Collection Technique

Cahier technique no. 203

Basic selection of MV public distribution networks

Didier Fulchiron

Merlin Gerin
Modicon
Square D
Telemecanique

Schneider Electric

“Cahiers Techniques” is a collection of documents intended for engineers and technicians, people in the industry who are looking for more in-depth information in order to complement that given in product catalogues.

Furthermore, “Cahiers Techniques” are often considered as helpful “tools” for training courses.

They provide knowledge on new technical and technological developments in the electrotechnical field and electronics. They also provide better understanding of various phenomena observed in electrical installations, systems and equipment.
Each “Cahier Technique” provides an in-depth study of a precise subject in the fields of electrical networks, protection devices, monitoring and control and industrial automation systems.

The latest publications can be downloaded from the Schneider Electric Internet web site.
Code: **http://www.schneider-electric.com**
Section: **The expert’s place**

Please contact your Schneider Electric representative if you want either a “Cahier Technique” or the list of available titles.

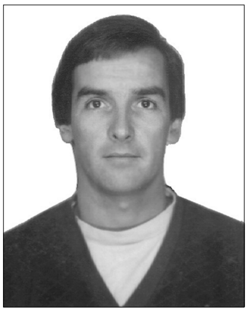
The “Cahiers Techniques” collection is part of Schneider Electric’s “Collection Technique”.

Foreword

The author disclaims all responsibility subsequent to incorrect use of information or diagrams reproduced in this document, and cannot be held responsible for any errors or oversights, or for the consequences of using information or diagrams contained in this document.

no. 203

Basic selection of MV public distribution networks



Didier FULCHIRON

After graduating from the Ecole Supérieure d'Electricité in 1980, he joined the technical department at Merlin Gerin's high-power testing station in 1981.
He then took part in various developments of medium-voltage equipment, mainly destined for public distribution.
He now works for the Medium Voltage Division of Schneider Electric, participating in the technical specification of Schneider equipment, and is also involved in work on international standards committees.

ECT 203 first issued May 2001

Basic selection of MV public distribution networks

Medium voltage - MV - public distribution networks are constructed on the basis of two fundamental parameters which influence the majority of their components as well as their operation. These parameters are the neutral management mode and the operating voltage. Selection of these parameters has a very high impact on the whole network, and it is very difficult, if not impossible or economically unrealistic, to alter them subsequently. It is therefore essential to fully understand the influence of these decisions on other network parameters such as the protection system, safety, fault management, etc.
This document details the limits imposed by these decisions and considers the various existing solutions, pointing out their advantages and disadvantages.

Contents

1 Introduction

1.1 The neutral plan

Impact on electrical characteristics

The neutral earthing mode for the HV/MV transformer, and the choice of whether or not the neutral conductor is distributed (hence the distinction between “4-wire” and “3-wire” networks) have a direct influence on a number of significant network parameters.

- The earth fault current: In the event of a fault between a phase and earth, the value of the fault current is principally determined by the neutral earthing impedance, and by the capacitance, between earth and phase conductors, present on the network (lines, cables and capacitors).
- Touch voltage and tread voltage: These two concepts concern the safety of people in the vicinity of an electrical fault. These voltages are directly linked to the value of the earth fault current and the impedances through which this current flows.
- The level of overvoltages: Neutral earthing has an effect on industrial frequency overvoltages when earth faults occur, and also on the amplitude and damping of possible oscillating or transient phenomena.
- The level of disturbance of the surrounding networks: In the case of overhead networks, the loop through which an earth fault current flows causes a strong magnetic field. Voltages are then induced in the circuits of neighboring networks, and typically in telecommunication cabled networks (copper technology). The level of these voltages may be unacceptable for operation or even insulation of neighboring equipment. Electromagnetic compatibility (EMC) studies must therefore be conducted before an MV line is installed.

Impact on the operating characteristics

A number of operating criteria are also affected by neutral earthing:

- The permitted duration of earth faults (extent of damage and safety)
- The behavior of flashovers in the air (whether self-extinguishing or not)
- The methods used to locate the fault on the network
- Voltage fluctuations at the load terminals during earth faults
- The number and duration of faults noted by customers
- The possibility and ease of reconfiguration following an incident

Impact on the construction specifications

The neutral earthing mode has a significant influence on the construction of networks:

- The values of earth connection impedances should be adapted to the fault current.
- The conductors affected by earth faults should have adequate thermal withstand.
- The insulation on the conductors and the equipment should take account of potential overvoltages, influenced by the neutral plan.

1.2 Principal effects of this decision on the network components

The table in **figure 1** lists certain significant effects generated by the initial choice of a neutral earthing system.

The earth fault hypothesis is always a major consideration, since multi-phase faults are not affected by neutral earthing.

This table demonstrates that several factors (safety, quality of service and cost) are directly affected by the value of the earth fault current. The same applies to the safety of people (tread and touch voltages), “voltage dips” on low voltage, EMC with neighboring electrical circuits (including telecommunications circuits), and damage at the location of the fault. It confirms there is no “perfect” neutral plan: advantages and disadvantages are evenly distributed.

Neutral situation	Isolated	Tuned (Petersen)	Impedant	Directly earthed
Earth fault current	Linked to stray capacitance: 2 to 200 A	Almost zero, dep. on tuning and quality factor (< 40 A)	Dep. on impedance: 100 to 2000 A	High: 2 to 25 kA, varies with the location
Damage	Low	Almost zero	Dep. on impedance	High
Voltage disturbance	None	None	Low	Significant
Restrictions	Possible overvoltages	Thermal on the coil	Thermal on the impedance	Thermal and electrodynamic
Protection against earth faults	Difficult	Complex	Easy (time discrimination)	“3-wire”: easy (current discrimination)

Fig. 1: Significant effects generated by the initial choice of a neutral earthing system

Moreover, the relative importance of these advantages varies according to how much of the network consists of overhead lines and underground cables, the feeder lengths, etc.

A decision thought to be judicious at a certain point in time may therefore be called into question once a network has evolved over a number of years.

1.3 System for protection against insulation failures (earth fault)

The concept of a protection system combines several aspects:

- Determination of the fault situations to be handled
- The selection and location of the switchgear used to eliminate faults
- The selection and configuration of the relays installed to monitor electrical values, diagnose fault situations, then issue commands to open to the switchgear
- The organization of discrimination between the various relays, so that the device closest to the fault is the only one to trip, minimizing the extent of the de-energized zone

Designing a protection system therefore requires analysis of the network and of the phenomena present in a normal situation and during a fault, familiarity with the possibilities for measurement and analysis (sensors, relays, control systems, etc) and a global approach to the subject in order to determine the appropriate settings.

