Key Aspects of High Voltage Industrial Network Design

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Introduction

Faced with increasingly furious competition, manufacturers need to enforce highly rigorous management and manufacturing facilities need to be highly available. Electrical networks provide the energy needed to operate the production facilities. The provision of an uninterrupted power supply to loads is strived for from the beginning of the network design, especially during preliminary design of a single line diagram. Reductions in electrical installation and operating costs, together with reliable uninterrupted operation, are key profitability conditions. This technical and economic optimization asks for comprehensive preliminary assessment that includes:

- Specific requirements and constraints related to the industry type;
- Integration of the limits and constraints of the public distribution network;
- Standards and local regulations; and
- Particularities of the operating staff, facilities manager and maintenance staff.

The scope of this course is limited to the assessment involved in the design of High Voltage (HV) high power industrial networks which have the following main characteristics:

- Total capacity in the 10 MVA range;
- Autonomous electrical energy generation;
- Power supplied by a national transmission or distribution network; and
- Private Medium Voltage (MV) electrical distribution.

Requirements and Main Constraints

Industrial electrical networks must provide electrical energy to all loads, at optimal investment, operating and loss of production costs, considering:

- People safety
- Safety of property
- Power supply continuity
- Network operating ease
- Minimum installation expanses
- Electrical energy optimization (cost / quality)
- Network modifications and future upgrades
- Constraints associated to:
    - The industrial production process

- The electrical process
- The electrical utility
- The climate and geography of the plant location
- Regulations and local practices

Clearly, not all requirements can be optimally met, meaning that the network designer must endeavour to reach the best compromise.

People safety

Principles that must be adhered to include:

- Preventing access to energized elements (protection against direct contact);
- A system to protect against the rise in potential of metal structures (protection against indirect contact);
- Preventing on-load line disconnecting switch actions;
- Preventing grounding of live conductors; and
- Quick fault clearance.

Property safety

Electrical installations should not be exposed to effects that they are not able to withstand. Hence, the selection of materials and devices is of vital importance. Two electrical phenomena need to be considered in order to prevent fire and to limit destructive effects:

- Overcurrent (short-circuits and overloads); and
- Overvoltage.

Implemented solutions need to ensure the following:

- Quick fault clearance and uninterrupted power supply to the unaffected sections of the network (discrimination); and
- Supply of information on the type of initial fault, for fast servicing.

Permanent power supply to loads

Permanent power supply to the loads is mandatory for the following reasons:

- People safety, e.g. lighting;
- Sustained production performance;
- Productivity; and

- Operating convenience, e.g. simplified machine or workshop restart process.

Loads are grouped according to their operating requirements:
- "Normal" loads;
- "Essential" loads; and
- "Sensitive" loads for which absence of power supply is not allowed.

Network operating ease

In order to complete their tasks safely and reliably, network operators need the following:
- An electrical network that is easy to operate in order to act correctly in the case of a problem or a manoeuvre;
- Adequately sized switchgear and equipment, which need minimal maintenance and are easy to fix; and
- Efficient methods of control and monitoring which allow remote control of the network by real time centralization in a single location of all the information relating to the state of the "electrical process", under normal and contingency conditions.

Minimum installation expenses

The minimum installation expenses do not mean the minimum initial cost, but the sum of three separate costs:
- Initial investment cost;
- Operating and maintenance costs; and
- Cost of production losses related to the network design and protection arrangement (used protection system, selection of elements and settings).

Electrical energy optimization

When a plant includes electrical generators, it is mandatory to manage the energy provided by the utility and the energy generated locally. A control and monitoring system allows optimizing the cost of plant power consumption in line with:
- the contract with the power utility (billing rates according to the time, day and season);
- the availability of the plant generators; and
- industrial process demands.

Network modifications and future extensions

When designing an industrial network, it is of vital importance to make a careful evaluation of the plant's future developments, particularly when extensions are foreseeable. Modifications that are liable or due to be made in the future need to be considered in:
- sizing the main power supply elements (cables, transformers, switching elements);
- designing the distribution network; and
- calculating the locations to be reserved for electrical rooms.
Timely planning will result in flexible energy management.

Network upgrades

Electrical energy consumption increases as extensions are made to meet the requirements of new types of manufacturing and more powerful equipment. This makes it necessary to upgrade and/or restructure the electrical network. Better care needs to be taken in network upgrading assessment than in assessment of new installations since extra constraints are involved. These constraints include:

- inadequate electro-dynamic and dielectric strength of existing elements or equipment;
- capacity to provide power to big loads (starting current, dynamic stability, etc.);
- area and height of existing electrical rooms that cannot be modified; and
- imposed geographical location of equipment and loads.

For example, the installation of a three-phase reactor between the old installation and the power transformer increases short-circuit current capacity and therefore utilizes already installed equipment.

Main constraints

Constraints associated with the industrial processes

Apart from the requirements for a high level of uninterruptable power supply in specific industrial processes, those processes also impose limitations:
- Power supply and especially starting of very large motors which drive crushers, grinders, fans, pumps and conveyor belts;
- Power supply to arc furnaces, the arc typically being unstable, which causes short but repeated unbalanced voltage drops (resulting in flicker), and can generate harmonics; and

- Power supply to high capacity electronic equipment (rectifiers, thyristors, etc.) which produce considerable voltage wave deformations (harmonics) in the network and decrease the power factor. This happens in the case of potlines, DC electric furnaces and variable speed devices.

Additionally, certain industrial processes create pollution. They produce particles (dust, gas) that are usually corrosive and can jam mechanisms or decrease the performance of electrical equipment (e.g. dielectric strength) or even cause explosions in the presence of electric arcs.

Constraints associated with the electrical process

During the assessment, it is mandatory to consider different "electro-technical" requirements that all electrical networks must fulfil, especially:

- limitation of short-circuit currents and their duration;
- starting of large motors without unacceptable voltage drops; and
- alternator stability after a disturbance has happened.

Limitations imposed by the electrical power distribution network

Short-circuit capacity - The short-circuit capacity of the upstream network supplying the private network is a decisive element when selecting:

- the structure of the private distribution network;
- the maximum load;
- special loads that are sensitive to voltage drops;

Utility grounding arrangement - The same type of grounding arrangement, as used by the utility, is typically used for the private network but is sometimes not compatible with particular loads. In those situations, it is mandatory to make a separate system with:

- Electrical protection for phase-to-ground faults; and
- Network operating method (fault tracking and/or clearing by operating staff in the case of isolated neutral systems);

Momentary voltage dips or substantial transient single-phase or multiphase voltage drops. The existence of such conditions can cause disturbances, or even production shutdowns and machine damage. These phenomena may end in:

- Operating errors and/or data loss in the industrial process computer systems, management control system as well as scientific calculation errors; and
- Motor mechanical damage. This happens during momentary dips (re-energizing of motors

that are still rotating), since coupling may take place with phase opposition between the mains voltage and the residual voltage created by the motor. This results in very high motor currents, i.e. 4 to 5 times the rated current, and they cause considerable electrodynamic stress.

Overvoltage of external origin, especially lightning strokes.

Value and quality of the supply voltage - The value of the supply voltage affects, to a certain extent, the level of private network voltages. If the power supply is in the High Voltage (HV) range, it may be beneficial to use that voltage level for the plant's main electrical distribution system. Different voltage fluctuations may affect or even stop production equipment operation. Table 1 presents these faults, the causes and consequences, as well as main mitigation actions.

Notes:

Regarding supply voltage quality, frequency fluctuations must be within ±2 % and harmonic voltages must be less than 3 %. Power quality analysers are used for these measurements. These devices measure:

- RMS voltage and current;
- Active and reactive power;
- Short and long power outages;
- Voltage dips;
- Harmonic voltages and currents; and
- Voltage unbalance.

Table 1. Voltage fluctuations, causes, consequences and main mitigation actions

Voltage fluctuations	A few %	5 to 25%	5 to 25%	100%
Duration	1/100 to 1 s	0.5 to 20 s	20 s to 1 hour	0.1 to 0.3 s to 10 to 30 s
Periodicity	YES	NO	NO	NO
Causes	Presence of electric arc furnace	-Starting of big motors -Single or multiphase fault	Absence of voltage regulation in primary substation	Fast and/or slow HV line reclosing system
Consequences	Variations in incandescent lightning (flicker)	Risk of network instability	- motor overload -high risk of network instability	Momentary suspension of power supply to all loads
Main mitigation actions	Use static Var compensation equipment	-change the starting method	Equip the transformers with on-load tap	Use shunt circuit breakers

		-increase protection plan speed	changers	

Geographical and climatic constraints

In order to find the best equipment specifications according to the different installation types, it is mandatory to know the following:

- Maximum and average daily temperatures;
- Relative humidity rate at maximum temperature;
- Maximum wind speed;
- Presence of frost, ice, sand-bearing winds;
- Environment (corrosive atmosphere or explosion risk);
- Altitude;
- Lightning strokes frequency; and
- Problems in accessing the site (transport requirements).

