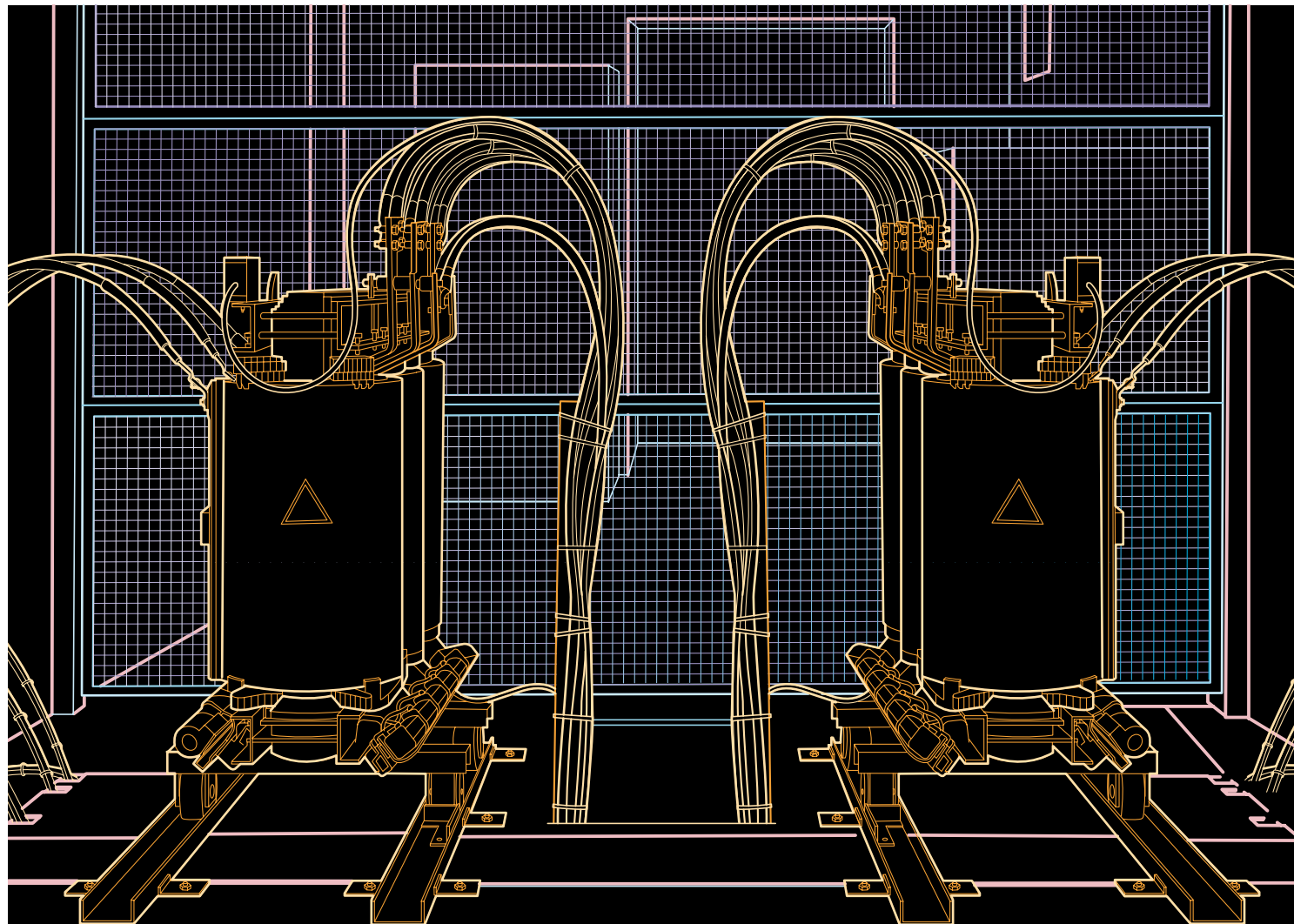




Technical Application Papers No.2

MV/LV transformer substations: theory and examples of short-circuit calculation

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1 General information on MV/LV transformer substations

1.1 Classic types

An electrical transformer substation consists of a whole set of devices (conductors, measuring and control apparatus and electric machines) dedicated to transforming the voltage supplied by the medium voltage distribution grid (e.g. 15kV or 20kV), into voltage values suitable for supplying low voltage lines with power (400V - 690V).

The electrical substations can be divided into public substations and private substations:

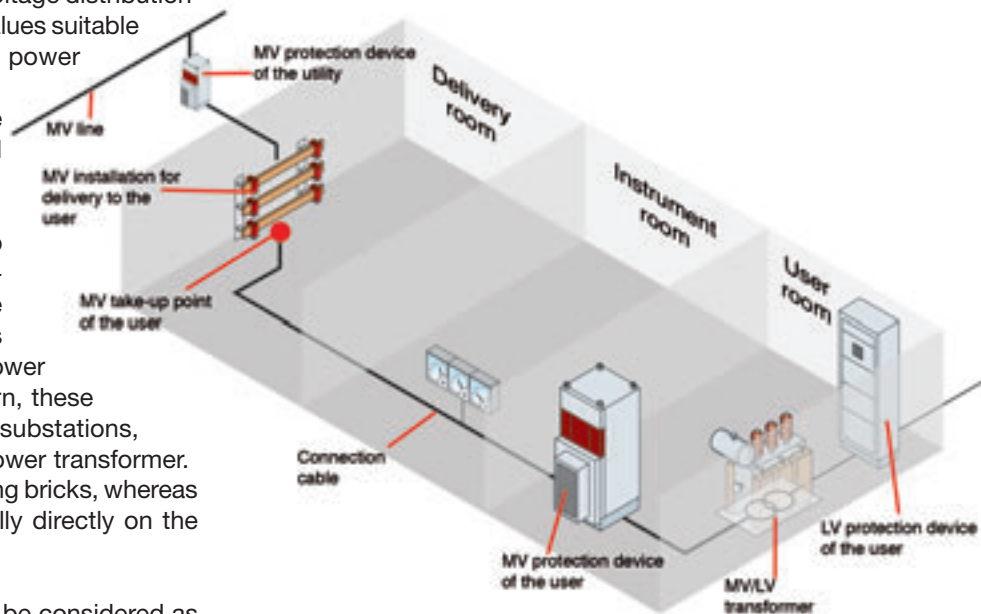
public substations: these belong to the electricity utility and supply private users in alternating single-phase or three-phase current (typical values of the voltage for the two types of power supply can be 230V and 400V). In turn, these are divided into urban or rural type substations, consisting of a single reduced-size power transformer. Urban substations are usually built using bricks, whereas rural ones are often installed externally directly on the MV pylon.

private substations: these can often be considered as terminal type substations, i.e. substations where the MV line ends at the point of installation of the substation itself. They belong to the user and can supply both civil users (schools, hospitals, etc.) with power and industrial users with supply from the public MV grid. These substations are mostly located in the same rooms of the factory they supply and basically consist of three distinct rooms:

- **delivery room:** where the switching apparatus of the utility is installed. This room must be of a size to allow any construction of the in-feed/output system which the utility has the right to realise even at a later time to satisfy its new requirements. The take-up point is found in the delivery room, which represents the border and connection between the public grid and the user plant.
 - **instrument room:** where the measuring units are located.
- Both these rooms must have public road access to allow intervention by authorised personnel whether the user is present or not.
- **user room:** destined to contain the transformer and the MV and LV switching apparatus which are the concern of the user. This room must normally be adjacent to the other two rooms.

Figure 1 shows the typical structure of a substation with division of the rooms as previously described.

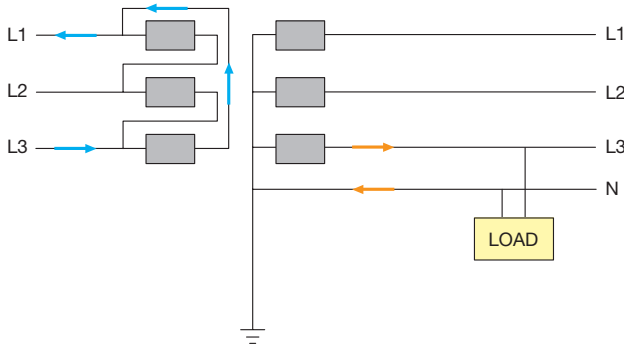
Figure 1: Conceptual diagram of the substation



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

- **delta primary winding (Δ),** because, thanks to this connection type, the third harmonics of the magnetizing currents (distorted due to the non-linearity of the magnetic circuit) and any possible homopolar current are free to circulate through the sides of the delta, without flowing into the network; thus, the magnetic fluxes remain sinusoidal and consequently also the fem induced at the secondary.
Besides, in case of unbalanced loads at the secondary winding, the reaction current absorbed by the primary flows only through the corresponding winding (as shown in the figure) without affecting the other two; if this should occur, as in the star connection, the currents in those windings would be magnetizing currents and would cause an asymmetry in the phase voltages. Only when special applications are provided (welding machines, actuators, etc.), the connection can be not of delta type and the choice shall be agreed on with the utility.
- **secondary winding with grounded star point ($\star$),** to make line and phase voltages easily available, but above all for safety reasons, since, in the event of a fault between the MV and LV sides, the voltage at the

secondary remains close to the phase value, thus guaranteeing higher safety for people and maintaining the insulation.



The utility prescribes and defines the criteria and methods for connection of normal customers (intended as those who are not other power producers or special users with disturbing loads characterised, for example, by harmonics or flicker) in its official documentation. These prescriptions specifically apply to connections to the MV grid with rated voltage of 15kV and 20kV whereas, for other MV voltage values, they can be applied for similarity.

As an example, below we give the prescriptions provided by an Italian distribution utility regarding the power of the transformer which can be used. The power values allowed are as follows:

- power not higher than 1600kVA for 15kV networks
 - power not higher than 2000kVA for 20kV networks.
- The powers indicated refer to a transformer with $v_k\% = 6\%$. The limit relative to the installable power is also established and, in order not to cause unwanted trips of the overcurrent protection of the MV line during the putting into service operations of their own plants, the customers cannot install more than three transformers, each

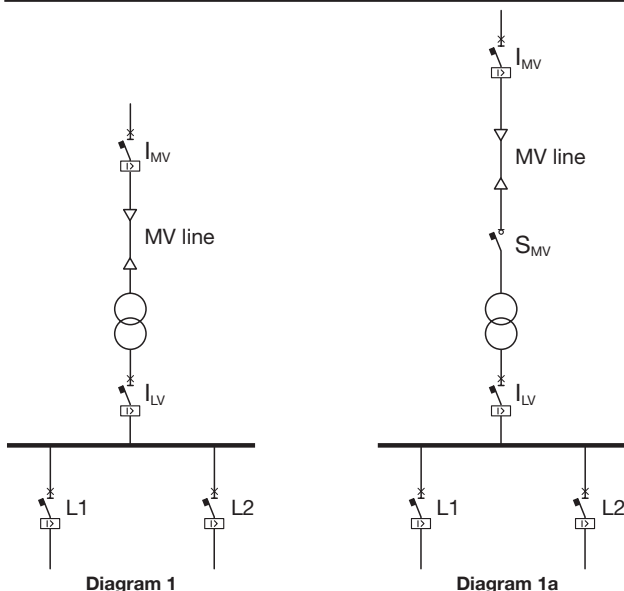
of them with size corresponding to the limits previously indicated and with separated LV busbars; otherwise, they shall have to provide suitable devices in their plants in order to avoid the simultaneous energization of those transformers which would determine the exceeding of the above mentioned limits. Moreover, the users cannot install transformers in parallel (voltage busbars connected) for a total power exceeding the mentioned limits so that, in case of a LV short-circuit on the supply side of the LV main circuit-breaker, only the MV circuit-breaker of the user, installed to protect the transformer, and not the line protection device of the utility, trips. In those cases when the customer's plant is not compatible with the aforesaid limitations, it will be necessary to take into consideration other solutions, for example providing power supply through a dedicated line and customizing the settings of the overcurrent protective device.

The transformer is connected to the take-up point in the delivery room by means of a copper connection cable which, regardless of the power supplied, must have a minimum cross-section of 95mm². This cable is the property of the user and must be as short as possible.

The present trend regarding management of the earthing connection of the system is to provide the passage from insulated neutral to earthed neutral by means of impedance. This modification, needed to reduce the single-phase earth fault currents which are continually on the increase due to the effect of growingly common use of underground or overhead cables, also implies upgrading the protections against earth faults both by the utility and by the customers. The intention is to limit unwanted trips as far as possible, thereby improving service.

After having indicated what the main electrical regulations for a MV/LV substation are, we now analyse what the most common management methods may be in relation to the layout of the power supply transformers for a substation supplied by a single medium voltage line.

Method 1

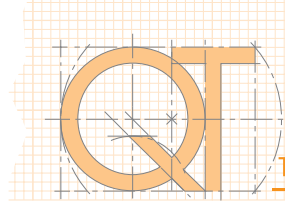


Substation with a single transformer

When the plant foresees installation of an “ I_{MV} ” overcurrent protection device where the line which supplies the substation originates, as shown in diagram 1, this device must ensure protection of both the MV line as well as the transformer.

In the case where the protection device also carries out switching and isolation functions, an interlock must be provided which allows access to the transformer only when the power supply line of the substation has been isolated.

Another management method is shown in diagram 1a, which foresees installation of the “ S_{MV} ” switching and isolation device positioned immediately to the supply side of the transformer and separate from the protection device which remains installed at the beginning of the line.



Method 2

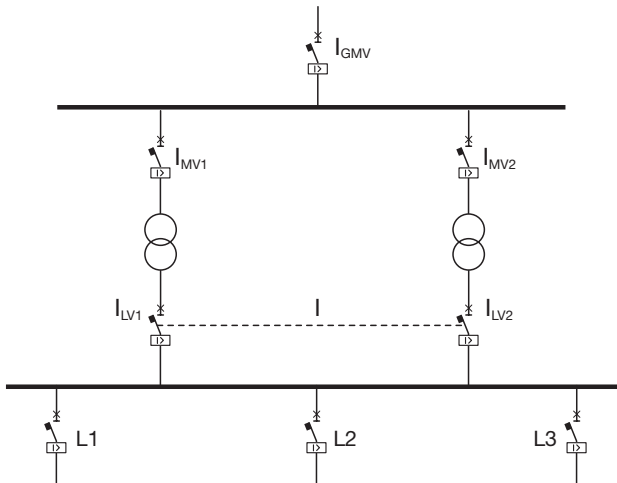


Diagram 2

Substation with two transformers with one as a spare for the other

When the plant foresees installation of a transformer considered as a spare, the circuit-breakers on the LV side must be connected with an “I” interlock whose function is to prevent the transformers from operating in parallel.

Apart from the switching and isolation device on the incoming MV line (I_{GMV}), it is advisable to provide a switching, isolation and protection device on the individual MV risers of the two transformers (I_{MV1} and I_{MV2}) as well. In this way, with opening of the device on the supply and load side of a transformer, it is possible to guarantee isolation and access the machine without putting the whole substation out of service.

Method 3

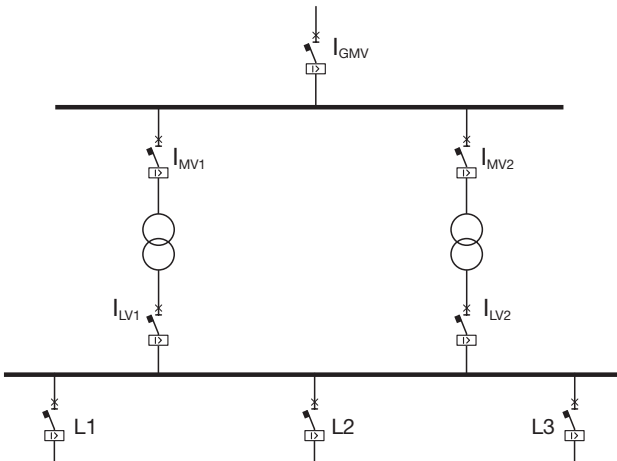


Diagram 3

Substation with two transformers which operate in parallel on the same busbar

When the plant foresees installation of two transformers operating in parallel at the same overall power required of the plant, it is possible to use two transformers with lower rated power. Compared with the management method described in the two previous cases, higher short-circuit currents could be generated for faults in the low voltage system due to reduction of the possible $v_{k\%}$ for lower power machines.

Operation in parallel of the transformers could cause greater problems in management of the network. Again in this case, however, outage of a machine might require a certain flexibility in load management, ensuring the power supply of those considered to be priority loads. When coordinating the protections, the fact that the overcurrent on the LV side is divided between the two transformers must be taken into consideration.

Method 4

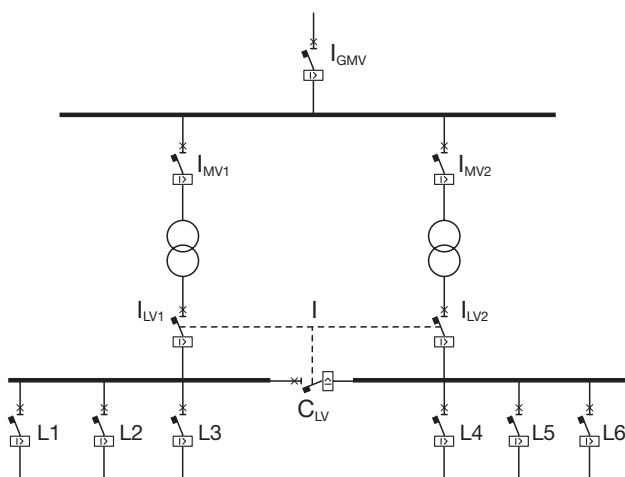


Diagram 4

Substation with two transformers which operate simultaneously on two separate half-busbars

Starting from the previous management method, by providing a “ C_{LV} ” bus-tie and an “I” interlock which prevents the bus-tie from being closed when both the incoming circuit-breakers from the transformer are closed, a substation managed as shown in diagram 4 is made, which foresees two transformers which individually supply the low voltage busbars, which are separate.

With the same power of the transformers installed, this management method allows a lower value of the short-circuit current on the busbar. In other words, each transformer establishes the short-circuit level for the busbar of its competence without having to consider the contribution of other machines. Again in this case, when a transformer is out of service, with any closure of the bus-tie you pass to a system with a single busbar supplied by the sound transformer alone, and a load management logic must be provided with disconnection of non-priority loads.

Plant management according to diagram 4 is possible, for example by using the Emax series of air circuit-breakers with a wire interlock (mechanical interlock) between three circuit-breakers.

1.2 General information about MV/LV transformers

The transformer is the most important part of the transformer substation. Its selection affects the configuration of the substation and is made on the basis of various factors.

Not being a specific subject of this paper and wanting to give some general indications, it can be stated that for the request for low powers (indicatively up to 630kVA - 800kVA), a single transformer can be installed, whereas for higher powers (indicatively up to 1000kVA - 1600kVA), the power is divided over several units in parallel.