1.4 Safety of people and animals

The value of earth fault currents has consequences on other aspects than simply the operation of the network (see fig. 1). In particular, during an earth fault, a current flows through the conductors which are normally de-energized (including the grounds and the earth) whose configurations and impedances are not always fully controlled. Voltage drops due to these impedances present risks of electrocution for living beings standing in the proximity of the fault.

Tread and touch voltages

In fact, if current is flowing through conductive parts which are normally de-energized, including the floor, the impedance of these conductive parts may result in two points which are accessible simultaneously being subjected to a dangerous difference in voltage. Depending on the type of contact made, we talk about touch voltage (between two parts of the body, most commonly between two hands) and tread voltage (between two feet or two paws) (see **fig. 2**).

Numerous standards and regulatory texts are concerned with limiting the risk of electrocution. But if the equipment impedances can be easily determined and are stable over time, the same cannot be said for the earth connection impedances, whose low values are difficult to maintain.

Safety is therefore enhanced by a greater tolerance vis-a-vis the earth connection impedances, and simultaneously limiting the value of the earth fault currents. International standards have introduced a voltage-duration formula to demonstrate what the human body can withstand. The longer it takes to eliminate a fault, the lower the maximum tread and touch voltage values to be respected will therefore be.

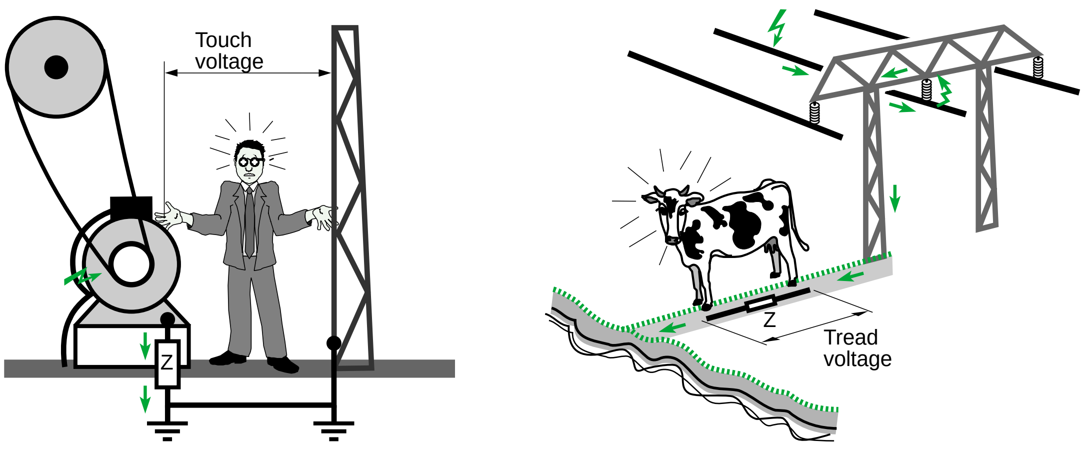


Fig. 2: Examples of touch and tread voltages

1.5 Electromagnetic compatibility

Induction with regard to telecommunication circuits

In "3-wire" networks, in a normal operating situation, no current is circulating in the earth. Only earth fault situations (see **fig. 3**) create a significant magnetic field emission and need to be considered in the electromagnetic compatibility (EMC) studies.

For "4-wire" networks, in a normal operating situation, the permitted load unbalance between the various phases results in a current in the neutral. This current is divided between the neutral conductor and earth, since this neutral conductor is earthed at a number of points. It is therefore necessary to create a permanent situation of emission of an industrial frequency

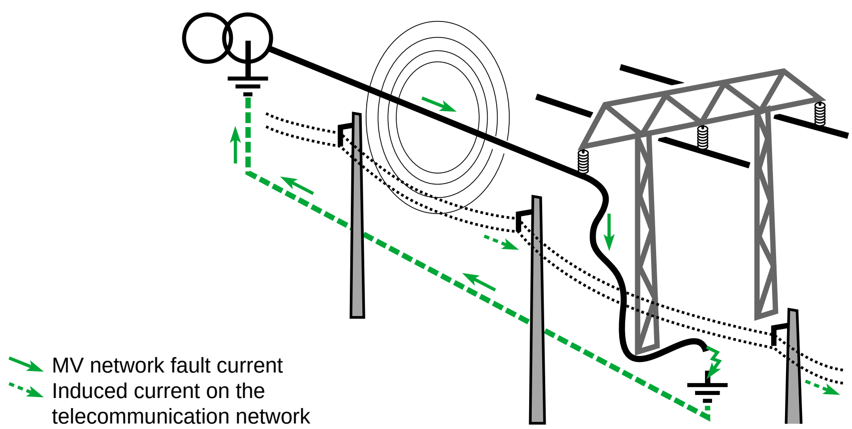


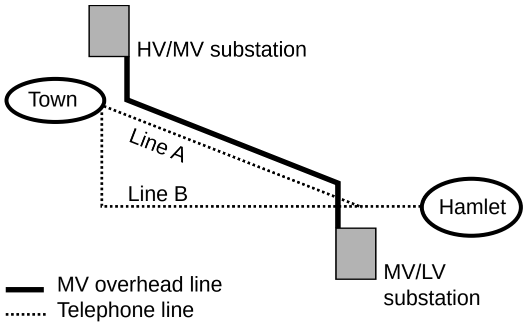
Fig. 3: Voltages induced by MV networks in telecommunication cabled network circuits

magnetic field. However, at a comparable fault current, the presence of the fourth conductor, generally placed on the line supports, reduces the emissive loop.

In all cases, radiation is due to the geometry of the lines and is difficult to reduce, particularly while adhering to a given system and overhead network technology. The reduction of earth fault currents, in 3-wire network systems, may therefore be a more appropriate solution, since it also participates in the safety of personnel as described earlier.

When the users of these networks (energy and communication) can work together, the establishment of installation rules for their respective lines can contribute to a reduction in the magnetic coupling between their networks, for example by reducing the “receptive” loop of the disturbed circuit by using twisted cables rather than parallel wires, or even by avoiding a parallel line too close to the two networks (see **fig. 4**).

But it is the increasing strictness of emission standards which is leading ever more energy distributors to reconsider their neutral management modes.



The telephone network along line B will be subject to less disturbance than that along line A.

***Fig. 4**: Reduction of the coupling between an MV network and a telecommunication cabled network*

Note: Networks comprising underground cables benefit from low earthing impedance of the ground connections and electromagnetic masking, due to the presence and interconnection of screens. They are therefore less affected by the factors discussed in sections 1.4 and 1.5.