Compliance with standards and local regulations

It is particularly important to be familiar with:

- National and/or international regulations and rules which apply specifically to the industrial equipment; and
- Local practices and regulations.

Key rules for industrial network design

The objective of this section is to explain how the industrial network design process considers all requirements. Since plants are made to work non-stop, any break in the electrical power supply needs to be examined during the analysis phase and the consequences examined in order to define the mitigation measures. The presented method includes two phases:

1 - endeavouring to reach an appropriate technical balance between requirements and limitations.

2 - technical and economic optimization through appropriate application of certain calculations and concepts.

Load survey, load and diversity factors

This is the first important step in designing an industrial electrical network. It needs to define and geographically locate the power requirements.

Load survey

A load survey is mandatory to:

- distinguish active, reactive and apparent power;
- group the power requirements by geographical area depending on the site size; and
- identify, for each location, the "normal", "essential" and "sensitive" loads.

General approximation of load and diversity factors is shown in Table 2.

Table 2. General approximation of load and diversity factors

	Motors	Lighting / Heating	Power outlets
Load factor	0.75	1	**
Diversity factor	0.7 *	1	0.1 to 0.3

* Depends on the process
** Depends on the location

Voltage selection

Voltage selection is determined by the function that is to be completed: transmission, distribution or consumption. In HV electrical networks, the distribution voltage is not necessarily the same as the consumer voltage. For example, 20 kV may be the optimal distribution voltage in a plant from the power flow perspective and the distance of workshops from the main substation, even if the ten largest motor loads need 6.6 kV voltage level.

Reactive power compensation

Typically, the local utility prescribes the minimum power factor (PF) for the client's supply point. Reactive power compensation is typically necessary to comply with this requirement and may be carried out at two levels:

- at the substation level, as global compensation; or
- at the load level, as distributed compensation.

Note: Strong compensation by means of fixed capacitor banks may cause overvoltage. A special case of this is the phenomenon of the self-excitation of asynchronous machines: the capacitors that are associated with an asynchronous motor (distributed compensation) may give rise to very high overvoltage when there is a break in the power supply. This phenomenon can happen when compensation is larger than 90% of the magnetizing current, which is roughly equal to the motor no-load current.

Backup and replacement sources

Backup sources are installed to protect people, e.g. emergency exit route lighting. Replacement sources are installed in order to sustain production facilities service or to provide bigger operating flexibility.

Autonomous electrical energy production

A plant may have its own methods of producing electrical power to supply its "sensitive" loads, for electricity billing rate reasons or when the plant's manufacturing process generates energy (thermal or mechanical). In the case where a utility network has adequate short-circuit capacity and voltage and frequency quality, it is best to operate the autonomous sources and the mains in parallel. In this arrangement, mains help to stabilize the operation of the plant's alternators (voltage and speed). When parallel operation is applied, a system for distributing active and reactive power between the different alternators and the mains needs to be installed.

When severe electrical issues occur in the private network or in the utility network near the plant, instability may occur. It may be mandatory to separate the private network from the utility network (isolated network supplied by the alternators) within an extremely short time (about 0.2 seconds) in order to avoid complete shutdown. Typically, separation of the networks is followed by the disconnection of non-essential loads from the private network in order to avoid overloads.

Division of sources

Certain loads create a high degree of interference in the utility supply network. The division of sources (as shown in Figure 1) is used to separate the fluctuating loads and provides two extra benefits:

- enhanced discrimination between the protection elements, therefore increasing continuous power supply to the other loads; and
- adaptation of the grounding system to suit the loads.

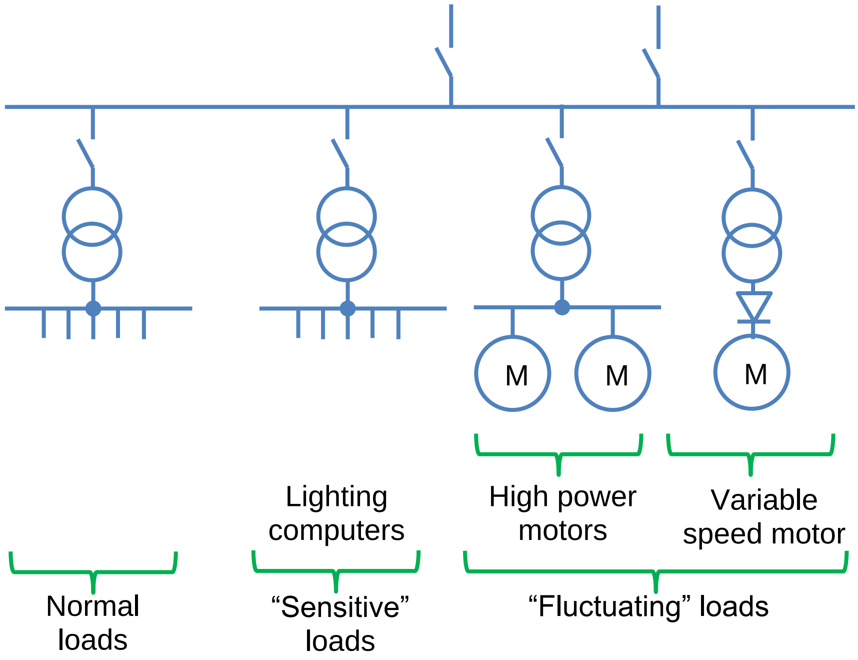

Figure 1. The division of source is a technique of separating the “fluctuating” loads from the other loads

Complete electrical scheme

The network designer uses different elements to define a preliminary structure, which is then fine-tuned in line with the limitations of the industrial site to obtain the "complete single-line diagram" of the plant's electrical distribution system. This is the starting point for technical and economic network optimization.

Validation - technical and economic optimization

Selection of the grounding system

Standards make protection against direct and indirect contact mandatory for all electrical installations. Typically, protection functions automatically interrupt the power supply (upon the first or second phase-to-ground fault according to the selected grounding system). There are also special protection elements made for specific situations. Nevertheless, it is often beneficial to use different grounding systems in the same industrial network, each of which give a predominant benefit.

Feeder definition and selection

Feeders make a considerable portion of the electrical installation’s investment. Hence, it is important, for safety and financial reasons, to:

- Select the best type of equipment (cables); and
- Do the most accurate calculations of the minimum cross section, while considering short-circuit and starting currents, voltage drops, losses, etc.

Insulation coordination studies

Insulation coordination study helps to make the best technical and financial compromise in protecting people and equipment against the overvoltage that may happen in electrical installations, regardless of overvoltage origin (network or lightning). Three overvoltage types may create flashovers and insulation faults:

- power frequency overvoltage (50 to 500 Hz);
- switching surges; and
- atmospheric overvoltage (lightning strokes);

Insulation coordination helps to obtain higher electrical power availability. Proper insulation coordination means:

- Knowledge of the overvoltage level that can happen in the network;
- Defining the required degree of performance or, more specifically, the acceptable insulation failure rate;
- Installing protection elements that are appropriate for network components (insulation level) and the types of overvoltage; and
- Selecting the different network elements based on their level of overvoltage withstand, which must meet the defined constraints.

Protection system definition

Once a fault happens in an electrical network, it may be discovered simultaneously by several protection elements installed in different parts of the network. The objective of selective tripping is to isolate as quickly as possible the part of the network that is impacted by the fault, and only that section, leaving all unaffected areas of the network energized. The network designer must choose a protection system that will allow specifying the most suitable protection equipment. The designer must also make a relay tripping plan, which consists of specifying the appropriate current and time delay settings to be used to get appropriate tripping discrimination. Various discrimination methods are currently used, which use or combine different data and variables such as current, time, digital information, etc.

Current discrimination

Current discrimination is used when short circuit current decreases quickly as the distance increases between the source and the short-circuit point being examined, or between the supply and transformer load sides.

Time discrimination

Time discrimination is used very often in High Voltage networks. Protection equipment (circuit breaker) tripping time delays are increased as the equipment is closer to the source. In order to eliminate transient current effects, the minimum time delay at the furthest point from the source is 0.2 s or even 0.1 s if the current setting is high, with a maximum time delay of 1 s at the starting point of the private network. Time delays may be definite time or short-circuit current dependent.

Discrimination by logical data transmission or logical discrimination

This discrimination is comprised of transmission "blocking signal" of a limited duration. The first protection unit is placed directly upstream of the fault, and is supposed to open the circuit. Other protection elements are placed further upstream. The tripping time delay is short and definite, regardless of the fault position in the network. This increases network dynamic stability and decreases the damaging effects of faults and thermal stress.

Discrimination using directional or differential protection

This discrimination type gives specific protection of a portion or particular network equipment. For example transformers, parallel feeders, loop systems, etc.

Discrimination using distance protection

This discrimination type consists of splitting the network into different zones. The protection elements locate the zone area in which the fault is situated by calculating the circuit impedance. This method is rarely used except when the private HV network is very widespread. A protection system that uses a few discrimination methods is shown in Figure 2.