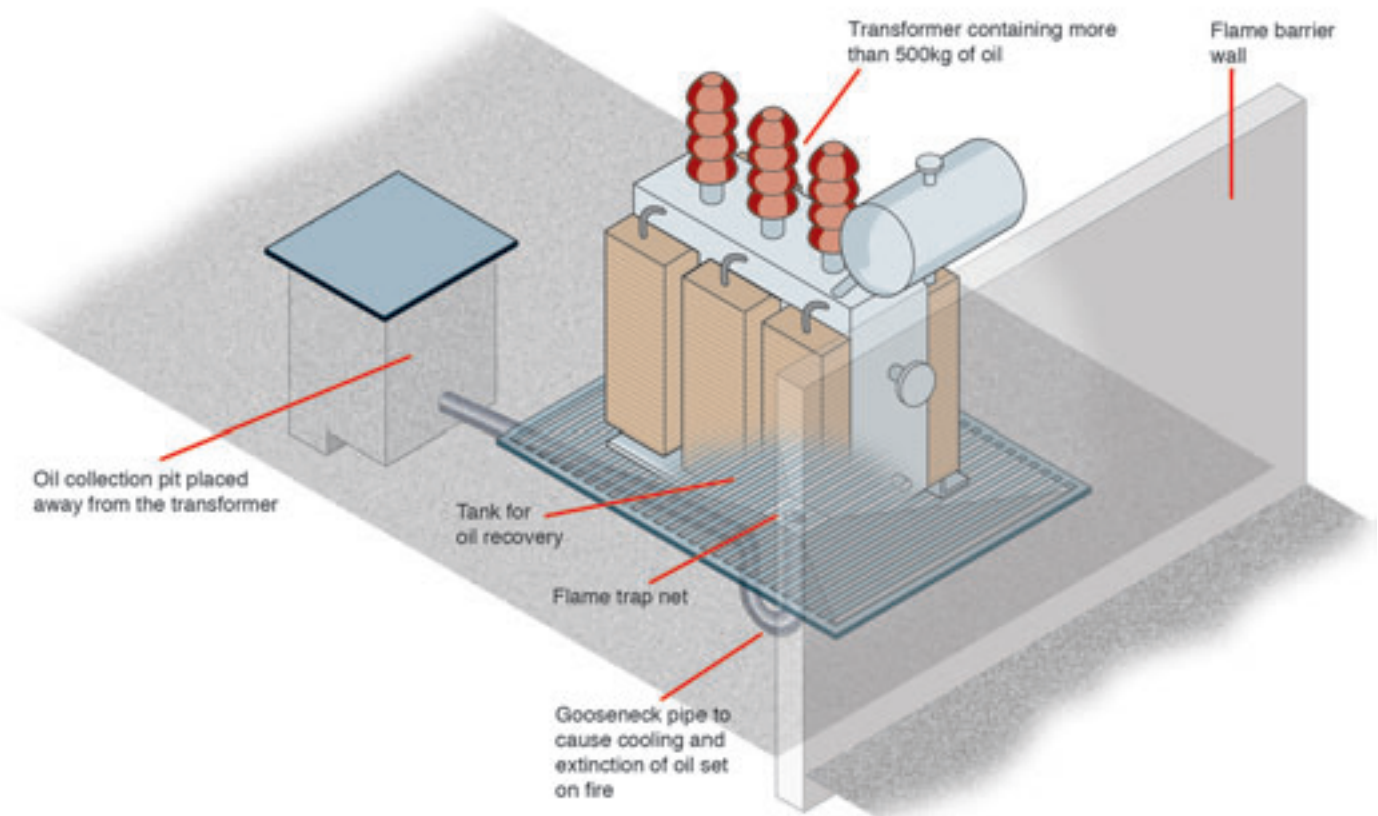
Another characteristic to take into consideration when selecting the machine is the type of cooling system, which can be either in air or in oil. With reference to air conditioning the structure of the substation, in the case

of oil cooled transformers, measures must be taken, for example those to prevent the oil spreading outside by providing an oil collection pit as shown in Figure 2. Furthermore, the substation must have a minimum flame resistance of 60 minutes (REI 60) and ventilation only towards the exterior. According to the type of cooling, the transformers are identified as follows:

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

The most frequent choice is for AN and ONAN types, as it is not advisable to use machines which use fans or oil circulators because it is rarely possible to man the substations.

Figure 2: ONAN transformers containing more than 500 kg of oil (> 800kVA)



Other important characteristics to be considered are those referring to the electrical parameters and, in addition to the usual quantities such as rated power, no-load secondary rated voltage, transformation ratio, rated short-circuit voltage in percent $v_{k\%}$, they acquire great importance above all when the transformers are functioning in parallel:

- the connection typology of the windings (delta/star grounded is the most used one for the substation transformers)
- connection system (*CEI group*), conventionally expressed by a number which, multiplied by 30, gives the delay angle of the phase voltage on the LV side compared with the MV side.

The presence of two or more MV/LV transformers and a possible bus-tie closed on the LV busbars allows the electricity network to be managed with the transformers in parallel.

In the presence of faults, this management method causes an increase in the short-circuit current value on the LV side, with a possible consequent increase in the size of the circuit-breakers outgoing from the busbar and heavier anchoring conditions for the busbars in comparison with operation with a single transformer. This is due to a smaller value of the $v_{k\%}$ which characterises the transformers with less power. On the other hand, when

suitably managed, the parallel method has the advantage of allowing power supply, at least to the users considered as primary users, through the possible bus-tie, even in the case of outage of one of the transformers.

The following example shows the increase in the short-circuit current value on the busbar in the case of transformers in parallel:

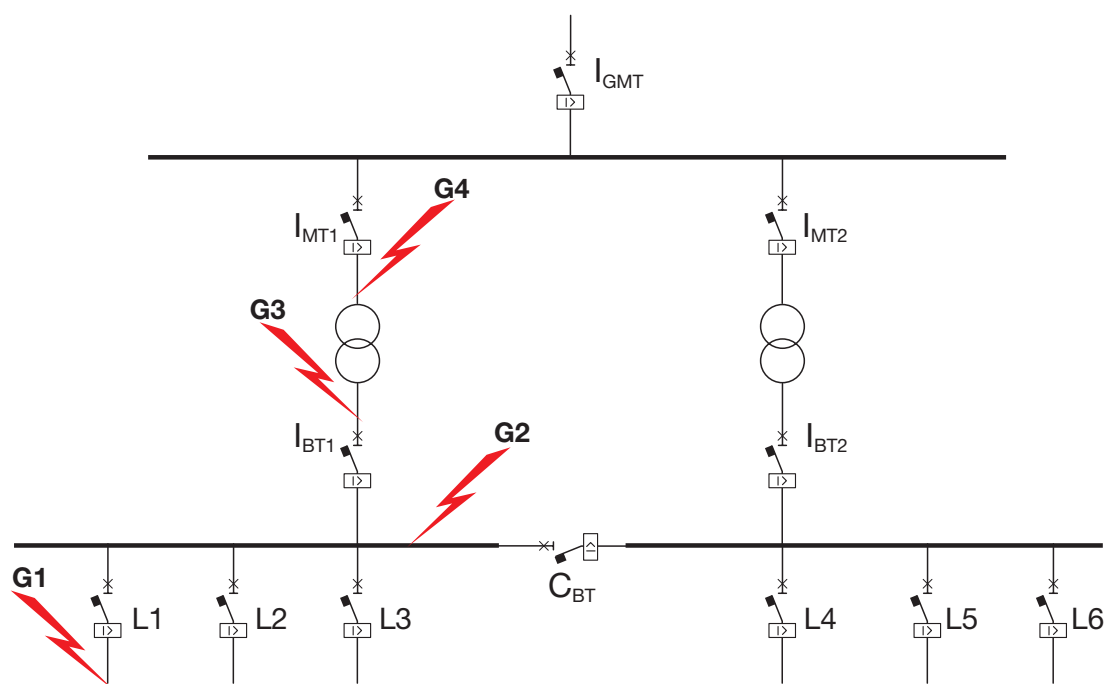
Supply network, short-circuit power	$S_{knet}=750\text{MVA}$
Plant secondary voltage.....	$V_{2n}=400\text{V}$
Power of the single transformer	$S_{nTR}=1600\text{kVA}$
Rated short-circuit voltage of the single transformer.....	$v_{k\%}=6\%$
Power of the transformer provided for the parallel	$S_{nTR}=800\text{kVA}$
Short-circuit voltage of the transformer in parallel	$v_{k\%}=4\%$

From these data and from quick calculations, a short-circuit current value of 37 kA is obtained on the busbar with the single 1600kVA transformer.

With two 800kVA transformers in parallel, the short-circuit current on the busbar shall be about 55kA.

With reference to the electricity network outlined in Figure 3, the following considerations have the aim of illustrating the management philosophy for the protections:

Figure 3



G1 Fault on one of the LV users

Regardless of the presence or absence of the bus-tie:
with appropriate selection of the protection devices and according to normal LV selectivity prescriptions, it is possible to discriminate the fault and ensure service continuity with opening just of the L1 circuit-breaker.

G2 Fault on the LV busbar

Without bus-tie:

the fault is extinguished by the two general LV side circuit-breakers (I_{LV1} and I_{LV2}) of the transformers, causing complete outage of the plant. The transformers remain no-load supplied. To prevent opening of the I_{MV} circuit-breakers, obtaining MV/LV selectivity is again important in this case.

With bus-tie:

the CLV bus-tie must open, with consequent separation of the busbars and complete elimination of the fault by means of the main I_{LV1} circuit-breaker opening. The action of the bus-tie allows power supply to be maintained to the half-busbar unaffected by the fault. The action of the LV devices ($I_{LV1} - C_{LV} - I_{LV2}$), which are all affected by the fault, may be co-ordinated by using devices for which *the directional zone selectivity is implemented*, such as for example protection releases PR123 for the Emax series and PR333 for the Emax circuit-breaker type X1.

G3 Fault on the LV bus riser of the transformer

Without bus-tie:

The fault current affects the two transformers and it may be such as to cause opening of the two devices I_{MV} and I_{LV} of the transformers. The consequence would be to have all the plant disconnected. In this case it becomes important to study and implement a dedicated management logic (for example directional selectivity) which allows I_{LV1} and I_{MV1} opening in order to isolate only the transformer affected by the fault. Also a logic for the disconnection of non-priority loads should be foreseen, since the plant is functioning with one transformer only.

With bus-tie:

the management logic remains the same and it could possibly foresee also the bus-tie opening.

G4 Fault on the MV bus riser of the transformer

Without bus-tie:

the management logic must allow immediate opening of the I_{MV1} circuit-breaker affected by the full fault current (I_{MV2} shall see a lower current limited by the impedance of the two transformers) and, if the plant management foresees pulling, the opening of the I_{LV1} circuit-breaker with isolation of the fault point will follow with service continuity of the whole plant ensured by power supply through the other transformer. Also a logic for the disconnection of non-priority loads should be foreseen, since the plant is functioning with one transformer only.

With bus-tie:

the management logic remains the same, and the bus-tie would have only the function of separating the busbars by eliminating that of competence of the excluded transformer.

After an analysis of the fault handling modalities, which under some circumstances result to be quite complex due to the double supply of the transformers in parallel, the minimum requirements to have two transformers operating in parallel are examined now:

a) the internal connections must belong to the same group (*CEI group*) and the transformers must have the same transformation ratio. By complying with these prescriptions, the two sets of voltage result to coincide and to be in phase opposition; consequently there are no vectorial differences between the secondary voltage of every single mesh and no circulation currents are generated. In the contrary case, circulation currents would be generated, which could damage the transformers also in no-load operation;

b) the short-circuit voltages ($V_{k\%}$) must have the same value. Thanks to this measure, the total load current is subdivided between the two transformers in proportion to their respective rated powers. If not, the two transformers would be differently loaded and the machine with the lower internal voltage drop would tend to be more loaded.

c) equal short-circuit power factor ($\cos\phi_{cc}$). Thanks to this measure, the total load current is divided into two or more currents in phase and consequently with value reduced to the minimum. Since the $\cos\phi_{cc}$ value changes according to the power of the transformer, it is not advisable to connect in parallel a transformer with a power exceeding the double, or being lower than the half, of the other.

1.3 MV protection devices: observations about the limits imposed by the utility companies

The MV distribution outgoing line supplying the user substation is provided with its own protections against overcurrent and earth faults; therefore the utility company shall not provide any protection device for the customer's plant.

In order to prevent any internal faults of the MV and LV plant from affecting the distribution network service, the consumer must install convenient protections. The selection of the protection devices and their co-ordination must guarantee safety for the personnel and the machines, by ensuring at the same time also good service reliability of the installation.

Some indications are provided hereunder regarding the characteristics the MV/LV side protection functions must have and the way they can interact.

The protection of the utility company usually operates with independent time tripping characteristics and the tripping threshold values communicated to the consumer represent the upper limit to comply with in order to avoid unwanted trips.

Hereunder we give an example of the setting range of the protection device for the different protection thresholds:

- Overcurrent threshold (overload 51):
Threshold (30÷600)A, with 15A steps (primary values)
Delay time (0.05÷5)s, with 0.05s steps.
- Overcurrent threshold (short-circuit 50):
Threshold (30÷600)A, with 15A steps (primary values)
Delay time (0.05÷5)s, with 0.05s steps.
- Protection against earth faults:
According to the characteristics of the user installation, the earth fault protection may be constituted either by a directional earth fault protection 67N, which detects homopolar currents and voltages, or by a simple zero-sequence overcurrent protection 51N.

For example, as regards the zero-sequence overcurrent protection the setting ranges are the following:
overcurrent threshold (0.5÷10) A, with 0.5A steps (primary values);
delay time (0.05÷1)s, with 0.05 s steps.

1.4 LV protection devices

LV protection devices are located on the load side of the transformer.

The protection functions usually available on a LV device are the functions of protection against overload, against short-circuit and against earth fault.

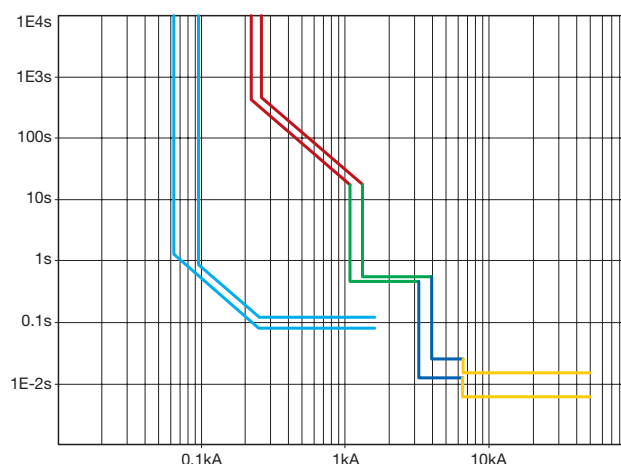
Here is a short description of these protection functions implemented on the micro-processor based electronic releases :

- *protection against overload*
identified as function "L", it is a protection with inverse long time-delay trip with adjustable current and time. On ABB electronic protection releases it is indicated also as function I1.
- *protection against short-circuit*
identified as function "S", against delayed short-circuit (on ABB electronic protection releases it is indicated also as function I2) and "I" against instantaneous short-circuit (on ABB electronic protection releases it is indicated also as function I3).
Function "S" can be with either inverse or definite time-delay trip, with adjustable current and time. Function "I" is a protection with definite time-delay trip and adjustable current only.
- *protection against earth-fault*
identified as function "G" can be with either inverse or definite time-delay trip, with adjustable current and time. This protection can be realized on the star point of the transformer with external toroid.

The curve in yellow colour represents the behaviour of the circuit-breaker at current values much higher than the set protection I3.

The diagram of Figure 4 shows an example of a time/current tripping curve of a LV circuit-breaker on which all the above mentioned protection functions have been activated.

Figure 4



The following example is aimed at explaining how it is possible to operate with the information which charac-

terize the inverse time-delay curve with characteristic I^2t constant as those available for functions L - S - G.

With reference to the protection function “L” implemented on the release which is fitted on the moulded case circuit-breakers of Tmax series, for example a T2...160 In100 (“In” indicates the size of the protection release mounted on the circuit-breaker), the possible tripping curves are type A and type B.

The curve of type A is characterized by its passing through the point identified as:

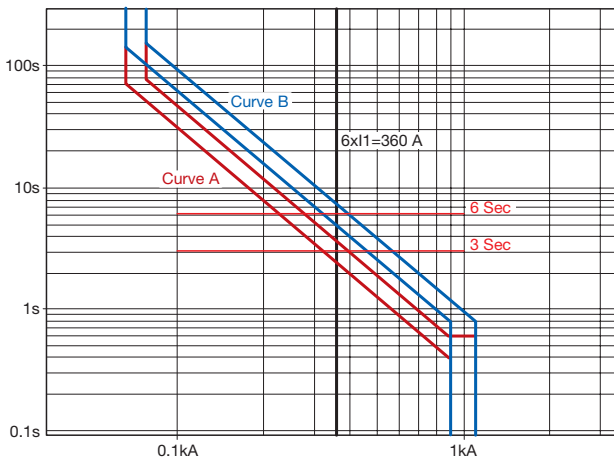
$$6 \times I_1 \text{ with a time } t_1=3s$$

The curve of type B is characterized by its passing through the point identified:

$$6 \times I_1 \text{ with a time } t_1=6s$$

Assuming for I_1 a generic setting $I_1=0.6 \times I_n=0.6 \times 100=60A$, the above means that, in correspondence of $6 \times I_1=360A$, the two setting curves shall be characterized by a tripping time of 3 or 6 seconds (without the tolerances) as the time/current diagram of Figure 5 shows.

Figure 5



Since these are curves with I^2t constant, the following condition shall be always verified:

for the curve A:

$$(6 \times I_1)^2 \times 3 = \text{const} = I^2t$$

for curve B:

$$(6 \times I_1)^2 \times 6 = \text{const} = I^2t$$

For example, under the above conditions, it is possible to determine the tripping time of the protection for an overload current equal to 180A.

Therefore, from the above formulas, the following conditions may be obtained:

$$(6 \times I_1)^2 \times 3 = 180^2 \times t_A$$

$$(6 \times I_1)^2 \times 6 = 180^2 \times t_B$$

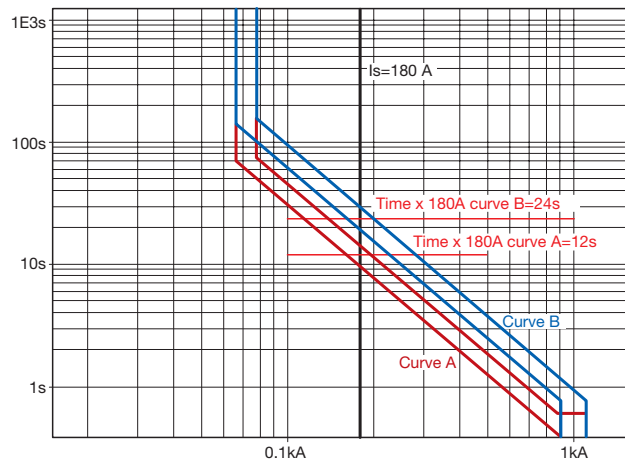
which respectively give:

$$t_A = 12s$$

$$t_B = 24s$$

These results mathematically obtained may be obviously verified with immediacy through the course of the tripping curves, as the time/current diagram of Figure 6 shows.

Figure 6



For example, should the installation requirements impose that the assumed overload of 180A is eliminated in a time lower than 15 seconds, from the analysis carried out it shall result that the tripping characteristic to be used and set on the protection release is defined as curve A (tripping time $t_1=3s$ for a current equal to $6 \times I_1$).

Still making reference to the condition

$$(6 \times I_1)^2 \times t = \text{const}$$

to select the curve which is suitable to eliminate the overload of 180 A in a time lower than 15 seconds, it is possible to proceed in the reverse way, by setting up the equation:

$$(6 \times 0.6 \times 100)^2 \times t = \text{const} = 180^2 \times 15$$

This relationship allows the calculation of the maximum delay of the tripping characteristic to comply with the installation requirements.

By making the time explicit, the following value is obtained:

$$t = 3.75s$$

The suitable curve shall be that with “ t_1 ” lower than “ t ”. Therefore the curve to be used is curve A, as resulted also by the above analysis.

The protections, above all the MV ones, are often identified by alphanumeric codes such as 50 – 51N – 67, which do not find an equivalent in the typical LV nomenclature. Hereunder, we give some information to explain the meaning of the most common codes and to create a correspondence, whenever possible, between the indications used to identify MV protections and those use for the LV ones.

The Standard IEC 60617-7 is currently in force; it defines the symbology and the relevant function of the releases typically used in the electrical installations. For many people operating in the electrical field, it is common praxis to use the codification of the Standard ANSI/IEEE C37.2.

Below there is an example of correspondence between IEC and ANSI/IEEE symbology for some of the main MV protection functions.

50 Instantaneous overcurrent relay

A device that operates with no intentional time-delay when the current exceeds a preset value. It can be compared with a protection "I" of a LV release.

51 Time-delayed overcurrent relay

A device that functions when the ac input current exceeds a predetermined value, and in which the input current and operating time are inversely related. It can be compared with a protection "S" of a LV release.

51N or 51G Time-delayed earth fault overcurrent relay

Devices that operate with a definite time-delay when an earth fault occurs. In details:

51N: residual current measured on the CT joint return. This device can be compared with a protection "G" of a LV release.

51G: residual current measured directly either on a CT or on toroidal CT only. This device can be compared with the protection which can be realized, for example, through an homopolar toroid operating a residual current device with adjustable trip times (e.g. a RCQ) or through the function "G" of the protection release supplied by an external toroid.

50N or 50G Instantaneous earth fault overcurrent relay

A device that operates with no intentional time-delay when an earth fault occurs. In details:

50N: residual current measured on the CT common return. It can be compared with a protection "G" with definite time of a LV release.

50G: residual current measured directly either only on a CT or on toroidal CT. It can be compared with a protection which can be realized, for example, through an homopolar toroid.

67 Alternating current directional power relay or directional overcurrent relay

A device that operates at a desired value of power flowing in a predetermined direction, or for overcurrent with power flowing in a predetermined direction. It can be compared with a protection "D" of a LV release.

49 Alternating current thermal relay

A device that operates when the temperature of the machine or of the ac apparatus exceeds a predetermined value. It can be compared with the overload protection "L" of a LV release, even though a real protection against overload is not provided for MV applications.

