13. Electrical network design methodology and application example
13. ELECTRICAL NETWORK DESIGN METHODOLOGY AND APPLICATION EXAMPLE

The profitability of an industrial installation is directly linked to the availability of the production tool.

Electrical networks supply the energy required for the production tool to operate. Thus, continuity of supply to loads is studied when the network is being designed and especially when the preliminary choices for the single-line diagram are being made.

The aim of designing an electrical network is to determine the electrical installation which will meet the requirements of the industrial process for the least investment, operation and failure cost.

The design methodology of a network has six main stages.

- **collection of data** (stage 1)

  This involves:
  
  - identifying problems, needs to be met and obligatory requirements
  
  - collecting the elements required for designing the network and defining equipment.

- **preparation of the preliminary single-line diagram** (stage 2)

  This involves preparing a single-line diagram which meets needs and obligatory requirements and which takes all the data into account.

- **technical studies and single-line diagram validation** (stage 3)

  This involves a validation and technical/economic optimisation study of the planned structure taking into account all the data and hypotheses. It requires network calculations (short-circuit currents, load flows, etc.) to be carried out.

- **choice of equipment** (stage 4)

  Once the single-line diagram has been validated, the equipment is chosen and sized using the results of the calculations carried out during the previous stage and the data collected during stage 1.
**choice and setting of protection devices** (stage 5)

This involves defining the protection devices allowing faults to be detected and cleared and protection settings to be determined.

**choice and installation of a control and monitoring system** (stage 6)

This involves choosing the structure of the control and monitoring system that will enable users to control and monitor the network and which will include automatic processes optimising the cost and availability of energy:

- source changeovers
- load-shedding/restoration
- automatic reconfigurations of distribution loops
- etc.
13.1. **Collection of data** (stage 1)

The maximum amount of data enabling the network to be designed and equipment to be defined must be collected.

13.1.1. **Environmental conditions**

The characteristics of equipment are given for standard environmental conditions. Knowing the parameters relating to the real conditions of the site will enable the designer to introduce correction or derating factors for equipment.

From among the environmental conditions, the designer will be concerned by:

- risks of explosion in the presence of gas or atmosphere-inflammable products, which determines the degree of equipment protection
- earthquake risks
- altitude
- average and maximum temperatures
- soil thermal and electrical resistivity
- presence of frost, wind and snow
- lightning density level of the region for the protection of the installation against lightning (see § 5.1.3)
- atmospheric pollution (dust, corrosion, humidity rate)
- site regulations (building frequented by public, high building, etc.).

13.1.2. **Classification of loads**

This involves listing the installation's loads by classifying them per type:

- motor
- lighting
- heating
- etc.

for which the following must be known:

- nominal powers (active, reactive and apparent)
- powers actually absorbed
- \( \cos \phi \)
- efficiency
- operating transients (motor starting, etc.)
- emitted and tolerated disturbance levels (harmonics, unbalance, flicker, interruptions, etc.).
13.1.3. Geographical or functional attachment of loads

It is necessary to record loads in relation to the factory layout plan and their respective roles in the industrial process.

Indeed, through their geographical position in the factory, or their attachment to a functional assembly, loads can be grouped together naturally.

For example:

- a chemical unit
- a production workshop
- a steam generator
- a waterworks
- etc.

Once they have been grouped together, it is necessary to determine the environmental conditions linked to the operation of these loads.

**Note:** load groupings may be imposed in order to carry out energy sub-metering.

13.1.4. Load operating conditions

To carry out a power analysis, it is necessary to specify the operating conditions of different loads.

There are three main operating cases:

- loads which operate **continuously** throughout installation operation time
- loads which operate **intermittently** in relation to installation operation time
- load which do not operate during normal circumstances and which **back up** loads whose operation is vital for safety reasons and possibly for the industrial process.
13.1.5. Disturbances generated and tolerated by loads

Some loads cause disturbances on the internal network, if not on the utility network.

The designer must therefore record the level of disturbances caused by each load (see § 3) in order to plan the means of reducing them to an acceptable level for the entire electrical installation.

The level of disturbance tolerated by electrical equipment must therefore be recorded. These levels are not always known or supplied by manufacturers. On the other hand, IEC standard 1000-2-4 defines the electromagnetic compatibility level on industrial networks (see table 3-1). It provides the disturbance level generally acceptable for medium and low voltage equipment.

13.1.6. Future extensions

The exact knowledge of extension possibilities of all or part of the installation allows the designer to take them into account notably:

- for sizing cables, transformers, circuit-breakers, etc.
- for choosing the distribution network structure
- for estimating the surface areas of premises.