Short-circuit current calculation

In order to determine the best technical and financial solution, it is essential to know the different short-circuit values:

- Making and breaking capacity according to the maximum peak and RMS short-circuit current;
- Equipment and switchgear resistance to electrodynamic stress, according to the maximum peak short-circuit current; and
- Protection tripping settings according to the maximum and minimum RMS short circuit current.

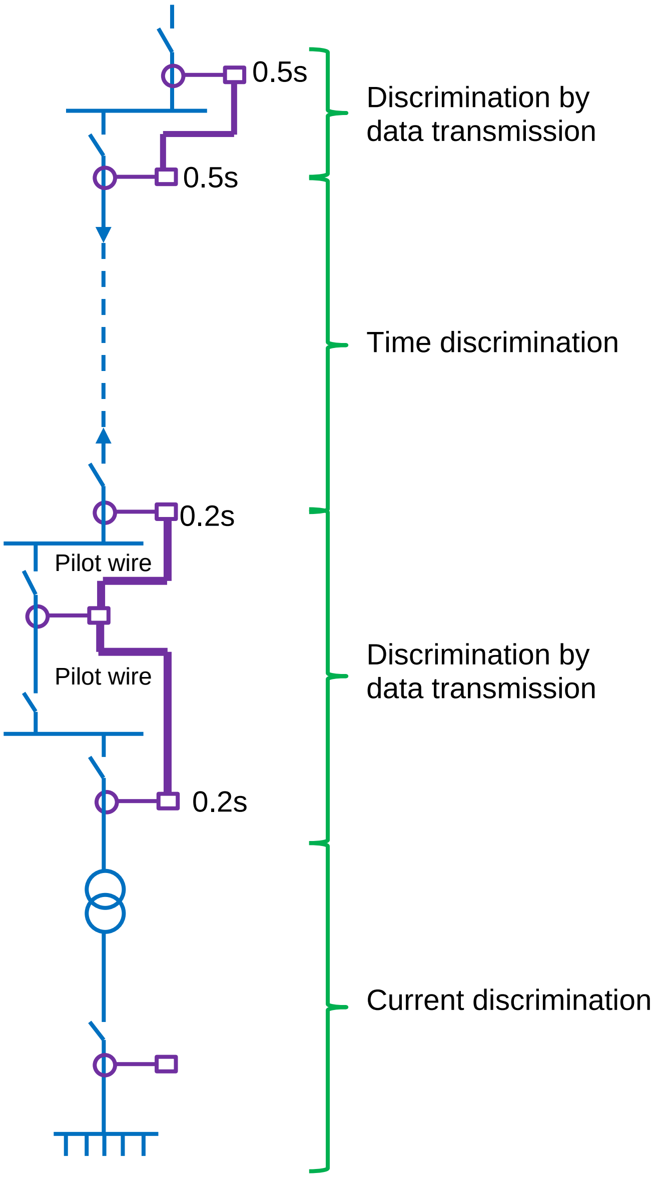

Figure 2. Protection arrangement using several discrimination methods (current, time and logic)

In the case rotating machines (alternators or motors) are part of the system, short circuit currents can be broken down into three categories:

- Sub-transient;
- Transient; and

- Steady-state.

The sub-transient and transient stages are linked to the extinction of the flux built up in the synchronous and asynchronous rotating machines. In these stages, it is mandatory to deal with the aspect of an asymmetrical component, also referred to as a DC component, the damping which depends on the R/X ratio of the upstream network and the fault timing with respect to the phase of the voltage.

Also, it is mandatory to consider motor contribution to short circuit current. When a three-phase short-circuit happens, asynchronous machines are no longer supplied with power by the network, but the magnetic flux of the machines cannot instantly disappear. The extinction of this flux generates a sub-transient and then transient current which intensify the short-circuit current in the network. The total short-circuit current is the vectorial sum of two short-circuit currents: source short-circuit current and machine short-circuit current.

Voltage fluctuation calculations under normal and contingency conditions

Normal operating conditions

A calculation of voltage fluctuations, under normal operating conditions, verifies the voltages throughout the network. In the case network voltages are too low, the network designer needs to check if:

- the active and reactive power flows are as expected;
- the feeders are properly sized;
- the transformer power ratings are adequate;
- the reactive power compensation scheme is adequate; and
- the correct network structure is applied.

Contingency conditions

It is mandatory to determine voltage fluctuations under contingency conditions in order to check if the following phenomena will result in excessive voltage drops or rises:

- Starting of big motors (as shown in Figure 3);
- Downgraded network operation (e.g. 2 transformers working instead of the 3 intended for normal service); and
- No-load network operation, with or without reactive power compensation.

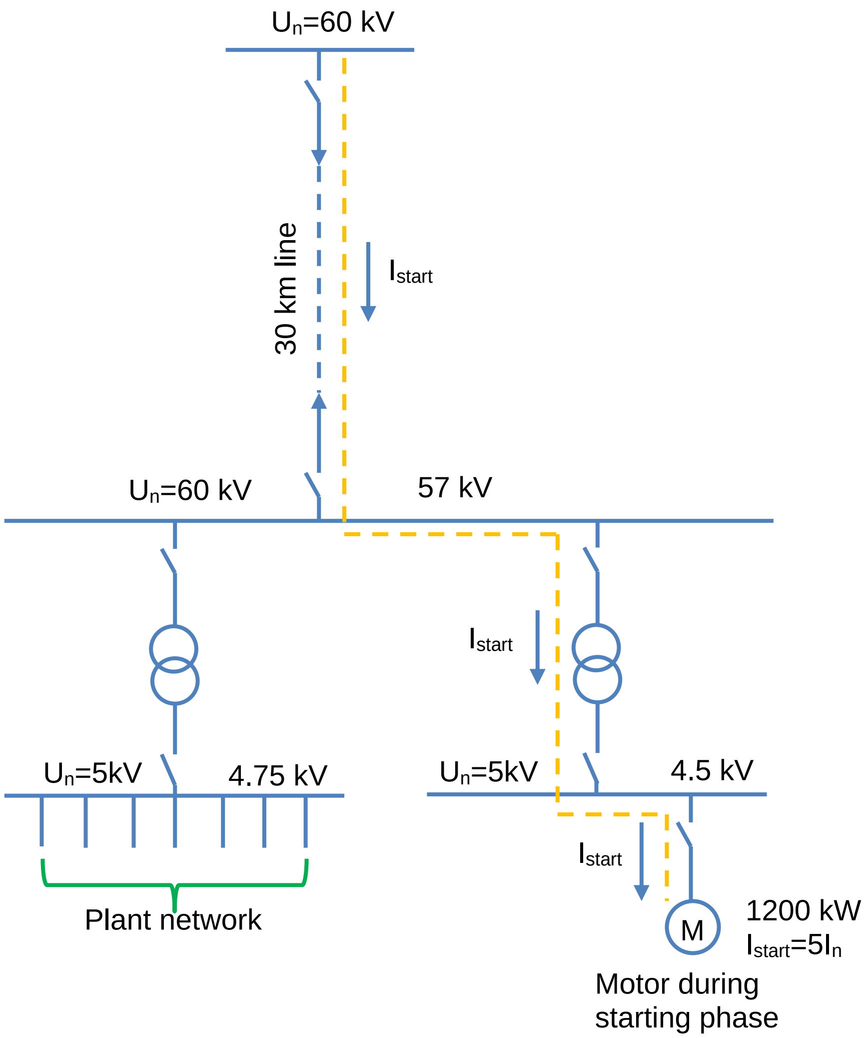

Figure 3. Voltage dips during motor starting for the installation of a 1200 kW motor supplied by a 30 km long, 60 kV line

Selection of motor starting method

The used starting method (delta-star, autotransformer, resistors or stator reactors, etc.) needs to give adequate accelerating torque (accelerating torque is typically higher than 0.15 times the rated torque), and cause acceptable voltage drops (< 15%). The formula governing the interaction of the motor with the driven mechanism is:

$$T'_m - T_r = J\frac{d\omega}{dt}$$

Where:

- T'_m - motor torque when energized at actual supply voltage (U_r);

- T_r - braking torque of the driven machine;

- J - inertia of all the driven masses; and

- dw/dt - angular acceleration;

$$T'_m = T_m \left(\frac{U_r}{U_n}\right)^2$$

- Where Tm is the motor torque when energized at rated voltage (U_n)

$$T_a = T'_m - T_r$$

- Where T_a is the accelerating torque.

The curve showing T_a as a function of speed is given in Figure 4 below. Table 3 presents the most frequently used starting techniques.

