 MVA

Instead, the short-circuit data related to the MV busbars are reported in Table 6.8.

Table 6.8: The MV busbars results obtained by the software are a bit different from the manually calculated ones. The difference is very small though

MV busbars short-circuit data							
Manual		**Software (MT00)**		**Software (MT10)**		**Software (MT20)**	
I_k [kA]	**P_k [MVA]**	**I_k [kA]**	**P_k [MVA]**	**I_k [kA]**	**P_k [MVA]**	**I_k [kA]**	**P_k [MVA]**
12.5 kA	325 MVA	12.5 kA	325 MVA	12.2 kA	317 MVA	12.1 kA	313 MVA

It is important to notice that the impedances of the MV cables were neglected in the preliminary calculations, while they were considered from the software. However, the difference is very small and it validates that the assumption made in the manual calculations were correct. The transformers secondary windings short-circuit data are reported below and since they have all the same features, Table 6.9 illustrates only one rating plate.

Table 6.9: The transformers data are identical both for the manual calculations and the DOC simulation since they do not depend on any approximation

Transformers short-circuit data			
Manual		**Software**	
I_k **[kA]**	P_k **[MVA]**	I_k **[kA]**	P_k **[MVA]**
38.5 kA	26.7 MVA	38.5 kA	26.7 MVA

The LV busbars results are the most interesting ones and they are reported below. Table 6.10 shows the comparison between the two resulting worst case scenarios.

Table 6.10: The short-circuit values are already comprehensive of the contribution of electrical motors, while they do not consider the PV system contribution for the reasons explained in sections 6.2.4 and 6.2.5

LV busbars short-circuit data			
Manual		**Software**	
I_k **[kA]**	P_k **[MVA]**	I_k **[kA]**	P_k **[MVA]**
36.6 kA	25.4 MVA	37.2 kA	26.7 MVA

As shown above, the LV busbars short-circuit values calculated from the software differ from the expected ones. Nevertheless, they are still in line with expectations and the difference is explained by the fact that the LV busbars are downstream from the POD and MV busbars, thus the calculations related to them are affected by the errors present in the previous results. That said, the software simulations and the results obtained with the preliminary calculations are in agreement and they both lead to the same choice of electrical components which is going to be described in the next section.

6.3. Cables and devices sizing

Once that the short-circuit currents have been calculated in the whole electrical system, all the other parameters cited in the criteria mentioned in Section 6.1. were evaluated. Nowadays the vast majority of the cables that are on the market are EPR (Ethylene-Propylene) insulated; this is a more expensive solution with respect to the PVC, but it is better from the thermal point of view. Hence, all the calculations in the following will be done considering EPR insulated cables.

6.3.1. Connection to the public grid

First of all, it was sized the cable which connects the plant with the public grid. The [1] states:

"The MV connection cable, including its terminals, must be as short as possible (max 20 meters) and made of copper with a cross section of at least 95mm²".

The minimum section of 95mm² referred to a copper conductor derives from coordination with the protection systems of the DSO, which ensure protection against short circuits with an adequate limitation of the I^2t for the aforementioned cable. In the case study, the calculation were made using Equation (6.21) where the power to be considered is 3.1MW, which corresponds to the contractual power agreed with the DSO. The result is a current value equal to 132.6A ($\cos\varphi = 0.9$), thus the abovementioned sectioned is not appropriate.

$$I_b = \frac{P_n}{\sqrt{3}V_n \cos\varphi} \tag{6.21}$$

The correct cross section that corresponds to that current is 120mm², however due to its reduced length (10m) and the importance of this connection, an oversized cable of 185mm² was chosen.

Table 6.11: Data of the cable used to connect the public grid with the User's plant

	POD
Type of insulator	EPR
Cable cross section [mm²]	185 mmq
Type of cable	SINGLE CORE
Length [m]	10 m
Type of laying [Tab. 52 CEI 64-8]	61
Active conductors same passage	3
I_0 [A]	323 A
I_Z [A]	226 A
ΔV [V]	0.55 V
ΔV [%]	0.00%

6.3.2. Ring configuration MV cables

For ring MV cables sizing the worst-case scenario was considered, which corresponds to the situation in which one of two columns is open (see Figure 4.5) and the entire electric load is powered by the conductor connected to the active column. In order to limit the costs, aluminium cables were chosen also due to the fact that the cables are sized to carry all the power with one side of the ring open at the origin, while the normal operating conditions are in a closed loop, and therefore the rated operating currents are half of the sizing ones.

Table 6.12: Data of MV cables used to connect substations among them

	C00 ---> C10	**C00 ---> C20**	**C10 ---> C20**
Type of insulator	EPR	EPR	EPR
Cable cross section [mm²]	185 mmq	185 mmq	185 mmq
Type of cable	SINGLE CORE	SINGLE CORE	SINGLE CORE
Length [m]	168 m	384 m	266 m
Type of laying [Tab. 52 CEI 64-8]	61	61	61
Active conductors same passage	20	20	20
I_b [A]	132.6 A		
I_0 [A]	283 A	283 A	283 A
I_Z [A]	170 A	170 A	170 A
ΔV [V]	6.36 V	14.55 V	10.08 V
ΔV [%]	0.04%	0.10%	0.07%

The let-through energy verifications were trivial in this case due to the fact that they were already been ensured on the connection to the public grid cable, which means that they are verified for this cables even more so.

6.3.3. Transformers connection MV cables

The rated current at the MV transformers terminals using Equation (6.22) was calculated. Then, the calculations have been made on copper conductors because the supplier requested to do so.

$$I_{1n} = \frac{A_n}{\sqrt{3}\, V_{1n}} \tag{6.22}$$

In this case, the I_{1n} represents the I_b used to make the considerations in Section 6.1.3. Below, since all the transformers have the same size, it is reported the calculation made for one of them and then that is applied to all the others.

Table 6.13: Data of cables used to connect transformers to their respective MV busbars

	MV side of the transformer	
Type of insulator	EPR	EPR
Cable cross section [mm²]	35 mmq	50 mmq
Type of cable	SINGLE CORE	SINGLE CORE
Length [m]	10 m	10 m
Type of laying [Tab. 52 CEI 64-8]	43	43
Active conductors same passage	20	20
I_{1n} [A]	61.6 A	
I_0 [A]	169 A	207 A
I_Z [A]	64 A	79 A
ΔV [V]	0.19 V	0.14 V
ΔV [%]	0.05%	0.03%

Due to the calculated current, the available cross sections are 35mm² or 50mm². In the first option, both the I_z and $\Delta V\%$ requirements stated in the [7] are satisfied, however, the value of ampacity is too close to the rated current and this means that the cable would always be used almost at its maximum capacity, causing a shortening of its lifetime. For this reason, a section equal to 50mm² for all the cables that connects the transformers with their respective MV circuit breakers was adopted, resulting in the adoption of RG26H16R model.

6.3.4. LV section cables

First of all, the current on the LV side of the transformer was calculated using Equation (6.23). The considerations that will be done in the following are valid for all the connections between each transformer and its related power centre since they have all the same size.

$$I_{2n} = \frac{A_n}{\sqrt{3}V_{2n}} \tag{6.23}$$

It was decided to install a busway that has an ampacity of 2500A, in order to connect the transformers with their respective power centre. This also satisfy the other constraints imposed by the standards.

Table 6.14: Data of busways used to connect transformers to their respective power centre

	LV side of the transformer
Type of cable	BUSWAY
Length [m]	10 m
I_{2n} [A]	2309.4 A
I_Z [A]	2500 A

In this case, due to the high current value, the busway represent a more handy and reliable solution. In fact, with equal current carrying capacity, the use of cables as in the MV section would have resulted in installing 7 conductors for each phase, which would have been very inconvenient due to the lack of available room. Then, for all the users connected to the power centres the same procedure as for the previous components was followed. Thus, for every load its operating current (I_b) was evaluated and a cable which satisfies the abovementioned criteria was chosen; then, following the standards, an adequate circuit breaker was associated to it. Every choice was made by evaluating safety first and then compromise between it and the economy.

6.3.5. MV switchboards

Based on network calculations made both on normal and fault conditions, the technical specifications of the MV switchboards were developed and they are reported below.

Table 6.15: In common characteristics of the MV switchboards installed in the substations and the interlocking strategies in order to ensure the safety of the users in case of manoeuvring

MV switchboards characteristics	
Rated voltage (kV)	24 kV
Operating voltage (kV)	15 kV
Rated current (A)	630 A
Rated frequency (Hz)	50 Hz
Short-time current 1s (kA)	12.5 kA
Internal Arc Containment (IAC) on the 3 sides	AFL
Short-circuit current breaking capacity (kA)	12.5 kA
Withstand voltage at rated frequency	50 kV / 1 min
Withstand voltage at impulse	125 kV – 1.2/50 μs
Internal lights and heaters voltage	220 Vac
Auxiliary circuits voltage	110 Vdc
Double keys on all the line disconnectors: RO + RC (Released when Open + Released when Closed)	
Double keys on all the earth disconnectors: RO + RC (Released when Open + Released when Closed)	
Double keys on all the load break switch: at least RO (Released when open)	
Double keys on all the circuit breakers: RO (Released when open)	

For constructive reasons, MV equipment such as switches, breakers, and busbars typically have rated currents of at least 630A. This current, at a voltage of 15kV, corresponds to a power of 16MVA and in the majority of cases is normally higher than the maximum powers involved (6/10MVA). In the case study, the maximum expected operating current is 170A and it already includes a significant amount of over-sizing for possible future expansions.

6.3.6. LV switchboards (power centres)

Regarding low voltage power centres, below are the main technical specifications for sizing based on the calculations made on the LV busbars:

Table 6.16: Features of the LV main switchboards (PW10 and PW20)

LV switchboards characteristics	
Rated insulation voltage (V)	500 V (a.c.)
Rated operational voltage (V)	400 V (a.c.)
Rated frequency (Hz)	50 Hz
Rated condition short-circuit current I_k (kA)	40 kA
Rated busbar current (A)	2500A
Industrial frequency withstand voltage (kV)	1.89 kV

7 Earthing system and electric shock protection

7.1. Direct contact protection

According to [7], the methods of preventing direct contact are mainly concerned with making sure that people cannot touch live conductors. These methods include:

- The insulation of live parts: this is the standard method for LV equipment. The insulated conductors should be further protected by sheathing, conduit, etc.
- The provision of barriers, obstacles or enclosures to prevent touching;
- Placing out of reach or the provision of obstacles to prevent people from reaching live parts. Placing out of reach should not be used in locations of increased shock risk, and barriers must not be used except where the area is accessible only to skilled or instructed persons.
- The use of very low voltage systems (50V a.c. and 120V d.c.) from "safe" sources. "Safe" sources is intended as those circuits whose voltage cannot reach dangerous levels for people in any occasion.

All the direct contact protections are "passive" protections that prevent the contact with live parts of the circuit. Preventative measures that acts in case of direct contact with live parts ("active" protections) cannot be used, as for voltages level greater than 50V a.c. it is impossible to guarantee the safety of people. The [7] allows the additional direct contact protection by means of a RCD (Residual Current Device) with a rated triggering current of 30mA, which triggers in case of failure of the other safety precautions or in case of negligence of the people. However, the use of these devices is not recognised as a sufficient direct contact protection and it must be integrated with the adoption of one of the protection methods listed above.

7.2. Indirect LV contact protection

There are several methods of providing protection from shock after contact with a conductor which would not normally be live and they depend on the particular environment in which they are applied. Nevertheless, in the vast majority of industrial and civil electrical systems, they can be grouped in these categories:

- Protection using of very low voltage systems, as in the case of direct contact protection (see Section 7.1);

- Protection by automatic interruption of the supply;
- Protection using class II electric equipment or with equivalent insulation.

7.2.1. Automatic interruption of the supply

This is the most diffuse method to realise indirect contact protection for LV systems. It is based on the fact that an insulation failure would generate a current which is great enough to trigger the protections upstream. In the case study for the realisation of the LV network, it was decided to use a TN-S system. In the case of a TN system, the first condition to be satisfied is to connect all the exposed conductive metalwork to the protective conductor (PE), which is connected to the star point of the secondary winding of the supply transformer. The PE is fundamental for this purpose, because without it, an earth fault could not be detected. Obviously, a device able to detect the earth-fault current (I_E) must be associated to the protective conductor: a RCD can be used, but in many cases and especially in TN systems, a thermal-magnetic circuit breaker can also be used.

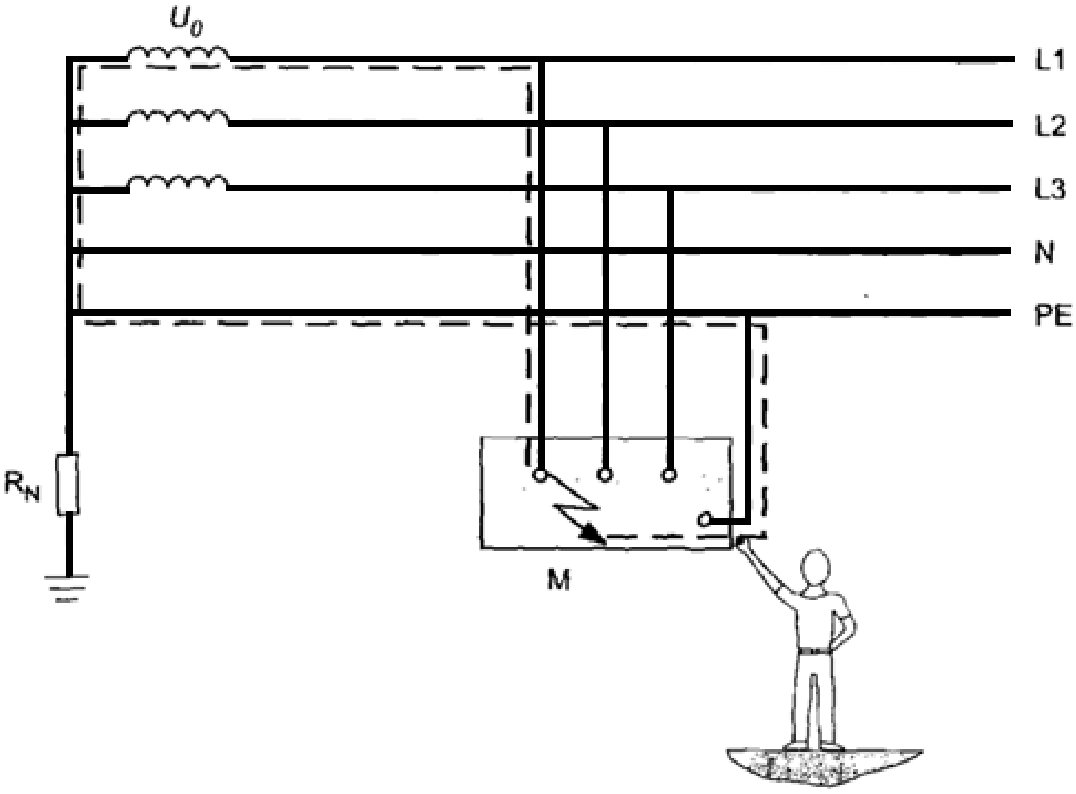


Figure 7.1: Current path in case of a fault in a TN system. The fault current does not flow in the earth but the fault loop includes the faulted phase and the PE only

In case of a fault in a TN system, a person is subject to a voltage (U_{ST}) which value is given by the product of the PE impedance times the earth-fault current flowing in it. The safety of people is ensured when the earth voltage does not last for a dangerous period of time, which is stated by the time/current safety characteristic.