1.6 The operating voltage

A compromise between conflicting parameters

The following information should be considered before choosing an operating voltage for a given network:

- the average length of the MV feeders
- the delivered power
- the losses
- the cost of insulation and equipment
- the history and the policy of the distributor

■ The average length of the MV feeders: In fact, the increased impedance of long feeders risks generating unacceptable voltage drops. Therefore, a vast geographical area, supplied with a small number of HV/MV substations, will require use of a somewhat higher operating voltage.

■ The delivered power: For zones with a high density of use, the feeders, even short ones, have to serve numerous loads; for a given voltage, their high currents then fix a limit on the system, making a higher operating voltage the preferred option.

■ The losses: Although the voltage drops and currents remain within acceptable limits, the energy losses due to the Joule effect may sometimes have a significant cost. Increasing the operating voltage allows the energy loss to be reduced for a given distributed power.

■ The cost of insulation and equipment: The higher the voltage, the greater the isolation distances need to be. As a result, the amount of work and the size of the switchgear has to be increased, thus increasing the costs. Moreover, certain technologies which are available for “low” voltages are not available for higher voltages.

■ The history and policy of the distributor: Apart from the fact that it is very difficult to change operating voltage, a distributor often chooses a single operating voltage in order to rationalize his equipment. If he has an extensive network, this single voltage does not correspond to the optimum, from a technical and cost point of view, which could be selected for smaller geographical areas. However, it does offer appreciable opportunities for economy of scale and reuse of equipment.

The choice is limited to standard values

In order to be able to access an important supplier market, and therefore benefit from favorable competition conditions, a distributor should limit his choice to standardized values so as to ensure the availability of the various equipment (isolators, cables, switchgear, etc) from different manufacturers. The use of these standardized values also means it is possible to benefit from experience acquired by manufacturers and by the standards organizations. Finally, the existence of reference standards simplifies contractual relations while ensuring a good level of performance and quality.

2 The existing network situation

2.1 Neutral earthing

Networks can be classified according to two major categories:

- Those where the neutral is distributed (4-wire networks)
- Those where the neutral is not distributed

In theory, each of these categories can use neutral earthing connections with varying impedance values (see **fig. 5**).

In fact, all “4-wire” networks use a neutral connection directly to earth; moreover the neutral conductor can be earthed directly at multiple points on the network and therefore never presents a dangerous voltage. This layout is used in the United States, more generally in North America, but also in parts of South America, Australia and other countries influenced by the USA.

“3-wire” networks use four types of earthing:

- Directly earthed neutral (Great Britain, Spain, etc)
- R//L low-impedance neutral (France, Germany, Spain, etc)
- Tuned or “Petersen” neutral (Germany, Hungary, Poland, etc)
- Isolated neutral (Spain, Sweden, Norway, Italy, China, etc)

These choices have been made on the basis of local features, such as the respective extents of the overhead and underground networks. Changes are possible, but often have serious financial implications (major work and expensive changes of equipment).

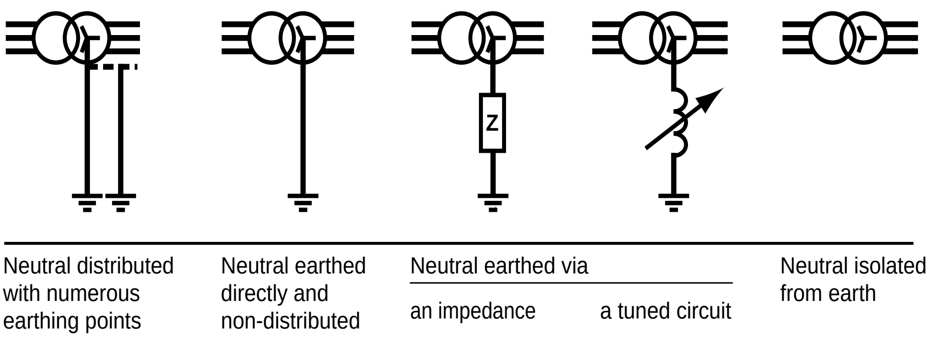


Fig. 5: Various earthing layouts for MV distribution networks

2.2 Operating voltages

The operating voltages used by energy distributors are between 5 and 33 kV. The lowest voltages are only found for networks with a limited coverage, usually in urban areas. Some operating voltages are currently being phased out, but this is happening over a long timescale due to the slow rate at which networks are upgraded.

Two important standards systems coexist and recommend various preferred voltage values:

- The International Electrotechnical Commission (IEC) is the reference for the majority of countries.
- The American National Standards Institute (ANSI) is the reference for countries which are, or have in the past been, influenced by the USA.

These standards systems have introduced the concept of “rated voltage”, a value which serves to define all the characteristics of the equipment.

The table in **figure 6** gives some of the values which are most commonly found, but the majority of countries use a number of voltage levels.

Operating voltage (kV)	Country	Rated voltage (kV)	Standard
6	Japan	7.2	IEC
10 to 12	United Kingdom, Germany, China	12	IEC
13.8	USA, Australia	15	ANSI
15	(being phased out)	17.5	IEC
20	France, Italy, Spain	24	IEC
25	USA	27	ANSI
33	Turkey	36	IEC

Fig. 6*: Examples of voltage values used for public distribution*

3 Characteristics of “4-wire” systems

“4-wire” systems are characterized by distribution of the MV neutral right to the loads. This type of distribution is used in the USA and in certain countries influenced by North America, and is always subject to ANSI regulations. It is only used in a “directly earthed” neutral plan, and applies a global earthing concept consisting of earthing the neutral conductor at multiple points on the network, approximately every 200 meters. The neutral-earth voltage is therefore fully controlled.

Distribution of the neutral conductor enables power to be supplied to the loads between the neutral and one phase (to the single voltage): a significant part of the energy is therefore consumed in single-phase. In a normal operating situation, this single-phase use, whose proliferation is not totally controlled by the distributor, results in the presence of a current in the neutral conductor or the earth. It is generally acknowledged that the load unbalance between the various phases can be as much as 40% of the rated current for a feeder.

Due to the direct earthing, the current for a directly earthed fault is mainly limited by the impedance of the network segment between the HV/MV transformer and the location of the fault. This situation calls for the use of “decentralized” protection, capable of managing increasingly low thresholds as the distance increases, and nonetheless capable of being coordinated. The resulting protection system is complex and poorly suited to network reconfiguration, in the event of an incident. This system should also be adapted to each significant modification for a feeder, whether in terms of impedance or topology, which constitutes a major constraint in terms of upgradability.