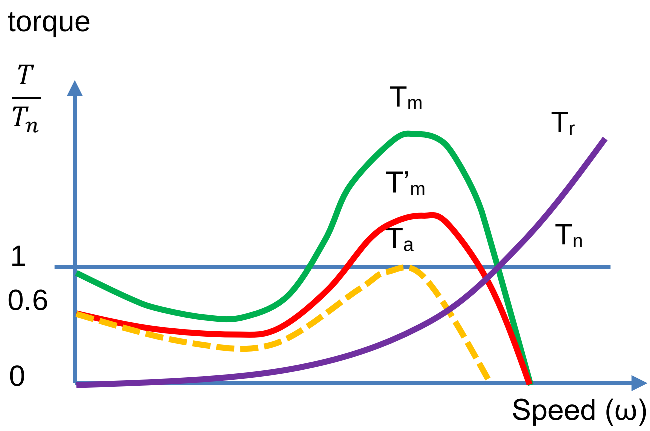

Figure 4. Scheme of different motor torques according to speed, with a voltage drop of about 15% (Tm'=0.7 Tm) and breaking torque TR=0 during starting.

T'_m – motor torque when energized at the actual supply voltage (U_r);

T_r – breaking torque of the driven machine;

T_m – motor torque when energized at the rated voltage (U_n); and

Ta – accelerating torque.

This voltage drop would not allow the motor to be started with $T_r > 0.6T_n$ when started, since $T_r > T'_m$

Table 3. Typically used motor starting techniques

Application	Application characteristics	Starting technique	Advantages/ Disadvantages
Continuous or virtually continuous process starts ≤1 per day	Equipment that requires strong starting torque	Direct	Simplicity, lower investment. Upon starting: -Strong torque -High inrush current -Strong mechanical stress
Frequent starts >1 per day	Motors with low inrush current or low power	Direct	
Pumps, fans,	Equipment that	Stator-reactor	Reduction of torque and

compressors, frequent starts	starts with weak torque		inrush current upon starting (adjustment possible)
Optimization of starting characteristics	When starting current needs to be decreased while maintaining the torque needed for starting	Stator-autotransformer	Optimization of torque (decreased) and inrush current upon starting (adjustment possible)
Optimization of strong torque starting characteristics	The most difficult starts	Rotor	Low inrush current and strong starting torque

Network dynamic stability

Under normal operating conditions, all the rotating machines (motors and alternators) make a stable system with the utility network. This balance may be impacted by a problem in one of the networks (utility or private) such as big load fluctuation, a change in the number of transformers, lines or supply sources, multiphase fault, etc. This leads to either short-lived instability, in the case of a well-designed electrical network, or a loss of stability in the case disturbing accident is very severe or in the case the network has a low recovery capacity (e.g. low short-circuit capacity).

Asynchronous motor operation in the presence of a three-phase fault

Assessment of asynchronous motor performance, in the presence of a three-phase fault, is shown in Figure 5.

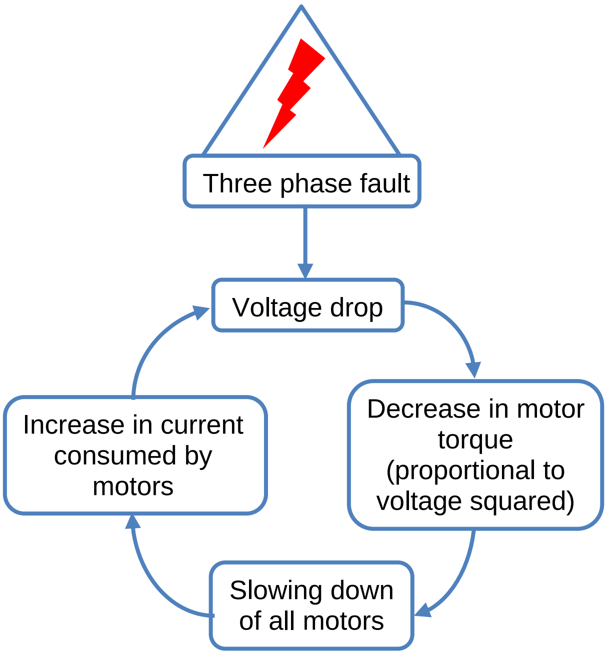

Figure 5. Asynchronous motors operation in the presence of a three-phase fault

After the fault has been cleared, two scenarios may occur:

- The motor torques are higher than the braking torques, in which case the motors can reaccelerate and return to their stable state; or

- The motor torques are lower than the braking torques, in which case the motors continue to decelerate, drawing large currents which are taken by the motor and/or network protection equipment, which trip associated circuit breakers

Motor reacceleration is favoured by:

- An appropriate load shedding plan (tripping of normal, non-essential motors in the case of severe faults);

- A powerful network (properly regulated alternators and low voltage drop); and

- Fast-operating protection equipment which decrease the duration of motor slowdown (e.g. logical discrimination).

Appropriate network structure with:

- Separation and regrouping in separate circuits of normal, nonessential loads and essential and sensitive loads, which facilitates load shedding; and

- Minimal impedance connections for essential and sensitive loads so as to limit voltage drops.

The duration of the return to normal motor speed depends on:

- Motor accelerating torque, and therefore voltage drop; and

- Rotating machine inertia.

Software tools can be used to assess the dynamic performance of electrical networks, making it easier to make the correct decisions, especially, when establishing the procedures to be used to separate power supply sources (creation of "isolated systems"), nonessential load shedding arrangements and protection logics (logical discrimination for very short tripping times). All of these elements contribute to maintaining the network dynamic stability when disturbances happen.

In the case disturbance is minor (two-phase short-circuit far from the load), stability is restored by speed and voltage regulators. In the case there is a high risk of instability, it is mandatory to include protection equipment that will clear the fault within a very short time (0.2 to 0.3 s) and/or equipment to divide the network so as to sustain it (load shedding) and avoid the risk of a complete shutdown (as shown in Figure 6).

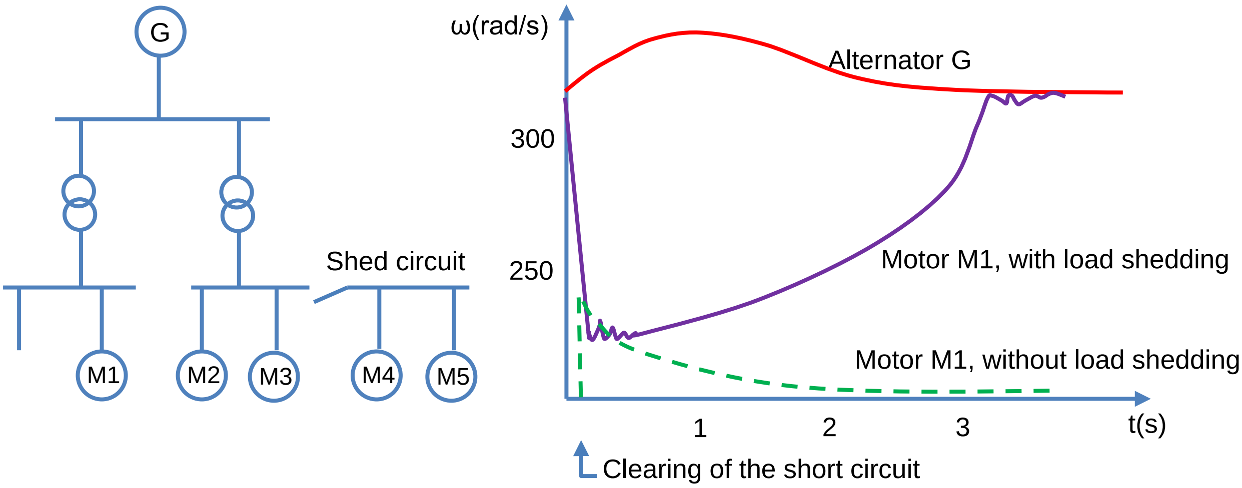

Figure 6. Network dynamic performance with and without load shedding

Selection of optimal network configuration and operation

Various network configurations are possible, the most typical of which are described in this section together with the main areas in which they are used.

The selection of a network configuration, which is always a decisive factor in terms of energy availability, is typically a difficult one to make. The most rational method consists of making a fast comparison of the unavailability of voltage at a particular point in the network for different configurations.

Standard network structures

Open or closed loop, also known as "primary loop system" is shown in Figure 7.

This configuration is suggested for very widespread networks, with considerable future extensions. Open loop operation is suggested.

Double radial feeder, also known as "primary selective system" (manual or automatic) is shown in Figure 8.