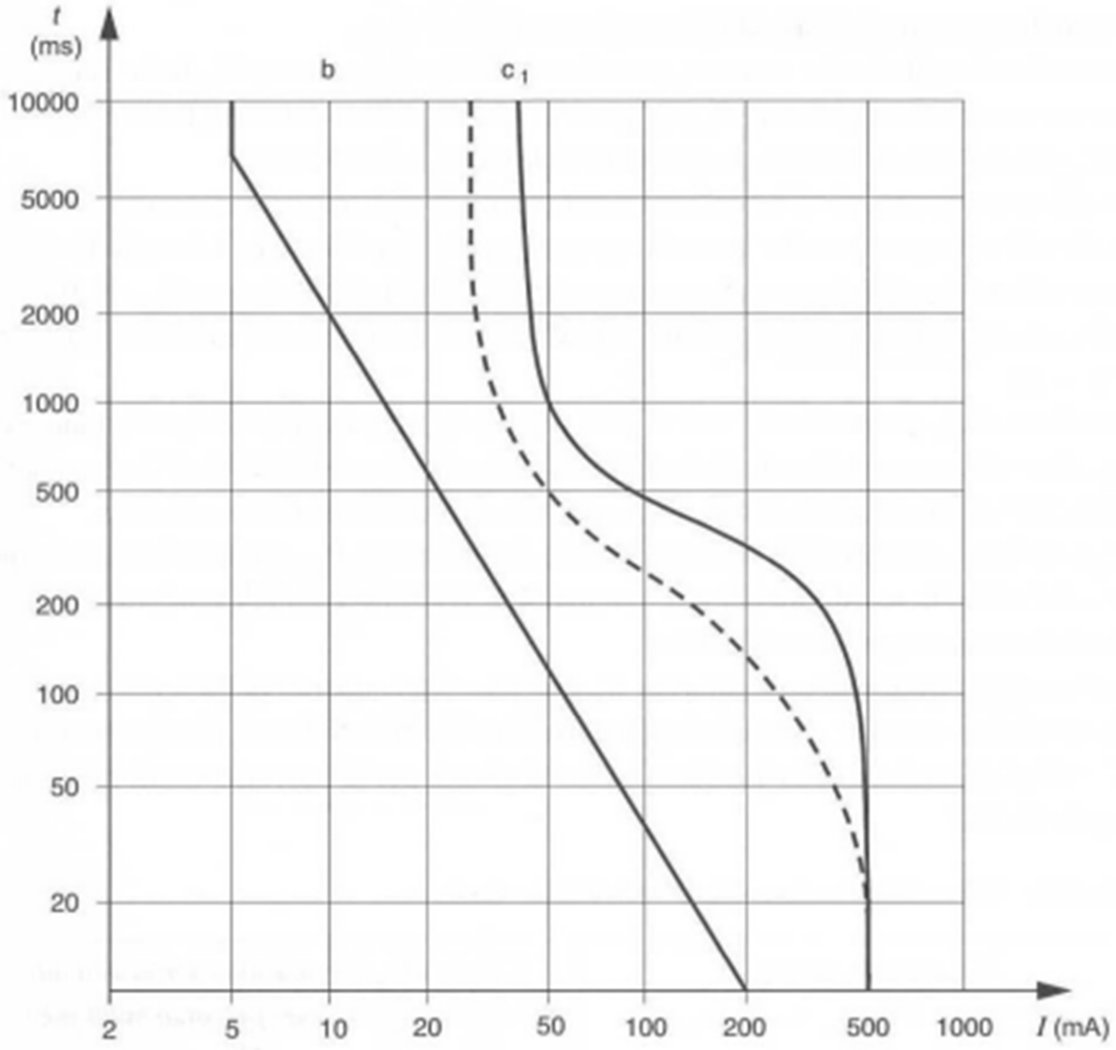


Figure 7.2: Time / Current characteristic showing the effect of current on the human body. The dashed line indicates standard values to ensure indirect contact protection using the automatic interruption of the supply strategy

The value of the voltage to which a person is subjected depends on the ratio between the protective conductor impedance (Z_{PE}) and the phase conductor impedance (Z_p) multiplied by the phase voltage (U_0).

$$\overline{U}_{ST} = \frac{\overline{U}_0}{\overline{Z}_p + \overline{Z}_{PE}} \overline{Z}_{PE} \tag{7.1}$$

Generally, due to the size of the grid formed by the PE which is connected in parallel to all the exposed conductive metalworks, its impedance is never greater than the phase conductor impedance, so that the voltage to which a person is subjected is never greater than 115V (which is given by 230V/2). In addition, it is also necessary to consider the equipotential bonding, which decreases the latter voltage by an additional 20%, resulting in a final value of 92V. The indirect contact protection device must have a time/current characteristic which makes it trigger in less than 0.4s when it detects the earth-fault current. This is described by the following equation:

$$Z_s \cdot I_a \leq U_0 \tag{7.2}$$

where:
Z_s indicates the earth-fault loop impedance;
I_a indicates the triggering current related to a time interval of 0.4s;

Nevertheless, the [7] allows a maximum triggering time of 5s in the case of distributing circuits in order to have a good selectivity of protections; this is accepted because of the low probability of a fault on that type of circuit. Finally, it is useful to do some consideration about the automatic interruption of the supply as indirect contact protection:

- In the TN systems, the earth fault can be treated as a short-circuit (see Figure 7.1) because the earth-fault currents are elevated; hence, it is possible to use thermal-magnetic circuit breakers as indirect contact protections. It is implied that to do so, the earth-fault current must be calculated. Approximately in the TN systems, the minimum earth-fault current can be assumed always greater than 100A.
- In the TN systems which adopt RCDs, the set-up thresholds of those may be of the order of tens of Ampere, while the triggering times must be lower than 0.4s (5s in the case of distributing circuits).
- For the purpose of LV earth faults calculations in the TN systems, the value of the earth resistance is meaningless. The earthing system is needed to realise the equipotential bonding of the extraneous conducting parts and for the earth-fault protection in the MV side of the circuit, which is going to be described in the next section (cf. Section 7.3.1).
- The set-up current of the RCDs is not of great importance, instead it is essential their triggering time.

7.2.2. Sizing of the protective conductor (PE)

The protective conductor must resist to corrosion and thermal and mechanical stress. In order to fulfil those requirements, the PE must have a minimum cross section which is established in the following table in accordance with the CEI standards.

Table 7.1: Minimum supply protective conductor (PE) cross section

Phase conductor cross section [mm^2]	Minimum PE cross section [mm^2]
$S \leq 16mm^2$	S
$16mm^2 < S \leq 35mm^2$	16 mm^2
$S > 35mm^2$	S / 2

Moreover, when the PE is not placed in the same conduit of the phase conductors, its cross section must be greater than:

- 2.5mm^2 if it has the mechanical protection;
- 4mm^2 if it does not have the mechanical protection.

If the PE is connected to different circuits, the greater phase conductor cross section must be considered. Following the indications reported in Table 7.1, if it is required a phase conductor with a minimum cross section of 35mm^2, then the PE conductor must have a cross section which is at least half of it. If that value of cross section (S/2) does not exist on the market, the CEI standards allow to use the closest valid cross section even if it is lower.

7.3. Indirect MV contact protection

In the case of a fault on the MV side of the circuit, every exposed conductive metalwork reach the earth-fault potential as if the live phase conductor touches them all at the same time; this also happens in the LV side. In Italy most of the MV public grids have their earthed neutral conductor using the Petersen coil. The art. 8.5.5.1 of [1] states that in the systems at 15kV with the earthed neutral conductor the general earth-fault current may be assumed equal to 40A; however, this value must be communicated by the DSO because it might be different.

7.3.1. Sizing of the earthing system

As said in the previous sections, the earthing system is needed only for the indirect MV contact protection purpose. The earthing system must resist to corrosion and thermal and mechanical stress. Also in this case, the CEI standards regulate the earth conductor minimum cross section:

Table 7.2: Minimum earth conductor cross section

Type of laying of the earth conductor	Minimum cross section [mm^2]
Shielded from corrosion, but not from mechanical stress	16mm^2 (copper) 16 mm^2 (zinc-coated iron)
Not shielded from corrosion	25 mm^2 (copper) 50 mm^2 (zinc-coated iron)
Shielded from corrosion and mechanical stress	Refer to Table 7.1

In order to be sized correctly, the earth conductor must fulfil two main constraints:

- Limit the value of the total earth voltage;
- Withstand the double earth-fault short-circuit current.

The earthing system of the case study plant was existing and it was realised using a copper conductor with a cross section of 50mm^2. Thus, it was only necessary to verify its compliance with the standards.

Total earth voltage

In order to verify that the earthing system is compliant with the two criteria listed above, it is necessary to know the value of the extinguish time of the protections and their earth-fault current set-up. These data are communicated by the DSO and the verification of the earthing system cannot neglect them. In the case study, the DSO has provided the following documentation:

Tensione nominale:	15	kV	± 10% (95% del tempo)
Frequenza nominale:	50	Hz	± 1% (99,5% del tempo)
Tensione massima per l'isolamento	17,5	kV	
Livello di isolamento a frequenza 50 Hz	38	kV	
Livello di isolamento impulso 1,2/50 μs	95	kV	
Corrente di cortocircuito trifase: (ai fini del dimensionamento delle apparecchiature)	12,5	kA	
Esercizio del neutro:	Neutro Compensato		
Corrente di guasto monofase a terra:	40 A		
Tempo di eliminazione del guasto a terra:	>>10		
Impianto di terra inserito in un imp. di terra globale:	NO		
Tensione di contatto ammissibile:	80 V		

Figure 7.3: DSO documentation reporting the earth-fault current (40A), the earth-fault extinguish time (>> 10s) and the maximum tolerable earth voltage (80V)

Since the measurement of the step potential and the earth-fault voltage require very long time and they are quite complex, the standards allow to measure the earth resistance (R_E): by multiplying this for the earth-fault current (I_E) it is possible to calculate the total earth voltage (U_E). From the data reported in Figure 7.3 it was evaluated the maximum tolerable earth resistance value:

$$R_E^{max} = \frac{U_E}{I_E} = 2\Omega \tag{7.3}$$

From the measurements on the existing earthing system, it resulted an actual earth resistance equal to 0.72Ω: this means that the earthing system is compliant with the standards.

Double earth-fault short-circuit current

The CEI standards impose that the earthing system must be able to withstand the abovementioned short-circuit current (I_{LLG}). To do so, it must withstand the let-through energy generated by the double earth-fault short-circuit current. Its value is retrieved from the short-circuit current communicated by the DSO (see Figure 7.3) using the following equation:

$$I_{LLG} = \frac{\sqrt{3}}{2} I_k \tag{7.4}$$

This resulted in a current of 10.8kA. According to the DSO specifications about the setup of the protections (please refer to Chapter 8), the latter current is interrupted within 0.17s. The cross section of the earth conductor can now be computed using the formula:

$$S = \frac{I\sqrt{t}}{K} \tag{7.5}$$

where:
I indicates the double earth-fault short-circuit current;
t indicates the time needed from the protection to open the circuit;
K is a coefficient which depends on the type of conductor and the insulating sheath (cf. Section 6.1.4).

The results are reported in the tale below:

Table 7.3: Earth conductor cross section calculations

Double earth-fault short-circuit current [kA]	**Opening time [s]**	**Earth conductor cross section [mm^2]**	
		PVC	**EPR/XLPE**
10.8 kA	0.17 s	39 mm^2	31 mm^2

The results must be rounded up to the next cross section value according to the existing ones on the market, which is 50mm^2. According to this results, the existing earthing system satisfies this criteria too and it was declared definitely compliant with the CEI standards.

8 Electrical protections coordination

The coordination between the different protection devices dedicated to specific areas and components must be studied in order to be able to understand what kind of failure has occurred and where, so as to intervene as quickly as possible to safeguard the continuity and the stability of the power supply. A protection system becomes more selective as it reduces the portion of the network that it disconnects in order to clear a fault. In the case study, it will be considered earth faults and overcurrents.

8.1. Concept of selectivity

The strategy which satisfies the aforementioned purpose is mainly based on the values of rated current (I_n) and short-circuit current (I_k). Overcurrent selectivity is defined by def. 2.5.23 of [13] as:

"Overcurrent selectivity is the coordination of the operating characteristics of two or more overcurrent protection devices in such a way that, when overcurrents occur within the established limits, the device intended to operate within these limits operates while the others do not operate."

In addition, it is possible to distinguish between:

- Total selectivity:

  "Overcurrent selectivity so that, in the case of two overcurrent protection devices in series, the load-side device provides protection without involving the other protection device." (see, def. 2.17.2. of [10]).

- Partial selectivity:

  "Overcurrent selectivity so that, in the case of two overcurrent protection devices in series, the load-side device provides protection up to a given limit without involving the other protection device." (see, def. 2.17.3 of [10]);
  "This overcurrent limit is called the limit current of selectivity I_s." (see, def. 2.17.4 of [10])

8.1.1. Current selectivity

The current selectivity is based on the fact that the intensity of the fault current is the greater the closer the fault point is to the power supply. Therefore, the location of the fault point is achieved by appropriately adjusting the threshold of the operating current of the protective devices: the upstream device is calibrated to a threshold higher than the limit value set for the downstream protection device. This strategy is used only in circuits with a low rated current and those in which a high fault impedance is interposed between the protections, that is able to limit the value of the short-circuit current. In addition, it has the advantage of being fast, easy to implement and economical; On the other hand, the thresholds for intervention against overcurrents rise rapidly, thus increasing the sizes of the switches installed in the circuit. In addition, it is not possible to have a redundancy of the protections that guarantees the elimination of the fault in case of failure of one of them.

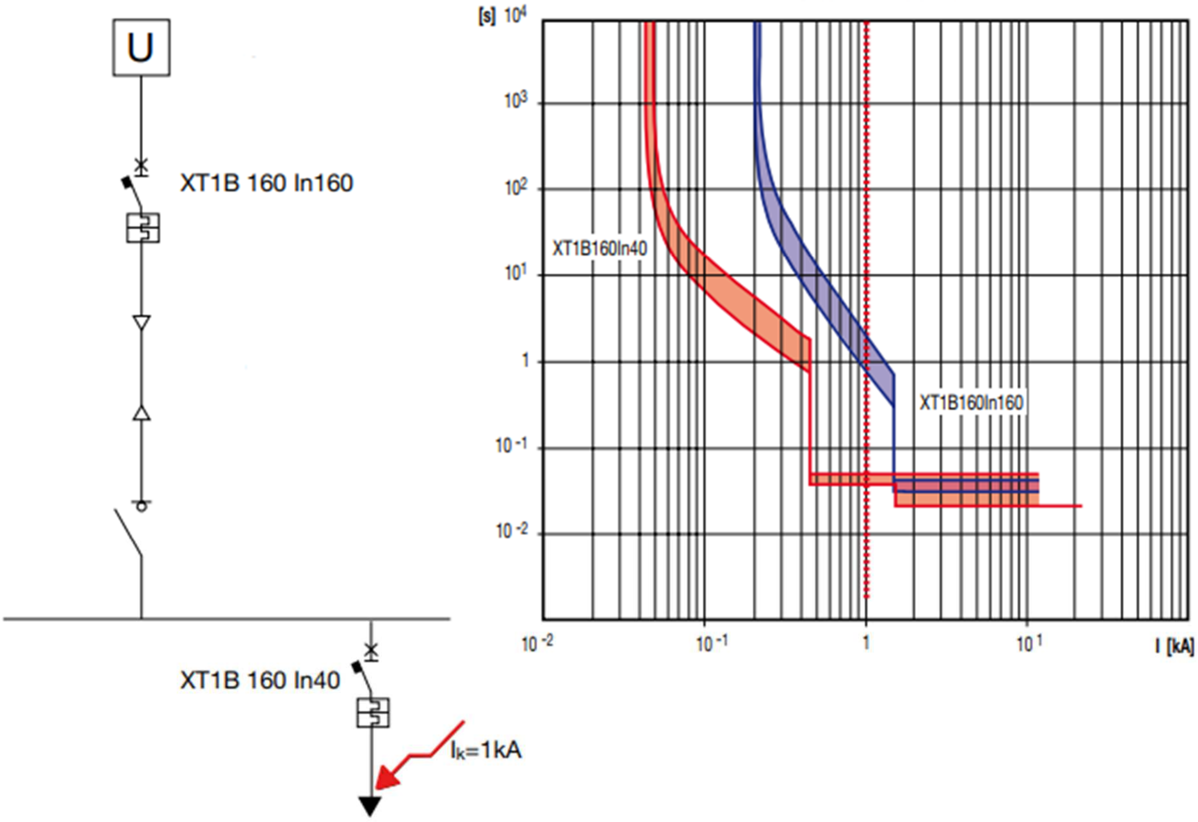


Figure 8.1: Example of current selectivity

8.1.2. Time selectivity

The time selectivity is an improvement of the previous one, where in addition to the intervention current threshold, an intervention time is also defined: a given overcurrent value causes the intervention of the protections after a defined time interval, such as to allow to protections placed closer to the fault to intervene, so that the area where the fault is located is excluded from the rest of the network. The time delays set on the overcurrent protections that are in series (Δ_t) must take into account the detection time and the elimination time of the downstream device failure, as well as the inertia time (over-shoot) of the upstream device (time interval during which the protection intervention can also occur when the phenomenon is exhausted).

$$\Delta_t = t_d + \varepsilon + t_e + t_i + \tau \tag{8.1}$$

where:

- t_d is the detection time (time in between the fault detection and the sending of the opening signal to the breaker, usually about at least 20ms);
- t_e is the elimination time (usually about 70 to 80ms in MV and 35 to 45ms in LV);
- t_i is the inertia time (usually about 20ms);
- ε is a time error that can occur on the downstream device (usually considered as a 10% of the opening time, which is the sum of t_d and t_e);
- τ is a safety margin;

This configuration has the advantage of being economical, easy to implement and allows redundancy of the protections. In opposition to this, it has the great disadvantage of stressing the protections close to the sources, as they are subject to considerable electrodynamic stresses and high levels of passing energy.