Table 1

ANSI/IEEE Code	Function definition	Simbology corresponding to the Standard IEC 60617-7
51	Time-delayed overcurrent	$I > \overline{I}$
50	Instantaneous overcurrent	$I > \overline{I}^0$
51N	Time-delayed earth fault overcurrent	$I > \overline{I}^0 \overline{I}$
50N	Instantaneous earth fault overcurrent	$I > \overline{I}^0 \overline{I}^0$
67	Directional phase overcurrent	$I > \overline{I}^0 \overline{I} \overline{I}$
67N	Directional zero-sequence overcurrent	$I > \overline{I}^0 \overline{I}^0 \overline{I}$

2 Calculation of short-circuit currents

2.1 Data necessary for the calculation

Some general indications regarding the typical parameters characterizing the main components of an installation are given hereunder.

Knowledge of the following parameters is fundamental to carry out a thorough analysis of the installation.

Distribution networks:

In a MV network the rated voltage is the unique parameter usually known.

To calculate the short-circuit currents it is necessary to know the network short-circuit power, which can indicatively vary from 250MVA to 500MVA for systems up to 30kV.

When the voltage level rises, the short-circuit power can indicatively vary between 700MVA and 1500MVA.

The voltage values of the MV distribution network and the relevant short-circuit power values accepted by the Standard IEC 60076-5 are reported in Table 1.

Table 1

Distribution network voltage practice	Short-circuit apparent power Current European practice	Short-circuit apparent power Current North-American
[kV]	[MVA]	[MVA]
7.2–12–17.5–24	500	500
36	1000	1500
52–72.5	3000	5000

Synchronous generator

The data usually known for an electrical machine are the rated voltage V_n and the rated apparent power S_n .

For synchronous generators, as for every electrical machine, to get a complete analysis it is necessary to evaluate also:

- the behaviour under steady state conditions for an analysis of the problems of static stability
- the behaviour under transitory conditions when the load suddenly varies for an analysis of the problems of dynamic stability, in particular when a three-phase short-circuit occurs.

Therefore, it becomes necessary to know the values of the machine reactance, in particular:

- as regards the first type of problem, the determining parameter is represented by the synchronous reactance;
- as regards the second type of problem, the transitory reactance with the relevant time constants and the sub-transitory reactance.

In this paper, the static and dynamic analysis of the phenomena connected to the generator shall not be dealt with in details, but only the following items shall be studied and determined:

- the maximum current value in the initial instants of the short-circuit, on which depend the stresses on the

windings, on the connections generator-to-transformer and on the foundations of the alternator;

- the waveform of the short-circuit current, which results fundamental for the proper co-ordination of the protections in the supplied network. The short-circuit current in the time-current curve presents a typical course: before reaching its steady state value, it gets to higher values which progressively falls.

This behaviour is due to the fact that the impedance of the generator, which is constituted practically by the reactance only, has no definite value, but it varies instant by instant, because the magnetic flux, which it depends on, does not reach immediately the steady state configuration. A different inductance value corresponds to any configuration of the flux, mainly because of the different path of the magnetic lines. Besides, there is not a single circuit and a single inductance, but more inductances (of the winding of the armature, of the winding of the field, of the damping circuits) which are mutually coupled. To simplify, the following parameters shall be taken into consideration:

subtransient reactance, direct axis	X''_d
transient reactance, direct axis	X'_d
synchronous reactance, direct axis	X_d

The evolution of these parameters during the time influences the course of the short-circuit current in the generator. Reactances are usually expressed in p.u. (per unit) and in percent, that is they are related to the nominal parameters of the machine.

They can be determined by the following relationship:

$$x_{\%} = \frac{\sqrt{3} \cdot I_n \cdot X}{V_n} \cdot 100$$

Where:

X is the real value in ohm of the considered reactance;

I_n is the rated current of the machine;

V_n is the rated voltage of the machine.

The following values can be indicated as order of quantity for the various reactances:

- subtransient reactance: the values vary from 10% to 20% in turbo-alternators (isotropic machines with smooth rotor) and from 15% to 30% in machines with salient pole rotor (anisotropic);
- transient reactance: it can vary from 15% to 30% in turbo-alternators (isotropic machines with smooth rotor) and from 30% to 40% in machines with salient pole rotor (anisotropic);
- synchronous reactance: the values vary from 120% to 200% in turbo-alternators (isotropic machines with smooth rotor) and from 80% to 150% in machines with salient pole rotor (anisotropic).

Transformer

A MV/LV transformer with delta primary winding (Δ) and secondary winding with grounded star point (Y_{gnd}). The electrical parameters which are usually known and which characterize the machine are:

- rated apparent power S_n [kVA]
- primary rated voltage V_{1n} [V]
- secondary rated voltage V_{2n} [V]
- short-circuit voltage in percent $v_{k\%}$ (typical values are 4% and 6%)

With these data it is possible to determine the primary and secondary rated currents and the currents under short-circuit conditions.

The typical values of the short-circuit voltage $v_{k\%}$ in relation to the rated power of the transformers are reported in Table 2 (reference Standard IEC 60076-5).

Table 2

Rated apparent power S_n [kVA]	Short-circuit voltage $v_{k\%}$
≤ 630	4
$630 < S_n \leq 1250$	5
$1250 < S_n \leq 2500$	6
$2500 < S_n \leq 6300$	7
$6300 < S_n \leq 25000$	8

The operating capacitance under overload conditions depends on the constructional characteristics of each single transformer. As general information, the operating capacitance of oil transformers under overload conditions can be considered as shown in the Standard ANSI C57.92 and according to the values shown in Table 3.

Table 3

Multiple of the rated current of the transformer	Time [s]
25	2
11.3	10
6.3	30
4.75	60
3	300
2	1800

Asynchronous motor

The data usually known for an asynchronous motor are the rated active power in kW, the rated voltage V_n and the rated current I_n . Among the ratings also the efficiency value and the power factor are available.

In case of short-circuit, the asynchronous motor functions as a generator to which a subtransient reactance from 20% to 25% is assigned. This means that a current equal to 4-5 times the rated current is assumed as contribution to the short-circuit.

2.2 Calculation of the short-circuit current

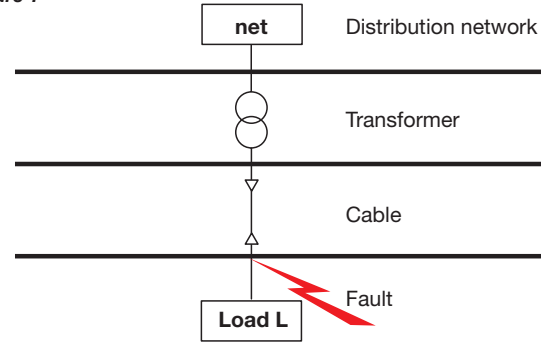
With reference to the electrical network schematised in Figure 1, a short-circuit is assumed on the clamps of the load. The network can be studied and represented by using the parameters “resistances” and “reactances” of each electrical component.

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

The passage from the impedance values Z_1 , related to a higher voltage (V_1), to the values Z_2 , related to a lower voltage (V_2), occurs through the transformation ratio:

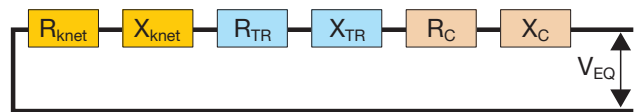
$$K = \frac{V_1}{V_2} \text{ in accordance with the following relationship: } Z_2 = \frac{Z_1}{K^2}$$

Figure 1



The structure of the electrical network taken into consideration can be represented through elements in series; thus an equivalent circuit is obtained as that shown in Figure 2, which allows to calculate the equivalent impedance seen from the fault point.

Figure 2



At the short-circuit point, an equivalent voltage source (V_{EQ}) is positioned, with value

$$V_{EQ} = \frac{c \cdot V_n}{\sqrt{3}}$$

The factor “c” depends on the system voltage and takes into account the influence of the loads and of the variation in the network voltage.

On the basis of these considerations, it is possible to determine the resistance and reactance values characterizing the elements which constitute the installation.

Supply network (net)

In the most cases, the installation results to be supplied by a medium voltage distribution network, whose supply voltage value V_{net} and initial short-circuit current I_{knet} can be easily found.

On the basis of these data and of a correction factor for the change of voltage caused by the short-circuit it is possible to calculate the short-circuit direct impedance of the network through the following formula:

$$Z_{knet} = \frac{c \cdot V_{net}}{\sqrt{3} \cdot I_{knet}}$$

For the calculation of the parameters network resistance and network reactance, the following relationships can be used:

$$\begin{aligned} X_{knet} &= 0.995 \cdot Z_{knet} \\ R_{knet} &= 0.1 \cdot X_{knet} \end{aligned}$$

If the short-circuit apparent power S_{knet} for the distribution network were known, it would be also possible to determine the impedance representing the network through the following relationship:

$$Z_{knet} = \frac{c^2 \cdot V_{net}^2}{S_{knet}}$$

Transformer

The impedance of the machine can be calculated with the nominal parameters of the machine itself (rated voltage V_{2n} ; apparent power S_{nTR} ; percentage voltage drop $v_{k\%}$) by using the following formula:

$$Z_{TR} = \frac{V_{2n}^2 \cdot v_{k\%}}{100 \cdot S_{nTR}}$$

The resistive component can be calculated with the value of the total losses P_{PTR} related to the rated current in accordance with the following relationship:

$$R_{TR} = \frac{P_{PTR}}{3 \cdot I_{2n}^2}$$

The reactive component can be determined by the classical relationship

$$X_{TR} = \sqrt{(Z_{TR}^2 - R_{TR}^2)}$$

Cables and overhead lines

The impedance value of these connection elements depends on different factors (constructional techniques, temperature, etc....) which influence the line resistance and the line reactance. These two parameters expressed per unit of length are given by the manufacturer of the cable.

The impedance is generally expressed by the following formula:

$$Z_c = L \cdot (r_c + x_c)$$

The resistance values are generally given for a reference temperature of 20°C; for different operating temperatures θ with the following formula it is possible to calculate the relevant resistance value:

$$r_\theta = [1 + (\alpha - 20)] \cdot r_{20}$$

where:

α is the temperature coefficient which depends on the type of material (for copper it is 3.95×10^{-3}).

Calculation of the short-circuit current

Determination of the short-circuit resistance and reactance values of the main elements of a circuit allow the short-circuit currents of the installation to be calculated.

With reference to Figure 2 and applying the reduction modality for elements in series, the following values can be determined :

- the short-circuit total resistance $R_{Tk} = \sum R$
- the short-circuit total reactance $X_{Tk} = \sum X$

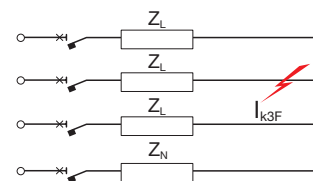
Once these two parameters are known, it is possible to determine the short-circuit total impedance value Z_{Tk}

$$Z_{Tk} = \sqrt{(R_{Tk}^2 + X_{Tk}^2)}$$

Once determined the equivalent impedance seen from the fault point, it is possible to proceed with the calculation of the three-phase short-circuit current:

Value of the three-phase symmetrical short-circuit current

$$I_{k3F} = \frac{c \cdot V_n}{\sqrt{3} \cdot Z_{Tk}}$$

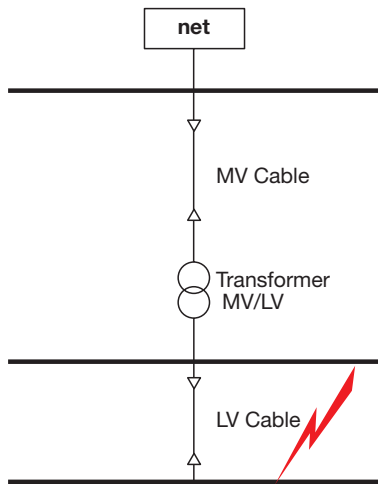


This is generally considered as the fault which generates the highest currents (except for particular conditions). When there are no rotary machines, or when their action has decreased, this value represents also the steady state short-circuit current and is taken as reference to determine the breaking capacity of the protection device.

An example of calculation of the three-phase short-circuit current using the above described relationship is given hereunder.

Example:

With reference to the schematized network, the electrical parameters of the different components are:



Short-circuit power and current of the supply network

$$S_{\text{knet}} = 500 \text{ MVA} \quad I_{\text{knet}} = 14.4 \text{ kA}$$

Rated voltage of the supply network $V_{\text{net}} = 20 \text{ kV}$

MV cable:

Resistance $R_{\text{CMV}} = 360 \text{ m}\Omega$

Reactance $X_{\text{CMV}} = 335 \text{ m}\Omega$

Rated power of the transformer $S_{\text{nTR}} = 400 \text{ kVA}$

Secondary rated voltage of the transformer $V_{2n} = 400 \text{ V}$

Short-circuit test for the transformer: $v_{\text{k}\%} = 4\%$; $p_{\text{k}\%} = 3\%$

LV cable with length $L = 5 \text{ m}$:

Resistance $R_{\text{CLV}} = 0.388 \text{ m}\Omega$

Reactance $X_{\text{CLV}} = 0.395 \text{ m}\Omega$

Making reference to the previous relationship, the calculation of the total impedance of the different elements is carried out in order to determine the three-phase short-circuit current at the given point.

Since the fault is on the LV side, all the parameters determined for the MV section of the network shall be related to the secondary rated voltage by applying the coefficient

$$K = \frac{20000}{400} = 50$$

Supply network

$$Z_{\text{knet}} = \frac{c \cdot V_{\text{net}}}{\sqrt{3} \cdot I_{\text{knet}}} = \frac{1.1 \cdot 20000}{\sqrt{3} \cdot 14.4 \cdot 10^3} = 0.88 \Omega$$

$$Z_{\text{knet 400V}} = \frac{Z_{\text{knet}}}{K^2} = \frac{0.88}{50^2} = 0.00035 \Omega$$

$$X_{\text{knet 400V}} = 0.995 \cdot Z_{\text{knet 400V}} = 0.000348 \Omega$$

$$R_{\text{knet 400V}} = 0.1 \cdot X_{\text{knet 400V}} = 0.0000348 \Omega$$

MV cable

$$R_{\text{CMV 400V}} = \frac{R_{\text{CMT}}}{K^2} = \frac{360 \cdot 10^{-3}}{50^2} = 0.000144 \Omega$$

$$X_{\text{CMV 400V}} = \frac{X_{\text{CMT}}}{K^2} = \frac{335 \cdot 10^{-3}}{50^2} = 0.000134 \Omega$$

Transformer

$$Z_{\text{TR}} = \frac{V_{2n}^2 \cdot v_{\text{k}\%}}{100 \cdot S_{\text{nTR}}} = \frac{400^2 \cdot 4}{100 \cdot 400 \cdot 10^3} = 0.016 \Omega$$

$$P_{\text{PTR}} = \frac{p_{\text{k}\%} \cdot S_{\text{nTR}}}{100} = \frac{3}{100} \cdot 400 \cdot 10^3 = 12 \text{ kW}$$

$$I_{2n} = \frac{S_{\text{nTR}}}{\sqrt{3} \cdot V_{2n}} = \frac{400 \cdot 10^3}{\sqrt{3} \cdot 400} = 577 \text{ A}$$

$$R_{\text{TR}} = \frac{P_{\text{PTR}}}{3 \cdot I_{2n}^2} = \frac{12000}{3 \cdot 577^2} = 0.012 \Omega$$

$$X_{\text{TR}} = \sqrt{(Z_{\text{TR}}^2 - R_{\text{TR}}^2)} = \sqrt{(0.016^2 - 0.012^2)} = 0.0106 \Omega$$

LV cable

$$R_{\text{CLV}} = 0.388 \text{ m}\Omega$$

$$X_{\text{CLV}} = 0.395 \text{ m}\Omega$$

The total short-circuit resistance value is given by: $R_{\text{TK}} = \Sigma R$

$$R_{\text{TK}} = R_{\text{knet 400V}} + R_{\text{CMV 400V}} + R_{\text{TR}} + R_{\text{CLV}}$$

$$R_{\text{TK}} = 0.0000348 + 0.000144 + 0.012 + 0.000388 = 0.01256 \Omega$$

The total short-circuit reactance value is given by: $X_{\text{TK}} = \Sigma X$

$$X_{\text{TK}} = X_{\text{knet 400V}} + X_{\text{CMV 400V}} + X_{\text{TR}} + X_{\text{CLV}}$$

$$X_{\text{TK}} = 0.000348 + 0.000134 + 0.0106 + 0.000395 = 0.01147 \Omega$$

Value of the three-phase symmetrical short-circuit current

Calculating the value of the total short-circuit impedance

$$Z_{\text{TK}} = \sqrt{(R_{\text{TK}}^2 + X_{\text{TK}}^2)} = \sqrt{(0.01256^2 + 0.01147^2)} = 0.017 \Omega$$

and assuming the factor $c^{(1)} = 1.1$ the short-circuit current value is:

$$I_{\text{k3F}} = \frac{c \cdot V_{2n}}{\sqrt{3} \cdot Z_{\text{TK}}} = \frac{1.1 \cdot 400}{\sqrt{3} \cdot 0.017} = 14943 \text{ A} = 14.95 \text{ kA}$$

For more detailed information and considerations about short-circuit current calculation, see the "Annex B" of this paper.

⁽¹⁾ The voltage factor "c" is necessary in order to simulate the effect of some phenomena which are not explicitly considered in the calculation, such as for example :

- the voltage changes in time
- the changes of transformer taps
- the subtransient phenomena of the rotary machines (generators and motors).

2.3 Calculation of motor contribution

In case of short-circuit, the motor begins to function as a generator and feeds the fault for a limited time corresponding to the time necessary to eliminate the energy which is stored in the magnetic circuit of the motor. By an electrical representation of the motor with its subtransient reactance "X", it is possible to calculate the numerical value of the motor contribution. This datum is often difficult to find; therefore the general rule is to consider motor contribution as a multiple of the rated current of the motor. The typical values of the multiplying factor vary from 4 to 6 times.

For a LV motor, with reference to the length of time, the effect of the contribution to the short-circuit current results to be negligible already after the first periods from the start of the short-circuit. The Standard IEC 60909 prescribes the minimum criteria for taking into consideration the phenomenon; it shall be:

$$(\sum I_{nM} > \frac{I_k}{100})$$

where:

$\sum I_{nM}$ represents the sum of the rated currents of the motors directly connected to the network where the short-circuit has occurred. I_k is the three-phase short-circuit current determined without motor contribution.

2.4 Calculation of the peak current value

The short-circuit current " I_k " may be considered as formed by two components:

- a symmetrical component " i_s " with sinusoidal waveform and precisely symmetrical with respect to the x-axis of times. This component is expressed by the following relationship:

$$i_s = \sqrt{2} \cdot I_k \cdot \sin(\omega \cdot t - \phi_k)$$

- the unidirectional component " i_u " with exponential curve due to the presence of an inductive component. This component is characterized by a time constant $\tau = L/R$ ("R" indicates the resistance and "L" the inductance of the circuit upstream the fault point) and dies out after 3 to 6 times τ .

$$i_u = \sqrt{2} \cdot I_k \cdot \sin\phi_k \cdot e^{-\frac{R}{L} \cdot t}$$

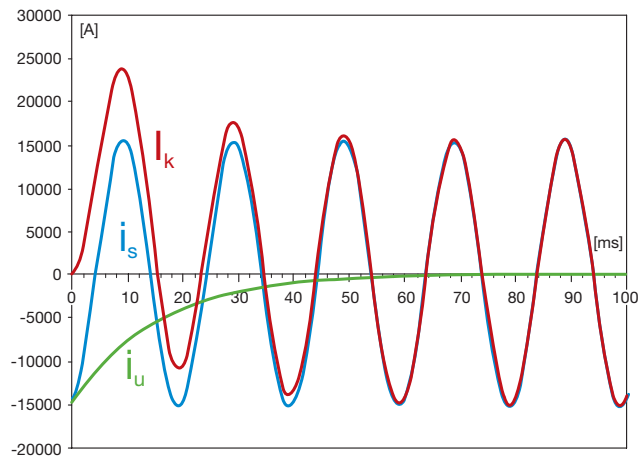
The unidirectional component during the transient period makes that the asymmetrical short-circuit current is characterized by a maximum value called peak value, which results to be higher than the value to be due to a

purely sinusoidal quantity. Generally speaking it is possible to state that, if considering the r.m.s. value of the symmetrical component of the short-circuit current I_k , the value of the first current peak may vary from to

$$\sqrt{2} \cdot I_k \text{ a } 2 \cdot \sqrt{2} \cdot I_k.$$

After the transient period has elapsed, the short-circuit current practically becomes symmetrical. The current curves are shown in Figure 3.