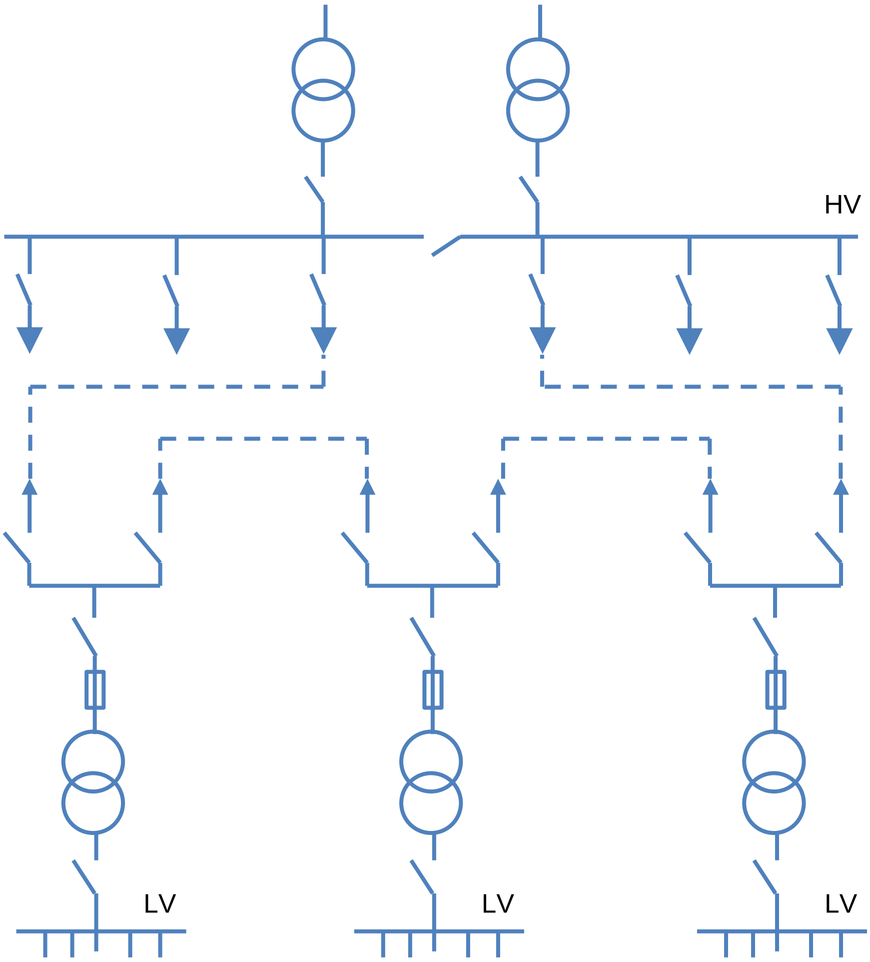

Figure 7. Primary loop scheme

A primary selective system is recommended for very widespread networks with limited future extensions demanding a high level of continuous power supply.

Radial feeder, also known as "single power supply", shown in Figure 9, is suggested when continuous power supply demands are limited. Typically, it is used for cement plant networks.

Dual power supply, shown in Figure 10, is suggested when a high level of continuous power supply is needed or when the operating and maintenance teams are small. It is typically used in the steel and petrochemical industries.

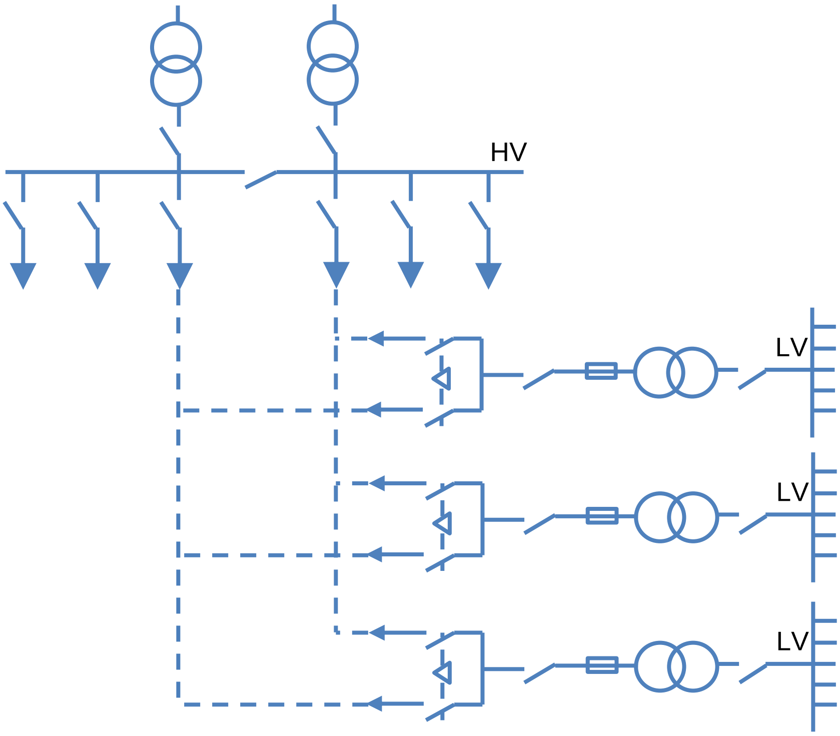

Figure 8. Primary selective network scheme

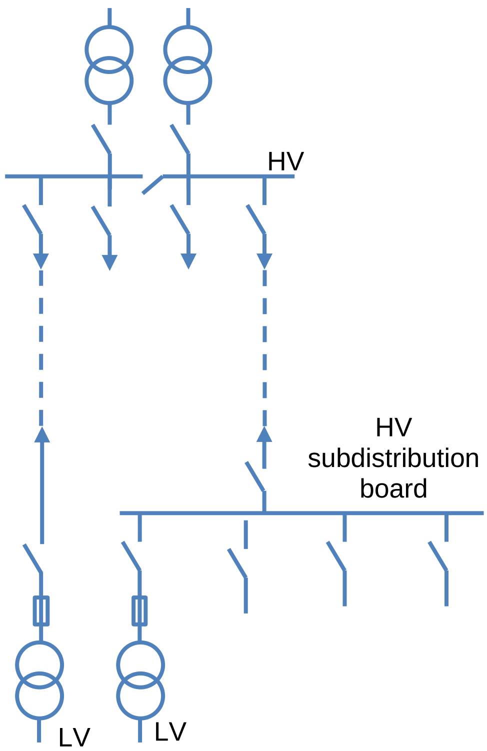

Figure 9. Single power supply network scheme

Dual busbar configuration is shown in Figure 11. It is suggested when a very high level of continuous power supply is needed or when there are very strong load changes. The loads may be distributed between the two busbars without any cut in the power supply.

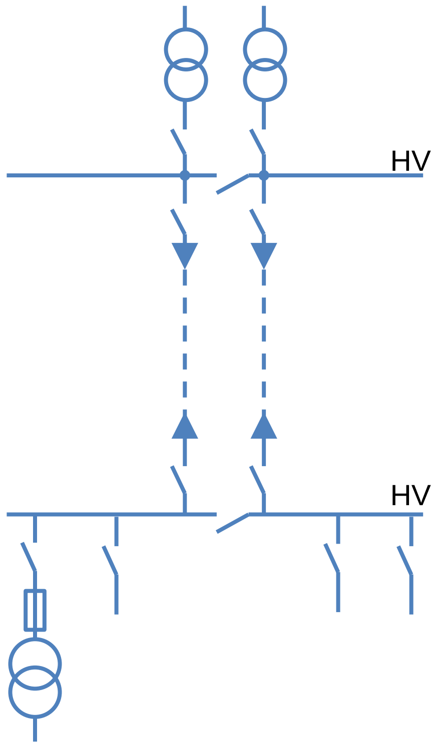

Figure 10. Dual power supply network scheme

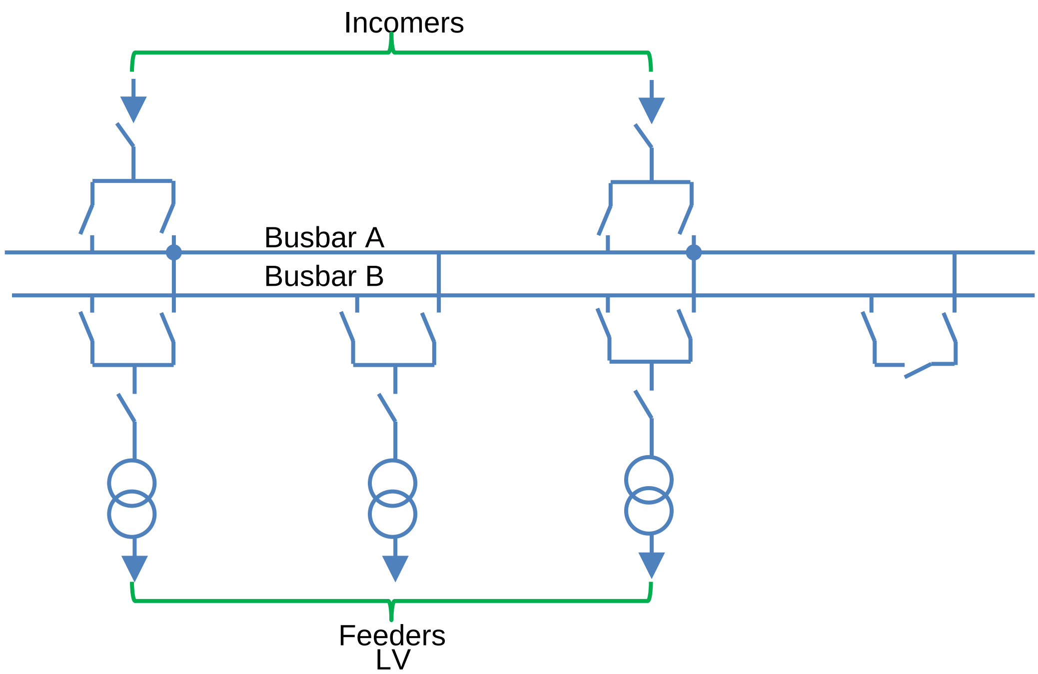

Figure 11. Dual busbar network scheme

A scheme with energy generating sets is shown in Figure 12. This is the simplest structure which is commonly used. Variation of this scheme with replacement source and load shedding is shown in Figure 13. This is a common configuration for an industrial network in which a high level of continuous power supply is needed using a single power supply source, i.e. the utility.