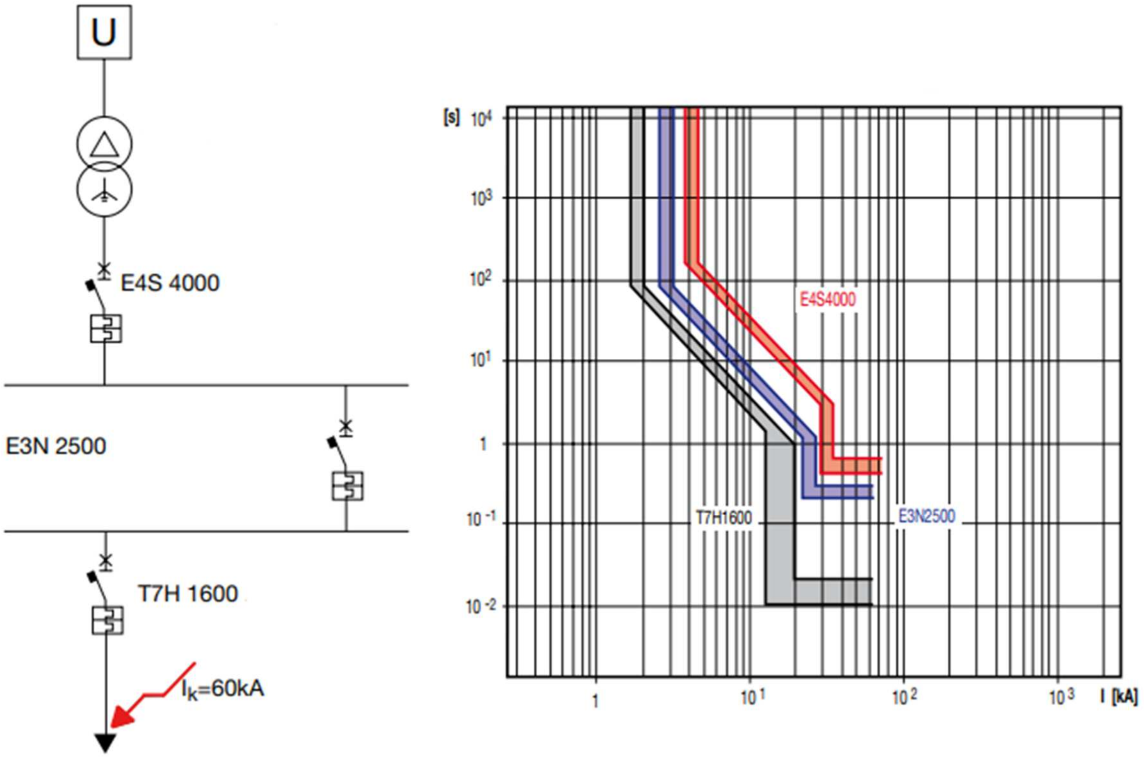


Figure 8.2: Example of time selectivity

8.1.3. Logic selectivity

The logical selectivity is based on the communication between protections regarding the states of the devices capable of opening or closing the circuit, so as to intervene strategically and preserve the continuity of service for as many loads as possible, requiring that the downstream protection inhibits the intervention of the upstream protections. The communication between the protections can be in cable, via pilot wire, or wireless, via optical fibre. This method has the advantage of having a reduced fault elimination time, as the opening time does not depend on the location of the fault, nor on the number of protections in cascade. However, it has the limit that it is not possible to have instantaneous interruptions of the circuit, as the technical transmission times of the signal must be considered and also its reliability depends entirely on that of the communication system. To overcome this, it is provided a time step of 100ms, so as to have a timed back-up intervention in the event that the data transmission system fails. Another disadvantage concerns the case in which the protections are very far away from each other, thus making it difficult to realise the cable connection. This problem can be solved either by combining logical selectivity with time selectivity for the most distant areas, or by making the interconnections between the most distant protections by means of optical fibre.

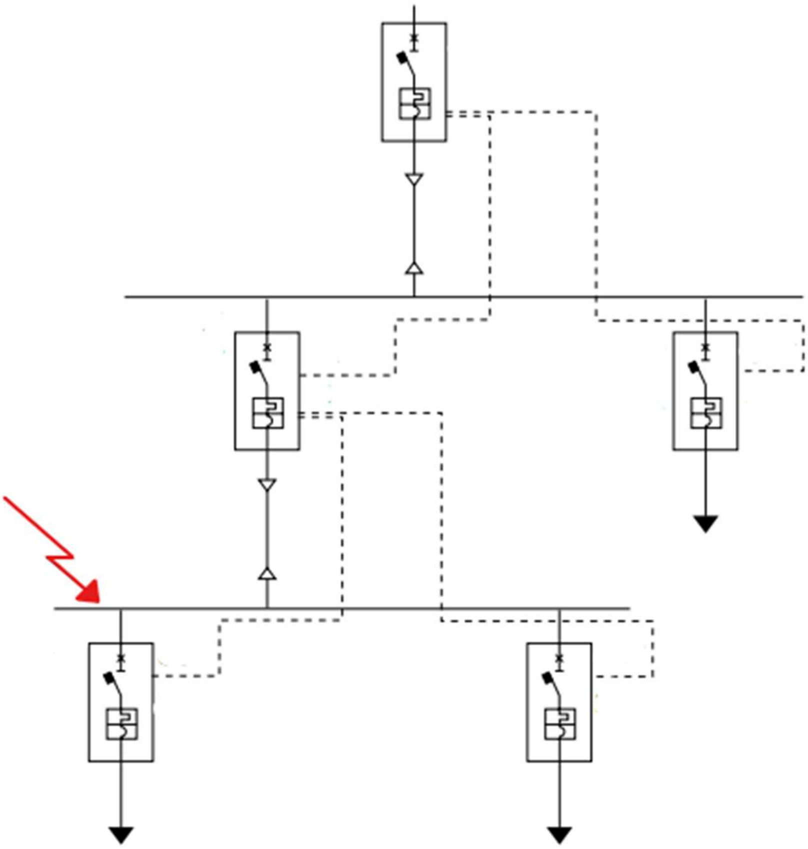


Figure 8.3: Example of logic selectivity

8.1.4. Energetic selectivity

This type of coordination exploits the characteristics of limiting switches: "automatic switch with a sufficiently short cut-off time to prevent the short-circuit current from reaching the peak value it would otherwise reach" (see, def. 2.3 of [10]). Therefore, it is not possible to carry out coordination by studying the time-current curves as in the previous cases, instead the specific let-through energy curves based on I^2t are analysed. In general, it is verified that the energy associated with the intervention of the downstream switch is lower than that related to the intervention of the upstream device. So, this type of coordination is more complex than the others, but it guarantees a quick interruption and a reduction in damage caused by the failure (thermal and electrodynamic stresses). It also allows a large number of levels of selectivity, even though it complicates coordination between switches of similar sizes. In addition, it has to be supported by the strategies of selectivity described previously in order to ensure fault extinguishment, even in the case of lower current values.

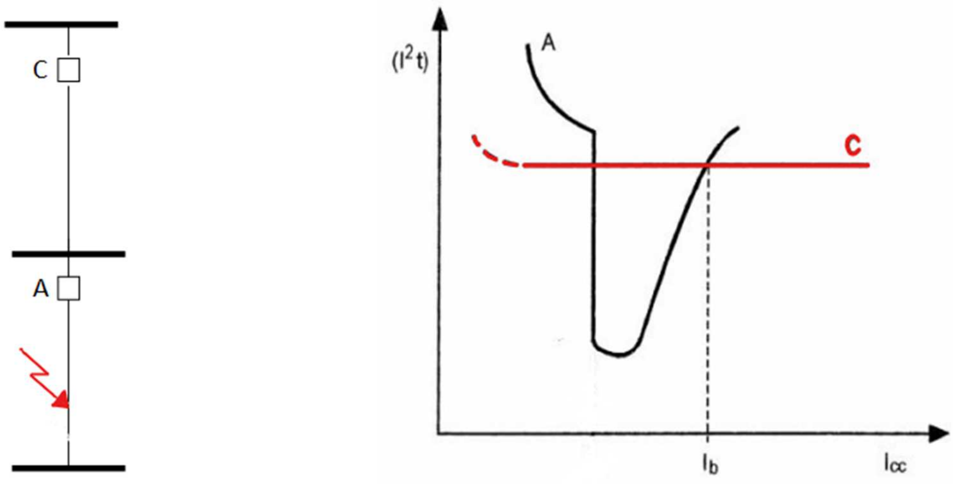


Figure 8.4: Example of energetic selectivity and limiting switches

In the right part of Figure 8.4, curve A represents the specific let-through energy (I^2t) of the downstream breaker, while curve C shows the energy that would trigger the breaker placed upstream. As it is reported, I_b represents the limit to implement selectivity.

8.2. Public grid connection specifications

The setting of protections (cf. Figure 8.5) depends both on the characteristics of the User's plant and the power supply network.

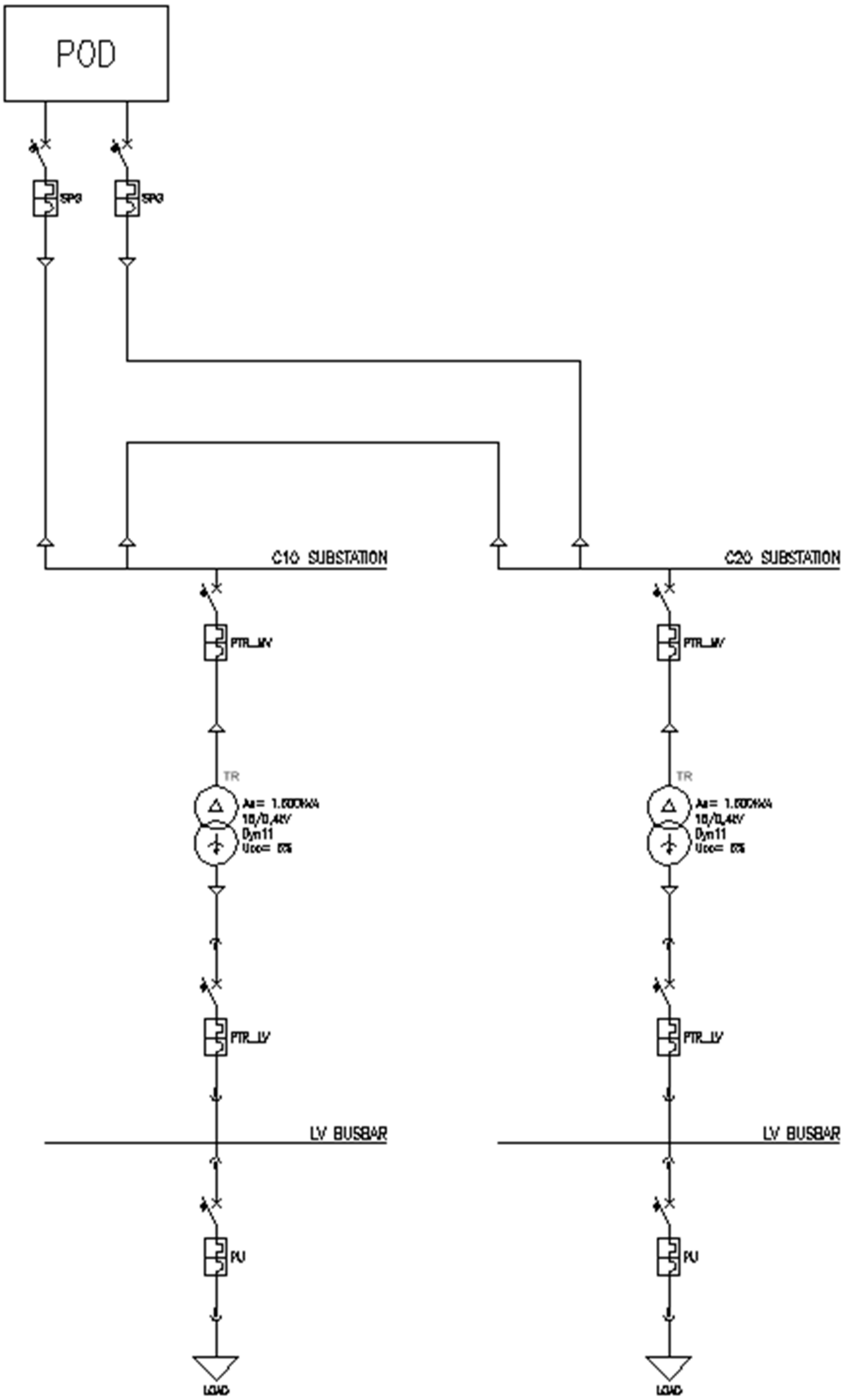


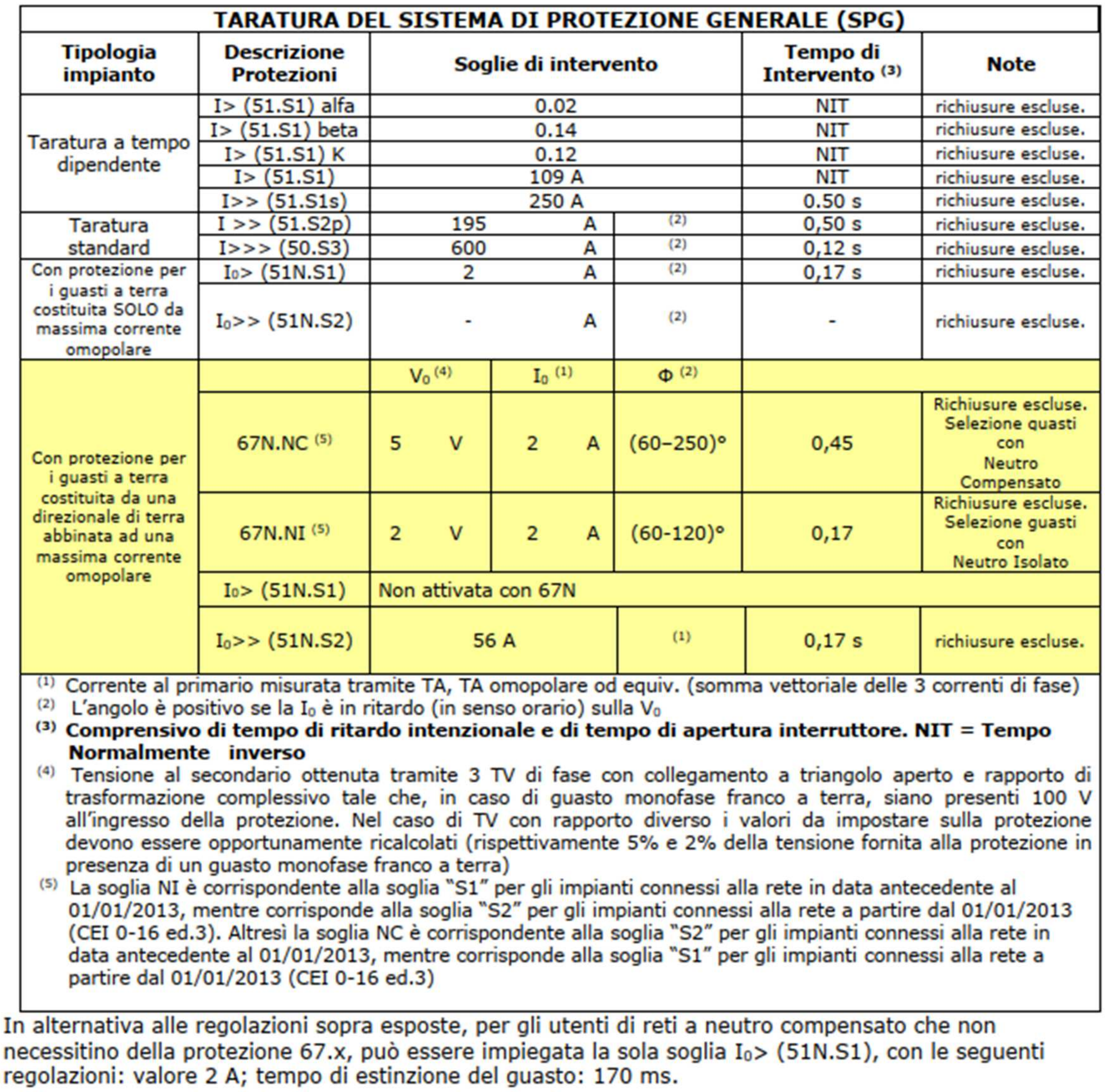
Figure 8.5: Representation of the protections locations into the plant electrical system. Since the transformers have all the same size, for the sake of simplicity it has been reported only one of them connected to its busbar

They must be set up by the User based on what is communicated by the DSO. The User cannot exceed the values given by the DSO, while the latter cannot indicate thresholds that are lower than the ones indicated in Table 8.1.