Figure 3



As known, the performances of a circuit-breaker under short-circuit conditions, making reference to the operating voltage of the device, are mainly defined by the following parameters:

I_{cu} = breaking capacity
 I_{cm} = making capacity

The *breaking capacity* I_{cu} is defined with reference to the r.m.s. value of the symmetrical component of the short-circuit current. It is possible to say that the r.m.s. value of a sinusoidal current represents that direct current value which, in an equal time, produces the same thermal effects. The sinusoidal quantities are generally expressed through their r.m.s. value. As r.m.s. value it is possible to consider that short-circuit current value which can be normally calculated by the classical relationship:

$$I_k = \frac{V}{\sqrt{(R^2 + X^2)}}$$

The *making capacity* I_{cm} is defined with reference to the maximum peak value of the prospective short-circuit current.

Since each element with an impedance modifies the short-circuit current on the load side, and since a circuit-breaker is an element with an impedance of its own, the prospective current is defined as the current flowing when the protection device is replaced by an element with null impedance.

The product Standard IEC 60947-2 gives a table allowing to pass from the r.m.s. value of the short-circuit current to its relevant peak value, through a multiplicative coefficient linked also to the power factor of the installation. This table is the necessary reference to determine the I_{cu} and I_{cm} values of the various circuit-breakers.

When passing from the characteristics of the circuit-breakers to those of the installation, whereas calculating the r.m.s. value of the symmetrical component of the current results immediate, determining the relevant peak value could be less immediate. The necessary parameters, such as the short circuit power factor or the ratio between the resistance and the inductance of the circuit on the load side of the fault point, are not always available.

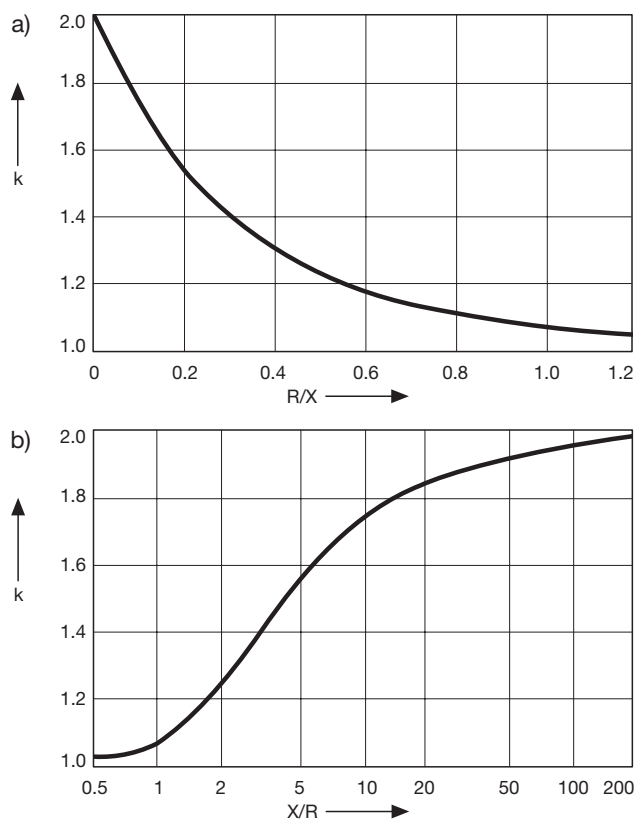
The Standard IEC 60909 gives some useful information for the calculation of the peak current and in particular reports the following relationship:

$$i_p = k \cdot \sqrt{2} \cdot I_k$$

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

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

or through the following diagrams which show the value of “k” as a function of the parameter “R/X” or “X/R”.



Example:

Assuming an r.m.s. value of the symmetrical component of the three-phase short-circuit current $I_k=33\text{kA}$ and a peak value under short-circuit conditions ($\cos\varphi_k=0.15$), it is possible to see how to proceed in order to determine the peak value:

from the value of $\cos\varphi_k$ it is possible to make the ratio X/R explicit through the tangent calculation.

After calculating the ratio $X/R = 6.6$, through the graph or the formula it is possible to find the value of $k = 1.64$, which gives a peak value $I_p=76.6\text{kA}$ in correspondence with the three-phase short-circuit current $I_k=33\text{kA}$.

Considering the need to choose a protection device for an installation at 400V rated voltage, with reference to the three-phase short circuit current only, a circuit-breaker with breaking capacity $I_{cu}=36\text{kA}$ could be used, to which a making capacity $I_{cm}=75.6\text{kA}$ would correspond, in compliance with the Standard IEC 60947-2. Such making capacity results to be lower than the peak value which can be made in the installation considered; thus the choice results to be incorrect and forces the use of a circuit-breaker version with higher breaking capacity (for example 50 kA) and consequently I_{cm} greater and suitable for the peak value of the installation.

From the example above it is possible to see how at first a circuit-breaker, version “N” (that is with 36 kA breaking capacity) would have been chosen incorrectly; on the contrary the considerations regarding the peak value shall lead to use a circuit-breaker version “S” or “H”.

3 Choice of protection and control devices

3.1 Generalities about the main electrical parameters of protection and control devices

Generally speaking, when it is necessary to analyse and select a protection and control device such as a circuit-breaker, some electrical parameters characterizing the device itself shall be evaluated, for example rated current and breaking capacity.

Hereunder a brief description of these parameters is given, relating them with the electrical quantities of the installation.

Rated operational voltage U_e : it is the value of voltage which determines the application limit of an equipment and to which all the other parameters typical of the equipment are referred to. It is generally expressed as the voltage between phases.

Rated uninterrupted current I_u : it is the value of current which the device is able to carry for an indefinite time (weeks, months, or even years). This parameter is used to define the size of the circuit-breaker.

Rated current I_n : it is the value of current which characterizes the protection release installed on board of the circuit-breaker and determines, based on the settings available for the release, the protective characteristic of the circuit-breaker itself. Such current is often related to the rated current of the load protected by the circuit-breaker.

Rated ultimate short-circuit breaking capacity I_{cu} : it is the r.m.s. value of the symmetrical component of the short-circuit current which is the maximum value that the circuit-breaker is able to break. Such value is established through a clearly defined test cycle (O-t-CO) and specified test modalities described in the product standard IEC 60947-2. The circuit-breakers are classified according to their performance levels identified with letters ("N" "S" "H" "L" etc.) referred to their breaking capacity.

Rated service short-circuit breaking capacity I_{cs} : it is the r.m.s. value of the symmetrical component of the

short-circuit current which the circuit-breaker is able to break. Such value is established through a clearly defined test cycle (O-t-CO-t-CO) and specified test modalities described in the product standard IEC 60947-2.

It is expressed as a percentage 25% - 50% - 75% - 100% of the rated ultimate short-circuit breaking capacity, for example it could be $I_{cs} = 75\% I_{cu}$.

The value of the breaking capacity must be put into relation with the short-circuit current value at the installation point of the circuit-breaker itself and the relationship $I_{cu} > I_k$ or $I_{cs} > I_k$ must be verified.

Rated short-circuit making capacity I_{cm} : it is the maximum prospective peak current which the circuit-breaker must be able to make. In alternate current, the rated making capacity of a circuit-breaker under short-circuit conditions shall not be lower than its rated ultimate short-circuit breaking capacity multiplied by the factor "n", thus being $I_{cm} = n \times I_{cu}$.

Such value of I_{cm} shall be put into relation with the peak value of the current measured in the installation point of the circuit-breaker and the relationship $I_{cm} > i_p$ must be verified.

Table 1 below shows the values of coefficient "n" as specified in the product Standard IEC 60947-2.

Table 1

Breaking capacity I_{cu}	Power factor	n
$4.5 \leq I_{cu} \leq 6$	0.7	1.5
$6 < I_{cu} \leq 10$	0.5	1.7
$10 < I_{cu} \leq 20$	0.3	2
$20 < I_{cu} \leq 50$	0.25	2.1
$50 < I_{cu}$	0.2	2.2

Rated short-time withstand current I_{cw} : it is the r.m.s. value of the alternate current component which the circuit-breaker is able to withstand without damages for a determined time, preferred values being 1s and 3s.

Moulded-case circuit-breakers

family	Tmax									
circuit breaker	T1			T2				T3		
rated service current (I _{ue})	690			690				690		
rated uninterrupted current (I _u)	160			160				250		
rated ultimate short-circuit breaking capacity (I _{cu})	B	C	N	N	S	H	L	N	S	
(AC) 50-60 Hz 220/230V	25	40	50	65	85	100	120	50	85	
(AC) 50-60 Hz 380/415V	16	25	36	36	50	70	85	36	50	
(AC) 50-60 Hz 440V	10	15	22	30	45	55	75	25	40	
(AC) 50-60 Hz 500V	8	10	15	25	30	36	50	20	30	
(AC) 50-60 Hz 690V	3	4	6	6	7	8	10	5	8	
rated service short-circuit breaking capacity (I _{cs})										
(AC) 50-60 Hz 220/230V	100%	75%	75%	100%	100%	100%	100%	75%	50%	
(AC) 50-60 Hz 380/415V	100%	100%	75%	100%	100%	100%	75% ⁽¹⁾	75%	50% ⁽²⁾	
(AC) 50-60 Hz 440V	100%	75%	50%	100%	100%	100%	75%	75%	50%	
(AC) 50-60 Hz 500V	100%	75%	50%	100%	100%	100%	75%	75%	50%	
(AC) 50-60 Hz 690V	100%	75%	50%	100%	100%	100%	75%	75%	50%	
rated short-circuit making capacity (I _{cm})										
(AC) 50-60 Hz 220/230V	52.5	84	105	143	187	220	264	105	187	
(AC) 50-60 Hz 380/415V	32	52.5	75.6	75.6	105	154	187	75.6	105	
(AC) 50-60 Hz 440V	17	30	46.2	63	94.5	121	165	52.5	84	
(AC) 50-60 Hz 500V	13.6	17	30	52.5	63	75.6	105	40	63	
(AC) 50-60 Hz 690V	4.3	5.9	9.2	9.2	11.9	13.6	17	7.7	13.6	

(1) 70kA (2) 27kA (3) 75% for T5 630 (4) 50% for T5 630 (5) only for T7 800/1000/1250 A

Air circuit-breakers

family	Emax									
circuit breaker	X1			E1		E2				
rated service current (I _{ue})	690			690		690				
performance level	B	N	L	B	N	B	N	S	L	
rated uninterrupted current (I _u)	630	630	630	800	800	1600	1000	800	1250	
	800	800	800	1000	1000	2000	1250	1000	1600	
	1000	1000	1000	1250	1250		1600	1250		
	1250	1250	1250	1600	1600		2000	1600		
	1600	1600						2000		
rated ultimate short-circuit breaking capacity (I _{cu})										
(AC) 50-60 Hz 220/230/380/415 V	42	65	150	42	50	42	65	85	130	
(AC) 50-60 Hz 440V	42	65	130	42	50	42	65	85	110	
(AC) 50-60 Hz 500/525V	42	55	100	42	50	42	55	65	85	
(AC) 50-60 Hz 660/690V	42	55	60	42	50	42	55	65	85	
rated service short-circuit breaking capacity (I _{cs})										
(AC) 50-60 Hz 220/230/380/415 V	42	50	150	42	50	42	65	85	130	
(AC) 50-60 Hz 440V	42	50	130	42	50	42	65	85	110	
(AC) 50-60 Hz 500/525V	42	42	100	42	50	42	55	65	85	
(AC) 50-60 Hz 660/690V	42	42	45	42	50	42	55	65	85	
rated short-circuit making capacity (I _{cm})										
(AC) 50-60 Hz 220/230/380/415 V	88.2	143	330	88.2	105	88.2	143	187	286	
(AC) 50-60 Hz 440V	88.2	143	286	88.2	105	88.2	143	187	242	
(AC) 50-60 Hz 500/525V	88.2	121	220	75.6	75.6	84	121	143	187	
(AC) 50-60 Hz 660/690V	88.2	121	132	75.6	75.6	84	121	143	187	
rated short-time withstand current (I _{cw})	(1s)	42	42	15	42	50	42	55	65	10
	(3s)				36	36	42	42	42	

(1) the performance at 600V is 100kA.

	T4					T5					T6				T7			
	690					690					690				690			
	250/320					400/630					630/800/1000				800/1000/1250/1600			
	N	S	H	L	V	N	S	H	L	V	N	S	H	L	S	H	L	V ⁽⁵⁾
	70	85	100	200	300	70	85	100	200	300	70	85	100	200	85	100	200	200
	36	50	70	120	200	36	50	70	120	200	36	50	70	100	50	70	120	150
	30	40	65	100	180	30	40	65	100	180	30	45	50	80	50	65	100	130
	25	30	50	85	150	25	30	50	85	150	25	35	50	65	40	50	85	100
	20	25	40	70	80	20	25	40	70	80	20	22	25	30	30	42	50	60
	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	75%	100%	100%	100%	100%
	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	75%	100%	100%	100%	100%
	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	75%	100%	100%	100%	100%
	100%	100%	100%	100%	100%	100%	100%	100%	100% ⁽³⁾	100% ⁽⁴⁾	100%	100%	100%	75%	100%	100%	75%	100%
	100%	100%	100%	100%	100%	100%	100%	100% ⁽³⁾	100% ⁽⁴⁾	100% ⁽⁴⁾	75%	75%	75%	75%	100%	75%	75%	75%
	154	187	220	440	660	154	187	220	440	660	154	187	220	440	187	220	440	440
	75.6	105	154	264	440	75.6	105	154	264	440	75.6	105	154	220	105	154	264	330
	63	84	143	220	396	63	84	143	220	396	63	94.5	105	176	105	143	220	286
	52.5	63	105	187	330	52.5	63	105	187	330	52.5	73.5	105	143	84	105	187	220
	40	52.5	84	154	176	40	52.5	84	154	176	40	48.4	55	66	63	88,2	105	132

	E3					E4			E6	
	690					690			690	
	N	S	H	V	L	S	H	V	H	V
	2500	1000	800	800	2000	4000	3200	3200	4000	3200
	3200	1250	1000	1250	2500		4000	4000	5000	4000
		1600	1250	1600					6300	5000
		2000	1600	2000						6300
		2500	2000	2500						
		3200	2500	3200						
		3200								
	65	75	100	130	130	75	100	150	100	150
	65	75	100	130	110	75	100	150	100	150
	65	75	100	100	85	75	100	130	100	130
	65	75	85 ⁽¹⁾	100	85	75	85 ⁽¹⁾	100	100	100
	65	75	85	100	130	75	100	150	100	125
	65	75	85	100	110	75	100	150	100	125
	65	75	85	85	65	75	100	130	100	100
	65	75	85	85	65	75	85	100	100	100
	143	165	220	286	286	165	220	330	220	330
	143	165	220	286	242	165	220	330	220	330
	143	165	187	220	187	165	220	286	220	286
	143	165	187	220	187	165	187	220	220	220
	65	75	75	85	15	75	100	100	100	100
	65	65	65	65		75	75	75	85	85

3.2 Criteria for the circuit-breaker choice

The various choice criteria for a circuit-breaker impose, in addition to a verification of the typical electrical parameters of the circuit-breaker (voltage – current – breaking capacity etc.), also the verification of the circuit-breaker ability to protect the devices which it has been assigned to.

Below there is a brief analysis of the verification modalities to be followed in order to obtain the protection of the devices which are most commonly used in an installation.

Protection of the feeders

The cable shall be protected against overload and short-circuit.

As regards protection against overload, the following condition shall be verified $I_B \leq I_1 \leq I_z$

where:

I_B is the load current,

I_1 is the overload tripping threshold (function “L”) set on the protection release;

I_z is the continuous current carrying capacity of the cable.

As regards protection against short-circuit, the following condition shall be verified $K^2 S^2 \geq I^2 t$

where:

$K^2 S^2$ is the specific energy which can be withstand by the cable and which results to be a function of the cross section S and of a constant K , which is equal to 115 for PVC insulated cables and 143 for EPR insulated cables.

$I^2 t$ is the specific let-through energy of the circuit-breaker in correspondence with the maximum short-circuit current of the installation.

Maximum protected length

For the secondary circuit of type TN-S on the LV side, the Standard IEC 60364 gives some indications for an approximate calculation to evaluate the minimum short-circuit current at end of cable. This Standard assumes that the minimum fault current condition occurs in case of a phase-to-neutral fault at end of the conductor.

The established difference depends on whether the neutral conductor is distributed or not, and the calculation formulas are as follows:

TN-S neutral conductor not-distributed

$$I_{kmin} = \frac{0.8 \cdot V \cdot S_F}{1.5 \cdot \rho \cdot 2 \cdot L}$$

TN-S neutral conductor distributed

$$I_{kmin} = \frac{0.8 \cdot V_0 \cdot S_F}{1.5 \cdot \rho \cdot (1 + m) \cdot L}$$

where:

0.8 – 1.5 – 2	characteristic constants of the formula under consideration
V	phase-to-phase voltage of the system
V ₀	phase-to-neutral voltage of the system
S _F	cross section of the phase conductor
ρ	resistivity of the conductive material of the cable
m	ratio between the resistance of the neutral conductor and that of the phase conductor. In the quite common case in which phase and neutral conductors are made of the same material, “m” becomes the ratio between the phase and the neutral cross-sections
L	cable length in meters [m]
I _{kmin}	minimum short-circuit current at end of cable.

If, in the formulas above, the value I_{kmin} is replaced by the tripping threshold I_{3Max} inclusive of higher tolerance of the used circuit-breaker and the formula is solved by making the length explicit, the result obtained indicatively gives the value of the maximum cable length which results to be protected by the magnetic threshold setting on the protection device.

The formulas thus obtained are:

$$L_{Max} = \frac{0.8 \cdot V_0 \cdot S_F}{1.5 \cdot \rho \cdot (1 + m) \cdot I_{3Max}}$$

$$L_{Max} = \frac{0.8 \cdot V \cdot S_F}{1.5 \cdot \rho \cdot 2 \cdot I_{3Max}}$$

Protection against indirect contact

Protection against indirect contact consists in protecting human beings against the risks deriving from touching exposed conductive parts usually not live, but with volt-

age presence due to a failure of the main insulation.

Protection by automatic disconnection of the supply is required when, due to a fault, contact voltages can occur on the metallic frame for a time and value such as to be dangerous for human beings.

The measures to obtain protection against indirect contact for LV installations are prescribed by the Standard CEI 64-8, whereas for MV installations the reference Standard is CEI 11-1.

For a verification of protection in LV systems, the Standard gives some prescriptions which differ based on the various distribution systems and refer to the fault loop impedance, to the voltage, to the current which causes the trip of the protection device and to the time by which the device trips.

In MV systems, the problem of protection against indirect contact occurs whenever the user plant has its own transformation substation. In compliance with the Standard CEI 11-1, the ground current I_g can be calculated through the relationship

$$I_g = V \cdot (0.003 \cdot L1 + 0.2 \cdot L2)$$

where L1 represents the extension of the overhead line and L2 that of the cable.

The value of the current to earth is difficult to evaluate, therefore it has to be asked and assigned by the manufacturer.

The Standard gives the maximum value which the step voltage and the touch voltage can reach based on the fault elimination time.

Protection of generators

With reference to the typical representation of the short-circuit current of a generator, for a good protection of the rotary machine the protection device shall have the following characteristics:

- setting of the overload protection L equal or higher than the rated current of the generator;
- tripping of the short-circuit protection (instantaneous I or delayed S) in the very first instant of the short-circuit;
- protection related to the overcurrent withstand capability of the machine which, according to the Standard IEC 60034-1 is given by the point $1.5 \cdot I_{nG}$ for 30s where I_{nG} is the rated current of the generator.

Protection of transformers

A LV/LV transformer is now taken into consideration in order to analyze the characteristics which the protection devices must have when located upstream or downstream the transformer.

As regards the circuit-breaker upstream, it is necessary to make reference to the magnetizing curve of the machine; its curve shall have no intersection with the circuit-breaker tripping curve. The breaking capacity must be adequate to the short-circuit current of the network upstream the transformer.

The downstream circuit-breaker shall have a tripping characteristic such as to guarantee protection against

an extreme thermal overload capacity of the machine in case of short-circuit. The Standard IEC 60076-5 indicates as a limit to the thermal stresses due to a short-circuit (overload threshold) the short-circuit current value let-through by the transformer for 2s.

This condition shall be verified also by the upstream circuit-breaker in case of a short-circuit on the secondary side not affecting the downstream circuit-breaker. For this analysis the current referred to the primary side must be obviously considered, being this the current really seen by the upstream circuit-breaker.

Generally, the analysis of the behaviour of the downstream and upstream circuit-breakers for a fault on the secondary side shall be carried out on the basis of the real currents affecting the two apparatus; as a matter of fact, the short-circuit current due to a fault on the secondary side shall be related to the primary through the transformation ratio.

Motor co-ordination

Going into the details of the considerations related to the study of the motor co-ordination is quite complicated and it is not specific subject of this paper. Generally speaking, the circuit-breaker for motor protection is only of magnetic type; the magnetic threshold shall have such a value to allow the inrush current to be absorbed without unwanted trips and besides, in case of short-circuits on the motor, to protect the contactor (switching device) and the external thermal release (overload protection).