3.1 Protection system for networks with distributed neutral (“4-wire”)

In these networks, the unbalanced current due to single-phase loads can “mask” an earth fault current. In fact, protection cannot discriminate between the current of a phase-neutral load and the current of a phase-earth fault if they have comparable values. The value of the phase-earth fault current is linked on the one hand to the expected impedance of the fault itself, and on the other hand to the network impedance between the HV/MV power supply transformer and the location of the fault. It therefore varies according to the distance from the fault to the substation. For rather long lines, a phase-earth fault a long way away can cause a lower current than the unbalanced current permitted at the substation feeder; in this case, a protection device placed in the substation will not be capable of detecting this fault. An additional protection device with lower thresholds is then necessary to extend the part of the network which is actually monitored, known as the “protection zone”. In a network, the higher the impedance of the faults to be eliminated, the smaller the protection zone for each device.

Therefore, in order to have adequate detection of faults on this type of network, where the normal load currents diminish the greater the distance from the substation, a number of protection devices should be placed in cascade (see **fig. 7**).

When the distributed power on the last segment is low, the protection furthest away from the substation is often in the form of fuses, for reasons of cost.

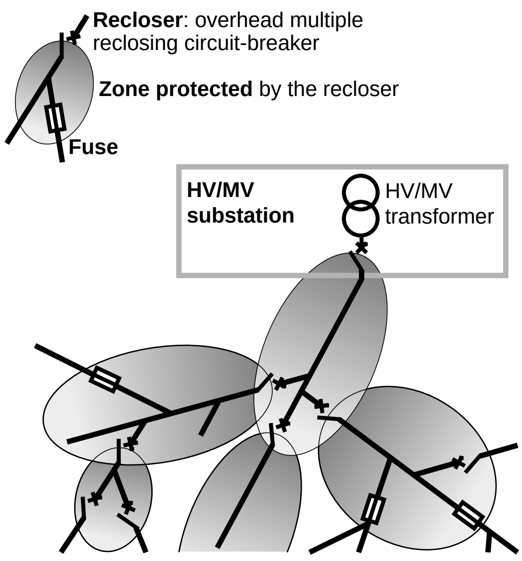


***Fig. 7**: Example of a North American distribution network comprising a number of protection devices placed in cascade: Note how the protection zones overlap.*

As far as the underground parts (using cables) of networks are concerned, they generally cover a smaller area than an overhead network and have lower impedance, therefore the value of a phase-earth fault current is only slightly affected by the distance from the fault to the substation. Nonetheless, in order to serve limited zones from a trunk cable, these networks also include single-phase junctions protected by fuses.

3.2 Operation of networks with distributed neutral ("4-wire")

Operation of this type of network may be characterized by two major difficulties:

- Electrical risks due to possible high-impedance faults which are difficult to detect easily
- When a loop is required for good continuity of service, it should be of sufficiently low impedance to be in the protection zone.

The previous sections explained the difficulty of diagnosing high-impedance earth faults. Recent American publications (1999) note the fact that, in more than half of the operations to re-erect conductors which had fallen to the ground, the conductors on the ground were still energized when the technicians arrived. These situations represent high risks for both people and equipment (electrocution or fire).

When the neutral is distributed, two network structures can be distinguished according to whether or not a loopable connection which does not incorporate decentralized protection is present.

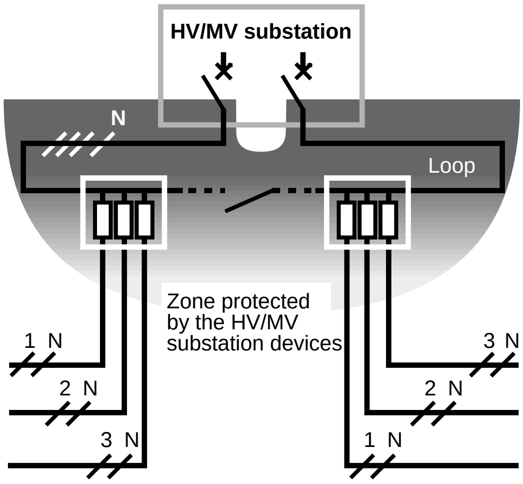


Fig. 8: For complete protection of a power supply loop against earth faults, this loop should be entirely contained in the protection zone for the HV/MV substation devices.

Presence of a loopable connection which does not incorporate decentralized protection

If such a loop exists, it is necessarily at low impedance so that it can be entirely in the protection zone of the HV/MV substation devices (see **fig. 8**). This is typically the case for dense urban geographical areas with underground distribution.

The loop can be used according to the open loop principle in order to benefit from the capacity to return to service associated with this layout, if an incident concerning the cable occurs on the loop itself. From this loop, junctions equipped with protection devices can be created in single-phase or three-phase (see **fig. 9**). They may be organized into sub-loops if necessary, to benefit from the same operating mode, but these sub-loops should be entirely in the protection zone of the junction devices.

Due to the limited impedances of the cable segments, and the existence of only two levels of protection to be managed, such a system may be considered to be satisfactory in terms of upgradability. Any geographical extension is nonetheless limited by the need to respect the protection zones.

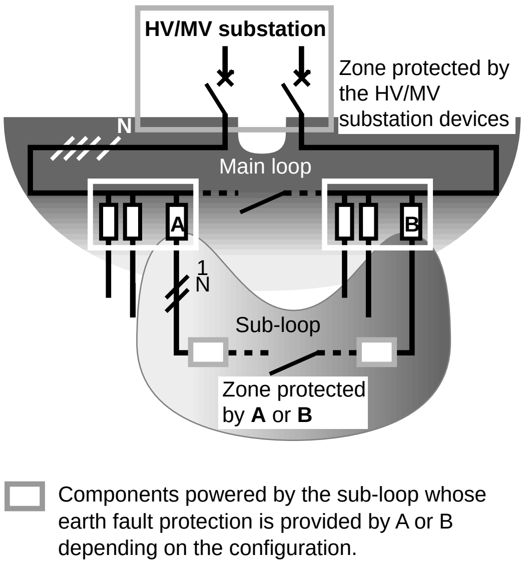


Fig. 9: These are the HV/MV substation devices which protect the main loop, and both ends of each junction organized as a sub-loop incorporate protection devices to ensure the safety of the various possible configurations.

Presence of connections which are physically capable of being looped, but incorporate decentralized protection devices

When the network is structured around radial feeders, with cascaded protection devices, “emergency” type layouts are not permitted, although the topology itself would allow it. In fact, a load reconnection, even temporary, which occurs at the end of a tree structure would necessitate redefining the protection thresholds and the discrimination stages of the various devices concerned. Since these settings are the result of fairly complex calculations, taking into account the lengths and the types of the various segments, there is no chance that incidents could be handled by modifying the settings.

Operation is therefore limited to radial mode, and the incident situations may entail long periods without power until they are repaired.
For similar reasons, any upgrading of the topology or the network load level involves checking the compatibility of the protection devices in place. Modifying this type of network is therefore a very delicate and expensive operation. Such a system can only be considered mediocre in terms of upgradability.