13.1.7. Classification of loads by importance

The consequences of a supply interruption with respect to safety of persons and equipment and production may be serious.

Thus, it is important to define the maximum interruption time for each category of loads and as a result choose the appropriate supply restoration mode.

Loads can be placed in three large families:

- loads unable to withstand any interruption
- loads requiring restoration times which cannot be met by human intervention
- loads having restoration times compatible with human intervention
For the first category of loads, it is necessary to have a highly reliable autonomous source:
- an uninterruptible power supply (UPS) (see § 1.6.3)
- a no-break generator set (see § 4.1.2).

This is the case of loads such as:
- automatic process control system
- computer systems.

For the second category, the maximum interruption time may vary from several tenths of a second to several dozen seconds. In this category there are:
- loads which only tolerate short supply interruptions or fast source changeover; which corresponds to the time required for switching to a back-up source or permanent internal source \( (t < 1\, s) \)
- loads which tolerate supply interruptions compatible with delayed automatic reclosing or automatic starting of a back-up source (automatic load-shedding/restoration system: \( t < 20\, s \)).

For the third category, the interruption time is generally greater than one minute, which remains compatible with manual intervention for network reconfiguration or starting of a back-up source.

13.1.8. Public network requirements

At the take-over point, the public network imposes certain requirements which may be decisive for the preliminary choices for the factory internal network structure.

- **short-circuit power and supply voltage available from the utility**

The short-circuit power required at the take-over point depends on the installation power, the power of large loads and the disturbances generated and tolerated by the installation.

The short-circuit power greatly depends on the take-over voltage level.

Because of this, it plays a determining role in the choice of factory internal network structure.
utility power supply characteristics

The main characteristics of the voltage supplied by a medium and low voltage public distribution network in normal operating conditions are defined by European standard EN 50160.

The purpose of this standard is to define and describe the values characterising the supply voltage, i.e. (see table 4-1):

- frequency
- magnitude
- wave form
- symmetry of the three-phase voltages.
13.2. Preparation of the preliminary single-line diagram (stage 2)

Using the data collected, a first single-line distribution diagram can be drawn up.

13.2.1. Power analysis

This is the first essential stage in studying the design of a network. It must assess and geographically locate the active and reactive power values.

Depending on the size of the site, the installed powers and the way they are shared, the installation will be divided into several geographical zones (3 to 8 zones).

The analysis of active and reactive powers will thus be carried out for each zone with the utilisation factors for each load (see § 6.1.2.) and the coincidence factor for the group of several loads or circuits being applied to the installed powers (see tables 6-1 and 6-2).

13.2.2. Choice of voltage levels

- **choice of utility supply voltage**

  The choice of supply voltage depends on:

  - the installation power
  - the minimum short-circuit power required
  - the disturbances generated and tolerated by the installation
  - the voltage levels available near the site.

- **choice of voltages**

  The choice of voltages inside the site depends on:

  - the site size and power sharing
  - whether or not there are MV loads such as motors, furnaces, etc.

  The choice of two or three voltage levels results in a technical/economic optimisation study which takes into account the advantages and drawbacks of each alternative.
In general, experience shows that:

- for powers up to 10 MVA, two voltage levels (MV, LV) are chosen
- for powers over 10 MVA, choosing three voltage levels may prove to be more economic (HV, MV, LV).

13.2.3. Energy sources

The main source of energy is generally constituted by the public distribution network.

For reasons of safety or service continuity, the main source of an industrial installation is often accompanied by a replacement source.

The different replacement sources possible are listed below.

- **Second utility power supply**

  This solution is advantageous when this second power supply comes from a different utility substation from the one which feeds the first.

  It may nevertheless also be worth using in the case where the two power supplies come from the same utility substation if the outgoing feeders are allocated to different busbars or transformers.

- **Permanent internal source**

  This solution may be chosen for reasons of safety or service continuity depending on the level of quality available on the public distribution network. It may also prove to be a good economic choice:

  - the factory has residual fuel at a marginal cost (incinerating plant, paper mill, iron and steel industry, petrochemical industry)
  - the factory produces steam for the industrial process which can be recovered to produce electrical energy (urban centralised heating).

  Generally, permanent internal sources are used connected with the public distribution network. The connection arrangement must nevertheless enable rapid disconnection of the sources and balance of the loads attached to each one of them respectively.
Connection can be carried out at any level of the distribution network structure, in relation to the following criteria:

- internal source power in relation to the total power
- presence of this source linked to specific needs which have or have not been located
- concentration or dispersion of loads to be saved, etc.

The generator of these internal sources may be driven by:

- a gas turbine
- back pressure steam turbine
- condensing steam turbine
- diesel motor
- etc.