ABB offers some co-ordination tables (available on the website <http://www.abb.com/lowvoltage>) for various motor powers and for various start-up typologies related to the voltage and the short-circuit current of the plant.

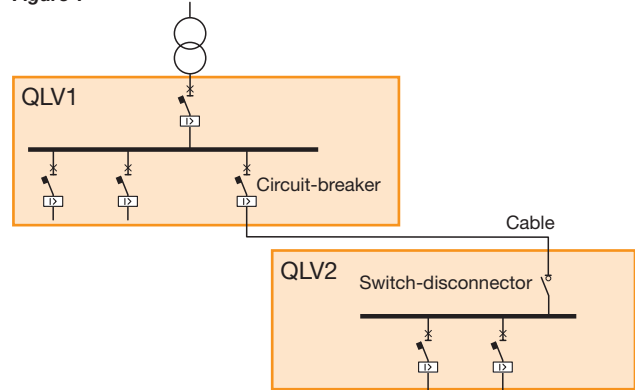
3.3 Co-ordination between circuit-breakers and switch-disconnectors

Disconnection must guarantee putting out of service of the whole installation or of part of it, by separating it safely from any power supply, thus guaranteeing safety for the human beings operating on it. Disconnection shall be carried out with devices which open all the poles in a single operation. As regards MV applications, the incoming line in the substation can be provided with a line switch-disconnector and an earth-connected switch-disconnector, which are interlocked one to the other; they are used, in case of maintenance operations, to put to earth automatically the upstream line when the line switch-disconnector is opened.

On the LV side, the switch-disconnector could be the incoming element into a secondary switchboard, as represented in Figure 1. The disconnector is a switching equipment, which in its open position guarantees a certain isolation distance between the contacts. In general, the switch-disconnector is suitable for opening or closing circuits where little currents - or however currents of

the order of the device rated current - flow, and it is not provided with a protection release.

Figure 1



Since the switch-disconnector is not provided with a device operating its opening, it is necessary that a protection device is present, for example a circuit-breaker to safeguard the integrity of the switch-disconnector in case of short-circuit. In case of short-circuit, this means that the electrical phenomena affecting the switch-disconnector and conditioned by the circuit-breaker behaviour must be withstand also by the switch-disconnector itself.

To this purpose, ABB puts some tables at disposal; from these tables, making reference to the type of circuit-breaker and of switch-disconnector respectively on the supply and on the load side, it is possible to find the maximum short-circuit current at which this combination results to be protected.

Tables 2 and 3 (extracted by the documentation ABB SACE "Co-ordination Tables") are shown below with an example of how to read it.

Moulded-case circuit-breaker and switch-disconnector derived by the moulded-case circuit-breakers:

Table 2

			Downstream	T1D	T3D	T4D	T5D	
			Icw [kA]	2	3.6	3.6	6	
Upstream	Version	Icu [kA]	Ith [A]	160	250	320	400	630
			Iu [A]					
T1	B	16	160	16	16	16	16	16
	C	25		25	25	25	25	25
	N	36		36	36	36	36	36
	N	36		36	36	36	36	36
T2	S	50	160	50	50	50	50	50
	H	70		70	70	70	70	70
	L	85		85	85	85	85	85

With reference to the highlighted combination between a circuit-breaker type T2S160 on the load side and a switch-disconnector type T1D160, the protection of the disconnector is possible up to a short-circuit value equal to 50kA 400Vac.

Moulded-case circuit-breaker and switch-disconnector OT and OETL

Table 3

		Downstream	OETL 200	OETL 250	OETL 315
		I _{cw} [kA]	8	8	8
Upstream	Release	I _{th} [A]	250	315	350
		I _u [A]	250	315	350
T5	TM	320	100*	100*	100*
		400	100*/***	100*	100*
		630			100***
	EL	320-630	100*/**	100*/**	100*/**

With reference to the highlighted combination between a circuit-breaker type T5..400 on the load side and a switch-disconnector type OETL200, the protection of the disconnector is possible up to a short-circuit value equal to 100kA 400Vac.

As regards the asterisks in the Table, the following notes are valid:

* Select the lower value between the I_{cu} of the circuit-breaker and the value shown

For example, if the circuit-breaker is version N with I_{cu}=36kA @ 400Vac, this means that the maximum short-circuit current of the installation shall be lower than 36kA (to use version "N") and the switch-disconnector shall be surely protected since the protection limit is 100 kA. If the circuit-breaker version is L, with I_{cu}=200kA @ 400Vac, this means that the maximum short-circuit current of the installation shall be 200kA and the switch-disconnector shall be protected since the protection limit is 100kA.

*** $I_1 = 0.7 \times I$

From this note, linked to the thermal protection of the switch-disconnector, it results that the maximum setting for the thermal protection of the circuit-breaker is $0.7 \times I_n$.

Analogous meaning has the note:

** Maximum setting of the overload threshold $PR_{2xx} = 1.28 \times I_{th} OT_{xx}/OETL_{xx}$

from which it can be understood why the maximum setting for the overload protection of the circuit-breaker shall not exceed 1.28 times the current carrying capacity of the switch-disconnector.

3.4 Co-ordination between automatic circuit-breakers and residual current devices (RCDs)

Residual current devices generally used in the terminal part of a LV installation guarantee effective protection against indirect contact, that is contact with metallic parts which should be normally not live, and under determined conditions also against direct contact, that is contact with parts normally live.

However, from a careful reading of the Standards, it results clear that the protection function of human beings against direct and indirect contacts is an auxiliary function which the circuit-breaker carries out, since the electrical installation must be designed and built so that the safety of human beings is guaranteed chiefly through an adequate earthing system.

Therefore, the metallic frameworks of the loads must be connected to an earthing system properly sized, so that dangerous contact voltages are avoided in every situation.

In an installation, besides the normal protection against overload and short-circuit, which are usually demanded to the thermomagnetic circuit-breaker, it is a good rule to provide also a residual current protection.

In a wide sense, protection in a plant can be carried out by two separate devices (thermomagnetic circuit-breaker and residual current device); in this case, the RCD, which is sensitive only to the earth fault current, shall be installed in series with a circuit-breaker which protects it against the thermal and dynamic stresses developing in the installation due to an overcurrent.

An alternative is represented by a single device as the thermomagnetic residual current circuit-breaker which unifies in a single device the protection functions, thus considerably reducing the possible risks deriving from an incorrect co-ordination between the two apparatus.

3.5 Example of study of a MV/LV network

Hereunder there is an example of how the analysis of a MV/LV installation can be carried out to evaluate the main electrical parameters of the network and to select the circuit-breakers for the protection and the proper handling of the installation, with reference to protection selectivity.

Description of the installation characteristics:

Distribution network:

rated voltage $V_{1n}=20\text{kV}$
short-circuit current $I_{kMV}=12.5\text{kA}$

Substation transformer with the following data :

primary rated voltage: $V_{1n}=20\text{kV}$
secondary rated voltage: $V_{2n}=400\text{V}$
rated power: $S_{nTR}=800\text{kVA}$
rated short-circuit voltage: $V_{k\%}=5\%$

An installation normally provides supply for different loads; to simplify and finalize the treatment of this subject, the following load typologies are now taken into consideration:

a passive load L with:

rated power $P_{nL}=300\text{kW}$
power factor $\cos\varphi = 0.8$

supplied by a cable C having the following characteristics:

formation $2\times(3\times240)\text{mm}^2$
current carrying capacity of the cable $I_z=590\text{A}$
length $L_c=15\text{m}$

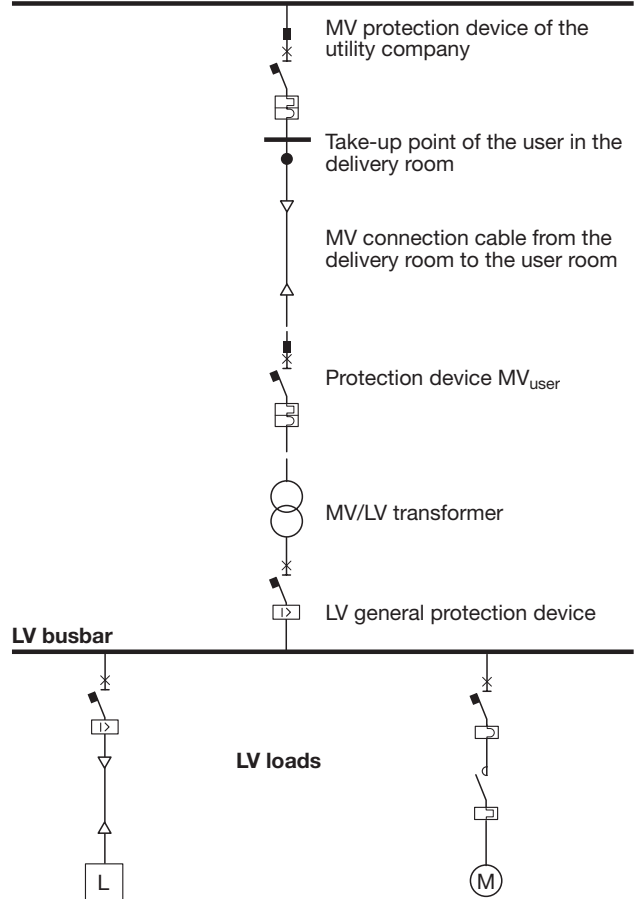
an active load M (three-phase asynchronous motor) with:

rated power $P_{nM}=90\text{kW}$
coefficient $\eta \times \cos\varphi = 0.8$
(efficiency per power factor)

The scheme of the installation analyzed is :

Figure 2

MV line of the utility company



In order to deal with the verification of the tripping characteristics of protections as best as possible, the electrical characteristics of the different components of the installation under study are analyzed hereunder.

Distribution network:

Starting from the power supply source, that is from the electrical network at 20kV owned by the utility company and having its own MV protection device usually characterized by independent time tripping curves with two steps, the following hypothetical but realistic values can be assumed for the protection of the utility company at 20kV:

Protections	Maximum current	
	51 (first threshold)	50 (second threshold)
Fault elimination time	< 0.5s	< 0.25s
Current setting values	< 72A	< 400A

Zero-sequence maximum current	
Protections	51N (first threshold)
Fault elimination time	< 0.12s
Current setting values	< 4A

Transformer:

The second element affecting the electrical parameters of the installation, above all on the LV side, is the 800kVA transformer, which has the following current values:

- primary rated current (20kV side):
$$I_{1n} = \frac{S_{nTR}}{\sqrt{3} \cdot V_{1n}} = \frac{800 \times 1000}{\sqrt{3} \times 20 \times 1000} = 23.1A$$

- secondary rated current (400V side):
$$I_{2n} = \frac{S_{nTR}}{\sqrt{3} \cdot V_{2n}} = \frac{800 \times 1000}{\sqrt{3} \times 400} = 1155A$$

By practical and quick formulas (for example by assuming the MV network on the load side with infinite short-circuit power), which give results acceptable as first approximation and which are useful to evaluate the intensity of the currents really present in the installation and the dimensioning of the protection devices, the short-circuit currents can be calculated:

- three-phase short-circuit current on the secondary side (400V side)

$$I_{2k3F} = \frac{S_{nTR}}{V_{k\%}} \times 100 \times \frac{1}{\sqrt{3} \times V_{2n}} = \frac{800 \times 1000}{5} \times 100 \times \frac{1}{\sqrt{3} \times 400} = 23kA$$

To this three-phase short-circuit current expressed as symmetric r.m.s. value, we associate also a short-circuit power factor $\cos\phi_k = 0.35$ and the relevant peak value equal to 43.6kA.

- three-phase short-circuit current related to the MV side because of a fault on the LV side

$$I_{1k3F} = \frac{S_{nTR}}{V_{k\%}} \times 100 \times \frac{1}{\sqrt{3} \times V_{1n}} = \frac{800 \times 1000}{5} \times 100 \times \frac{1}{\sqrt{3} \times 20 \times 1000} = 462A$$

or calculable by the relationship:
$$I_{1k3F} = \frac{I_{2k3F}}{V_{1n}} \cdot V_{2n} = \frac{23000}{20000} \cdot 400 = 460A$$

The functioning of the transformer can be represented through its magnetizing curve and through the maximum short-circuit withstand capacity considered from the thermal point of view.

The magnetizing curve of the transformer can be obtained through the formula:

$$i_{inrush} = \frac{k_i \cdot I_{1nTR}}{\sqrt{2}} \cdot e^{-\frac{t}{\tau_{inrush}}}, \text{ for further details see Annex A of this paper.}$$

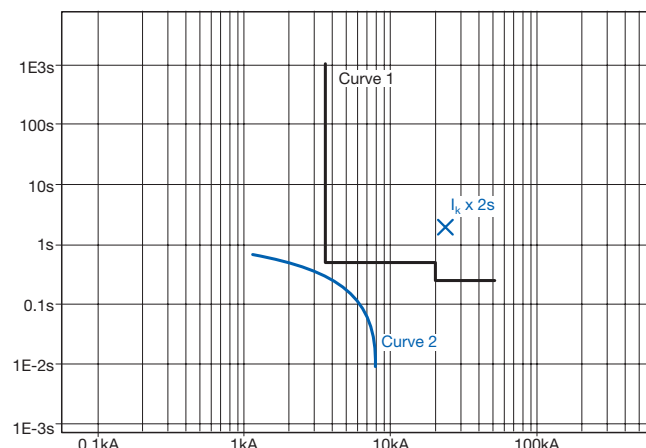
The short-circuit withstand capacity considered from the thermal point of view can be expressed as indicated in the Standard IEC 60076-5 as the capacity of the transformer to withstand for 2 seconds the short-circuit current of the transformer itself.

In Figure 3 there is a representation of the time/current diagram with the following curves:

Curve 1: tripping curve of the MV overcurrent protection;
Curve 2: characteristic curve of the electrical parameters of the transformer described above.

All the curves are represented at the reference voltage of 400V of the LV side; as a consequence the current values related to the voltage of 20kV of the MV side must be multiplied by the transformation ratio 20000V/400V.

Figure 3



Passive load L

- rated current of the load:

$$I_{nL} = \frac{P_{nL} \times 1000}{\sqrt{3} \times V_{2n} \times \cos\varphi} = \frac{300 \times 1000}{\sqrt{3} \times 400 \times 0.8} = 541A$$

Active load M

- rated current of the motor:

$$I_{nM} = \frac{P_{nM} \times 1000}{\sqrt{3} \times V_{2n} \times \eta \times \cos\varphi} = \frac{90 \times 1000}{\sqrt{3} \times 400 \times 0.8} = 160A$$

- short-circuit current of the motor:

$$I_{kM} = 4 \times I_{nM} = 4 \times 160 = 640A$$

Considering the size and the limited duration of this phenomenon, the short-circuit current calculated without motor contribution shall be used as short-circuit current value at the busbar.

The study of the co-ordination and of the selection of MV and LV protections under the competence of the customer, can start by analyzing the characteristic and the tripping values imposed by the utility company (curve 1). These information, as already said, are usually reported in the supply contract agreement and define the field of action for the setting the MV protection of the user towards the supply side.

Towards the load side, the limit for the protection MV_{user} is given by the waveform of the magnetizing current of the transformer (curve 2).

Considering a user installation having on the load side of the protection device MV_{user} a cable with a length such as the MV/LV transformation unit results to be located in a unique room, the MV protections which can be used could be constituted by a maximum current protection (51) and by a maximum positive-sequence current protection (51 N).

MV protection device of the user (MV_{user})

The overcurrent protection on the MV side of the user has usually two tripping thresholds:

- one with low currents and which can be identified with the overload protection, also indicated with $I>$
- the other one with high currents and which can be identified with the short-circuit protection, also indicated with $I>>$

The setting values of currents and times for each threshold shall be set, whenever possible, at a level lower than the protections of the utility company; it is also important not to stay "too low with the settings" so that there are no intersections with the magnetizing curve of the transformer, so that there is no trip when the transformer itself is put into service and so that the space for the positioning of the tripping curves of LV protections remains free.

Of course, this means that the protection MV_{user} shall be selective upstream with respect to the protection there-

shold of the utility company, and downstream with the LV general protection, guaranteeing also the protection functions of its own competence.

Generally, to the two thresholds previously identified for the protection MV_{user} the following protection functions can be assigned:

- protection against the transformer overload, not strictly necessary if already provided by the circuit-breaker on the LV side or by other dedicated devices, such as for example thermometric equipment which control the temperature inside the machine through thermal probes;
- protection against short-circuits on the secondary of the transformer on the supply side of the LV circuit-breaker;
- protection against short-circuits on the MV side pertaining to the user, with instantaneous trip;
- protection against overload for the cable constituting the connection between the take-up point from the delivery room and the protection device MV_{user} .

Trying to comply with the above described conditions, here is an indication of the values to be set for the protection device MV_{user} . The selected values can be the following ones and form the curve 3 represented in the diagram of Figure 4.

threshold with low currents $I>$

65A - 0.4s related to 20kV

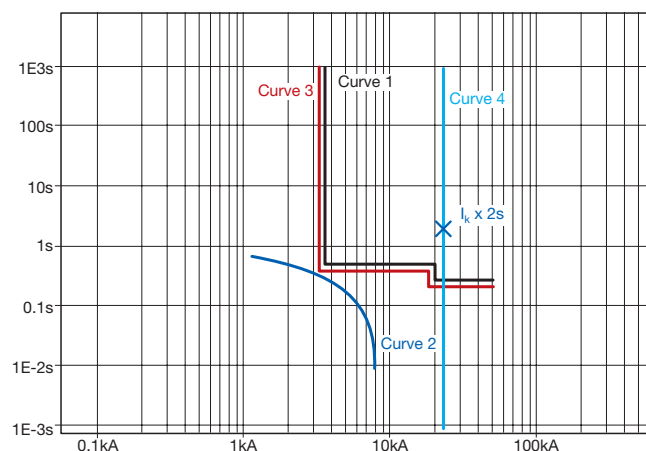
which corresponds with $65 \times 20000 / 400 = 3250A$

threshold with high currents $I>>$

360A - 0.2s related to 20kV

which corresponds with $360 \times 20000 / 400 = 18kA$

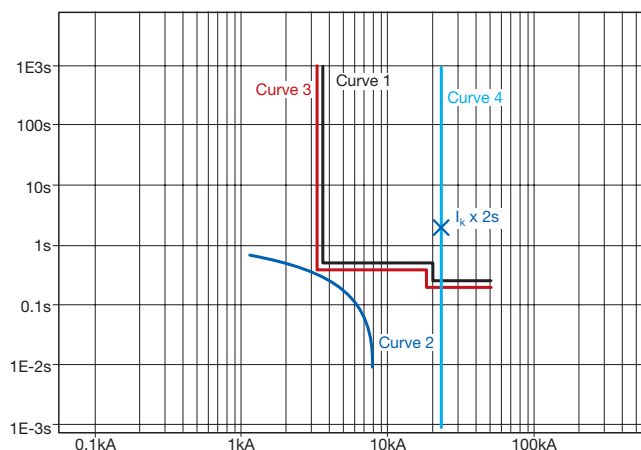
Figure 4



Putting into relation the curves of the protection devices and their relevant short-circuit currents, the diagram

of Figure 5 is obtained, where curve 4 represents the short-circuit current value, on the LV side, affecting the MV devices.

Figure 5



From the course of the time/current curves it results that:

- the tripping curves of the device of the utility company (curve 1) and of the user (curve 2), do not overlap in the whole current range and in particular in correspondence with the short-circuit current on the secondary winding side (curve 4); therefore, without considering the tripping tolerances typical of each device, it is possible to state that, in the given example, selectivity is guaranteed between the two devices. If there were no selectivity, the two MV circuit-breakers would open simultaneously, and the MV circuit-breaker of the utility company would restart service through its rapid reclosing, remaining closed because in the meantime the fault has been extinguished by the opening of the circuit-breaker MV_{user};
- both MV circuit-breakers do not intersect the magnetizing curve of the transformer.

Thanks to these considerations, the MV protection curves can be held to be set properly and it is possible then to proceed with selection and setting of the LV devices.

LV general protection device

With reference to the short-circuit current values previously defined ($I_{2k3F}=23\text{kA}$, $i_p=43.6\text{kA}$) and to the secondary rated current of the transformer ($I_{2n}=1155\text{A}$) the LV general circuit-breaker shall have:

- a breaking capacity “Icu” related to the voltage on the LV side, greater than the r.m.s. short-circuit current value on the LV busbar ($I_{cu}>I_{2k}$);

- a making capacity “Icm” higher than the peak value of the short-circuit current on the LV busbar ($I_{cm}>i_p$);
- a rated uninterrupted current “Iu”, suitable for the maximum current of the installation, coinciding with the rated current of the transformer secondary winding;
- a size which, through proper settings, guarantees selectivity with the MV protection device upstream and with the circuit-breakers provided for the loads downstream.