Whatever the network structure, faults which cause the current protection devices to work can be located easily using detectors which react to overcurrents. These fault detectors, placed on the phase conductors, work with both faults between phases and earth faults.

4 Characteristics of “3-wire” systems

In these systems, the neutral is not distributed and therefore is not available to users. Loads, even single-phase, can only be connected to phases of the network. They do not therefore generate any neutral current in the distribution system and, excluding any capacitive unbalance between the phase conductors, the residual current of such a system is zero.

The network neutral point, which remains exclusively available to the distributor, can be earthed via an impedance of any value and type. In practice, four main neutral plans are used: isolated, tuned, impedant or directly earthed.

If the value of the neutral earthing impedance is significant compared to the network impedances, the resulting zero-sequence impedance fixes, de facto, the maximum value of the earth fault current. In this zero-sequence impedance, the neutral impedance should be considered to be in parallel with all the network phase-earth capacitances. These capacitances may reach high values and contribute significantly to the earth fault current. In all cases, due to the absence of residual current during operation, all earth faults can be detected at the substation. Depending on the neutral impedance, the adopted protection method may vary, but there is no technical obligation to use decentralized protection devices. The protection system can therefore be kept fairly simple, with the advantage that it does not require modification if changes are made to the network configuration.

4.1 Protection system for networks with non-distributed neutral (“3-wire”)

General

In networks with non-distributed neutral, loads are necessarily connected between phases and when the neutral earthing connection exists, no continuous current flows through it. This situation is purely theoretical: capacitive currents which exist between the phase conductors and earth are never perfectly balanced. This unbalance is due to the differences in geometry on overhead lines, inside transformers, on the cable runs for the various phases, etc. However, if when the network is constructed, the distributor takes the precaution of swapping over the phase conductors along each feeder, the residual continuous current for each feeder can be reduced to less than 1 A, or even much less with an isolated neutral. This type of natural residual current can then be used to diagnose the presence of low-value earth fault currents from the substation.
Since the orders of magnitude of these fault currents can be noticeably different from those for a “4-wire” system, the protection to be provided is also different.

Network with isolated neutral

The network is said to be with “isolated neutral” when there is no deliberate physical connection between the transformer MV neutral point and earth. The transformer can also have a delta-connected MV winding. The network average voltage in relation to the earth is therefore fixed by the stray impedance between the phase conductors and earth. These impedances include the capacitance of the lines and cables, which are predominant, but also the leakage impedances of different types of equipment (lightning arresters, measurement sensors, etc) and those of any faults. The residual voltage, which is the vectorial sum of the three phase-earth voltages, of such a network is never perfect zero. Monitoring this voltage can provide a good indication of the network insulation quality, since any fault between a phase and earth causes a marked unbalance in impedance and increase in the residual voltage. However, this information, which is common to the whole network, does not make it possible to locate the fault.

In the case of a clear fault to earth (negligible impedance direct contact), the phase-earth voltage is zero for the phase concerned and equals the phase-to-phase network voltage for the two other phases. The currents present in the phase-earth capacitance of the three phase conductors then no longer form a balanced three-phase set: a residual current which is not zero circulates throughout the network. Its intensity, at each feeder circuit-breaker, depends on the length and type of the connections and of the equipment placed downstream. Use of an overcurrent protection device does not therefore make it possible to discriminate simply and efficiently which of the healthy feeders is faulty.

Networks with isolated neutral can be used with a sustained earth fault (detected and not eliminated). This operating mode is sometimes used to improve continuity of service, since it enables location of the fault while continuing to serve customers. The risk associated with sustaining an earth fault is that a second fault of the same type may appear on one of the other phases. This second fault creates a short-circuit while the healthy phases are, vis-a-vis the earth, maintained at a voltage which equals the phase-to-phase voltage during the whole time of operation with a sustained fault.

Network with tuned neutral (Petersen coil)

The network is called “tuned” or “earthed via a Petersen coil” when, in connecting the neutral to earth, a high-quality coil whose inductance value is adjusted in order to obtain tuning (resonance conditions) is placed between the capacitances of the network and this coil (see **fig. 10**). When earthing one of the network phases, this tuning results in a very low current in the fault ($Id = I_C - I_L$). This current is only due to the imperfection in tuning, the capacitive unbalance between the phases and the coil resistive losses.

The normal order of magnitude of this type of fault current is a few amps (typically 2 to 20 A). The resonance condition is expressed by the formula $LC\omega^2 = 1$, where:
L = neutral inductance
C = zero-sequence capacitance of the network (sum of the phase-earth capacitances of the three phases)
ω = network pulsation ($\omega = 2\pi F = 100\pi$ for a network at 50 Hz).

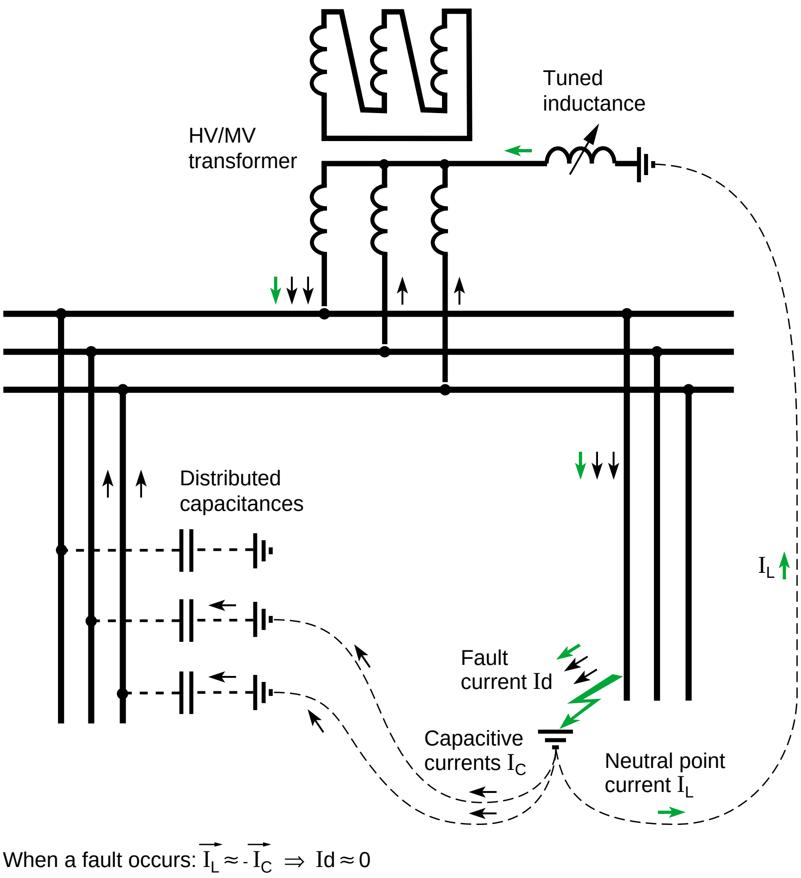


***Fig. 10**: Operating principle for an earthing coil whose inductance value is tuned to the capacitive value of the network*

If this resonance condition is sustained, during variations of the network configuration and even during variations in climatic conditions, it implies that the coil can be adjusted with good definition. Tuning is generally performed by a control system.