Table 8.1: Minimum values that protections can be set up according to the DSO specifications

1st threshold (51) I >	2nd threshold (51) I >>	3rd threshold (50) I >>>
To be decided	250 A – 500 ms	600 A – 120 ms

Below, it is reported the letter with the DSO specifications for the case study:



TARATURA DEL SISTEMA DI PROTEZIONE GENERALE (SPG)

Tipologia impianto	**Descrizione Protezioni**	**Soglie di intervento**			**Tempo di Intervento (3)**	**Note**
Taratura a tempo dipendente	I> (51.S1) alfa	0.02			NIT	richiusure escluse.
	I> (51.S1) beta	0.14			NIT	richiusure escluse.
	I> (51.S1) K	0.12			NIT	richiusure escluse.
	I> (51.S1)	109 A			NIT	richiusure escluse.
	I>> (51.S1s)	250 A			0.50 s	richiusure escluse.
Taratura standard	I >> (51.S2p)	195 A		(2)	0,50 s	richiusure escluse.
	I>>> (50.S3)	600 A		(2)	0,12 s	richiusure escluse.
Con protezione per i guasti a terra costituita SOLO da massima corrente omopolare	I_0> (51N.S1)	2 A		(2)	0,17 s	richiusure escluse.
	I_0>> (51N.S2)	- A		(2)	-	richiusure escluse.
Con protezione per i guasti a terra costituita da una direzionale di terra abbinata ad una massima corrente omopolare		V_0 (4)	I_0 (1)	Φ (2)		
	67N.NC (5)	5 V	2 A	(60–250)°	0,45	Richiusure escluse. Selezione quasti con Neutro Compensato
	67N.NI (5)	2 V	2 A	(60-120)°	0,17	Richiusure escluse. Selezione guasti con Neutro Isolato
	I_0> (51N.S1)	Non attivata con 67N				
	I_0>> (51N.S2)	56 A		(1)	0,17 s	richiusure escluse.

(1) Corrente al primario misurata tramite TA, TA omopolare od equiv. (somma vettoriale delle 3 correnti di fase)

(2) L'angolo è positivo se la I_0 è in ritardo (in senso orario) sulla V_0

(3) Comprensivo di tempo di ritardo intenzionale e di tempo di apertura interruttore. NIT = Tempo Normalmente inverso

(4) Tensione al secondario ottenuta tramite 3 TV di fase con collegamento a triangolo aperto e rapporto di trasformazione complessivo tale che, in caso di guasto monofase franco a terra, siano presenti 100 V all'ingresso della protezione. Nel caso di TV con rapporto diverso i valori da impostare sulla protezione devono essere opportunamente ricalcolati (rispettivamente 5% e 2% della tensione fornita alla protezione in presenza di un guasto monofase franco a terra)

(5) La soglia NI è corrispondente alla soglia "S1" per gli impianti connessi alla rete in data antecedente al 01/01/2013, mentre corrisponde alla soglia "S2" per gli impianti connessi alla rete a partire dal 01/01/2013 (CEI 0-16 ed.3). Altresì la soglia NC è corrispondente alla soglia "S2" per gli impianti connessi alla rete in data antecedente al 01/01/2013, mentre corrisponde alla soglia "S1" per gli impianti connessi alla rete a partire dal 01/01/2013 (CEI 0-16 ed.3)

In alternativa alle regolazioni sopra esposte, per gli utenti di reti a neutro compensato che non necessitino della protezione 67.x, può essere impiegata la sola soglia I_0> (51N.S1), con le seguenti regolazioni: valore 2 A; tempo di estinzione del guasto: 170 ms.

Figure 8.6: DSO letter with setting guidelines. The time indicated are comprehensive of the 70ms necessary to the circuit breakers to open

From now on, all the cited time associated to the protections will be considered comprehensive of the 70ms opening time of the circuit breakers. As shown in Figure 8.6, it is possible to calibrate the overcurrent protections in two different configurations, both compliant with [1].

- The first option consists in setting a time-dependent first action threshold (I >) to a current value of 109A, while the second threshold (I >>) must be set up to 250 A with an extinction time of 500ms.
- The second option consists of neglecting the first threshold; instead, it configures a second threshold at a lower current value (195A), while the extinguishing time is kept unchanged.

However, in both configurations, it is necessary to calibrate the short-circuit current protection (50), by setting a third threshold (I >>>) to a current value of 600A, associated with an extinguish time equal to 120ms. The letter also shows the values of the coefficients α, β, K, to be used in the formula (8.2):

$$t = \beta \cdot \left\| \frac{K}{\left[\left(\frac{I}{I >} \right)^{\alpha} - 1 \right]} \right\| \tag{8.2}$$

This formula is necessary to calculate the abscissa of the points of the time-dependent portion of the curve, while the following iterative method was used to calculate the ordinates:

$$I^{(n+1)} = I^{(n)} \cdot \left(\frac{I \gg}{I^{(n)}} \right)^{\frac{1}{N-1}} \tag{8.3}$$

where:
n is an integer number that represents the iteration counter: initially it is equal to 1 and increments its value by one unit at each cycle;
N indicates the number of points of the curve and it was set to 10;
I^n indicates the current value referred to the n-th iteration;
$I^{(1)}$ is the first value to start with the iterative method and it is equal to the first threshold current (I >).

The recursion is repeated until the value of n becomes equal to N. That said, the first option was chosen and, in the next paragraph, it is described how it was adapted to this case scenario.

8.3. Protection settings

Looking at Figure 8.5, it was decided to install:

- A general protection downstream the point of delivery installed in cabin C00 (SPG);
- A protection on the MV side of each transformer (PTR_MV);
- A protection on the LV side of each transformer (PTR_LV);
- A protection on each line connected to the switchboards (PU).

Usually, a directional protection in the ring insertion cells of the substations should be installed as well (please refer to cell 10.1 and 10.2 of Figure 4.6 and cell 20.1 and 20.2 of Figure 4.7). In fact, they would detect a fault on the MV lines that realise the ring configuration. In practice, since the network is not very extended, it is very unlikely that a fault happens in that section and it was decided to not install any protection, saving money for other purposes.

8.3.1. Protection banks

Due to the ring configuration chosen for connecting the substations (see Section 4.1), it is necessary to provide two protective configurations, which in this case were called "A" bank and "B" bank.

- The "A" bank configuration is referred to the case in which both columns are closed and therefore, the second threshold communicated by the DSO were halved, while the third threshold remained unchanged. The thresholds were modified as mentioned above, as the two sides of the ring of the network have the same length.
- The "B" bank configuration is referred to the situation in which one of the two columns is open, so, the whole electric load is managed by the SPG of the uninterrupted column (cf. Figure 4.3).

8.3.2. General protections (SPG) setup

First of all, the SPGs were set up as indicated by the DSO and the values of the second threshold (I >>) for the “A” bank configuration was halved.

Table 8.2: SPGs setup in the “A” bank configuration including the opening time of the circuit breakers of 70ms

SPG “A”	**I >**	54.5 A	NIT	($\alpha = 0.02$; $\beta = 0.14$; $K = 0.12$)	
	I >>	125 A	500 ms	2nd harmonic block (15% - 700 ms)	
	I >>>	600 A	200 ms		
	51N.S1	Turned off with 67N			
	51N.S2	56 A	170 ms		
	67N.NC	$V_0 = 5$ V	$I_0 = 2$ A	$\Phi_0 = (60\text{-}250)°$	t = 450 ms
	67N.NI	$V_0 = 2$ V	$I_0 = 2$ A	$\Phi_0 = (60\text{-}120)°$	t = 170 ms

Table 8.3: SPGs setup in the "B" bank configuration including the opening time of the circuit breakers of 70ms

SPG "B"	**I >**	109 A	NIT	(α = 0.02; β = 0.14; K = 0.12)	
	I >>	250 A	500 ms	2nd harmonic block (15% - 700 ms)	
	I >>>	600 A	200 ms		
	51N.S1	Turned off with 67N			
	51N.S2	56 A	170 ms		
	67N.NC	V_0 = 5 V	I_0 = 2 A	Φ_0 = (60-250)°	t = 450 ms
	67N.NI	V_0 = 2 V	I_0 = 2 A	Φ_0 = (60-120)°	t = 170 ms

The only difference with the DSO specifications is the time associated to the second threshold (I >>), which is 200ms instead of 50ms. In fact, as mentioned in Section 4.1.2 and Section 4.1.3 it was implemented a communication system via optical fibre between the MV protections in order to realise logical selectivity. However, using the 50ms communicated by the DSO would make any type of selectivity impossible to realise. The [1] allows the User to regulate the SPG so that the complete extinction of the fault is guaranteed in a maximum period of time of 200ms. This extended time allows to the protection downstream (PTR_MV) to detect the fault, communicate its trigger to the SPG and extinguish it. It is essential to underline that the SPG must detect the fault in 50ms and, in case of missed signal from the protection downstream, it must open the circuit even if the fault current has already been interrupted by the circuit breaker of the DSO upstream, which usually takes between 70ms and 150ms to do so.

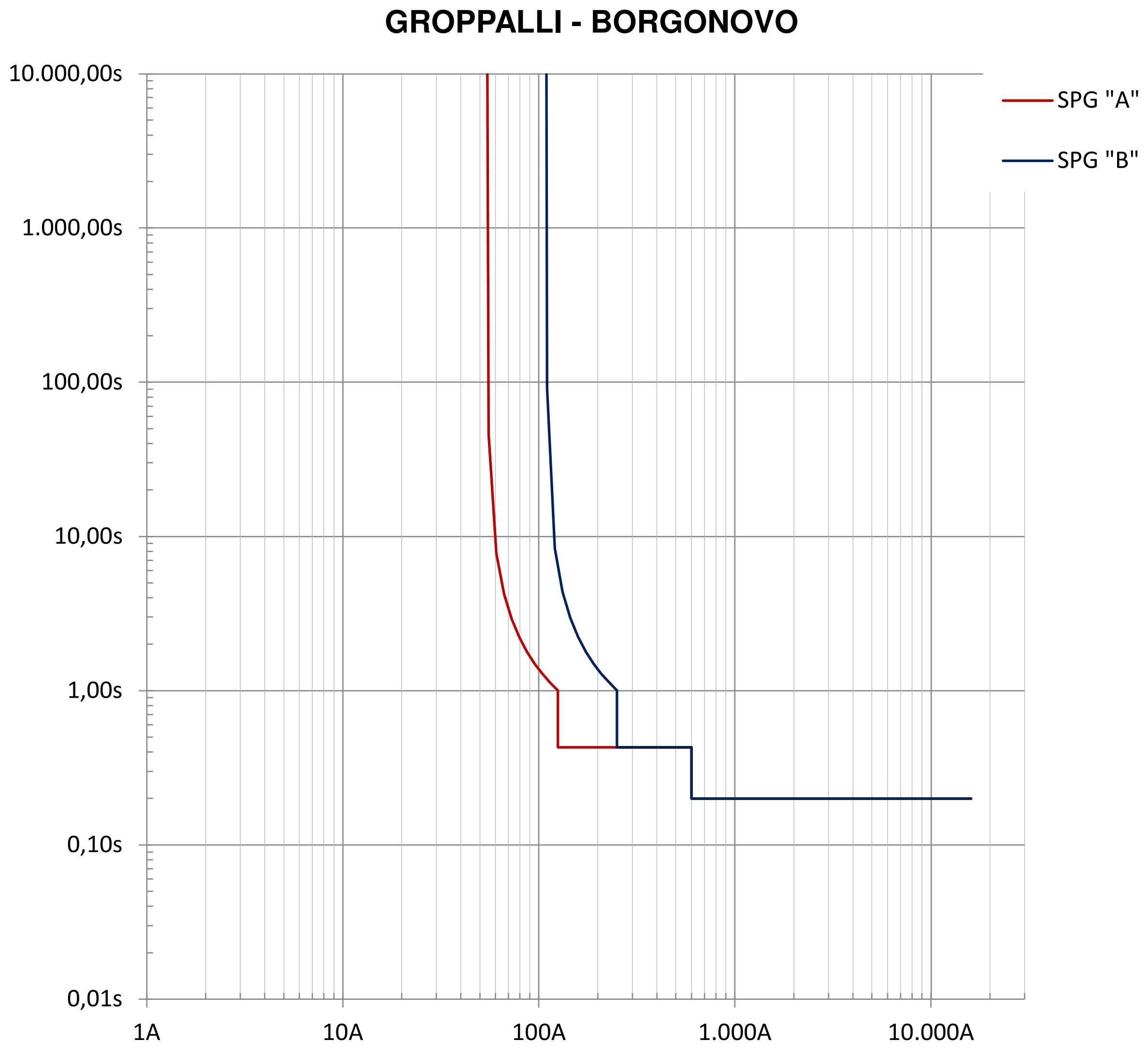


Figure 8.7: SPGs characteristics both for “A” bank and “B” bank configurations

As expected, there is a initial time dependent section in both curves since it was decided to follow the first possibility described in Section 8.2. and then the two instantaneous threshold.

8.3.3. Transformer inrush current

The curves of Figure 8.7 must be compared with the transient curve of the load, which is obtained by the formula:

$$I(t) = I_r + \frac{I_{0i}}{\sqrt{2}}\left(e^{-\frac{t}{\tau}}\right) \tag{8.4}$$

where:
I_r indicates the continuous component present in the transient;
I_{0i} indicates the inrush current of the transformer.

In this case, the load is represented by only one 1600kVA transformer even if there are more installed, because protection (27) inserts them into the network one at a time (see Section 4.1.2). Moreover, a time constant (τ) of 400ms and a ratio between inrush current and the rated current $\left({}^{I_{0i}}/_{I_n} \right)$ equal to 9 was considered to perform the calculations. Below, it is shown the resulting curve called "1x1600":

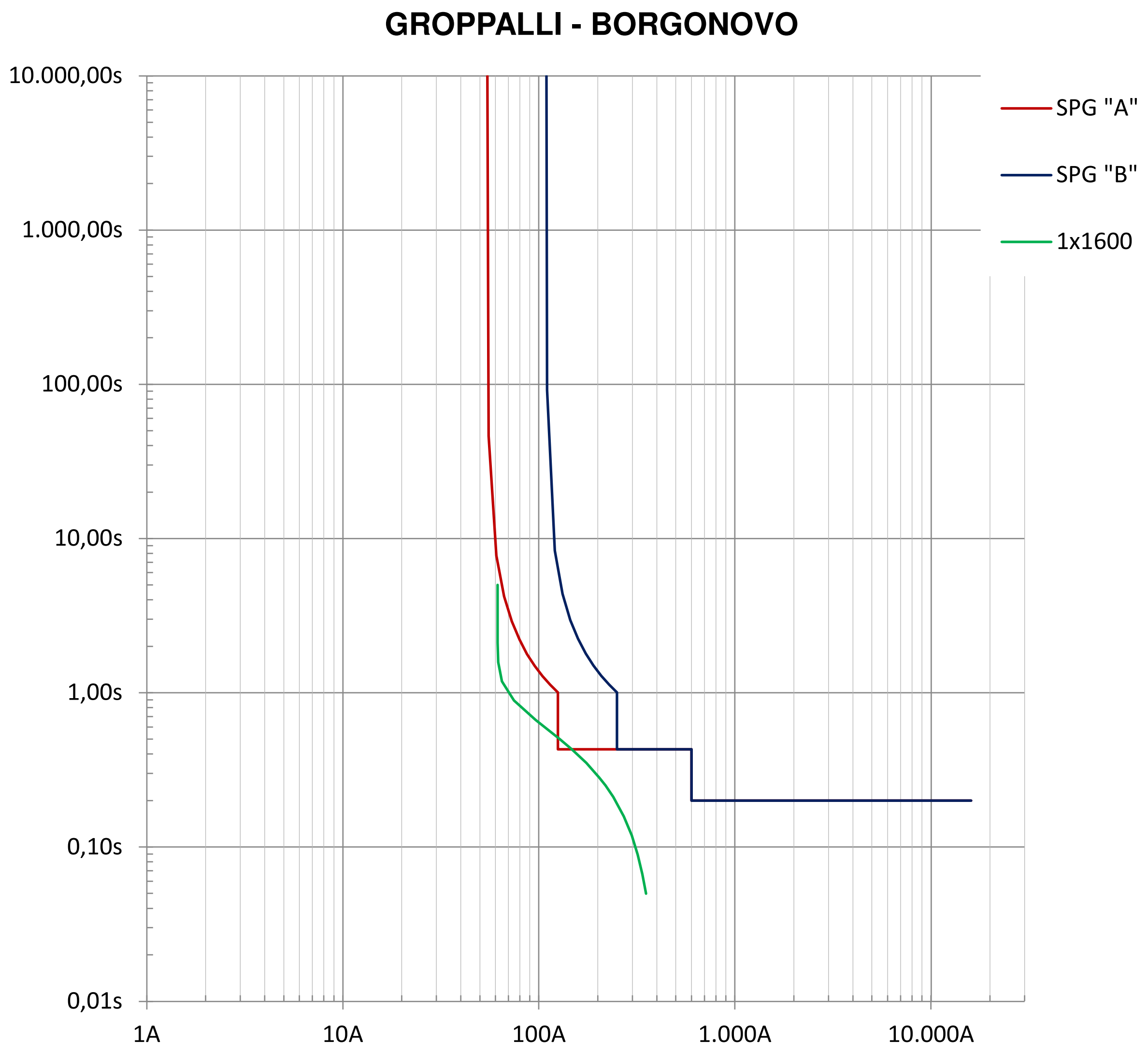


Figure 8.8: 1600 kVA transformer insertion transient curve

In Figure 8.8, it is clear that the insertion of the transformer would trigger the SPGs in the "A" bank configuration, so to solve this, a 2nd harmonic block was implemented. In fact, the inrush current has a big 2nd harmonic contribute. The block analyses the spectrum of the current and estimates the amount of that component: if it is greater than the setup value, it disables the protection for a determined time and this allows the operation without experiencing any SPGs trigger. Moreover, notice that in "B" bank configuration the two curves are pretty near from each other, even if they do not cross. Hence, for the sake of reliability, the filter was implemented also on this configuration in order to avoid accidental triggers of the protection.