With reference to the electrical parameters thus calculated, the circuit-breaker to be used could be a moulded-case circuit-breaker Tmax series T7S1250 PR332-LSI In1250, with Icu=50kA at 400V and Icm=105kA.

Protection device for the passive load L

The selection of this device shall be made making reference to:

- short-circuit current value at the installation point; since the limitation imposed by the cable is negligible, the short-circuit value of the LV busbar is considered, disregarding the limitation of the cable. Therefore $I_{2k3F}=23\text{kA}$ and Icu shall be $> I_{2k3F}$;
- a rated uninterrupted current “Iu”, suitable for the load maximum current;
- a size which, through proper settings, allows cable protection to be obtained:
 - against overload $I_b \leq I \leq I_z$
 - against short-circuit $K^2 S^2 \geq I^2 t$

Further to these conditions, the apparatus chosen is a molded-case circuit-breaker Tmax series T5N630 PR221DS-LS/I In630.

Protection device for the active load L (motor)

The choice of the devices to start the motors up requires an accurate analysis of different factors, so ABB SACE put at disposal of the final user some motor coordination tables related to the different start up typologies.

In this case, by assuming a normal direct start up type 2, making reference to a table 400V 35kA, the apparatus to use are the following:

circuit-breaker: T3N250 MA 200 I3=2400A

contactor: A185

thermal release: TA200DU200

At this point, after the selection of the circuit-breakers for the loads, the bigger size circuit-breaker is taken into consideration as representative for the verification of selectivity towards the LV main circuit-breaker.

By using the co-ordination tables at 400V (see an extract relevant to the cases under consideration in Table 4), the

combination T7S1250 PR332-LSI In1250 - T5N 630 PR221DS-LS/I In630 allows total selectivity (indicated with "T") to be guaranteed up to the lowest breaking capacity between those of the circuit-breakers used, which is equal to 36 kA of T5N.

Table 4

		Upstream		T6		T7				
		Version				N,S,H,L		S,H,L		
		Release				TM	EL	EL		
		I _u [A]				800		1250	1600	
Downstream	T5	N, S, H, L, V	TM	400	I _n [A]	800	800	1000	1250	1600
					320	30	30	T	T	T
				400	30	30	T	T	T	
				630	500		30	T	T	T
					630			T	T	T
				EL	400	320	30	30	T	T
			400			30	30	T	T	T
			630		630			T	T	T
					630			T	T	T

Once the circuit-breaker sizes have been identified, a more detailed study shall be carried out, to define the proper settings and find a confirmation for the choices made.

The first step is to analyze the settings of the LV main circuit-breaker. The protection settings of these devices are conditioned by the following factors:

- course of the curve 2, previously determined for the circuit-breaker MV_{user};
- protection against transformer overload;
- search for selectivity towards the circuit-breaker downstream.

In particular, with reference to the point b), the following conditions shall be complied with:

- the trip in correspondence with the short-circuit current for a time lower than 2 seconds (thermal ability of the transformer to withstand short-circuit);
- the setting of the protection against overload shall be made taking into consideration the fact that product Standard IEC60947-2 prescribes for the circuit-breaker, as tripping characteristic under overload conditions, the following behaviour:
 - from the cold state, non-tripping in less than the conventional time (2 hours) shall be guaranteed for current values equal to 1.05 x I₁ (I₁ is the current set on the protection)
 - from the hot state, tripping in less than the conventional time (2 hours) shall be guaranteed for current values equal to 1.3 x I₁

- for current values between 1.05 and 1.3 times I₁, the product Standard does not prescribe a definite behaviour for the circuit-breaker, even if normally the circuit-breaker tripping occurs without the time being exactly known.

According to this behaviour, which is accepted by the product Standards, if the setting of the protection release has a value $I_1 = I_{2n}$ of the transformer, the situation shall be as follows:

- $I < 1.05 \times I_1$: non-tripping guaranteed, with the consequent 5% overload for the transformer;
- $1.05 \times I_1 < I < 1.3 \times I_1$: tripping time not defined, and consequently in the worst hypothesis, the transformer could be subject to an overload up to 30% for 2 hours (even if the circuit-breaker usually trips in much shorter times);
- $I > 1.3 \times I_1$: tripping of the protection guaranteed in compliance with the times of the characteristic curve.

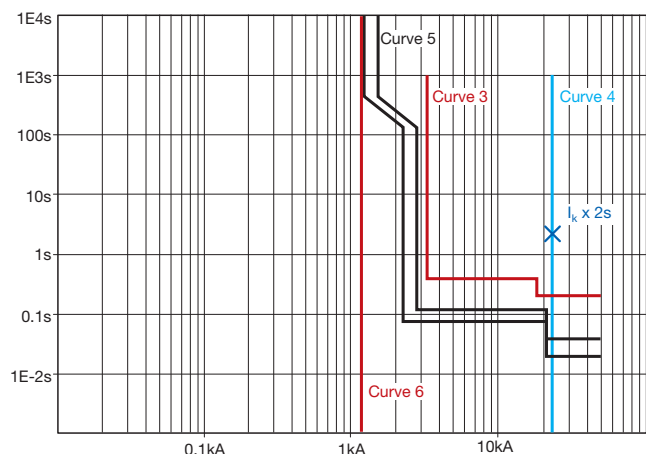
As regards item "c", in order to get the selectivity value previously determined, it is necessary that the function of protection against instantaneous short-circuit I3 is set in OFF.

Based on these considerations, Figure 6 reports the time/current diagram showing how curve 5 and curve 3 are selective.

In this diagram the settings assumed for the LV main circuit-breaker are the following:

- L (overload; protection I1-t1):
 $I_1 = 0.925 \times I_n = 1156.25A$ $t_1 = 18s$
S (delayed short-circuit; protection I2-t2):
 $I_2 = 2 \times I_n = 2500A$ $t_2 = 0.1s$
I (instantaneous short-circuit; protection I3): OFF

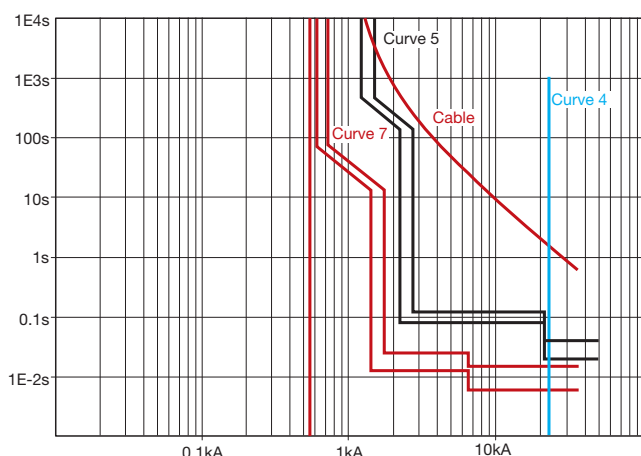
Figure 6



Once the tripping curve of the LV main device has been defined, the possible settings for the circuit-breaker of the passive load are analyzed. As already said, the protection of the relevant cable shall be verified and no intersections with the LV main device shall occur.

Based on these considerations, Figure 7 shows the time/current diagram from which it results that the curve of the cable lies above the curve 7 of the relevant circuit-breaker and that there are no intersection points between the curves of the two LV devices.

Figure 7



In this diagram, the settings assumed for the load circuit-breaker are:

- L (overload; protection I1-t1):
 $0.88 \times I_n = 554.4A$ Curva: 3s
- S (delayed short-circuit; protection I2-t2):
 not present
- I (instantaneous short-circuit; protection I3):
 $2.5 \times I_n = 1575A$

Protections against earth fault

Protections against earth faults shall be studied now. In case no earth fault protection is present in the transformer star point, the overcurrent protection on the MV side of the transformer meets also the protection requirements against phase-to-earth faults on the secondary upstream the LV main circuit-breaker.

For a typical transformer with connection Δ/Y_{ground} a phase-to-earth fault occurring on the LV side in an installation area immediately downstream the transformer causes on the MV primary side a current which results to be $\sqrt{3}$ times lower than the value calculated for the three-phase fault on the secondary side.

If the fault is assumed to be upstream the LV protection

device, the setting of the current threshold of the protection release should have an adequate value so that the protection MV_{user} trips due to such a fault.

In compliance with these considerations, in correspondence with the LV side three-phase short-circuit value previously calculated, it is possible to determine the fault current, related to the LV side, affecting the circuit-breaker on the MV side:

$$I_{2kF-PE} = \frac{I_{2k} \times 1000}{\sqrt{3}} = \frac{23 \times 1000}{\sqrt{3}} = 13.28kA$$

Since the first threshold of the protection device MV_{user} related to 400 V, has been set at 3250A, this means that the protection is able to trip due to a phase-to-earth fault on the LV side.

With reference to the MV side, through the transformation ratio it results

$$I_{1kF-PE} = \frac{I_{2kF-PE}}{k} = \frac{13280}{50} = 265.6A$$

which must be compared with the first protection threshold of the MV circuit-breaker set at 65A.

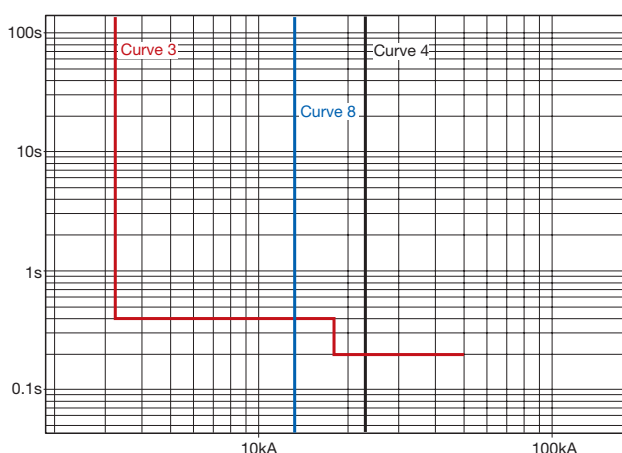
The diagram shown in Figure 8 represents:

curve 4, with the three-phase short-circuit current value on the LV side;

curve 8, with the current value related to the LV current affecting the MV circuit-breaker (value of curve 4, reduced by $\sqrt{3}$);

curve 3, relevant to the protection device MV_{user} related to the LV side, from which the tripping times can be derived.

Figure 8

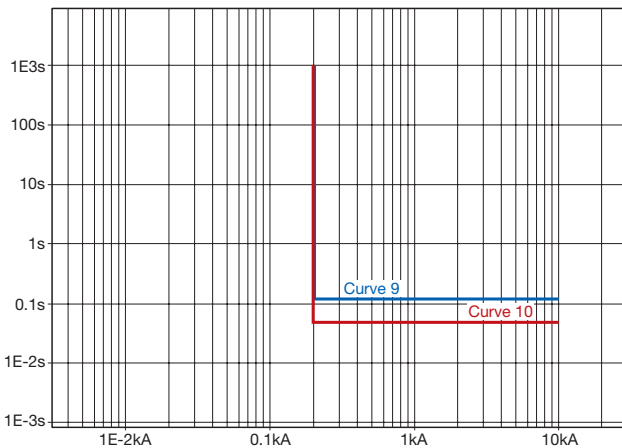


If the zero-sequence protection is present, its tripping threshold shall be lower than the threshold $51N$ defined by the utility company and declared in the electrical connection agreement.

This value has been fixed in $4A \cdot 0.12s$; therefore, the tripping characteristic of the device MV_{user} could be set at the following values: $4A \cdot 0.05s$.

Thus, tripping curves as those represented in the diagram of Figure 9 are obtained. This diagram refers to a voltage of 400V. In particular, curve 9 shows the threshold established by the utility company and curve 10 the positive-sequence tripping threshold.

Figure 9



Obviously, the behaviour of the two protections shall be studied with reference to the earth fault current given by the utility company. Such value varies significantly according to the fact whether the neutral is compensated or isolated and, however, it shall be higher than the protection threshold fixed by the utility company.

If the state of the neutral were changed, it would be necessary to revise the protection modalities currently in use on the lines to detect the single-phase earth fault.

The directional earth protection currently used processes the module and phase of the electrical parameters (zero-sequence voltage and current) which appear during the fault:

- zero-sequence voltage (voltage of the transformer star point with respect to earth), detected through the phase voltage transformer with open delta-connected secondary windings, at the ends of which the sum of the three phase voltages is measured;

- zero-sequence current of the line, detected through a toroidal current transformer measuring the sum of the three phase currents.

These protections, used in the network with isolated neutral, do not function in the network with the neutral earthed through an impedance. In these types of network, directional protections (67) with two separate setting thresholds must be used:

- the first one detects the fault when the network is managed with the neutral earthed through an impedance
- the second one detects the fault when the network is managed with the neutral isolated (situation occurring for short periods in the year, that is during faults or maintenance operations).

Annex A

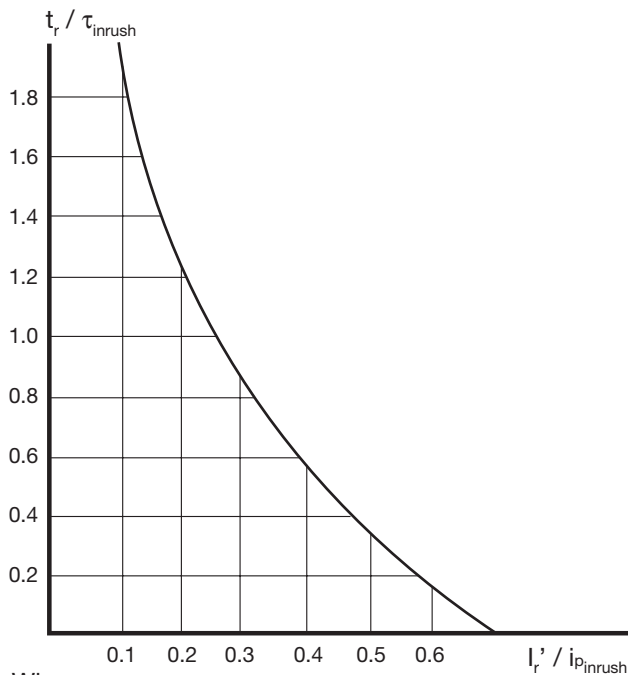
Calculation of the transformer inrush current

Here are some considerations about the evaluation of the magnetizing current of a transformer.
In the normal lay-out of a MV/LV installation, the phenomenon described below occurs at the put into service

of the transformer and involves the protection device on the MV side.

By using the data shown in Tables 1 and 2 below and with the help of the diagram of Figure 1, an approximate method is illustrated to define the minimum delay time necessary to avoid unwanted trips of the protection device upstream the transformer.

Figure 1



Where:

S_{nTR} is the rated power of the transformers;
 i_{p_inrush} is the inrush current of the transformers;
 I_{1nTR} primary rated current of the transformers;
 t_{inrush} time constant of the inrush current.

Table 1: Oil transformer

S_{nTR} [kVA]	$k_i = \frac{i_{p_inrush}}{I_{1nTR}}$	τ_{inrush} [s]
50	15	0.10
100	14	0.15
160	12	0.20
250	12	0.22
400	12	0.25
630	11	0.30
1000	10	0.35
1600	9	0.40
2000	8	0.45

Table 2: Cast resin transformer

S_{nTR} [kVA]	$k_i = \frac{i_{p_inrush}}{I_{1nTR}}$	τ_{inrush} [s]
200	10.5	0.15
250	10.5	0.18
315	10	0.2
400-500	10	0.25
630	10	0.26
800-1000	10	0.3
1250	10	0.35
1600	10	0.4
2000	9.5	0.4

The diagram of Figure 1 shows the curve which separates the range of the possible tripping (on the left of the curve) of a generic protection from that of guaranteed non-tripping (on the right of the curve).

t_r = setting of the delay time

I'_r = setting threshold (primary value)

Example:

Considering as example an oil transformer with rated power $S_{nTR}=630\text{kVA}$ and primary rated voltage $V_{1n}=10\text{kV}$, the calculation of the primary rated current gives a value of $I_{1nTR} = 36.4\text{A}$.

With reference to the rated power S_{nTR} of the transformer, the values corresponding to $k_i=11$ and $\tau_{inrush}=0.30\text{s}$ can be read in the table.

From the definition of k_i the maximum value of the inrush current can be obtained $i_{p_{inrush}} = 36.4 \cdot 11 = 400\text{A}$

By assuming a setting threshold for the primary protection $I_r' = 40\text{A}$ it results

$$\frac{I_r'}{i_{p_{inrush}}} = \frac{40}{400} = 0.1$$

corresponding on the curve to the value

$$\frac{t_r}{\tau_{inrush}} = 1.82$$

from which it results $t_r = 1.82 \cdot 0.30 = 0.546\text{s}$

representing the minimum delay for the MV protection to avoid unwanted trips.

A verification of the magnetizing current phenomenon must be carried out also for a LV/LV transformer and in this case the LV circuit-breaker is involved.

The foregoing considerations can be left out and through the following formula it is possible to trace the curve of the magnetizing current, making more direct the interpretation of the way the magnetizing curve and the protection curve of the LV circuit-breaker may interact:

$$i_{inrush} = \frac{k_i \cdot I_{1nTR}}{\sqrt{2}} \cdot e^{-\frac{t}{\tau_{inrush}}}$$

When not explicitly specified by the manufacturer, the

various quantities expressed in the formula can be associated with the values previously indicated in the Tables 1 and 2.

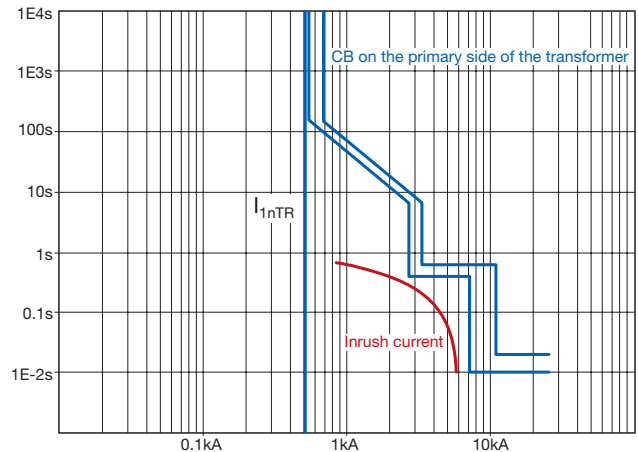
The various parameters have the same meaning.

A generic LV/LV transformer and the relevant LV circuit-breaker on its supply side are considered.

With reference to the parameters already given, which correspond to a transformer with a defined rated power, this formula allows the magnetizing curve shown in the diagram of Figure 2 to be represented.

The same diagram shows also the tripping curve of the circuit-breaker on the supply side of the transformer. It is highlighted how the setting of the magnetic protection (function "S" and "I") must not intersect the magnetizing curve, and how the protection function "L" is set with reference to the rated current of the transformer primary.

Figure 2



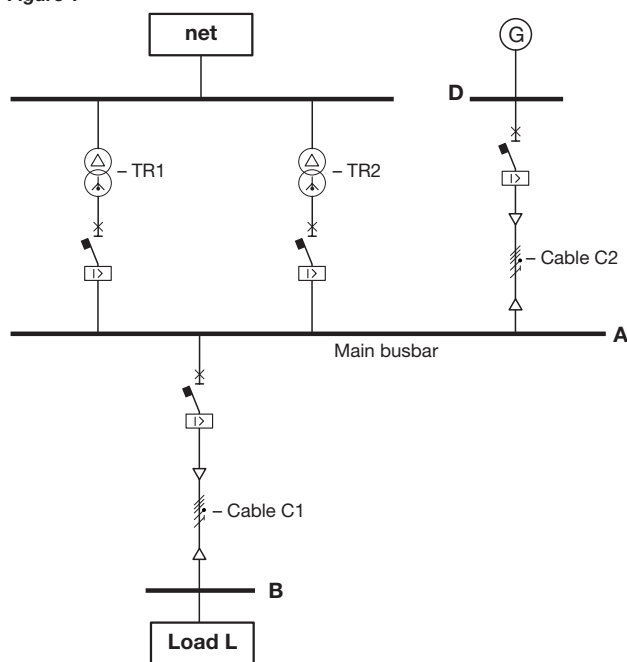
Annex B

Example of calculation of the short-circuit current

The study of the short-circuit currents is one of the classic problems plant engineers have to face; knowledge of the values of such currents is fundamental for the proper dimensioning of lines and transformers, but above all of protection devices.

If an accurate analysis which takes into account the electromagnetic and electromechanical transients is not the aim, the study of the short-circuit currents is quite easy from a conceptual point of view, since it is based on a few concepts, which however have to be understood in depth and correctly used. But this study may be more complex from a computational point of view, in particular when the network has remarkable dimensions or when meshed networks and asymmetric faults are dealt with. Here is an example of short-circuit current calculation in an electric network by using first an exact method based on the theory of symmetrical components, and then an approximate method defined as "power method".