**back-up source**

This equipment allows the vital parts of the installation to be backed up in the event of a utility failure. It is also used to reduce the energy bill by being used during periods when the kWh cost is high.

Generally speaking, these sources do not operate connected to the utility network. Depending on the size of the installations and the powers to be backed up, they may either be installed locally near the loads or centralised in such a way that source multiplication is avoided. In the latter case, these sources are connected to the distribution MV side, if not the HV side. The generators of these back-up sources may be driven by diesel motors or by gas turbines.
- **Power supply sources of substation auxiliaries**

These are the loads which are linked to the electrical distribution such as:

- protective relays
- operating mechanisms carrying out opening and closing of circuit-breakers, switches and isolators
- contact coils of contactors
- switchgear which is linked to the substation control and monitoring system
- air conditioning systems of electrical rooms or switchboards and anti-condensation resistors
- electrical room ventilator
- electrical room lighting
- cooling radiators, fans and tap changers of transformers.

These loads must be supplied by specific sources having a high level of reliability.

If these sources are lost, two operating principles are used:

- substation tripping; this principle makes the safety of persons and equipment a priority
- non-tripping; this principle makes service continuity a priority.

Monitoring the state of these sources is essential.

They generally come from:

- a specific substation auxiliary transformer
- storage batteries
- an uninterruptible power supply (UPS).
13.2.4. Choice of earthing systems

choice of MV network earthing systems

The choice of earthing system in medium voltage is a compromise between the following parameters (see § 2.12.2):

- service continuity
- level of overvoltages generated
- equipment phase-earth insulation level
- thermal stress relating to the earth fault current value
- complexity of protections
- operation and maintenance requirements
- network size.

choice of earthing systems in LV networks

The choice of earthing system in low voltage is a compromise between the following parameters (see § 2.11.2):

- service continuity
- level of overvoltages generated
- risk of an electrically caused fire
- level of electromagnetic disturbances
- design and operation requirements.

There may be a high number of low voltage networks (several dozen); the appropriate earthing system must be determined for each one.
13.2.5. Choice of network structure

The choice of network structure is a determining stage for energy availability.

Among the different possible structures, it is important to base this choice notably on the requirements of availability, on limiting disturbances (voltage dips, unbalance, harmonics, flicker) and on operation and maintenance requirements.

The different structures are described in paragraph 1.

- **HV/MV utility substation structure**

  Depending on the size of the installation and the availability required, the following arrangements are used:
  - single power supply (see fig. 1-2)
  - dual power supply (see fig. 1-3)
  - dual fed double bus system (see fig. 1-4).

- **MV network structure**

  MV distribution inside the site is designed in relation to the availability required for each zone.

  Thus, a distinction is made between the following:
  - single fed radial network (see fig. 1-17). This is used when the availability required is low. It is often chosen for cement plant networks.
  - dual fed radial network (with or without coupler - see fig 1-18 and 1-19). This is often used (with coupler) in the iron and steel industry and in the petrochemical industry for its good availability.
  - loop system (open or closed - see fig. 1-20-a and 1-20-b). This is well suited to widespread networks with large future extensions. The closed loop has a better performance than the open loop. It is, on the other hand, more costly.
  - parallel feeder system (see fig. 1-21). This is well suited to widespread networks with limited future extensions and requiring very good availability.
structure of low voltage networks

Depending on the level of availability required, LV switchboards may be fed by several sources, a back-up generator set or an uninterruptible power supply (see § 1.6).

The parts of the installation that must be fed with a specific earthing system must be fed through a specific transformer (see § 2). Sensitive or highly disturbing loads may require a specific transformer to feed them (see § 3).

13.2.6. Energy management - Choice of optimum tariff rating

Electrical energy utilities offer tariff rating which is adapted both to their production cost and the specific characteristics of users.

The user often does not fully understand his real energy needs and his contract with the utility is often badly adapted to his needs.

A tariff optimisation study always proves to be profitable and allows up to 10 to 20 % to be gained on the energy bill if real "energy management" is implemented, notably with the help of a high performing control and monitoring system (see § 12).

tariff components

Electrical utilities offer their customers supply contracts whose basic characteristics are in essence identical (see § 11).

The energy tariff comprises:

- a standing charge related to the subscribed demand (not to be exceeded). The lower the subscribed demand, the lower the standing charge.

- a charge for active energy consumption in kWh.

- any penalty payments related to power consumption exceeding the subscribed demand.

- an eventual charge for reactive power consumption, in units of kvarh, once its value exceeds the utility's uninvoiced consumption threshold during certain tariff periods (see § 11.4.4).