8.3.4. Transformers protections (PTR_MV) setup

The transformers protections (PTR_MV) must satisfy the following three conditions:

- Be selective with the SPG installed upstream;
- Provide the protection to short-circuit currents in the LV side of the transformer, upstream the PTR_LV;
- Be insensitive to inrush transient currents.

Below, the setup used in order to be compliant with the requirements listed above is reported:

Table 8.4: Transformers protections (PTR_MV) setup including the opening time of the circuit breakers of 70ms

PTR_MV	**I >**	-	-	-
	I >>	195 A	420 ms	2nd harmonic block (15% - 700 ms)
	I >>>	500 A	50 ms	
	51N	1 A	250 ms	-
	27	Opening	-	170 ms
		Reclosure	TR 20.1	22 s
			TR 20.2	24 s
			TR 20.3	26 s

Selectivity with the SPG

A logic selectivity strategy between the PTR_MV and the SPG was implemented. The second threshold (I >>) was set up with a lower value of current than the SPGs to realise current selectivity, but this is not enough. In fact, it was associated to a time of 420ms. In this way, the transformers protections open the circuit in 420ms (350ms + 70ms), while the SPGs are setup in order to take 430ms to detect the fault. The third threshold (I >>>) was setup to a lower current value with respect to the SPG and it was associated to an extinguish time of 50ms (cf. Section 8.3.2.).

Short circuit on the LV side

The CEI standards impose to calculate the minimum and the maximum short-circuit current on the LV side of the transformers in order to correctly regulate the protections. Nevertheless, the minimum short-circuit current (I_k^{min}) is more interesting for the sake of selectivity.

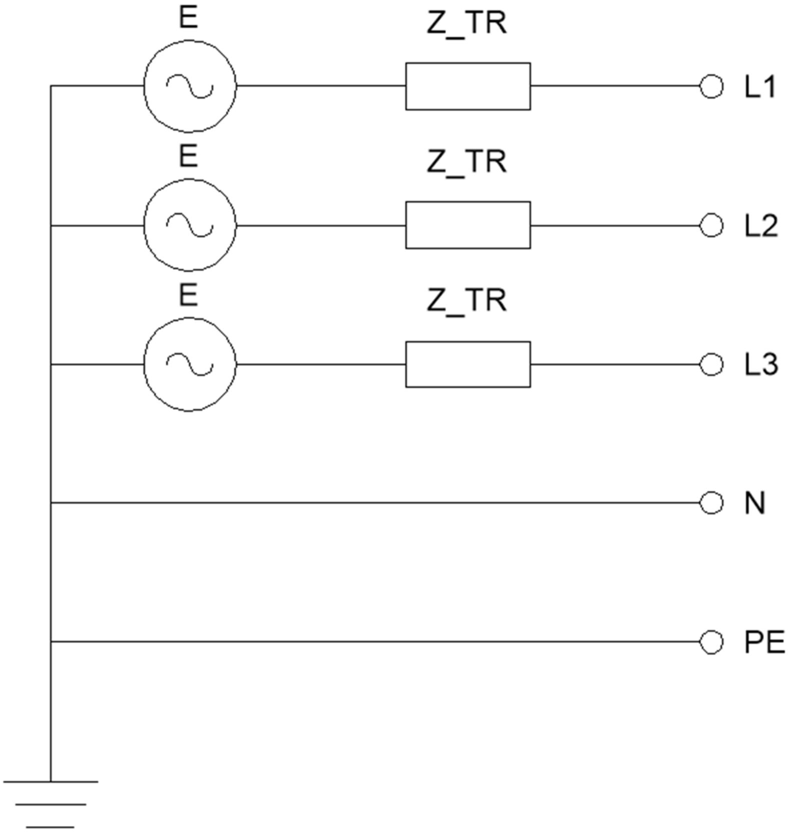


Figure 8.9: Equivalent circuit at the secondary winding terminals of the transformer

In this portion of circuit, the lower fault current corresponds to the line-to-line fault current due to the negligible impedance of the PE conductor.

$$I_{LG} = I_{LLL} = \frac{E}{Z_{TR}} \tag{8.5}$$

$$I_{LL} = \frac{U}{2Z_{TR}} = \frac{\sqrt{3}E}{2Z_{TR}} = 0.866\ I_{LG} \tag{8.6}$$

As shown in the latter equations, the line-to-line fault current (I_{LL}) is 0.866 times the line-to-ground fault current (I_{LG}), which is equal to the three-phase fault current (I_{LLL}). In order to calculate the I_k^{min}, the CEI standards impose to consider a voltage which is 10% lower than the rated one and an additional correction factor of 0.8, which takes into account the variation of some parameters due to the short-circuit. Thus, minimum short-circuit current is the following:

Table 8.5: Minimum short-circuit currents on both sides of the transformers

I_{LLL} [kA]	I_{LL} [kA]	I_{1k}^{min} [A]	I_{2k}^{min} [kA]
36.6 kA	31.7 kA	610 A	22.8 kA

By the comparison of this value with the third threshold (I >>>) reported in Table 8.4, it results that even in the case of a fault on the LV terminals of the transformers that produces the lowest short-circuit current, the protection installed upstream is able to detect it and open the circuit. Bear in mind that the second threshold (I >>) setup would have been enough due to the rated short-time withstand current (I_{cw}) value of the PW10 and PW20 LV switchboards (see Section 6.3.6). Finally, the zero-sequence current protection (51N) was setup in order to give the time to the PTR_MV protection to communicate with the SPG in case of earth fault: there is a difference of 180ms between the two which is enough for this purpose. The setup of protection (27) was implemented to satisfy the CEI standard specifications described in Section 4.1.2.

Inrush currents

Even in this case, the PTR_MV characteristic is really close to the inrush transient curve, so it was configurated a 2nd harmonic block with the same setup as before.

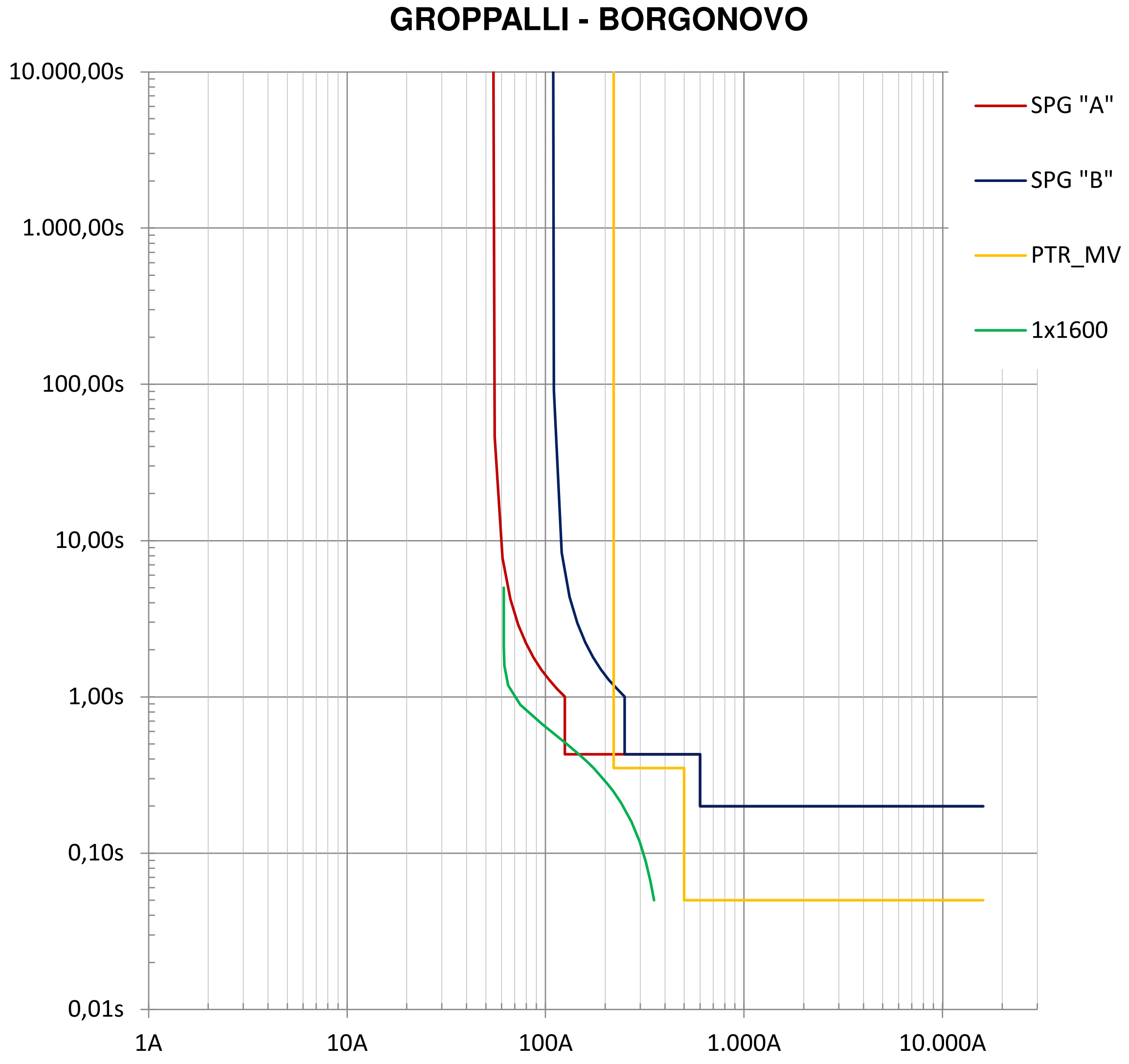


Figure 8.10: Transformer protection characteristic

The only selectivity issue with this protections is in the case of a fault on the LV side of the transformers. In fact, the short-circuit current measured at the LV busbars is 36.6kA (see Table 6.5) that corresponds to a current of 976A reported to the MV side of the transformers. By the comparison of this with the setup of short-circuit current protection (51) of the PTR_MV, it results that a fault on the LV busbars would trigger the latter protections other than the ones on the LV side of the transformers (PTR_LV); in addition, due to the LV side network configuration (TN-S system), an earth fault is treated as an overcurrent as well (cf. Section 7.2). Thus, any fault on the LV side that causes a current greater than 18.75kA at the secondary windings terminals of the transformers (500A reported to the MV side) triggers both the PTR_MV and the PTR_LV. Nevertheless, this is not an important issue since it does not cause long-lasting out of services and it can be easily solved.

8.3.5. LV busbars protections (PTR_LV) setup

These protections do not play a key role as the others described previously; however they were installed to increase the reliability of the network. The thermal threshold (I_{th}) of these protections is used as a back-up of the temperature sensor central unit thermal protection installed in the transformers compartments; to do so, these were set up to 2300A. On the other hand, the magnetic threshold must be set up to a lower value than the fault current value on the LV side that would trigger the PTR_MV, which is 18.75kA. This allows to detect even non-zero fault impedance currents that may occur between the transformers and the LV busbars. Thus, the magnetic threshold were set up to 6 times the trip unit rated current, which is equal to 2500A.

Table 8.6: LV busbars protections (PTR_LV) setup

PTR_LV	I_{th}	2300 A
	I_{sd}	15 kA

The value of the magnetic threshold is the result of a compromise between two conditions:

- The higher its value, the higher is the level of selectivity with the circuit breakers downstream (PU);
- The lower its value, the more effective is its back-up function with respect to PTR_MV.

Nevertheless, the first condition is more important and so it has a bigger influence on the choice of the magnetic threshold value.

8.3.6. Load protections (PU) setup

The setup of these protections is based on specifications listed in [7], which are described in Section 6.1. and must ensure the protection of the loads and the cables downstream.

- The thermal threshold is set up on the basis of the overcurrents protection criterion shown in Section 6.1.3;
- The magnetic threshold is set up following the short-circuit current protection criterion mentioned in Section 6.1.4.

Table 8.7: Load protections (PU) setup

PU	I_{th}	cf. Section 6.1.3
	I_{sd}	cf. Section 6.1.4

The second condition must be verified for the whole range between the minimum short-circuit current and the maximum short-circuit current. However, due to the art. 435.1 of [7], the second condition may not be verified (see Section 6.1.4.). In the case study, the vast majority of the installed circuit breakers are short-circuit current-limiting circuit breakers except for the ones connected to the PV system. Hence, the verification of the let-through energy was necessary only on the latter circuit breakers.

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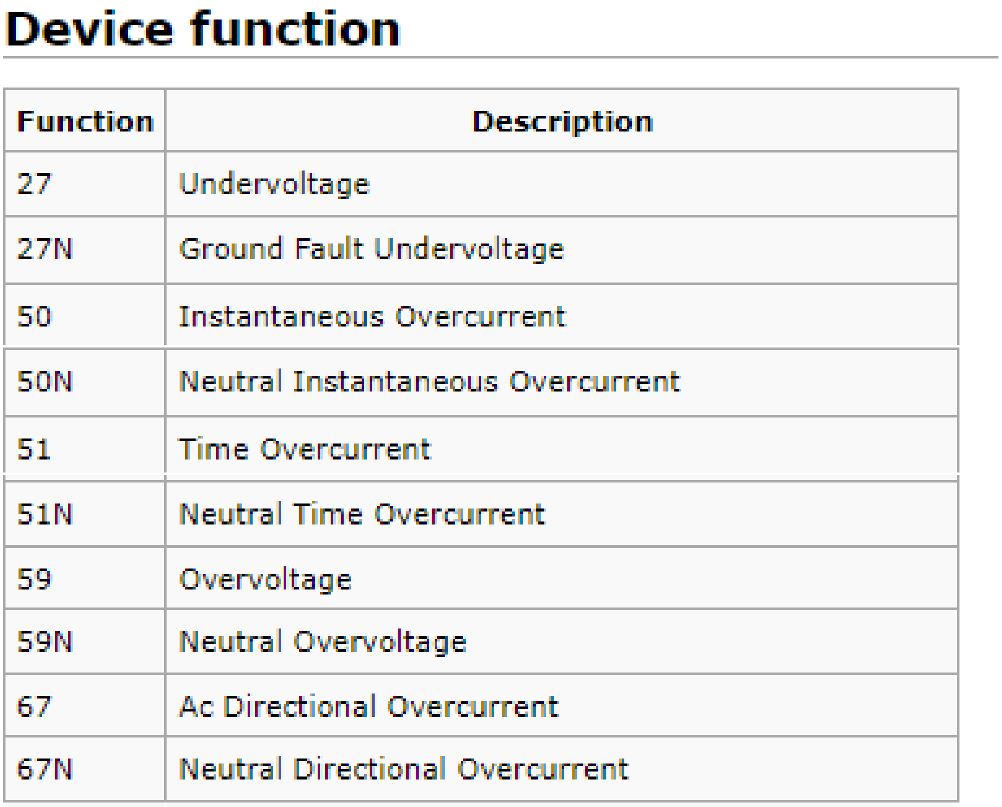
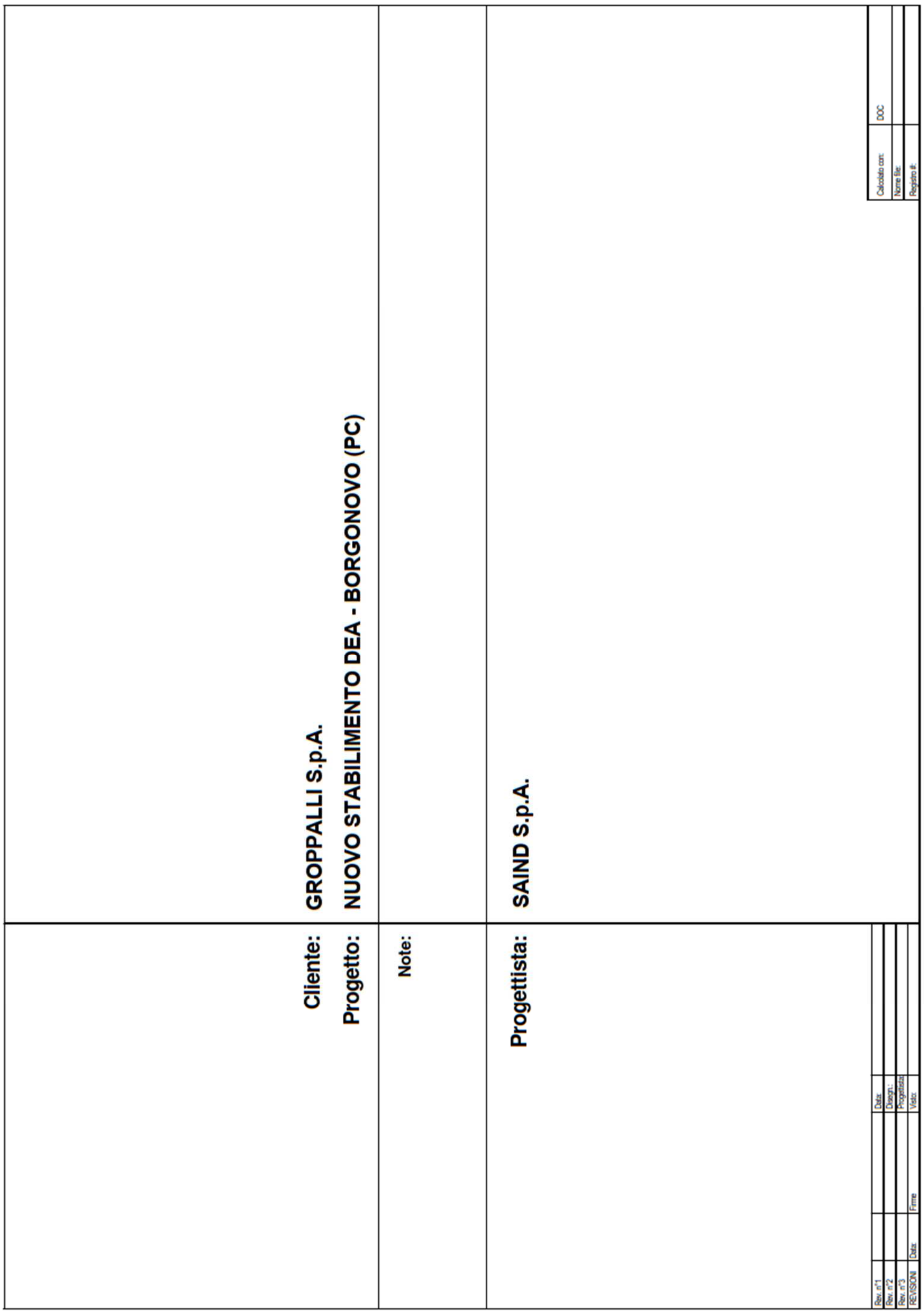
A Ansi/IEEE C37.2 protections codes