This neutral plan has a major advantage in that numerous faults are self-extinguishing, typically all air gap flashovers. It therefore offers good continuity of service for networks which incorporate lots of overhead lines. It is clear that insulation faults within equipment and cables (especially underground) do not benefit from this behavior. In addition, networks with tuned neutral can be used with a sustained earth fault, like networks with isolated neutral. The limit of this operation is most commonly associated with the thermal withstand of the neutral impedance which is subjected to single voltage for the whole duration of the fault.

The main disadvantage of the tuned neutral resides in the difficulty in locating a continuous fault and certain recurrent faults. This difficulty comes from the low value of the current flowing across a fault compared to the high value of the capacitive currents which circulate simultaneously on all the lines. Simple residual current detection cannot therefore tell the difference between a healthy feeder and the faulty feeder. It is necessary to introduce directional residual overcurrent protection, or even residual overpower protection in order to ensure high-performance discrimination. The use of such protection is possible at the source substations, but is totally unrealistic (complex and expensive) in the plants installed along the network. Finally, fault detectors operating on the same principle (directional) would be too expensive and do not therefore exist. For this reason, use of the network is seriously compromised when continuous fault type incidents occur: the power can only be switched back on once the lines have been inspected and successive attempts at reclosing made.

These difficulties make this neutral plan unworthy of consideration for networks with a high proportion of underground cables. However, recent technological developments have enabled the creation of new detectors which operate with inexpensive sensors. This development could remove some of the present operating difficulties for networks with compensated neutral.

Network with impedant neutral

For this type of network, a limiting impedance, generally resistive, is inserted in the neutral earth connection. It can also include an inductive part, in order to compensate partially for the capacitive contribution from the network. With public distribution, no networks are earthed by a single non-tuned inductance.
The value of the impedance is always high compared to the line impedances and, therefore, a directly earthed fault current varies according to the location of the fault: it is a few hundred amps (100 to 2000 A approx). This high level of earth fault currents, as well as the preponderance of the component circulating in the neutral impedance, make it easy to detect earth faults:

- A “residual overcurrent” type protection device, with sufficiently high threshold values to not be affected by capacitive or transient phenomena, works correctly on these networks.
- Discrimination between feeders is easy due to the significant value of the fault current, and discrimination between protection devices arranged in cascade is obtained by time-based operation (defined time or IDMT protection) However, the possible existence of impedance earth faults which are not insignificant compared to the neutral impedance makes it desirable to search for the lowest settings, while guarding against unintentional tripping. For faults with very high impedance, residual current protection devices can no longer discriminate, and additional devices, such as automated detection systems with successive opening of the various feeders, are added in the source substations.

In numerous situations, when the load downstream of the protection device is low, protection against directly earthed faults can be provided by phase overcurrent detection. This is why certain distributors do not systematically put residual current protection on these types of circuit (for example: junction supplying an MV/LV transformer).
Locating faults on these networks is made easier by the fact that simple, reasonably-priced fault detectors can be used, which are capable of reacting to a directly earthed fault current. Their nonetheless limited sensitivity means that certain faults with significant impedance, although diagnosed by the source substation protection devices, do not cause them to react (insufficient current). It is, however, possible to choose lower thresholds with the single inconvenience of causing unnecessary signaling, since the unintentional operation of a fault detector does not generally have significant consequences.

Network with directly earthed neutral

The directly earthed neutral can be interpreted as a special case (as is insignificant neutral impedance) of the impedant neutral. These are therefore exclusively impedances concerning the network (source and line), the fault and return via the earth, which fix the intensity of the fault current. Therefore, the generally high fault current intensities can present significant variations depending on the fault location and type, and as a consequence lead to reconfiguration difficulties; for example when reconfiguring a network with notably longer feeders in an emergency situation than in a normal situation. This effect can be achieved by the adoption of detection thresholds, as low as possible, designed to diagnose directly earthed faults and also impedant faults.

The detection of earth faults is simple. Very often the same type of protection can be used in respect of faults between phases and earth faults. The “fault detector” function is simple to provide using phase overcurrent detection, or possibly residual overcurrent detection.
In this layout, where earth faults can have high intensities, they may result in significant damage. It is therefore desirable to choose short protection intervention times. This situation, associated with the ever-present need for discrimination in a distribution network, favors the use of IDMT protection (often known as “inverse time” protection).

4.2 Operation of networks with non-distributed neutral ("3-wire")

The structure of these networks is mainly radial, or radial with the option of looping, or looped. Numerous other configurations exist which combine these basic structures.
They operate most commonly on an open circuit. However, in order to ensure a high level of availability of energy for their customers, some distributors use closed loops equipped with circuit-breakers at each MV/LV transformer substation. But such installations are expensive and require delicate handling.

In open-circuit operation, the main characteristic of "3-wire" networks is that they allow detection of all earth faults, whatever their location, from the HV/MV substation. Faults between phases are also managed from the HV/MV substation: decentralized protection is only necessary if there is an exceptionally long line, in fact once it becomes impossible to discriminate a distant fault between two phase conductors, in the permitted load current for the feeder.

Centralized protection offers total freedom to modify the network. Hence it is possible to provide a number of emergency layouts with numerous loop feeders to cope with different types of incident: if the basic layout for normal operation of a high-density consumption area encompassing numerous customers is the open loop, loop feeders can also be provided at the end of lines with a radial structure, which may limit the loads which can be resupplied after the interruption (see **fig. 11**).

Freedom of modification also allows extensions or restructuring of the network to be carried out, without implications for the protection methods and settings. This ease of upgradability offers a very appreciable level of flexibility.
In contrast, if only centralized protection is in place, all customers of a single feeder are affected in the event of an incident. This could involve very large numbers… hence the motivation which is then equally important to correct the situation quickly!