Figure 1



Plant data

Hereunder the electrical data of the objects in the network are defined:

Supply network (net)

$V_{1n} = 20 \text{ kV}$	rated voltage
$f = 50 \text{ Hz}$	rated frequency
$S_k = 750 \text{ MVA}$	short-circuit power of the supply network
$\cos\phi_k = 0.2$	power factor under short-circuit conditions

Transformers TR1-TR2

$V_{1n} = 20 \text{ kV}$	primary rated voltage
$V_{2n} = 400 \text{ V}$	secondary rated voltage
$S_n = 1600 \text{ kVA}$	rated power
$v_{k\%} = 6 \%$	voltage drop in percent under short-circuit conditions
$p_{k\%} = 1 \%$	rated losses in percent

Generator G

$V_{2n} = 400 \text{ V}$	rated voltage
$S_n = 1250 \text{ kVA}$	rated apparent power
$\cos\phi_n$	rated power factor
$x''_{d\%} = 14 \%$	subtransient reactance in percent, direct axis
$x''_{q\%} = 20 \%$	subtransient reactance in percent, quadrature axis
$x'_{d\%} = 50 \%$	synchronous transient reactance in percent
$x_{d\%} = 500 \%$	synchronous reactance in percentage
$x_{2\%} = 17 \%$	negative-sequence short-circuit reactance in percent
$x_{0\%} = 9 \%$	zero-sequence reactance in percent
$T''_d = 40 \text{ ms}$	subtransient time constant
$T'_d = 600 \text{ ms}$	transient time constant
$T_a = 60 \text{ ms}$	armature time constant (that is of the unidirectional component)

Cable C1

Length $L = 50 \text{ m}$	
Formation: $3 \times (2 \times 185) + (2 \times 95) + G185$	
$R_{F1} = 2.477 \text{ m}\Omega$	phase resistance
$X_{F1} = 1.850 \text{ m}\Omega$	phase reactance
$R_{n1} = 4.825 \text{ m}\Omega$	neutral resistance
$X_{n1} = 1.875 \text{ m}\Omega$	neutral reactance
$R_{PE1} = 4.656 \text{ m}\Omega$	PE resistance
$X_{PE1} = 1.850 \text{ m}\Omega$	PE reactance

Cable C2

Length $L = 15 \text{ m}$	
Formation: $3 \times (2 \times 500) + (2 \times 300) + G500$	
$R_{F2} = 0.2745 \text{ m}\Omega$	phase resistance
$X_{F2} = 1.162 \text{ m}\Omega$	phase reactance
$R_{n2} = 0.451 \text{ m}\Omega$	neutral resistance
$X_{n2} = 1.177 \text{ m}\Omega$	neutral reactance
$R_{PE2} = 0.517 \text{ m}\Omega$	PE resistance
$X_{PE2} = 1.162 \text{ m}\Omega$	PE reactance

B1 Method of symmetrical components

This method is based on the principle that any set of three vectors may be resolved into three sets of vectors:

- a balanced positive sequence set formed by three vectors of equal magnitude shifted by 120° and having the same phase sequence as the original system;
- a balanced inverse sequence set formed by three vectors of equal magnitude shifted by 120° and having inverse phase sequence to that of the original system;
- a zero sequence set formed by three vectors of equal magnitude in phase.

Based on this principle, a generic asymmetric and unbalanced three-phase system can be reduced to the separate study of three single-phase equivalent circuits which correspond respectively to the positive, negative and zero-sequence.

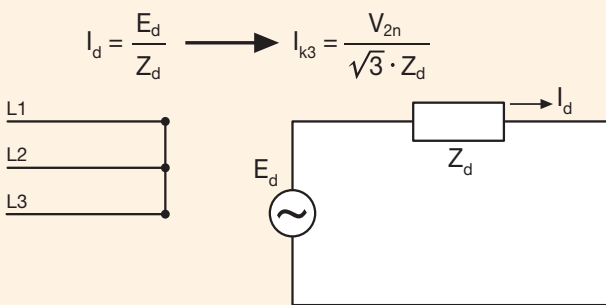
The sequence impedances can be found by replacing the

network components with the equivalent circuits for that sequence. As regards positive and negative sequences, the equivalent circuits do not differ when rotary machines are not present in the installation, whereas when there are rotary machines (asynchronous motors and synchronous generators) the equivalent impedances – positive and negative sequence – are considerably different. The impedance of the zero-sequence is also considerably different from the previous ones and depends on the state of the neutral.

Without going into the details of a theoretical treatment, we report below how the positive, negative and zero-sequence circuits represent the three-phase fault, the two-phase fault and the line-to-earth fault and the relevant formulas for the calculation of the fault current.

This schematization can be useful to fully understand the treatment.

Three-phase fault

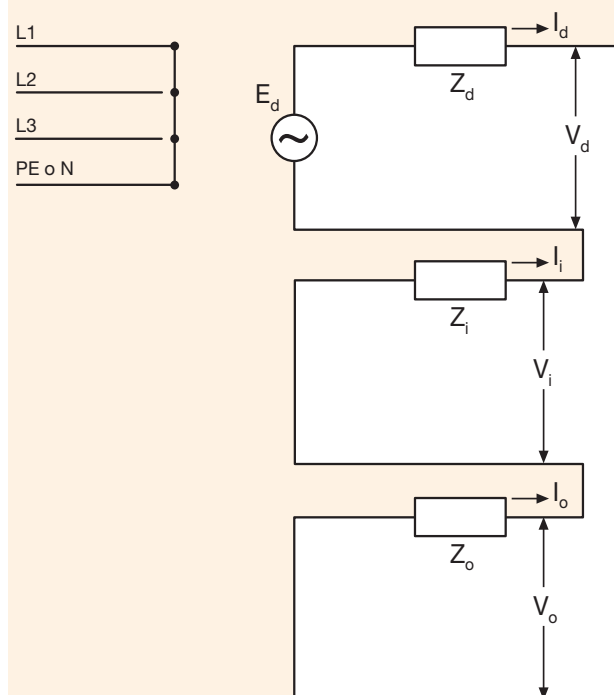


Line-to-earth fault

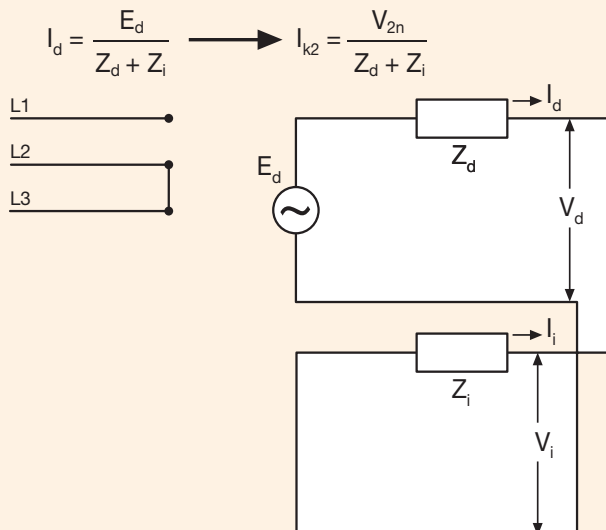
$$I_d = \frac{E_d}{(Z_d + Z_i + Z_o)} \longrightarrow I_{k1(F-PE)} = \frac{\sqrt{3} \cdot V_{2n}}{Z_d + Z_i + Z_{o(F-PE)}}$$

Line-to-neutral fault

$$I_d = \frac{E_d}{(Z_d + Z_i + Z_o)} \longrightarrow I_{k1(F-N)} = \frac{\sqrt{3} \cdot V_{2n}}{Z_d + Z_i + Z_{o(F-N)}}$$



Two-phase fault



The installation typology represented by the single line diagram of Figure 1 may be significant of a generic industrial plant, where a unique overall outgoing feeder has been considered for simplification. Only the passive load has been taken into account, by considering also as negligible the contribution of possible motors to the short-circuit current (complying with the condition: $\sum I_{nM} \leq I_k/100$ prescribed by the Standard IEC 60909, where I_{nM} is the rated current of the various motors and I_k is the initial symmetrical short-circuit current on the busbar without motor contribution).

The values of the impedances to be used in the sequence networks for the calculation of the fault currents can be derived from the data above. The subscripts have the following meaning:

- d positive sequence component;
- i negative sequence component;
- o zero-sequence component.

Supply network

The parameters of positive and negative sequence of the network impedance related to 400 V are:

$$\begin{aligned} Z_{dnet} = Z_{inet} &= \frac{V_{2n}^2}{S_k} = 2.133 \cdot 10^{-4} \Omega \\ R_{dnet} = R_{inet} &= Z_{dnet} \cdot \cos \phi_k = 4.266 \cdot 10^{-5} \Omega \\ X_{dnet} = X_{inet} &= Z_{dnet} \cdot \sin \phi_k = 2.090 \cdot 10^{-4} \Omega \end{aligned}$$

The zero-sequence impedance of the supply is not considered, since the delta windings of the transformers block the zero-sequence component.

Transformers TR1-TR2

A classic type delta/star grounded transformer ($\Delta/Y_{\text{grounded}}$), which allows to have a distribution system LV side of TN-S type, is taken into consideration.

The impedances of the various sequences (o-d-i) take the same value:

$$\begin{aligned} Z_{dTR} = Z_{iTR} = Z_{oTR} &= \frac{v_{k\%}}{100} \cdot \frac{V_{2n}^2}{S_n} = 0.006 \Omega \\ R_{TR} &= \frac{p_{k\%}}{100} \cdot \frac{V_{2n}^2}{S_n} = 0.001 \Omega \\ X_{TR} &= \sqrt{Z_{dTR}^2 - R_{dTR}^2} = 5.916 \cdot 10^{-3} \Omega \end{aligned}$$

Generator G

In this example, only the subtransient reactance value determining the greatest short-circuit current value for the generator is considered.

Real part of the expression of the impedances of sequence o-d-i:

$$R_G = \frac{X_d''}{2 \cdot \pi \cdot f \cdot T_a} = 9.507 \cdot 10^{-4} \Omega$$

Imaginary part of the expression of the positive sequence impedance :

$$X_d'' = \frac{x_d''\%}{100} \cdot \frac{V_{2n}^2}{S_n} = 0.018 \Omega$$

Imaginary part of the expression of the negative sequence impedance:

$$X_2 = \frac{x_2\%}{100} \cdot \frac{V_{2n}^2}{S_n} = 0.022 \Omega$$

X_2 is a parameter of the machine among the data given by the manufacturer.

As an alternative, the imaginary part of the negative sequence impedance could have been calculated as the average value between the subtransient positive sequence reactance and that in quadrature:

$$X_i = \frac{X_d'' + X_q''}{2}$$

Imaginary part of the expression of the zero-sequence impedance :

$$X_o = \frac{x_o\%}{100} \cdot \frac{V_{2n}^2}{S_n} = 0.0115 \Omega$$

Therefore:

$$Z_{dG} = R_G + i \cdot X_d'' \quad Z_{iG} = R_G + i \cdot X_2 \quad Z_{oG} = R_G + i \cdot X_o$$

Cables C1 - C2

$$Z_{dC..} = Z_{iC..} = R_{F..} + i \cdot X_F$$

$$Z_{o(F-N)C..} = (R_{F..} + 3 \cdot R_{N..}) + i \cdot (X_{F..} + 3 \cdot X_{N..})$$

zero-sequence impedance due to line-to-neutral fault

$$Z_{o(F-PE)C..} = (R_{F..} + 3 \cdot R_{PE..}) + i \cdot (X_{F..} + 3 \cdot X_{PE..})$$

zero-sequence impedance due to line-to-earth fault

Having defined all the sequence impedances of the different plant components, an analysis of the various fault situations can be carried out.

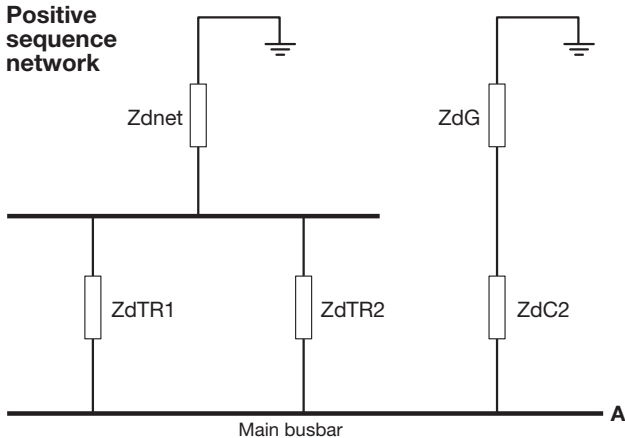
Making reference to the network schematization of Figure 1, the three points A-B-D are highlighted where the fault is assumed and where the current values for the different fault typologies are calculated.

Still with reference to the network represented in Figure 1, the sequence networks with impedances in series or in parallel are drawn according to the way they are seen by an imaginary observer located at the fault point and looking at the supply source.

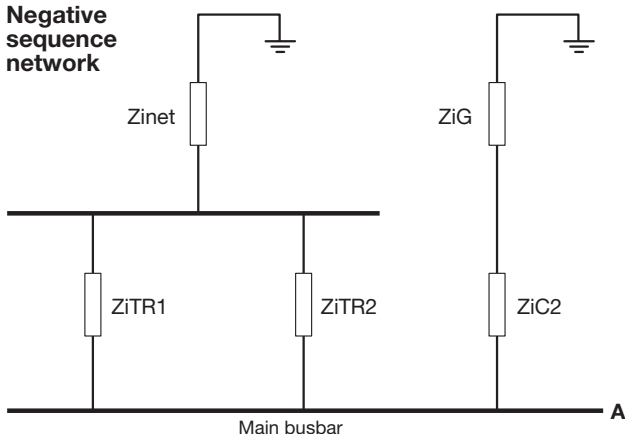
Fault in A

Based on the above considerations, the following sequence networks can be drawn for a fault at point A.

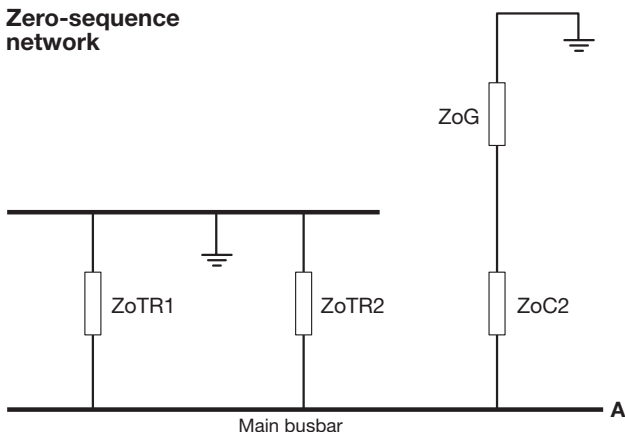
Positive sequence network



Negative sequence network



Zero-sequence network



Once identified the three sequence networks, the calculation of the short-circuit currents for the different fault typologies can be carried out:

Three-phase fault

Since the three-phase fault is a symmetrical fault, only the equivalent impedance of the positive sequence network shall be considered, complying also with what expressed by the formula for the calculation of currents.

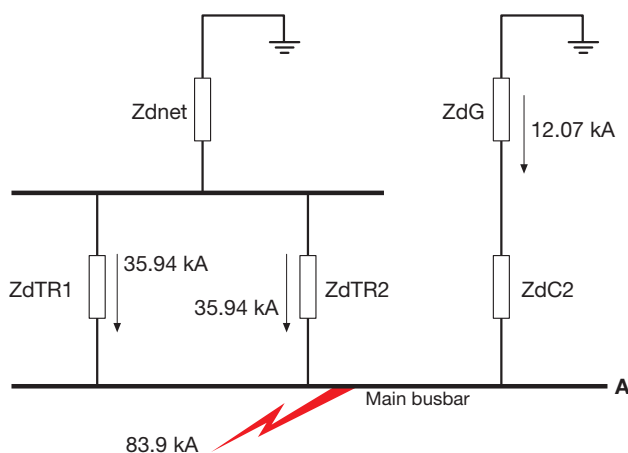
Therefore the equivalent impedance which is obtained by the reduction of the positive sequence network is:

$$Z_{dEq,A} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet}) \parallel (Z_{dG} + Z_{dC2}) = 4.237 \cdot 10^{-4} + i \cdot 0.0027 \Omega$$

["||" means "in parallel"] and the three-phase fault current value is expressed by the following formula:

$$I_{k3A} = \frac{V_{2n}}{\sqrt{3} \cdot Z_{dEq,A}} = 83.9 \cdot 10^{-3} \angle -81.15^\circ \text{ A}$$

By using the current divider rule, the contributions of the single electrical machines (generator and transformer) to the short-circuit current on the main busbar can be determined. In particular, the contributions are subdivided as follows:



Two-phase fault

In this case the fault affects only two of the three phases; as a consequence it is necessary to evaluate the equivalent impedance not only of the positive sequence network but also that of the negative sequence network seen from the fault point A, as shown in the fault current formula.

The equivalent positive sequence impedance is:

$$Z_{dEq,A} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet}) \parallel (Z_{dG} + Z_{dC2}) = 4.237 \cdot 10^{-4} + i \cdot 0.0027 \Omega$$

The equivalent negative sequence impedance is:

$$Z_{IEq,A} = ((Z_{iTR1} \parallel Z_{iTR2}) + Z_{inet}) \parallel (Z_{iG} + Z_{iC2}) = 4.367 \cdot 10^{-4} + i \cdot 0.0028 \Omega$$

The two-phase fault current value is therefore equal to:

$$I_{k2A} = \frac{V_{2n}}{Z_{dEq,A} + Z_{IEq,A}} = 71.77 \cdot 10^{-3} \angle -81.12^\circ \text{ A}$$

Single-phase fault

As regards the single-phase fault a distinction must be made between:

- single-phase fault to earth, then return through the protection conductor, being a distribution system of TN-S type
- line-to-neutral fault, then return through the neutral conductor.

As expressed in the formulas for the calculation of the fault current, it is necessary to take into consideration the contribution of the three sequence circuits.

To this purpose, it should be noted how the zero-sequence network is topologically different from the other sequence networks, since it is strongly influenced by the typology of the transformer windings.

Besides, the values of the zero-sequence impedances of the cables depend on the type of single-phase fault (F-N or F-PE).

The equivalent positive sequence impedance is:

$$Z_{dEq,A} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet}) \parallel (Z_{dG} + Z_{dC2}) = 4.237 \cdot 10^{-4} + i \cdot 0.0027 \Omega$$

The equivalent negative sequence impedance is:

$$Z_{IEq,A} = ((Z_{ITR1} \parallel Z_{ITR2}) + Z_{inet}) \parallel (Z_{IG} + Z_{IC2}) = 4.367 \cdot 10^{-4} + i \cdot 0.0028 \Omega$$

The equivalent zero-sequence impedance line-to-neutral is:

$$Z_{o(F-N)Eq,A} = ((Z_{oTR1} \parallel Z_{oTR2}) \parallel (Z_{oG} + Z_{o(F-N)C2})) = 4.189 \cdot 10^{-4} + i \cdot 0.0025 \Omega$$

The equivalent zero-sequence impedance line-to-earth is:

$$Z_{o(F-PE)Eq,A} = ((Z_{oTR1} \parallel Z_{oTR2}) \parallel (Z_{oG} + Z_{o(F-PE)C2})) = 4.237 \cdot 10^{-4} + i \cdot 0.0025 \Omega$$

The value of the fault current line-to-neutral instead is equal to:

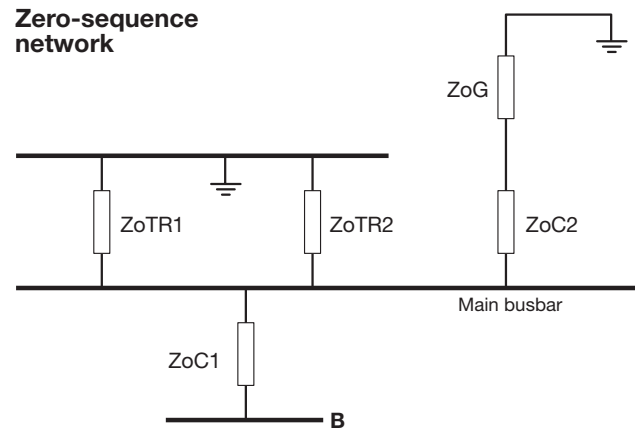
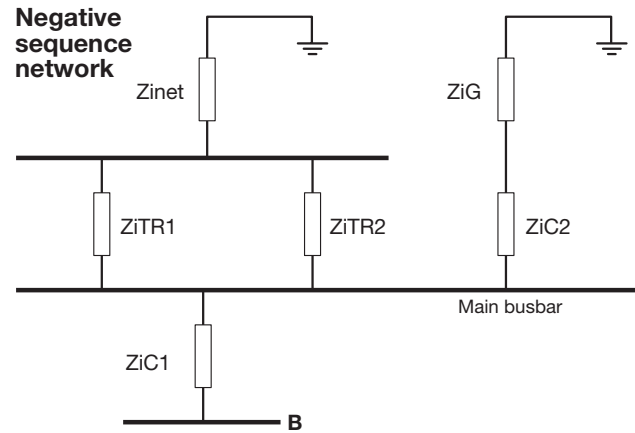
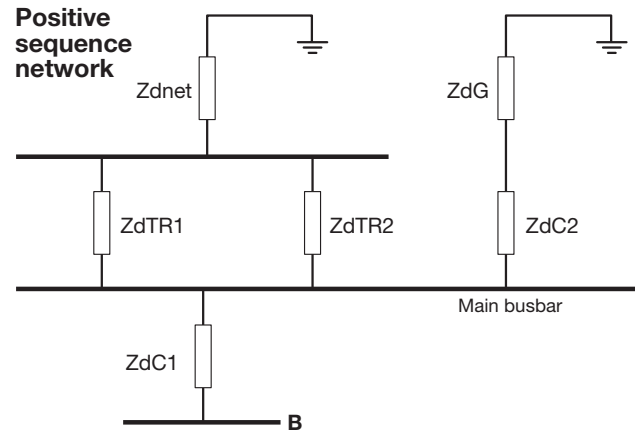
$$I_{k1(F-N)A} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq,A} + Z_{IEq,A} + Z_{o(F-N)Eq,A}} = 85.43 \cdot 10^{-3} \angle -80.92^\circ \text{ A}$$

The value of the fault current line-to-earth is equal to:

$$I_{k1(F-PE)A} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq,A} + Z_{IEq,A} + Z_{o(F-PE)Eq,A}} = 85.43 \cdot 10^{-3} \angle -80.89^\circ \text{ A}$$

Fault in B

Complying with what described for the fault at point A, the three sequence networks are drawn now taking into consideration the impedances as seen from point B. As it results evident in this new case, also the cable C1 is to be considered in the sequence circuits.