Figure 12. Scheme of a network with local generation

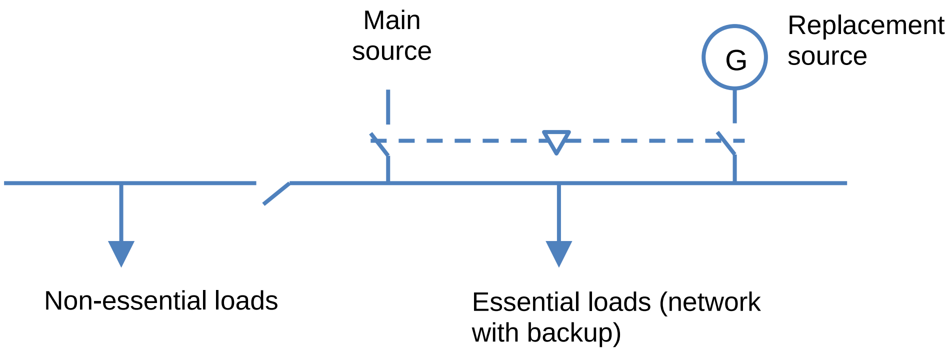

Figure 13. Scheme of a network with a replacement source and load shedding

Configuration example

Configuration shown in Figure 14 was made for a mine. It includes various network structures. The power supply to the different workshops is secured by a loop, a duplicate feeder, or a main source and replacement source.

Equipment selection

Regardless of the selected configuration, the equipment must comply with:

- Standards;
- Network characteristics;
- Rated current and voltage;
- Short-circuit current (making and breaking capacity, electrodynamic and thermal withstand);

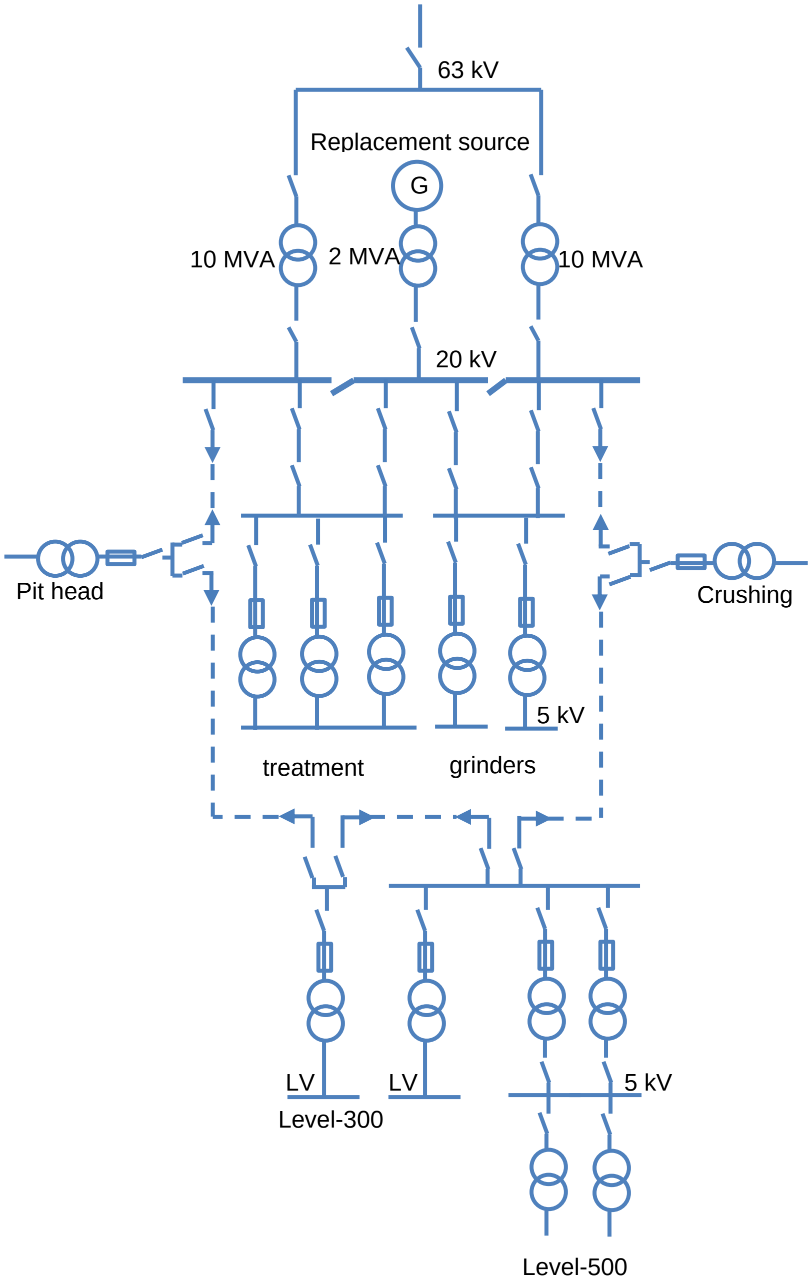

Figure 14. Electrical network configuration of a mine

- The required characteristics (fault breaking, breaking in normal operation, frequency control, circuit isolation, etc…);
- Permanent power supply demands (fixed, disconnectable, withdrawable switchgear);
- Operating and maintenance staff qualifications (interlocks, different degrees of automatic control, breaking methods requiring maintenance or maintenance-free); and
- Demands related to maintenance and possible upgrades and extensions (extra space for future use, modular system, etc.).

Optimal operation

Optimal system operation considers finding:
- The best level of continuous power supply;
- Minimum energy consumption cost; and
- Optimization of the operating and maintenance methods which contribute to proper network service, both steady state and transient, and in the presence of a fault.

The solution is implementation of an electrical Energy Management System (EMS) for the complete network. The Energy Management Systems make full use of microprocessor performance. These elements, installed in local and remote management centres and in the protection and control gear, are foundation of the concept of "decentralized intelligence". The term "decentralized intelligence" means that the control centres and equipment autonomously complete their assignments at their levels and do not call upon the "upper" level except when faults happen. The remote monitoring and control system permanently informs the network manager or user of changes. This highlights the importance of clearly defining the network configuration.

Energy Management System

Energy Management Systems (as shown in Figure 15) are set up in four levels:
- Level 0: sensors (position, electrical variables, etc.) and actuators (trip units, coils, etc.)
- Level 1: protection and control elements, e.g. HV cubicle
- Level 2: local control, e.g. a HV/LV substation of a plant or LV switchboard in a workshop
- Level 3: remote control of an complete private network

These devices, especially levels 1 to 3, are linked by digital communication buses (networks via which the information is transferred).