The use of remote control in conjunction with fault detectors responds to this imperative for speed of intervention: depending on the amount of remotely controlled switchgear, it allows a significant part of the affected customer base to be reconnected to the supply (usually over 60%).
A three-stage approach is used by the distributor’s teams to get the power supply reconnected:

- 1: Reconfiguration by remote control
- 2: Manual reconfiguration, in the field, using isolation switchgear which is not remotely controlled
- 3: Repair if necessary

Special remote control points can be introduced with the sole aim of improving quality of service, since no technical imperative makes it necessary to use a particular location on the network.
Some distributors install decentralized protection device, simply in order to provide quality of service and not because of a fundamental need to eliminate faults. It should be noted that the defined discrimination criteria which need to be respected between these protection devices and those of the HV/MV substation are markedly less sensitive than for networks with distributed neutral. Moreover, modifications to the topology or load do not generally have any adverse effect on these settings.

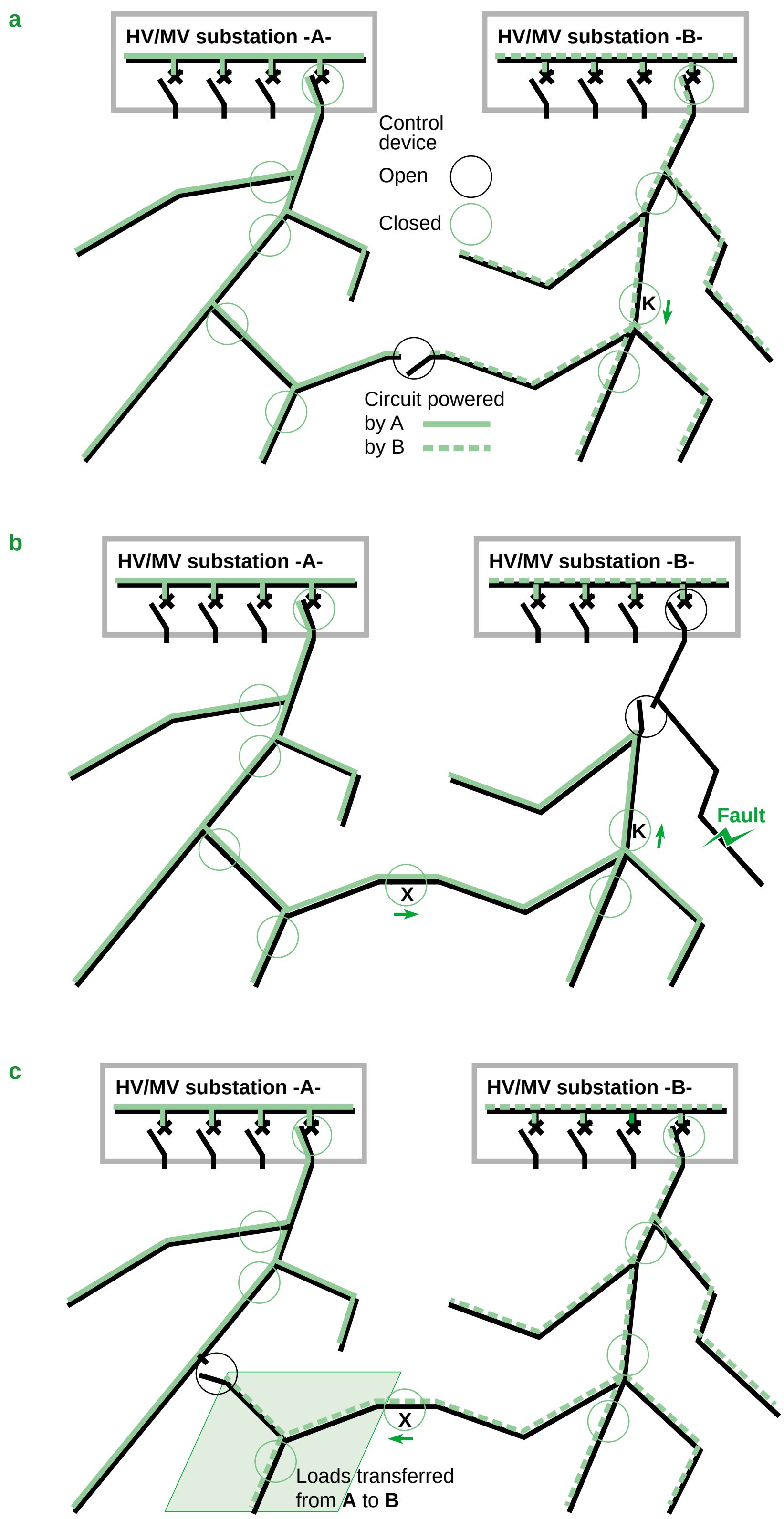


*Fig. 11: Example of a distribution network layout where the centralized protection allows different operating configurations to be used (**a** = configuration for normal operation, **b** = configuration after an incident reducing the number of customers affected, **c** = configuration for resupply with limitations on the load)*
Note**: The current flows through switch K in opposite directions in configurations **a** and **b**; the same applies to switch X in configurations **b** and **c

5 Operating voltage, selection criteria

5.1 Voltage losses and drops

The losses for an MV distribution network essentially correspond to the heat dissipation due to the Joule effect in the conductors. This is therefore a cost criterion, since they downgrade the global efficiency coefficient for the network. They are proportional to the square of the current and, with a given distributed power, are inversely proportional to the square of the operating voltage. For this reason, it is desirable to use a high operating voltage in order to minimize them, but other factors, mainly cost-related, may counter this advantage.

Voltage drops at the perimeter of the customer delivery area (see **fig. 12**) correspond to the difference (ΔU) between the no-load (e) and on-load voltages for the network (U_{Load}). The current magnitude and phase (φ) are determined by the power and nature of the load. Since the network behaves in an essentially inductive way, the voltage drop for the line (U_{Line}) is almost 90° out of phase with the current.

Different regulations define the limit voltage values that distributors should comply with at the point of delivery. For example, a tolerance of ± 10% on the low voltage network and a tolerance of ± 7.5% on the medium voltage network may be required simultaneously. It becomes increasingly difficult to comply with these tolerances as the distributed power increases. For given conductor lengths and cross-sections, a higher power supply voltage authorizes a higher delivered power with the same tolerances. Where a maximum voltage drop is imposed, the table in **figure 13** illustrates the transmission capacity of a line according to its cross-section and operating voltage.

Appreciation of the capacitance of a network is a planning tool: it can be used to initiate operations to reinforce lines or create new lines when the potential growth of the inrush power is approaching the permitted limits. Although it is technically possible to change operating voltage, it is rarely done in this situation, since such an operation presents numerous difficulties: replacement of all the transformers, a large part of the conductors, the switchgear and the isolators, etc. It is therefore very important that this voltage is selected correctly at the time of creating the network, at a suitable level which takes account of the anticipated development of loads over a period of several decades.