Device function

Function	Description
27	Undervoltage
27N	Ground Fault Undervoltage
50	Instantaneous Overcurrent
50N	Neutral Instantaneous Overcurrent
51	Time Overcurrent
51N	Neutral Time Overcurrent
59	Overvoltage
59N	Neutral Overvoltage
67	Ac Directional Overcurrent
67N	Neutral Directional Overcurrent

B DOC simulations results



Cliente: **GROPPALLI S.p.A.**

Progetto: **NUOVO STABILIMENTO DEA - BORGONOVO (PC)**

Note:

Progettista: **SAIND S.p.A.**

Rev. n°1			Data:	
Rev. n°2			Disegn.:	
Rev. n°3			Progettista:	
REVISIONI	Data:	Firme	Visto:	

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Criteri di dimensionamento e verifica

Norma di calcolo	CEI 11-25
Norma per il dimensionamento cavi	CEI 64-8

Sovraccarico	Le verifiche di sovraccarico sono eseguite tramite la relazione Ib <= Ith <= Iz e If <= 1,45*Iz
	Legenda:
	IB = corrente di linea
	Ith = taratura della soglia termica del dispositivo di protezione
	If = corrente di sicuro intervento del dispositivo di protezione
	Iz = portata del cavo definita secondo norma attuale

Corto circuito	Interruttori e fusibili sono dimensionati per un potere di interruzione maggiore della massima corrente di guasto
	Gli interruttori dimensionati per la norma IEC 60947-2 devono avere un potere di chiusura Icm maggiore della massima corrente di picco
	La protezione contro il guasto sulle linee deve soddisfare la verifica $I^2t <= K^2S^2$
	Legenda:
	I^2t= energia lasciata passare alla massima corrente di guasto (dato fornito dal produttore)
	S = sezione dei conduttori
	K = fattore definito in CEI 64-8/5 nelle tabelle 54B, 54C, 54D e 54E

Contatti indiretti	Sistemi TT: la verifica è Idn * Ra <= Vo , oppure Im <= Icc min
	Sistemi TN: la verifica è Im <= Icc min
	Legenda:
	Idn = sensibilità dello sganciatore differenziale
	Ra = resistenza di messa a terra
	Uo = tensione di contatto max ammissibile
	Im = valore di intervento del dispositivo di protezione al tempo limite
	Icc min = corrente di guasto minima a fondo linea

Selettività e Back-up	I valori di selettività e Back-up sono determinati dal costruttore tramite prove di laboratorio
	Selettività non richiesta nell'installazione
	Backup non richiesto nell'installazione

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Ipotesi per il calcolo di cortocircuito per CEI 11-25 (EN 60909-0/EN 60909-1)

Algoritmo di calcolo
Il calcolo dei valori massimi e minimi, simmetrici ed asimmetrici delle correnti di cortocircuito è eseguito con il metodo dei componenti simmetrici.

Condizioni generali
Il calcolo dei valori delle correnti di cortocircuito si basa sulle seguenti semplificazioni:
a) non c'è, durante il cortocircuito, modifica del tipo di cortocircuito interessato (un cortocircuito trifase rimane trifase per tutta la durata del cortocircuito)
b) durante il cortocircuito, non ci sono modifiche della rete interessata;
c) l'impedenza dei trasformatori è riferita al variatore di presa in posizione principale;
d) non vengono prese in considerazione le resistenze d'arco;
e) vengono trascurati tutte le capacità di linea, le ammettenze in derivazione e i carichi rotanti, salvo quelli dei sistemi di sequenza omopolare.

Correnti di cortocircuito massime
Il calcolo delle correnti cortocircuito massime tiene conto delle seguenti condizioni:
- è tenuto in considerazione il fattore di tensione cmax conformemente alla tabella 1 di CEI 11-25
- è scelta la configurazione di rete per ottenere il valore di corrente di cortocircuito massima nel punto di cortocircuito considerato
- il contributo motori è considerato quando è superiore al 5% del corto circuito calcolato senza motori
- le resistenze RL delle linee (aeree e in cavo) sono calcolate alla una temperatura di 20°C

Correnti di cortocircuito minime
Il calcolo delle correnti cortocircuito minime tiene conto delle seguenti condizioni:
- è tenuto in considerazione il fattore di tensione cmin conformemente alla tabella 1 di CEI 11-25
- è scelta la configurazione di rete per ottenere il valore di corrente di cortocircuito minima nel punto di cortocircuito considerato
- il contributo motori deve essere trascurato
- le resistenze RL delle linee (aeree e in cavo) sono calcolate alla una temperatura di 250°C (EPR),160°C (PVC) o 140°C (PVC >300m²)

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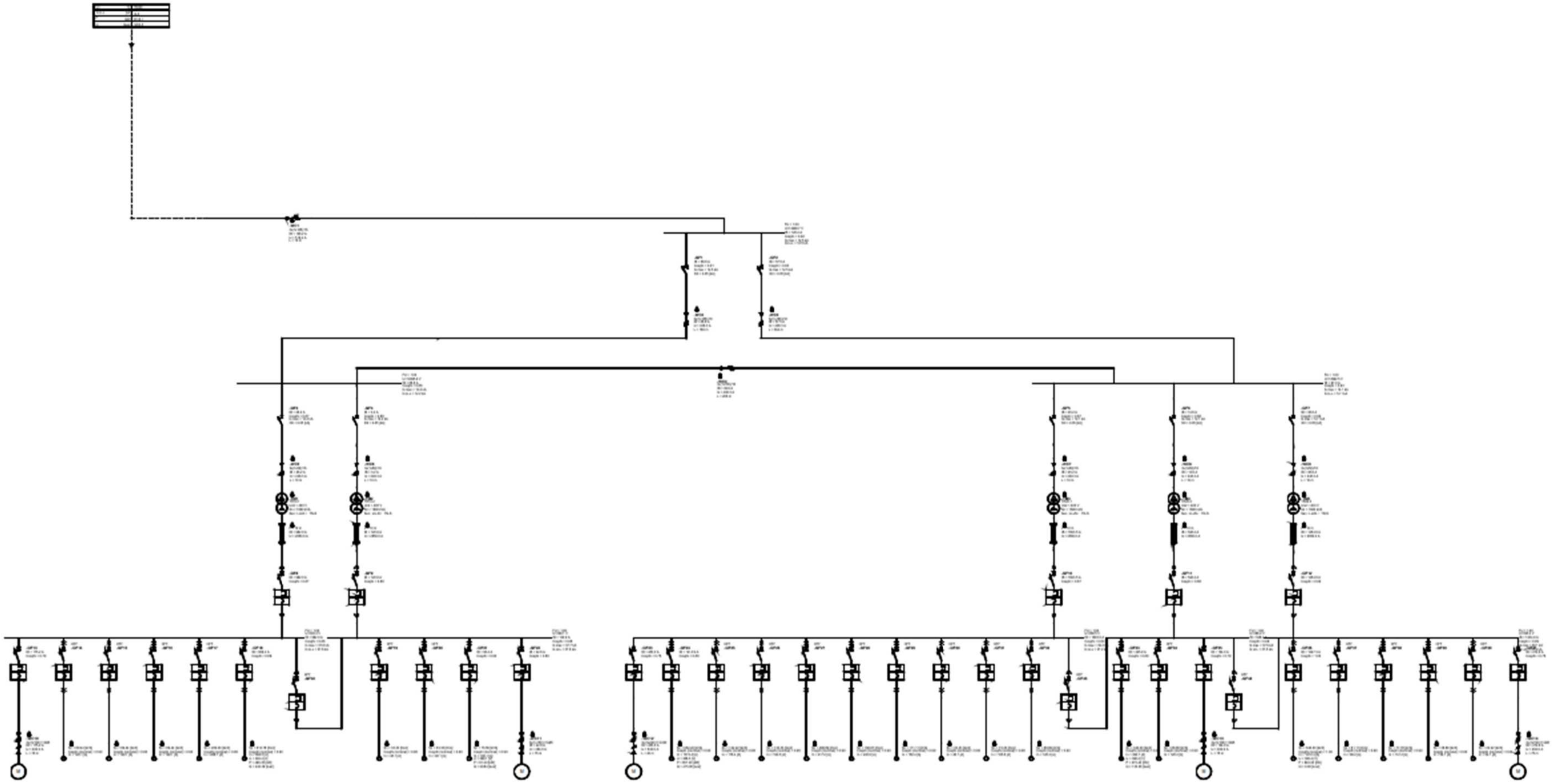

Fornitura

Tensione nominale	[V]	15000
Circuito		LLL
Sistema di distribuzione		IT
Potenza attiva P	[kW]	3018.09
Potenza reattiva Q	[kvar]	1283.52
IB (A)	[A]	126.23
Cosphi		0.92

Corrente di corto-circuito simmetrica LLL	[kA]	12.50
Corrente di corto-circuito Fase-Neutro LN	[kA]	
Corrente di corto-circuito Fase-Terra LPE	[kA]	
Cmax		1.10
Resistenza alla tensione nominale	[mOhm]	76.210
Reattanza alla tensione nominale	[mOhm]	758.282
Impedenza alla tensione nominale	[mOhm]	762.102

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Trasformatori

-TM1 **IEC 60076-11 Cast Res.Tr.15000/400V 1600KVA** **TR10.1**

Potenza nominale	[kVA]	1600
Tensione di corto-circuito Vcc	[%]	6
Perdite	[%]	0.81
Cmax		1.10
KT		1.009033

Avvolgimento		Triangolo	Stella a terra
Tensione nominale Un	[V]	15000	400
Tensione a vuoto	[V]		400
Regolatore di tensione di presa	[%]		0.0
Circuito		LLL	LLLN
Sistema di distribuzione		IT	TN-S
Resistenza RT	[mOhm]	1181.250	0.840
Reattanza XT	[mOhm]	8354.403	5.941
Impedenza Zt	[mOhm]	8437.500	6.000
Impedenza Z x KT	[mOhm]	8513.712	6.054

-TM2 **IEC 60076-11 Cast Res.Tr.15000/400V 1600KVA** **TR10.2**

Potenza nominale	[kVA]	1600
Tensione di corto-circuito Vcc	[%]	6
Perdite	[%]	0.81
Cmax		1.10
KT		1.009010

Avvolgimento		3	2
Tensione nominale Un	[V]	15000	400
Tensione a vuoto	[V]		400
Regolatore di tensione di presa	[%]		0.0
Circuito		LLL	LLLN
Sistema di distribuzione		IT	TN-S
Resistenza RT	[mOhm]	1142.578	0.813
Reattanza XT	[mOhm]	8359.780	5.945
Impedenza Zt	[mOhm]	8437.500	6.000
Impedenza Z x KT	[mOhm]	8513.524	6.054

-TM3 **IEC 60076-11 Cast Res.Tr.15000/400V 1600KVA** **TR20.1**

Potenza nominale	[kVA]	1600
Tensione di corto-circuito Vcc	[%]	6
Perdite	[%]	0.81
Cmax		1.10
KT		1.009010

Avvolgimento		3	2
Tensione nominale Un	[V]	15000	400
Tensione a vuoto	[V]		400
Regolatore di tensione di presa	[%]		0.0
Circuito		LLL	LLLN
Sistema di distribuzione		IT	TN-S
Resistenza RT	[mOhm]	1142.578	0.813
Reattanza XT	[mOhm]	8359.780	5.945
Impedenza Zt	[mOhm]	8437.500	6.000
Impedenza Z x KT	[mOhm]	8513.524	6.054

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Trasformatori

-TM4 **IEC 60076-11 Cast Res.Tr.15000/400V 1600KVA** **TR20.2**

Potenza nominale	[kVA]	1600
Tensione di corto-circuito Vcc	[%]	6
Perdite	[%]	0.81
Cmax		1.10
KT		1.009010

Avvolgimento		Triangolo	Stella a terra
Tensione nominale Un	[V]	15000	400
Tensione a vuoto	[V]		400
Regolatore di tensione di presa	[%]		0.0
Circuito		LLL	LLLN
Sistema di distribuzione		IT	TN-S
Resistenza RT	[mOhm]	1142.578	0.813
Reattanza XT	[mOhm]	8359.780	5.945
Impedenza Zt	[mOhm]	8437.500	6.000
Impedenza Z x KT	[mOhm]	8513.524	6.054

-TM5 **IEC 60076-11 Cast Res.Tr.15000/400V 1600KVA** **TR20.3**

Potenza nominale	[kVA]	1600
Tensione di corto-circuito Vcc	[%]	6
Perdite	[%]	0.81
Cmax		1.10
KT		1.009010

Avvolgimento		3	2
Tensione nominale Un	[V]	15000	400
Tensione a vuoto	[V]		400
Regolatore di tensione di presa	[%]		0.0
Circuito		LLL	LLLN
Sistema di distribuzione		IT	TN-S
Resistenza RT	[mOhm]	1142.578	0.813
Reattanza XT	[mOhm]	8359.780	5.945
Impedenza Zt	[mOhm]	8437.500	6.000
Impedenza Z x KT	[mOhm]	8513.524	6.054

Potenza nominale	[kVA]	
Tensione di corto-circuito Vcc	[%]	
Perdite	[%]	
Cmax		
KT		

Avvolgimento			
Tensione nominale Un	[V]		
Tensione a vuoto	[V]		
Regolatore di tensione di presa	[%]		
Circuito			
Sistema di distribuzione			
Resistenza RT	[mOhm]		
Reattanza XT	[mOhm]		
Impedenza Zt	[mOhm]		
Impedenza Z x KT	[mOhm]		

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Calcolo corto circuito

Quadro	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)	Icc LN (kA)	Ip LN (kA)	Icc LPE (kA)	Ip LPE (kA)
QMT00	12.48	33.54	10.81	29.05				
QMT10	12.20	33.54	10.57	29.05				
QMT20	12.06	32.65	10.44	28.27				
PW10.1	37.56	98.15	32.53	85.00	37.64	98.36	36.16	94.50
PW10.2	37.57	98.63	32.53	85.41	37.65	98.85	36.18	94.98
PW20.1	37.24	101.72	32.25	88.09	37.42	100.15	35.88	96.05
PW20.2	37.53	98.42	32.50	85.23	37.63	98.67	36.15	94.80
PW20.3	37.22	101.38	32.24	87.79	37.41	99.96	35.88	95.88