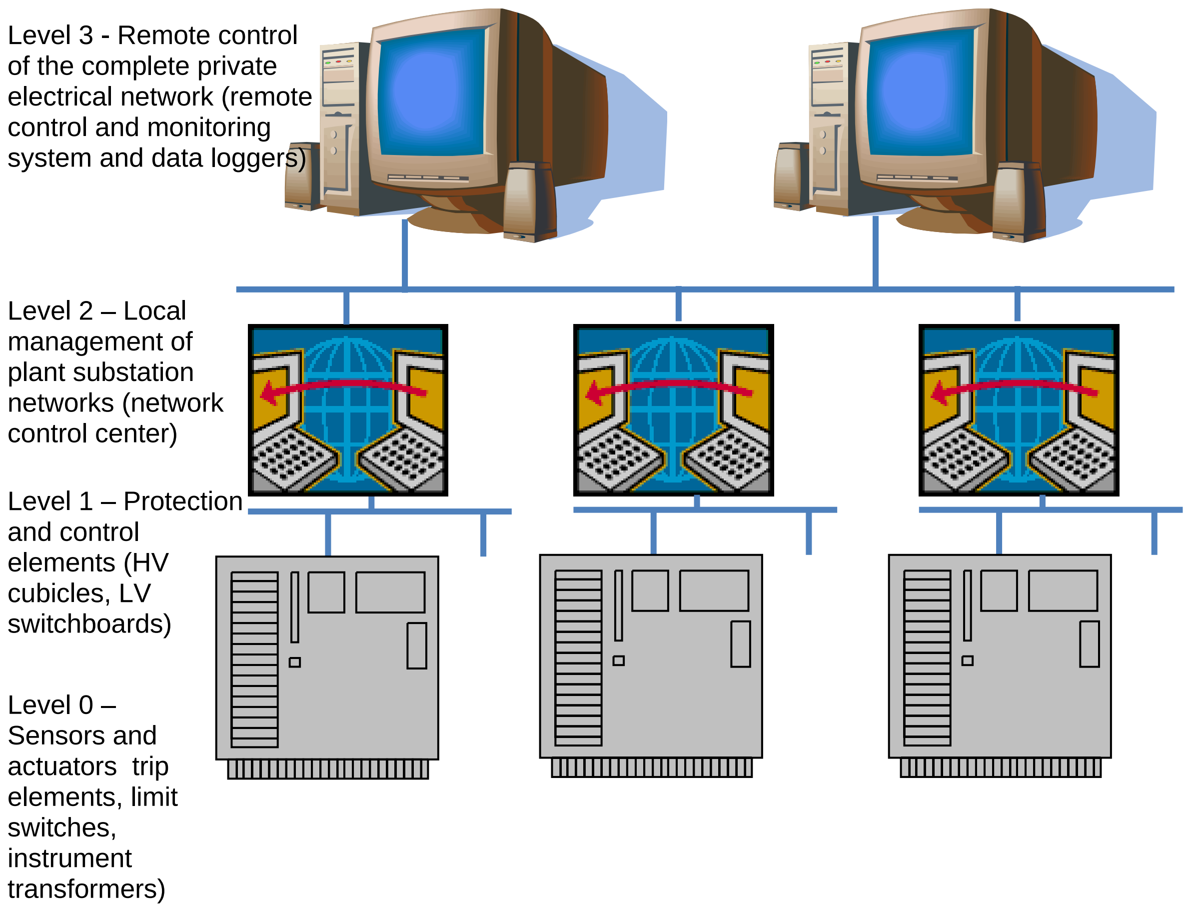

Figure 15. Typical Energy Management System (EMS) architecture

Energy Management Systems Actions

These actions include managing energy supply and consumption according to:

- Subscribed power;

- Utility billing rates;

- Availability of the private generating station; and

- Industrial process demands

Additionally, the actions included maintaining permanent power supply through:

- Fast, discriminating protection (e.g. logical discrimination system)

- Automatic power supply source changeover

- Effective load shedding/reconnection, the options of which can be set via the man/machine interface with the establishment of load shedding plan (load shedding/reconnection plan)

- Sequential workshop restarting

- Adjustment of voltage, power factor, etc.

- Securing power supply to essential loads during outages of the utility supply

- Allowing man/machine interface
- Real time display of network and equipment status via mimic schemes (single-line diagrams, detail diagrams, curves, etc.)
- Remote control of switching equipment
- Data and measurement logging
- Chronological recording of faults and alarms (10 ms)
- Recording and saving of events
- Metering, statistics
- Archiving

All of this information is used to plan corrective maintenance and create "User Guide" booklets which:

- Prohibit the starting of certain motors according to the power available from the generating station, the time, or the degree of priority of the motors;
- Prohibiting the use of particular High Voltage switchboard power supply configurations;
- Suggesting the most appropriate backup configuration for severe faults in a main feeder or a generator; and
- Suggesting operating instructions and maintenance procedures (electrical, mechanical, etc.).

Benefits of an Energy Management System

The development of level 1 digital protection and control systems and the fast rise in the characteristic/cost ratio of hardware and software (level 2) gives technical and financial advantages, especially:

- Improved operating dependability
- A wider range of accessible characteristics, particularly data logging, preventive maintenance and remote control
- Easier commissioning and more effective operation

A well-designed electrical network allows optimal service under normal and contingency conditions. The best cost does not always mean the minimum capital investment, but rather the design of an electrical network which proves to be the most affordable from the viewpoint of initial investment, operating costs and production losses. The best operating conditions give a level of permanent power supply to loads which is compatible with installation requirements, in the aim of getting maximum productivity and maximum people safety. The new generations of electrical equipment are made to communicate, via digital communication buses, with several control centres. And it is the mix of the energy network and the information network, which gives optimal fulfilment of clients' requirements.

Example: Extension of an existing industrial network

The extension of an existing industrial network by installing a power transformer that can be connected in parallel to the existing power transformer has the disadvantage of increasing short-circuit current strength. In that case, it is also necessary to increase:

- The breaking and making capacity of the existing equipment; and
- The old installation's resistance to electrodynamic stress.

The installation of a three-phase reactor between the old and new equipment eliminates these problems (as shown in Figure 16).

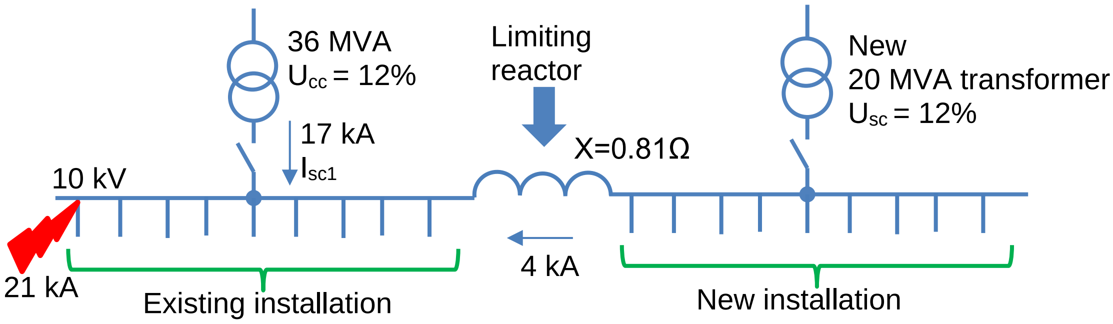

Figure 16. Extension of an existing industrial network by installing an extra power transformer

Input information:

- Short-circuit current of the existing equipment: 17 kA (I_{sc1}); and
- Short-circuit current in the existing busbar must be limited to 21 kA (I_{sc2}), $X_{Tr} = 0.63\ \Omega$.

The current going through the reactor needs to be equal to:

10 kV

$$21 - 17 = 4\ kA = I_{SCL}$$

$$I_{SCL} = current\ limited\ by\ the\ reactor = \frac{V}{X}$$

$$X = total\ reactance\ (20\ MVA\ transformer\ and\ limiting\ reactor)$$

$$X = \frac{V}{I_{SCL}} = \frac{10000}{\sqrt{3} \times 4000} = 1.44\ \Omega$$

$$X = X_{react} + X_{Tr}$$

$$X_{Tr} = 0.63$$

$$X_{react} = 1.44 - 0.63 = 0.81\ \Omega$$

Computerized means used for network assessment

Different software calculation tools are available on the market, however all of them need to provide vital calculation functions such as:

- Load flow study module;
- Short-circuit current module;
- Voltage drop module;
- Network dynamic stability module;
- Harmonic currents and voltages module;
- Lightning and switching voltage surges module;
- Transformer and capacitor switching module; and
- Unavailability of electrical power supply module;

High level principle of reactive power compensation

The overall principle of reactive power compensation using capacitors may be presented by the following two figures.

- Figure 17 presents the vectoral composition of the different currents and for a given active current, the reduction in the total current in the conductors.

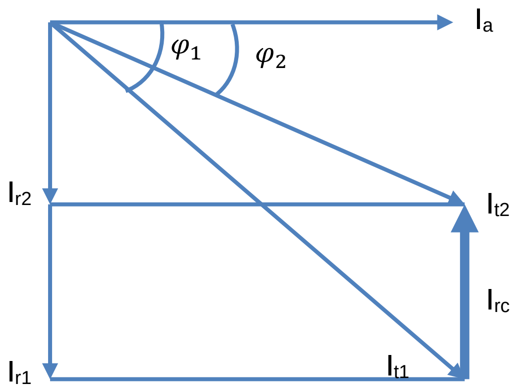

Figure 17. Phasor diagram of the currents and the effect of compensation

Where,

I_a = active current consumed;

I_{t1} = total current before compensation;

I_{r1} = reactive current supplied via the transformer before compensation;

I_{t2} = total current after compensation;

I_{rc} = reactive current supplied by the capacitor; and

I_{r2} = reactive current supplied by the transformer after compensation ($I_{r2} = I_{r1}-I_{rc}$).

- **Figure 18** presents the local reactive power exchange which takes place between the load and the capacitor. The total current supplied by the network I_{t2} is decreased and the output is improved since losses due to the Joule effect are proportional to the square of the current.