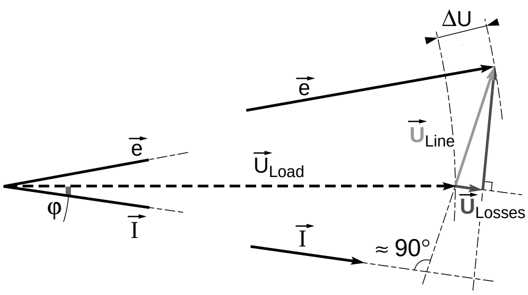


***Fig. 12**: Graphic representation of voltage losses and drops on the line*

MW x km
Where ΔU / U = 7.5% and cos φ = 0.9

mm²	kV 15	20	33
54.6	22	39	105
75.5	28	49	133
117	37	66	175
148.1	42	76	205

***Fig. 13**: Relationships between power transported by a line and the cross-section and length of this line, for aluminium conductors with a steel core*

5.2 Insulation difficulties and associated costs

Although the criteria discussed earlier encourage the use of a high operating voltage, a compromise must nonetheless be found in order for the network to be cost-effective. It goes without saying that the price of the various components increases significantly with the operating voltage.

Impact of the voltage on the equipment

The various types of equipment used should be designed with insulation adapted to the operating voltage as well as to the various exceptional constraints which apply to this voltage level.

Standardization has resulted in coherent sets of values, known as “insulation levels”, which associate a maximum operating voltage with withstand voltages in specific conditions. These conditions are usually described as “lighting impulse withstand”, and “power frequency withstand”. Hence a device for a 10 or 11 kV

network should be selected in a 12 kV range with a power frequency withstand of 28 kV for one minute, and a lightning impulse withstand of 75 kV with the standard test wave (example of IEC values).
In terms of equipment design, these various constraints result in insulation thicknesses and distances which differ in the air or in a gas, and therefore in different overall dimensions.
Example: “switch” cells with air insulation and SF6 cells, using the same technology have, depending on the voltage, the following dimensions (Height x Depth x Width):

- Un = 24 kV : 1600 x 910 x 375 mm
- Un = 36 kV : 2250 x 1500 x 750 mm

The same applies to all the network components. Only overhead line conductors escape this criterion: they are insulated by the ambient air and the distances are fixed by the construction (rails and isolators) of the masts.
Another consideration is that technologies are only available for certain voltage levels, for example, air break switchgear for indoor use is only available for the 36 kV level and has practically disappeared at the 24 kV level.

Finally, use of cables may be limited for transporting alternating current. In fact, their capacity relative to earth being a function of their length and insulation (and therefore of the voltage level) seriously reduces the current available at the end of the cable connections (see **fig. 14**). As a consequence, in very high voltage transmission networks, the length of the cable segments is always limited. This is a major reason why direct current is most commonly chosen for high-voltage insulated connections where overhead lines cannot be used.

Impact on cost

The criteria discussed previously have a direct impact on equipment manufacturing costs, and on market prices. Moreover, equipment manufacturers are not all able to offer comprehensive ranges that include the highest operating voltages (36 to 52 kV). The “supplier” market is therefore more restricted and less competitive than for the lowest operating voltages (7.2 to 24 kV). Nonetheless, this effect on the price is sometimes minimal, as is the case for cables with synthetic insulation which have a broadly similar transmission capacity, for example:

- 240 mm^2 alu / 24 kV: 7.31 k€ / km
- 150 mm^2 alu / 36 kV: 7.77 k€ / km ie. + 6% (1999 list prices)

But the user should also consider the associated costs, such as those concerning accessories, the external dimensions of an installation, and safe distances to be maintained with respect to lines, etc.

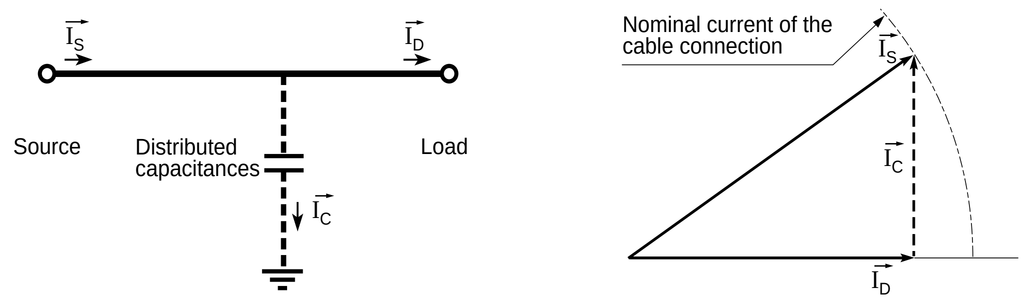


***Fig. 14**: Effect of leakage capacitances on the available current, and therefore on the output power, at the end of a cable connection*

5.3 Evolution of MV networks throughout the world

As we enter the twenty-first century, there is still a wide disparity in energy requirements between different countries.

Major growth in MV public distribution can be observed in numerous countries, with a clear bias in the selection of network structures towards the intermediate range of operating voltages, between 15 and 25 kV, for example:

- Japan, where the majority of the distribution network is 6 kV, is preparing to upgrade to 22 kV
- France is gradually replacing its 5.5 kV and 15 kV networks with 20 kV networks, whereas the 33 kV level is stagnating, if not regressing
- China, who is looking to use 20 kV in order to support its strong economic growth and improve the overall operation of its networks, presently 12 kV

6 Conclusions

The various systems and options discussed in this document share a fundamental aspect common to any MV distribution network, in that they all have numerous implications. They are therefore particularly difficult to consider on existing networks. However, with the regular general increase of electricity consumption, certain situations mean that barriers to development are reached and have to be overcome, or that opportunities for re-examining these basic decisions present themselves.

In this context, it is therefore sensible to initiate or implement far-reaching changes in the context of large-scale upgrade operations, following generalized obsolescence or exceptional events.

Moreover, the historical situations which justified the initial decisions often no longer apply, and new factors gain importance. In particular, aspects relating to safety, quality and continuity of service, respect for the living environment, compatibility with other equipment, etc, are now overwhelmingly important criteria. A number of social or macro-economic phenomena underlie or encourage these changes.

The major electrical equipment manufacturers have already taken on board the resulting needs of energy distributors, due to these changes. The equipment offered responds to these needs.
But it is the distributors who, in response to rapid developments in their environment, both political and geographical, need to think ahead, and view the upgradability of a system as a basic selection criterion.

Schneider Electric

Direction Scientifique et Technique,
Service Communication Technique
F-38050 Grenoble cedex 9
Fax: 33 (0)4 76 57 98 60

Transl: Lloyd International - Tarporley - Cheshire - GB.
Edition: Schneider Electric.
Printing: Imprimerie du Pont de claix - Claix - 1000.
- 100 FF-

17177

05-2001