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Protezione dei cavi MT

-WC1 Arrivo da ENEL

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	126.2
	Cosphi		0.92
Cavo	Sezione cavo		3x(1x185)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	519.2
	cdt (%)		0.00
	Temp lavoro (°C)	[°C]	24.1
	Perdite	[W]	46.22
	K²S²	[A2s]	698634710

Verifiche di protezione

1 → 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da**	
1 ← 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da**	

-WC2 PG1 Da C00 a C10

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	68.8
	Cosphi		0.91
Cavo	Sezione cavo		3x(1x185)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	168
	Iz (A)	[A]	406.3
	cdt (%)		0.03
	Temp lavoro (°C)	[°C]	22.0
	Perdite	[W]	378.09
	K²S²	[A2s]	305979537

Verifiche di protezione

1 → 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da -QF1 VD4/UniMix-R 24.06.16 P230** Protezione garantita fino a Icc max (12.48[kA]); Vrif=15000V	**Ok**
1 ← 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da -QF2 VD4/UniMix-R 24.06.16 P230** Protezione garantita fino a Icc max (9.70[kA]); Vrif=15000V	**Ok**

-WC3 PG2 Da C00 a C20

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	57.5
	Cosphi		0.93
Cavo	Sezione cavo		3x(1x185)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	384
	Iz (A)	[A]	406.3
	cdt (%)		0.05
	Temp lavoro (°C)	[°C]	21.4
	Perdite	[W]	601.78
	K²S²	[A2s]	305979537

Verifiche di protezione

1 → 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da -QF2 VD4/UniMix-R 24.06.16 P230** Protezione garantita fino a Icc max (12.48[kA]); Vrif=15000V	**Ok**
1 ← 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da -QF1 VD4/UniMix-R 24.06.16 P230** Protezione garantita fino a Icc max (6.40[kA]); Vrif=15000V	**Ok**

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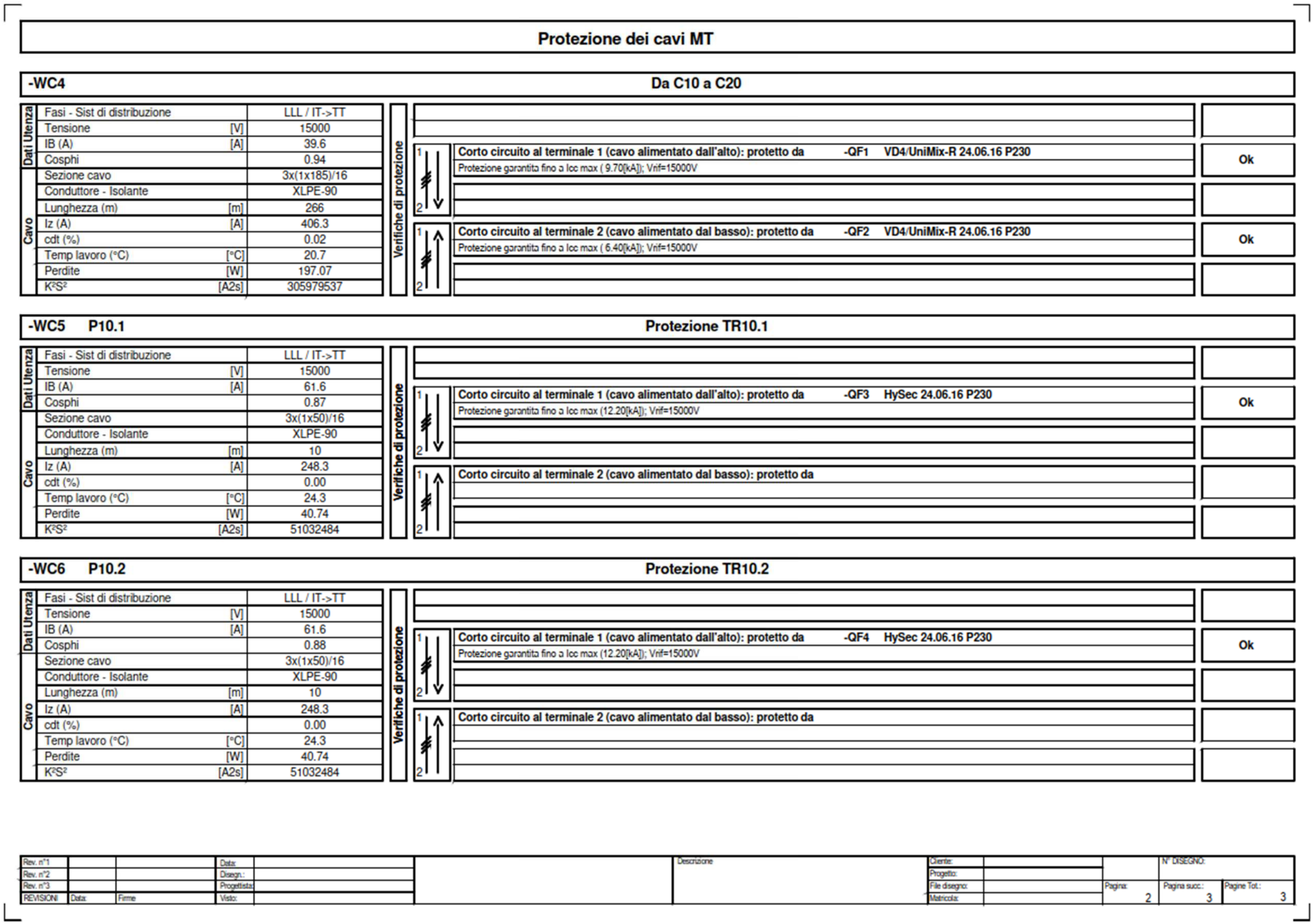

Protezione dei cavi MT

-WC4 — **Da C10 a C20**

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	39.6
	Cosphi		0.94
Cavo	Sezione cavo		3x(1x185)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	266
	Iz (A)	[A]	406.3
	cdt (%)		0.02
	Temp lavoro (°C)	[°C]	20.7
	Perdite	[W]	197.07
	K²S²	[A2s]	305979537

Verifiche di protezione

1 ↓ 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da -QF1 VD4/UniMix-R 24.06.16 P230** Protezione garantita fino a Icc max (9.70[kA]); Vrif=15000V	**Ok**
1 ↑ 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da -QF2 VD4/UniMix-R 24.06.16 P230** Protezione garantita fino a Icc max (6.40[kA]); Vrif=15000V	**Ok**

-WC5 P10.1 — **Protezione TR10.1**

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	61.6
	Cosphi		0.87
Cavo	Sezione cavo		3x(1x50)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	248.3
	cdt (%)		0.00
	Temp lavoro (°C)	[°C]	24.3
	Perdite	[W]	40.74
	K²S²	[A2s]	51032484

Verifiche di protezione

1 ↓ 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da -QF3 HySec 24.06.16 P230** Protezione garantita fino a Icc max (12.20[kA]); Vrif=15000V	**Ok**
1 ↑ 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da**	

-WC6 P10.2 — **Protezione TR10.2**

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	61.6
	Cosphi		0.88
Cavo	Sezione cavo		3x(1x50)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	248.3
	cdt (%)		0.00
	Temp lavoro (°C)	[°C]	24.3
	Perdite	[W]	40.74
	K²S²	[A2s]	51032484

Verifiche di protezione

1 ↓ 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da -QF4 HySec 24.06.16 P230** Protezione garantita fino a Icc max (12.20[kA]); Vrif=15000V	**Ok**
1 ↑ 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da**	

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Protezione dei cavi MT

-WC7 P20.1 — Protezione TR20.1

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	61.6
	Cosphi		0.87
Cavo	Sezione cavo		3x(1x50)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	248.3
	cdt (%)		0.00
	Temp lavoro (°C)	[°C]	24.3
	Perdite	[W]	40.74
	K²S²	[A2s]	51032484

Verifiche di protezione

1 → 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da -QF5 HySec 24.06.16 P230** Protezione garantita fino a Icc max (12.06[kA]); Vrif=15000V	**Ok**
1 ← 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da**	

-WC8 P20.2 — Protezione TR20.2

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	61.6
	Cosphi		0.88
Cavo	Sezione cavo		3x(1x50)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	248.3
	cdt (%)		0.00
	Temp lavoro (°C)	[°C]	24.3
	Perdite	[W]	40.74
	K²S²	[A2s]	51032484

Verifiche di protezione

1 → 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da -QF6 HySec 24.06.16 P230** Protezione garantita fino a Icc max (12.06[kA]); Vrif=15000V	**Ok**
1 ← 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da**	

-WC9 P20.3 — Protezione TR20.3

Dati Utenza	Fasi - Sist di distribuzione		LLL / IT->TT
	Tensione	[V]	15000
	IB (A)	[A]	61.6
	Cosphi		0.99
Cavo	Sezione cavo		3x(1x50)/16
	Conduttore - Isolante		XLPE-90
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	248.3
	cdt (%)		0.00
	Temp lavoro (°C)	[°C]	24.3
	Perdite	[W]	40.74
	K²S²	[A2s]	51032484

Verifiche di protezione

1 → 2	**Corto circuito al terminale 1 (cavo alimentato dall'alto): protetto da -QF7 HySec 24.06.16 P230** Protezione garantita fino a Icc max (12.06[kA]); Vrif=15000V	**Ok**
1 ← 2	**Corto circuito al terminale 2 (cavo alimentato dal basso): protetto da**	

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Protezione dei condotti sbarra

-BW1 Da TR10.1

Dati Utenza	Fasi - Sist di distribuzione		LLLN / TN-S
	Tensione	[V]	400
	IB (A)	[A]	2309.4
	Cosphi		0.87
Cavo	Modello		2500A Cu Busway
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	2650.0
	cdt (%)		0.24

Dispositivo di protezione	**Sovraccarico**	Ok
	-QF8 E2.2N 2500 Ekip Dip LSIG 2500	
	IB (26.19[A]) <= Ith (63.33[A]) <= Iz (70.67[A]) e If (82.33[A]) <= 1.45*Iz (102.47[A]); Vrif=15000V	
	Corto circuito	
	Contatti indiretti	Ok

-BW2 Da TR10.2

Dati Utenza	Fasi - Sist di distribuzione		LLLN / TN-S
	Tensione	[V]	400
	IB (A)	[A]	2309.4
	Cosphi		0.88
Cavo	Modello		2500A Cu Busway
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	2650.0
	cdt (%)		0.24

Dispositivo di protezione	**Sovraccarico**	Ok
	-QF9 E2.2N 2500 Ekip Dip LSIG 2500	
	IB (3.22[A]) <= Ith (63.33[A]) <= Iz (70.67[A]) e If (82.33[A]) <= 1.45*Iz (102.47[A]); Vrif=15000V	
	Corto circuito	
	Contatti indiretti	Ok

-BW3 Da TR20.1

Dati Utenza	Fasi - Sist di distribuzione		LLLN / TN-S
	Tensione	[V]	400
	IB (A)	[A]	2309.4
	Cosphi		0.87
Cavo	Modello		2500A Cu Busway
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	2650.0
	cdt (%)		0.24

Dispositivo di protezione	**Sovraccarico**	Ok
	-QF10 E2.2N 2500 Ekip Dip LSIG 2500	
	IB (45.16[A]) <= Ith (63.33[A]) <= Iz (70.67[A]) e If (82.33[A]) <= 1.45*Iz (102.47[A]); Vrif=15000V	
	Corto circuito	
	Contatti indiretti	Ok

-BW4 Da TR20.2

Dati Utenza	Fasi - Sist di distribuzione		LLLN / TN-S
	Tensione	[V]	400
	IB (A)	[A]	2309.4
	Cosphi		0.88
Cavo	Modello		2500A Cu Busway
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	2650.0
	cdt (%)		0.24

Dispositivo di protezione	**Sovraccarico**	Ok
	-QF11 E2.2N 2500 Ekip Dip LSIG 2500	
	IB (14.62[A]) <= Ith (63.33[A]) <= Iz (70.67[A]) e If (82.33[A]) <= 1.45*Iz (102.47[A]); Vrif=15000V	
	Corto circuito	
	Contatti indiretti	Ok

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Protezione dei condotti sbarra

-BW5 Da TR20.3

Dati Utenza	Fasi - Sist di distribuzione		LLLN / TN-S
	Tensione	[V]	400
	IB (A)	[A]	2309.4
	Cosphi		0.99
Cavo	Modello		2500A Cu Busway
	Lunghezza (m)	[m]	10
	Iz (A)	[A]	2650.0
	cdt (%)		0.24

Dispositivo di protezione	**Sovraccarico**	**Ok**
	-QF12 E2.2N 2500 Ekip Dip LSIG 2500	
	IB (38.80[A]) <= Ith (63.33[A]) <= Iz (70.67[A]) e If (82.33[A]) <= 1.45*Iz (102.47[A]); Vrif=15000V	
	Corto circuito	
	Contatti indiretti	**Ok**

Dati Utenza	Fasi - Sist di distribuzione		
	Tensione	[V]	
	IB (A)	[A]	
	Cosphi		
Cavo	Modello		
	Lunghezza (m)	[m]	
	Iz (A)	[A]	
	cdt (%)		

Dispositivo di protezione	**Sovraccarico**	
	Corto circuito	
	Contatti indiretti	

Dati Utenza	Fasi - Sist di distribuzione		
	Tensione	[V]	
	IB (A)	[A]	
	Cosphi		
Cavo	Modello		
	Lunghezza (m)	[m]	
	Iz (A)	[A]	
	cdt (%)		

Dispositivo di protezione	**Sovraccarico**	
	Corto circuito	
	Contatti indiretti	

Dati Utenza	Fasi - Sist di distribuzione		
	Tensione	[V]	
	IB (A)	[A]	
	Cosphi		
Cavo	Modello		
	Lunghezza (m)	[m]	
	Iz (A)	[A]	
	cdt (%)		

Dispositivo di protezione	**Sovraccarico**	
	Corto circuito	
	Contatti indiretti	

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Lista dei cavi MT

-WC1 Arrivo da ENEL

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	126.2	R Ph 20°C	[mOhm]	0.95
Tensione	[V]	15000	IB L2	[A]	126.2	R Ph 160-250°C	[mOhm]	1.83
Sezione cavo		3x(1x185)/16	IB L3	[A]	126.2	X Ph	[mOhm]	1.13
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.92			
Fattore rid		1.13	Iz (A)	[A]	519.2			
Lunghezza (m)	[m]	10	cdt (%)	[%]	0.00			
Icc max (kA)	[kA]	12.50	Pot Diss (W)	[W]	46.2			
Icc min (kA)	[kA]	9.82	Temp lavoro (°C)	[°C]	24.1			

-WC2 PG1 Da C00 a C10

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	68.8	R Ph 20°C	[mOhm]	26.43
Tensione	[V]	15000	IB L2	[A]	68.8	R Ph 160-250°C	[mOhm]	50.74
Sezione cavo		3x(1x185)/16	IB L3	[A]	68.8	X Ph	[mOhm]	18.99
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.91			
Fattore rid		1.13	Iz (A)	[A]	406.3			
Lunghezza (m)	[m]	168	cdt (%)	[%]	0.03			
Icc max (kA)	[kA]	12.48	Pot Diss (W)	[W]	378.1			
Icc min (kA)	[kA]	1.97	Temp lavoro (°C)	[°C]	22.0			

-WC3 PG2 Da C00 a C20

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	57.5	R Ph 20°C	[mOhm]	60.40
Tensione	[V]	15000	IB L2	[A]	57.5	R Ph 160-250°C	[mOhm]	115.97
Sezione cavo		3x(1x185)/16	IB L3	[A]	57.5	X Ph	[mOhm]	43.41
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.93			
Fattore rid		1.13	Iz (A)	[A]	406.3			
Lunghezza (m)	[m]	384	cdt (%)	[%]	0.05			
Icc max (kA)	[kA]	12.48	Pot Diss (W)	[W]	601.8			
Icc min (kA)	[kA]	4.43	Temp lavoro (°C)	[°C]	21.4			

-WC4 Da C10 a C20

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	39.6	R Ph 20°C	[mOhm]	41.84
Tensione	[V]	15000	IB L2	[A]	39.6	R Ph 160-250°C	[mOhm]	80.34
Sezione cavo		3x(1x185)/16	IB L3	[A]	39.6	X Ph	[mOhm]	30.07
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.94			
Fattore rid		1.13	Iz (A)	[A]	406.3			
Lunghezza (m)	[m]	266	cdt (%)	[%]	0.02			
Icc max (kA)	[kA]	9.70	Pot Diss (W)	[W]	197.1			
Icc min (kA)	[kA]	1.97	Temp lavoro (°C)	[°C]	20.7			