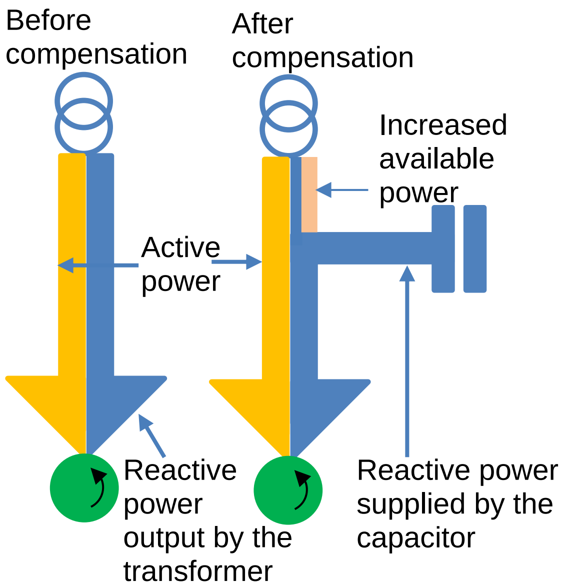

Figure 18. Diagram showing the energy exchange in a consumer circuit and the benefits of reactive power compensation

Selection of the grounding arrangement in a HV industrial network

Selection of the grounding arrangement for a high voltage industrial network involves the following considerations:

- General policy;
- Legislation in effect;
- Network constraints;
- Network operation constraints; and
- Type of load constraints.

Several different grounding configurations can be considered:

- Directly grounded neutral;
- Reactance- grounded neutral;
- Resonant- grounded neutral;
- Resistance- grounded neutral; and
- Isolated neutral.

Each of these grounding arrangements provides benefits and drawbacks with which the network designer needs to be familiar before making the final selection. A summary of these characteristics is provided in Table 4.

Table 4. Benefits and drawbacks of the various grounding arrangements used for a HV industrial network

Directly grounded neutral diagram	Benefits	Drawbacks	In practice
Directly grounded neutral	-Facilitates ground fault detection and protection discrimination -Limits overvoltage	Causes high ground fault currents (dangerous for people and risk of major equipment damage)	Not used
Reactance-grounded	Limits ground fault currents	-Requires more complex protection than direct grounding -May cause dangerous overvoltage, depending on installation arrangements	Applicable without any special precautions only if the limiting impedance is low with respect to the circuit's ground fault resistance
Resonance-grounded	Is conductive to self-extinction of ground fault current	Requires complex protection (directional devices that are difficult to implement	Rarely used
Resistance-grounded	-Limits ground fault currents -Facilitates ground fault current detection and protection discrimination -Limits overvoltage		The most beneficial for industrial distribution: It combines all the benefits
Isolated from ground	Limits ground fault currents	-Risk of overvoltage -Requires the use of over-insulated equipment (line voltage between phase and ground when a zero impedance fault happens) -Overvoltage protection advisable -Insulation monitoring obligatory -Complex	No tripping when the first ground fault happens entails: -Begin granted special dispensation -That the capacitance between active network conductors and ground do not cause ground fault current that is dangerous for people and equipment

Directly grounded neutral diagram	Benefits	Drawbacks	In practice
		discrimination between ground fault protection equipment	

Network voltage drops

Voltage drop in a network can be determined using the following mathematical formula:

$$\Delta V = R\,I\cos\varphi + X\,I\sin\varphi$$

The electrical diagram and vector diagram which correspond to this formula are presented in Figure 19.

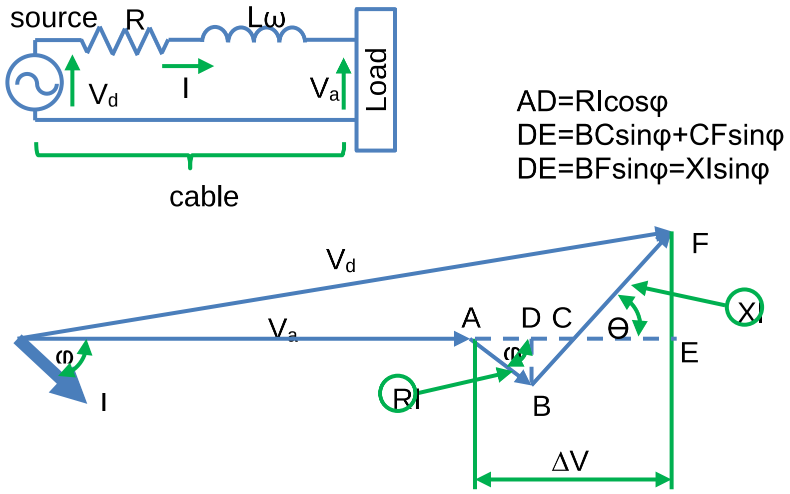

Figure 19. Voltage drop phasor diagram

Industrial network design stages

This logic diagram contains two loops:

- The first one, the analysis and selection loop, starts at "Needs and constraints to be met" and leads to the organization of a network structure in an "Overall single-line diagram".

- The second loop is aimed at structure optimization.

Industrial network design logic diagram is presented in Figure 20.

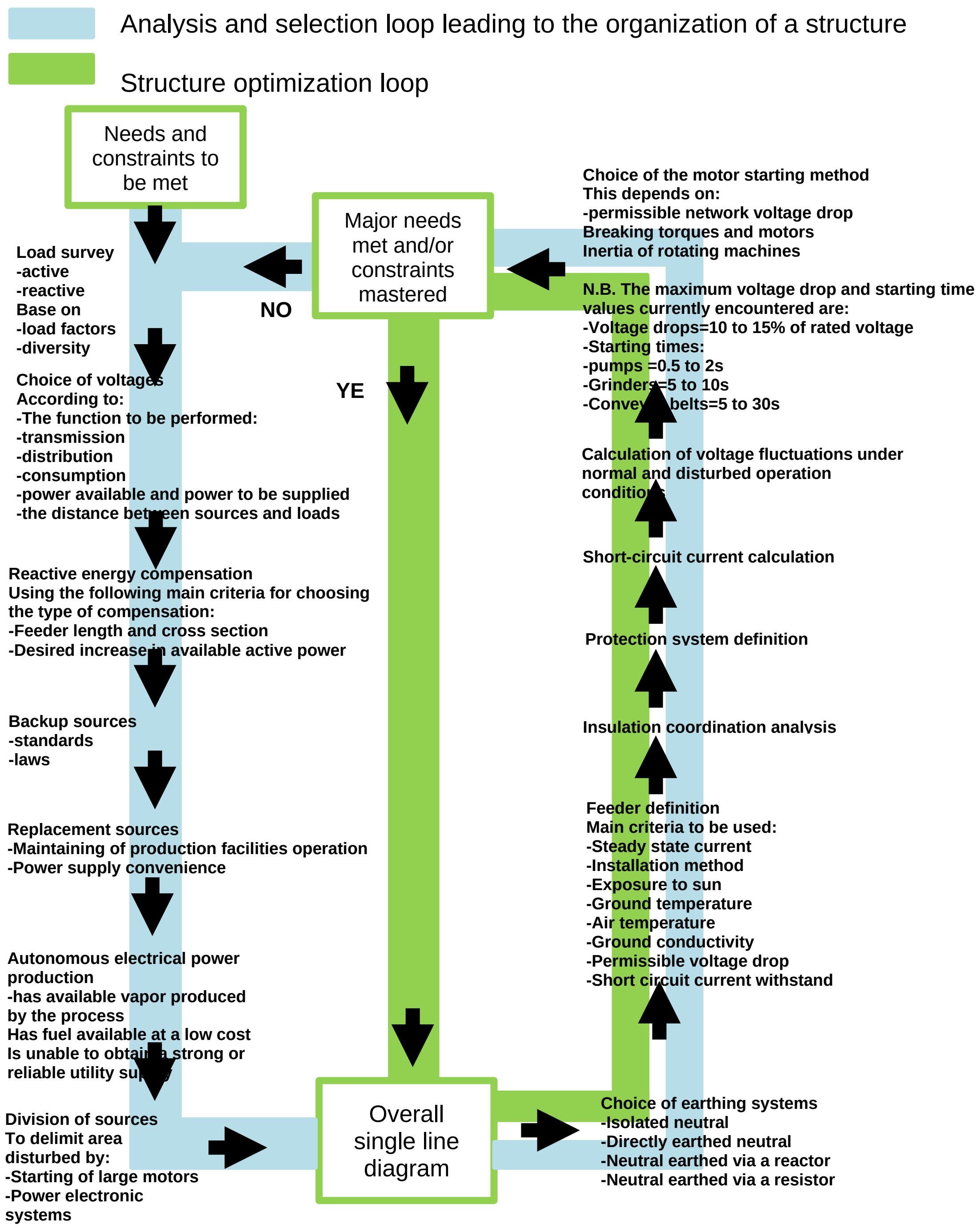

Figure 20. Industrial network design logic diagram

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- Cahier Technique Merlin Gerin n° 169
- Protection of electrical distribution networks by the logic selectivity system Cahier Technique n° 2
- Lightning and HV electrical installations, Cahier Technique n° 168