Through a process and considerations analogous to the above case, the equivalent impedances are obtained and calculation of the short-circuit currents for the different fault typologies can be carried out.

Three-phase fault

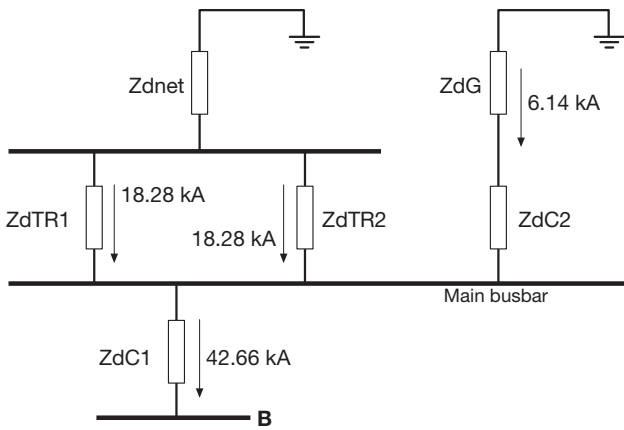
The equivalent positive sequence impedance deriving from the reduction of the relevant sequence network is:

$$Z_{dEq,B} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet}) \parallel (Z_{dG} + Z_{dC2}) + Z_{dC1} = 0.003 + i \cdot 0.0046 \Omega$$

Then the three-phase fault current value is equal to:

$$I_{k3B} = \frac{V_{2n}}{\sqrt{3} \cdot Z_{dEq,B}} = 42.66 \cdot 10^3 \angle -57.59^\circ \text{ A}$$

The contributions are subdivided as follows:



Two-phase fault

The equivalent positive sequence impedance is:

$$Z_{dEq,B} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet}) \parallel (Z_{dG} + Z_{dC2}) + Z_{dC1} = 0.003 + i \cdot 0.0046 \Omega$$

The equivalent negative sequence impedance is:

$$Z_{IEq,B} = ((Z_{ITR1} \parallel Z_{ITR2}) + Z_{inet}) \parallel (Z_{IG} + Z_{IC2}) + Z_{IC1} = 0.003 + i \cdot 0.0046 \Omega$$

Then the two-phase fault current value is equal to:

$$I_{k2B} = \frac{V_{2n}}{Z_{dEq,B} + Z_{IEq,B}} = 36.73 \cdot 10^3 \angle -57.72^\circ \text{ A}$$

Single-phase fault

The equivalent positive sequence impedance is :

$$Z_{dEq,B} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet}) \parallel (Z_{dG} + Z_{dC2}) + Z_{dC1} = 0.003 + i \cdot 0.0046 \Omega$$

The equivalent negative sequence impedance is:

$$Z_{IEq,B} = ((Z_{ITR1} \parallel Z_{ITR2}) + Z_{inet}) \parallel (Z_{IG} + Z_{IC2}) + Z_{IC1} = 0.003 + i \cdot 0.0046 \Omega$$

The equivalent zero-sequence impedance line-to-neutral is:

$$Z_{o(F-N)Eq,B} = ((Z_{oTR1} \parallel Z_{oTR2}) \parallel (Z_{oG} + Z_{o(F-N)C2})) + Z_{o(F-N)C1} = 0.017 + i \cdot 0.010 \Omega$$

The equivalent zero-sequence impedance line-to-earth is:

$$Z_{o(F-PE)Eq,B} = ((Z_{oTR1} \parallel Z_{oTR2}) \parallel (Z_{oG} + Z_{o(F-PE)C2})) + Z_{o(F-PE)C1} = 0.017 + i \cdot 0.010 \Omega$$

The fault current value line-to-neutral is then equal to:

$$I_{k1(F-N)B} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq,B} + Z_{IEq,B} + Z_{o(F-N)Eq,B}} = 23.02 \cdot 10^3 \angle -39.60^\circ \text{ A}$$

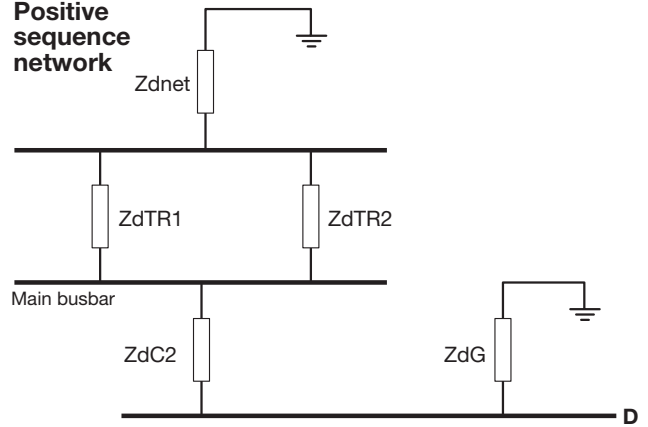
whereas the fault current value line-to-earth is equal to:

$$I_{k1(F-PE)B} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq,B} + Z_{IEq,B} + Z_{o(F-PE)Eq,B}} = 23.35 \cdot 10^3 \angle -40.09^\circ \text{ A}$$

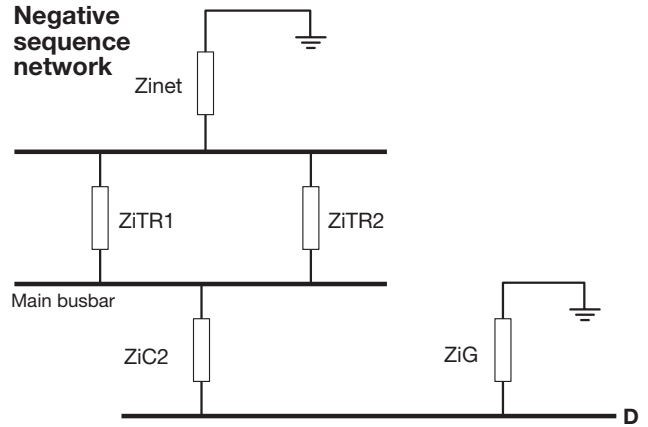
Fault in D

Assuming a fault in D, we take into consideration the case when the fault occurs immediately on the load side of the transformer. In accordance with what described in the cases above, the three sequence networks are drawn considering the impedances as seen from point D.

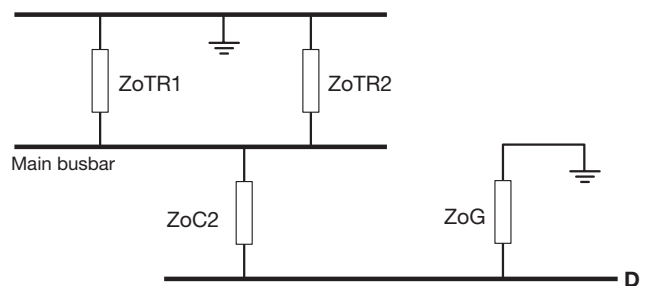
Positive sequence network



Negative sequence network



Zero-sequence network



Through a process and considerations analogous to the above ones, the equivalent impedances are obtained and calculation of the short-circuit currents for the different fault typologies can be carried out.

Three-phase fault

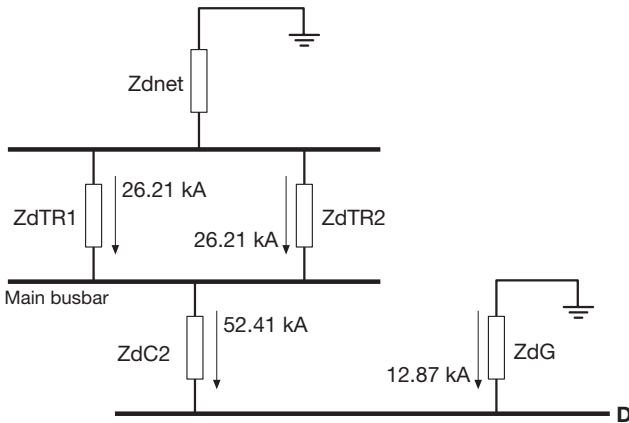
The equivalent positive sequence impedance is:

$$Z_{dEq,B} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet} + Z_{dC2}) \parallel (Z_{dG}) = 5.653 \cdot 10^{-4} + i \cdot 0.0035 \Omega$$

Then the three-phase fault current value is:

$$I_{k3D} = \frac{V_{2n}}{\sqrt{3} \cdot Z_{dEq,D}} = 65.19 \cdot 10^3 \angle -80.82^\circ \text{ A}$$

The contributions are subdivided as follows:



Two-phase fault

The equivalent positive sequence impedance is:

$$Z_{dEq,D} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet} + Z_{dC2}) \parallel (Z_{dG}) = 5.653 \cdot 10^{-4} + i \cdot 0.0035 \Omega$$

The equivalent negative sequence impedance is:

$$Z_{IEq,D} = ((Z_{ITR1} \parallel Z_{ITR2}) + Z_{inet} + Z_{IC2}) \parallel (Z_{IG}) = 5.94 \cdot 10^{-4} + i \cdot 0.0036 \Omega$$

The two-phase fault current value is therefore equal to:

$$I_{k2D} = \frac{V_{2n}}{Z_{dEq,D} + Z_{IEq,D}} = 55.46 \cdot 10^3 \angle -80.75^\circ \text{ A}$$

Single-phase fault

The equivalent positive sequence impedance is:

$$Z_{dEq,D} = ((Z_{dTR1} \parallel Z_{dTR2}) + Z_{dnet} + Z_{dC2}) \parallel (Z_{dG}) = 5.653 \cdot 10^{-4} + i \cdot 0.0035 \Omega$$

The equivalent negative sequence impedance is:

$$Z_{IEq,D} = ((Z_{ITR1} \parallel Z_{ITR2}) + Z_{inet} + Z_{IC2}) \parallel (Z_{IG}) = 5.94 \cdot 10^{-4} + i \cdot 0.0036 \Omega$$

The equivalent zero-sequence impedance line-to-neutral is:

$$Z_{o(F-N)Eq,D} = ((Z_{oTR1} \parallel Z_{oTR2}) + Z_{o(F-N)C2}) \parallel (Z_{oG}) = 9.127 \cdot 10^{-4} + i \cdot 0.0046 \Omega$$

The equivalent zero-sequence impedance line-to-earth is:

$$Z_{o(F-PE)Eq,D} = ((Z_{oTR1} \parallel Z_{oTR2}) + Z_{o(F-PE)C2}) \parallel (Z_{oG}) = 9.85 \cdot 10^{-4} + i \cdot 0.0046 \Omega$$

The fault current value line-to-neutral is therefore:

$$I_{k1(F-N)D} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq,D} + Z_{IEq,D} + Z_{o(F-N)Eq,D}} = 58.03 \cdot 10^3 \angle -80.01^\circ \text{ A}$$

whereas, the fault current value line-to-earth is equal to:

$$I_{k1(F-PE)D} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq,D} + Z_{IEq,D} + Z_{o(F-PE)Eq,D}} = 57.99 \cdot 10^3 \angle -79.66^\circ \text{ A}$$

B2 Power method

This method allows a quick but approximate evaluation of the three-phase short-circuit current in a network. It is necessary to calculate the power short-circuits of the various elements constituting the network (transformers – generators – cables), before determining the total short-circuit power at the point where the fault current has to be evaluated.

Power fluxes due to elements operating in parallel can be reduced by applying the formula of the resistances in series, whereas power fluxes due to elements working in series can be reduced by applying the formula of the resistances in parallel.

Here is an example of calculation applied to the network previously examined.

It can be observed how, for the same typology of fault (three-phase short-circuit at points A – B – D), this “approximate” method gives results quite similar to those obtained by applying the method of the symmetrical components.

Making reference to the plant data previously reported, it is possible now to proceed with the calculation of the short-circuit powers of the different elements of the installation:

Supply network

$S_{knet} = 750 \text{ MVA}$ is a plant datum

Transformer TR1-TR2

$$S_{kTR1} = \frac{S_{nTR1}}{v_{k\%}} \cdot 100 \quad S_{kTR1} = 26.67 \text{ MVA}$$

$$S_{kTR2} = \frac{S_{nTR2}}{v_{k\%}} \cdot 100 \quad S_{kTR2} = 26.67 \text{ MVA}$$

Generator G

$$S_{kG} = \frac{S_{nG}}{x_d''\%} \cdot 100 \quad S_{kG} = 8.93 \text{ MVA}$$

Cables C1-C2

$$S_{kC1} = \frac{V_{2n}^2}{Z_{FC1}} \quad S_{kC1} = 51.75 \text{ MVA}$$

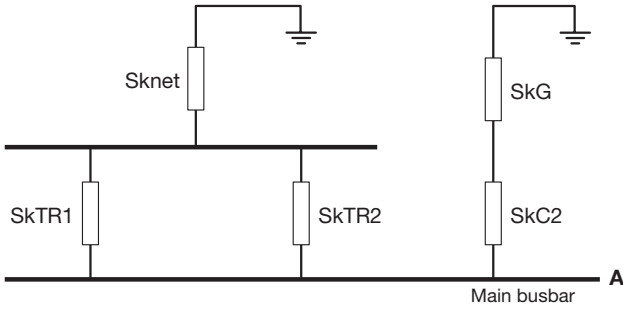
$$S_{kC2} = \frac{V_{2n}^2}{Z_{FC2}} \quad S_{kC2} = 133.95 \text{ MVA}$$

where:

$$Z_{FC1} = \sqrt{(R_{F1}^2 + X_{F1}^2)} \quad Z_{FC1} = 0.0031 \Omega$$

$$Z_{FC2} = \sqrt{(R_{F2}^2 + X_{F2}^2)} \quad Z_{FC2} = 0.0012 \Omega$$

Taking into consideration the fault in A, the network schematising the contribution of the short-circuit powers is the following:

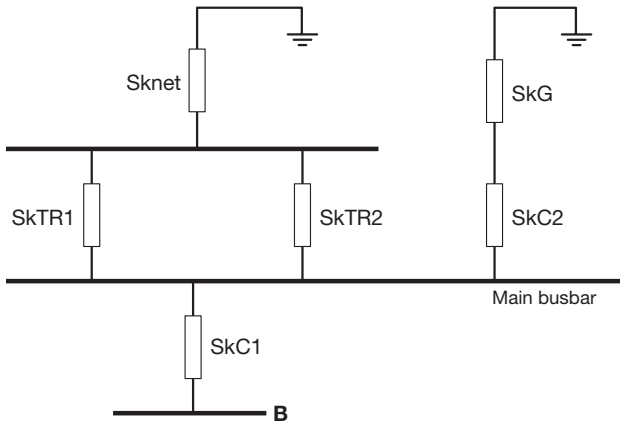


By the reduction of the elements in series – in parallel, the following expression for the total power is obtained:

$$S_{kTOT(A)} = ((S_{kTR1} + S_{kTR2}) // S_{kR}) + (S_{kG} // S_{kC2}) = 58.16 \text{MVA}$$

$$I_{k3A} = \frac{S_{kTOT(A)}}{\sqrt{3} \cdot V_{2n}} \text{ from which it results } I_{k3A} = 83.95 \text{kA}$$

Taking into consideration the fault in B, the network schematising the contribution of the short-circuit powers is the following:

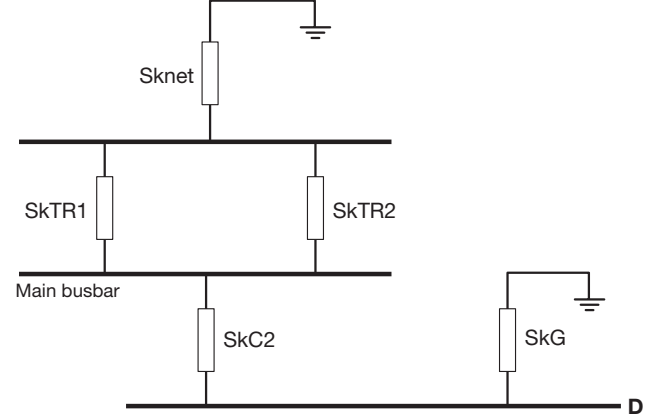


By the reduction of the elements in series – in parallel, the following expression for the total power is obtained:

$$S_{kTOT(B)} = [((S_{kTR1} + S_{kTR2}) // S_{kR}) + (S_{kG} // S_{kC2})] // S_{kC1} = 27.38 \text{MVA}$$

$$I_{k3B} = \frac{S_{kTOT(B)}}{\sqrt{3} \cdot V_{2n}} \text{ from which it results } I_{k3B} = 39.52 \text{kA}$$

Taking into consideration the fault in D, the network schematising the contribution of the short-circuit powers is:



By the reduction of the elements in series – in parallel, the following expression for the total power is obtained:

$$S_{kTOT(D)} = \{[(S_{kTR1} + S_{kTR2}) // S_{kR}] // S_{kC2}\} + S_{kG} = 45.23 \text{MVA}$$

$$I_{k3D} = \frac{S_{kTOT(D)}}{\sqrt{3} \cdot V_{2n}} \text{ from which it result } I_{k3D} = 65.28 \text{kA}$$

Considerations about the results obtained

From the above example, it is evident that the use of the power method offers the advantage of simplicity and speed, but it could give results less precise compared with the method of the symmetrical components.

The most evident difference regards the three-phase fault calculated at point B, where the presence of the cable C2, characterized by particular values for “L” and “R”, introduces a different ratio between the imaginary and the real parts of the expressions as regards to the other elements, thus highlighting the approximate character of the power method.

However, the effect of the approximation is not such as to invalidate this method, in particular if it is used to carry out preliminary calculations, as often happens.

Glossary

$V_{k\%}$	short-circuit voltage in percent
$P_{k\%}$	short-circuit power in percent
V_n	rated voltage
S_n	rated power
I_n	rated current
V_{1n}	primary rated voltage
V_{2n}	secondary rated voltage
X''_d	subtransient reactance, direct axis
X'_d	transient reactance, direct axis
X_d	synchronous reactance, direct axis
S_k	short-circuit apparent power
I_k	short-circuit current
i_p	peak current
Z_k	short-circuit impedance
X_k	short-circuit reactance
R_k	short-circuit resistance
$Z...$	impedance of a generic element
$R...$	resistance of a generic element
$X...$	reactance of a generic element
i_s	symmetrical component of the short-circuit current
i_u	unidirectional component of the short-circuit current
η	efficiency
$\cos\varphi$	power factor
$a\angle b$	polar representation: "a" is the modulus; "b" is the phase displacement angle
$a+ib$	rectangular representation: "a" is the real-part and "b" is the imaginary-part

Subscripts:

...L	passive generic load
...TR	transformer
...G	generator
...M	motor
...n	rated
...C	cable
...net	plant supply network
...N	neutral
...F	phase
...PE	protection conductor
...1F-PE	single-phase to earth
...1F-n	line-to-neutral
...2	two-phase
...3	three-phase
...LV	low voltage
...MV	medium voltage
...k	short-circuit condition



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