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Lista dei cavi MT

-WC5 P10.1 **Protezione TR10.1**

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	26.2	R Ph 20°C	[mOhm]	3.52
Tensione	[V]	15000	IB L2	[A]	26.2	R Ph 160-250°C	[mOhm]	6.76
Sezione cavo		3x(1x50)/16	IB L3	[A]	26.2	X Ph	[mOhm]	1.41
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.87			
Fattore rid		1.13	Iz (A)	[A]	248.3			
Lunghezza (m)	[m]	10	cdt (%)	[%]	0.00			
Icc max (kA)	[kA]	12.20	Pot Diss (W)	[W]	40.7			
Icc min (kA)	[kA]	9.54	Temp lavoro (°C)	[°C]	24.3			

-WC6 P10.2 **Protezione TR10.2**

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	3.2	R Ph 20°C	[mOhm]	3.52
Tensione	[V]	15000	IB L2	[A]	3.2	R Ph 160-250°C	[mOhm]	6.76
Sezione cavo		3x(1x50)/16	IB L3	[A]	3.2	X Ph	[mOhm]	1.41
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.88			
Fattore rid		1.13	Iz (A)	[A]	248.3			
Lunghezza (m)	[m]	10	cdt (%)	[%]	0.00			
Icc max (kA)	[kA]	12.20	Pot Diss (W)	[W]	40.7			
Icc min (kA)	[kA]	9.54	Temp lavoro (°C)	[°C]	24.3			

-WC7 P20.1 **Protezione TR20.1**

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	45.2	R Ph 20°C	[mOhm]	3.52
Tensione	[V]	15000	IB L2	[A]	45.2	R Ph 160-250°C	[mOhm]	6.76
Sezione cavo		3x(1x50)/16	IB L3	[A]	45.2	X Ph	[mOhm]	1.41
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.87			
Fattore rid		1.13	Iz (A)	[A]	248.3			
Lunghezza (m)	[m]	10	cdt (%)	[%]	0.00			
Icc max (kA)	[kA]	12.06	Pot Diss (W)	[W]	40.7			
Icc min (kA)	[kA]	9.41	Temp lavoro (°C)	[°C]	24.3			

-WC8 P20.2 **Protezione TR20.2**

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	14.6	R Ph 20°C	[mOhm]	3.52
Tensione	[V]	15000	IB L2	[A]	14.6	R Ph 160-250°C	[mOhm]	6.76
Sezione cavo		3x(1x50)/16	IB L3	[A]	14.6	X Ph	[mOhm]	1.41
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.88			
Fattore rid		1.13	Iz (A)	[A]	248.3			
Lunghezza (m)	[m]	10	cdt (%)	[%]	0.00			
Icc max (kA)	[kA]	12.06	Pot Diss (W)	[W]	40.7			
Icc min (kA)	[kA]	9.41	Temp lavoro (°C)	[°C]	24.3			

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Lista dei cavi MT

-WC9 P20.3 Protezione TR20.3

Fasi - Sist di distribuzione		LLL / IT	IB L1	[A]	38.8	R Ph 20°C	[mOhm]	3.52
Tensione	[V]	15000	IB L2	[A]	38.8	R Ph 160-250°C	[mOhm]	6.76
Sezione cavo		3x(1x50)/16	IB L3	[A]	38.8	X Ph	[mOhm]	1.41
Conduttore - Isolante		XLPE-90						
Posa			Cosphi		0.99			
Fattore rid		1.13	Iz (A)	[A]	248.3			
Lunghezza (m)	[m]	10	cdt (%)	[%]	0.00			
Icc max (kA)	[kA]	12.06	Pot Diss (W)	[W]	40.7			
Icc min (kA)	[kA]	9.41	Temp lavoro (°C)	[°C]	24.3			

Fasi - Sist di distribuzione			IB L1	[A]		R Ph 20°C	[mOhm]	
Tensione	[V]		IB L2	[A]		R Ph 160-250°C	[mOhm]	
Sezione cavo			IB L3	[A]		X Ph	[mOhm]	
Conduttore - Isolante								
Posa			Cosphi					
Fattore rid			Iz (A)	[A]				
Lunghezza (m)	[m]		cdt (%)	[%]				
Icc max (kA)	[kA]		Pot Diss (W)	[W]				
Icc min (kA)	[kA]		Temp lavoro (°C)	[°C]				

Fasi - Sist di distribuzione			IB L1	[A]		R Ph 20°C	[mOhm]	
Tensione	[V]		IB L2	[A]		R Ph 160-250°C	[mOhm]	
Sezione cavo			IB L3	[A]		X Ph	[mOhm]	
Conduttore - Isolante								
Posa			Cosphi					
Fattore rid			Iz (A)	[A]				
Lunghezza (m)	[m]		cdt (%)	[%]				
Icc max (kA)	[kA]		Pot Diss (W)	[W]				
Icc min (kA)	[kA]		Temp lavoro (°C)	[°C]				

Fasi - Sist di distribuzione			IB L1	[A]		R Ph 20°C	[mOhm]	
Tensione	[V]		IB L2	[A]		R Ph 160-250°C	[mOhm]	
Sezione cavo			IB L3	[A]		X Ph	[mOhm]	
Conduttore - Isolante								
Posa			Cosphi					
Fattore rid			Iz (A)	[A]				
Lunghezza (m)	[m]		cdt (%)	[%]				
Icc max (kA)	[kA]		Pot Diss (W)	[W]				
Icc min (kA)	[kA]		Temp lavoro (°C)	[°C]				

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Condotti sbarra

-BW1 Da TR10.1

Fasi - Sist di distribuzione		LLLN / TN-S	IB L1	[A]	982.0	R0 Ph Icc max	[mOhm]	0.22
Tensione	[V]	400	IB L2	[A]	982.0	R0 Ph Icc min	[mOhm]	0.32
Modello		2500A Cu Busway	IB L3	[A]	982.0	X Ph	[mOhm]	0.12
			IB N	[A]	0.0	R0 N Icc max	[mOhm]	0.22
			Cosphi		0.87	R0 N Icc min	[mOhm]	0.32
						X N	[mOhm]	0.12
Lunghezza (m)	[m]	10	Iz (A)	[A]	2650.0	R0 PE Icc max	[mOhm]	0.44
Icc max (kA)	[kA]	39.5	cdt (%)	[%]	0.24	R0 PE Icc min	[mOhm]	0.63
Icc min (kA)	[kA]		Pot Diss (W)	[W]	38.2	X PE	[mOhm]	0.35

-BW2 Da TR10.2

Fasi - Sist di distribuzione		LLLN / TN-S	IB L1	[A]	120.9	R0 Ph Icc max	[mOhm]	0.22
Tensione	[V]	400	IB L2	[A]	120.9	R0 Ph Icc min	[mOhm]	0.32
Modello		2500A Cu Busway	IB L3	[A]	120.9	X Ph	[mOhm]	0.12
			IB N	[A]	0.0	R0 N Icc max	[mOhm]	0.22
			Cosphi		0.88	R0 N Icc min	[mOhm]	0.32
						X N	[mOhm]	0.12
Lunghezza (m)	[m]	10	Iz (A)	[A]	2650.0	R0 PE Icc max	[mOhm]	0.44
Icc max (kA)	[kA]	39.5	cdt (%)	[%]	0.24	R0 PE Icc min	[mOhm]	0.63
Icc min (kA)	[kA]		Pot Diss (W)	[W]	38.2	X PE	[mOhm]	0.35

-BW3 Da TR20.1

Fasi - Sist di distribuzione		LLLN / TN-S	IB L1	[A]	1693.5	R0 Ph Icc max	[mOhm]	0.22
Tensione	[V]	400	IB L2	[A]	1693.5	R0 Ph Icc min	[mOhm]	0.32
Modello		2500A Cu Busway	IB L3	[A]	1693.5	X Ph	[mOhm]	0.12
			IB N	[A]	0.0	R0 N Icc max	[mOhm]	0.22
			Cosphi		0.87	R0 N Icc min	[mOhm]	0.32
						X N	[mOhm]	0.12
Lunghezza (m)	[m]	10	Iz (A)	[A]	2650.0	R0 PE Icc max	[mOhm]	0.44
Icc max (kA)	[kA]	39.5	cdt (%)	[%]	0.24	R0 PE Icc min	[mOhm]	0.63
Icc min (kA)	[kA]		Pot Diss (W)	[W]	38.2	X PE	[mOhm]	0.35

-BW4 Da TR20.2

Fasi - Sist di distribuzione		LLLN / TN-S	IB L1	[A]	548.4	R0 Ph Icc max	[mOhm]	0.22
Tensione	[V]	400	IB L2	[A]	548.4	R0 Ph Icc min	[mOhm]	0.32
Modello		2500A Cu Busway	IB L3	[A]	548.4	X Ph	[mOhm]	0.12
			IB N	[A]	0.0	R0 N Icc max	[mOhm]	0.22
			Cosphi		0.88	R0 N Icc min	[mOhm]	0.32
						X N	[mOhm]	0.12
Lunghezza (m)	[m]	10	Iz (A)	[A]	2650.0	R0 PE Icc max	[mOhm]	0.44
Icc max (kA)	[kA]	39.5	cdt (%)	[%]	0.24	R0 PE Icc min	[mOhm]	0.63
Icc min (kA)	[kA]		Pot Diss (W)	[W]	38.2	X PE	[mOhm]	0.35

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Condotti sbarra

-BW5 Da TR20.3

Fasi - Sist di distribuzione		LLLN / TN-S	IB L1	[A]	1454.9	R0 Ph Icc max	[mOhm]	0.22
Tensione	[V]	400	IB L2	[A]	1454.9	R0 Ph Icc min	[mOhm]	0.32
Modello		2500A Cu Busway	IB L3	[A]	1454.9	X Ph	[mOhm]	0.12
			IB N	[A]	0.0	R0 N Icc max	[mOhm]	0.22
			Cosphi		0.99	R0 N Icc min	[mOhm]	0.32
						X N	[mOhm]	0.12
Lunghezza (m)	[m]	10	Iz (A)	[A]	2650.0	R0 PE Icc max	[mOhm]	0.44
Icc max (kA)	[kA]	39.5	cdt (%)	[%]	0.24	R0 PE Icc min	[mOhm]	0.63
Icc min (kA)	[kA]		Pot Diss (W)	[W]	38.2	X PE	[mOhm]	0.35

Fasi - Sist di distribuzione			IB L1	[A]		R0 Ph Icc max	[mOhm]	
Tensione	[V]		IB L2	[A]		R0 Ph Icc min	[mOhm]	
Modello			IB L3	[A]		X Ph	[mOhm]	
			IB N	[A]		R0 N Icc max	[mOhm]	
			Cosphi			R0 N Icc min	[mOhm]	
						X N	[mOhm]	
Lunghezza (m)	[m]		Iz (A)	[A]		R0 PE Icc max	[mOhm]	
Icc max (kA)	[kA]		cdt (%)	[%]		R0 PE Icc min	[mOhm]	
Icc min (kA)	[kA]		Pot Diss (W)	[W]		X PE	[mOhm]	

Fasi - Sist di distribuzione			IB L1	[A]		R0 Ph Icc max	[mOhm]	
Tensione	[V]		IB L2	[A]		R0 Ph Icc min	[mOhm]	
Modello			IB L3	[A]		X Ph	[mOhm]	
			IB N	[A]		R0 N Icc max	[mOhm]	
			Cosphi			R0 N Icc min	[mOhm]	
						X N	[mOhm]	
Lunghezza (m)	[m]		Iz (A)	[A]		R0 PE Icc max	[mOhm]	
Icc max (kA)	[kA]		cdt (%)	[%]		R0 PE Icc min	[mOhm]	
Icc min (kA)	[kA]		Pot Diss (W)	[W]		X PE	[mOhm]	

Fasi - Sist di distribuzione			IB L1	[A]		R0 Ph Icc max	[mOhm]	
Tensione	[V]		IB L2	[A]		R0 Ph Icc min	[mOhm]	
Modello			IB L3	[A]		X Ph	[mOhm]	
			IB N	[A]		R0 N Icc max	[mOhm]	
			Cosphi			R0 N Icc min	[mOhm]	
						X N	[mOhm]	
Lunghezza (m)	[m]		Iz (A)	[A]		R0 PE Icc max	[mOhm]	
Icc max (kA)	[kA]		cdt (%)	[%]		R0 PE Icc min	[mOhm]	
Icc min (kA)	[kA]		Pot Diss (W)	[W]		X PE	[mOhm]	

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Lista delle sbarre

-B1

Dati del carico		
Fasi - Sist di distribuzione		LLL / IT
Fattore di contemporaneita'		1.00
Tensione nominale	[V]	15000
Tensione calcolata	[V]	14999.7
IB	[A]	126.2
Cosphi		0.92

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
12.48	12.48	33.54	10.81	29.05

Icc LN (kA)	Icc LN (kA)	Ip LN (kA)	Icc LPE (kA)	Ip LPE (kA)

-B2

Dati del carico		
Fasi - Sist di distribuzione		LLL / IT
Fattore di contemporaneita'		1.00
Tensione nominale	[V]	15000
Tensione calcolata	[V]	14995.9
IB	[A]	68.8
Cosphi		0.88

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
12.20	12.20	33.54	10.57	29.05

Icc LN (kA)	Icc LN (kA)	Ip LN (kA)	Icc LPE (kA)	Ip LPE (kA)

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Dati del carico		
Fasi - Sist di distribuzione		LLL / IT
Fattore di contemporaneita'		1.00
Tensione nominale	[V]	15000
Tensione calcolata	[V]	14992.5
IB	[A]	97.0
Cosphi		0.93

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
12.06	12.06	32.65	10.44	28.27

Icc LN (kA)	Icc LN (kA)	Ip LN (kA)	Icc LPE (kA)	Ip LPE (kA)

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Dati del carico		
Fasi - Sist di distribuzione		LLLN / TN-S
Fattore di contemporaneita'		1.00
Tensione nominale	[V]	400
Tensione calcolata	[V]	393.4
IB	[A]	982.0
Cosphi		0.88

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
37.56	37.56	98.15	32.53	85.00

Icc LN (kA)	Icc LN (kA)	Ip LN (kA)	Icc LPE (kA)	Ip LPE (kA)
37.64	37.64	98.36	36.16	94.50

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Dati del carico		
Fasi - Sist di distribuzione		LLLN / TN-S
Fattore di contemporaneita'		1.00
Tensione nominale	[V]	400
Tensione calcolata	[V]	399.1
IB	[A]	120.9
Cosphi		0.88

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
37.57	37.57	98.63	32.53	85.41

Icc LN (kA)	Icc LN (kA)	Ip LN (kA)	Icc LPE (kA)	Ip LPE (kA)
37.65	37.65	98.85	36.18	94.98

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Dati del carico		
Fasi - Sist di distribuzione		LLLN / TN-S
Fattore di contemporaneita'		1.00
Tensione nominale	[V]	400
Tensione calcolata	[V]	388.5
IB	[A]	1693.5
Cosphi		0.89

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
39.61	39.61	101.72	34.30	88.09
Icc LN (kA)	**Icc LN (kA)**	**Ip LN (kA)**	**Icc LPE (kA)**	**Ip LPE (kA)**
39.00	39.00	100.15	37.41	96.05

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Dati del carico		
Fasi - Sist di distribuzione		LLLN / TN-S
Fattore di contemporaneita'		1.00
Tensione nominale	[V]	400
Tensione calcolata	[V]	396.2
IB	[A]	548.4
Cosphi		0.88

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
37.53	37.53	98.42	32.50	85.23
Icc LN (kA)	**Icc LN (kA)**	**Ip LN (kA)**	**Icc LPE (kA)**	**Ip LPE (kA)**
37.63	37.63	98.67	36.15	94.80

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Dati del carico		
Fasi - Sist di distribuzione		LLLN / TN-S
Fattore di contemporaneita'		1.00
Tensione nominale	[V]	400
Tensione calcolata	[V]	395.2
IB	[A]	1454.9
Cosphi		0.99

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
39.44	39.44	101.38	34.16	87.79
Icc LN (kA)	**Icc LN (kA)**	**Ip LN (kA)**	**Icc LPE (kA)**	**Ip LPE (kA)**
38.89	38.89	99.96	37.30	95.88

Dati del carico		
Fasi - Sist di distribuzione		
Fattore di contemporaneita'		
Tensione nominale	[V]	
Tensione calcolata	[V]	
IB	[A]	
Cosphi		

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
Icc LN (kA)	**Icc LN (kA)**	**Ip LN (kA)**	**Icc LPE (kA)**	**Ip LPE (kA)**

Dati del carico		
Fasi - Sist di distribuzione		
Fattore di contemporaneita'		
Tensione nominale	[V]	
Tensione calcolata	[V]	
IB	[A]	
Cosphi		

Correnti di c.c.

Icc LLL (kA)	Icc LLL (kA)	Ip LLL (kA)	Icc LL (kA)	Ip LL (kA)
Icc LN (kA)	**Icc LN (kA)**	**Ip LN (kA)**	**Icc LPE (kA)**	**Ip LPE (kA)**

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