The different energy cost components vary according to the month of the year, the day of the week and the hour of the day or night, i.e. the tariff periods.

reactive energy compensation

To get over costs relating to an excessive consumption of reactive energy, the designer determines the compensations to be installed (see § 7).
load curves

Daily and seasonal load curves representing the installation's variations in active and reactive power allow:

- tariff rating and reactive energy compensation to be optimised
- the decision whether or not to put the back-up supply into service, notably during peak tariff periods, to be taken
- the power to be shed and the shedding times to be determined in relation to the tariff period.

identifying loads that can be shed

This is a question of identifying loads which can be shed without this having repercussions on the industrial process and the possible load-shedding time.

advantage of installing a generator set to supply the installation during peak tariff periods

The load curve runs, load-shedding possibilities and tariff ratings may be used to determine whether it is useful or not to install a utility supply replacement generator set.

In general, the installation of a replacement generator set is accompanied by an advantageous change in the type of tariff.

The energy cost must be simulated and the following compared:

- annual cost of energy without the generator set
- annual cost of energy with the generator set operating during peak tariff periods.

The energy cost difference will be used to determine whether it is preferable or not to invest in the purchase of a replacement generator set.

The designer must include the maintenance costs of the generator set.

It must be added that the replacement generator set can also, in certain cases, provide the installation with a back-up supply. The investment will thus be all the more worthwhile.
**advantage of installing a cogeneration plant**

In installations simultaneously consuming electrical and thermal energy, a cogeneration plant may prove to be highly profitable. Indeed, recovering the thermal energy produced by a diesel set greatly improves energy efficiency. This can reach 80 to 90 % instead of 35 to 40 % without a recovery system.

In some cases, part of the electrical energy is sold back to the utility.

A technical/economical study must be carried out and it must notably take into account:

- cost of purchasing and selling electrical energy from and to the utility
- cogeneration plant investment and maintenance costs
- gains made through the recovery of electrical energy
- advantage of benefiting from a replacement source.

**Note:** another type of cogeneration exists, i.e. incinerating plants and heating stations. These have thermal energy at a lower cost which can be used to produce electrical energy.
13.3. technical studies and single-line diagram validation (stage 3)

At this stage of the design study, the previously defined structure must be validated using calculations.

This is a repetitive stage insofar as certain pre-defined parameters may be modified to comply with certain standard conditions or provisions. In this case, the calculations concerned will be revised each time to match the changed parameters.

13.3.1. Nominal current calculation

On the basis of the power analysis carried out in paragraph 13.2.1., the nominal currents that flow in each wiring system, transformers and other network elements will be determined.

13.3.2. Choice of transformers

The transformer is chosen on the basis of the maximum power which corresponds to the most heavily loaded day in the year. This power is the result of a power analysis, taking into account the utilisation and coincidence coefficients (see § 13.2.1).

A more accurate method can be used to determine the transformer power based on the installation load curves and transformer overload curves (see IEC 76-2).

Note: it is sometimes worth installing a range of transformers of the same power in order to facilitate maintenance and interchangeability.

13.3.3. Choice of generators

The power of the generators will be determined in relation to the replacement power required or the power to be shed during peak tariff periods.

For use continuously connected to the public distribution network, it may be worthwhile installing an asynchronous generator (see § 4.3)
13.3.4. Determining conductor cross-sectional areas

The detailed conductor cross-sectional area determination method is described in paragraph 6.

The method consists in:

- calculating the maximum design current
- determining the overall correction factor relating to the installation method and conditions
- determining the cross-sectional area necessary for the flow of the maximum design current in normal operating conditions
- checking thermal withstand in the event of a short circuit, with respect to the protective device
- checking voltage drops during normal operating conditions and during starting of large motors
- for low voltage, checking maximum wiring system lengths for the protection of persons against indirect contact, with respect to the protective device and the earthing system
- checking the thermal withstand of cable screens during earth faults in MV
- determining the earthing conditions of cable screens in MV
- determining neutral, protective and equipotential bonding conductor cross-sectional areas.

The cross-sectional area to be chosen is the minimum area meeting all these conditions.

It may be worthwhile to determine the economic cross-sectional area (investment, joule losses - see § 6.3) on the basis of an economic analysis.

13.3.5. Study of earth circuits and earth electrodes

The values of earth circuit and earth electrode impedances determine the overvoltage levels in relation to earth which may appear on electrical equipment (see § 5 and § 2). It is notably useful to make equipotential bonding zones at the bottom of the trench to reduce overvoltages between equipment and earth.
13.3.6. Calculating short-circuit currents (see § 4 of the Protection guide)

All electrical installations must be protected against short circuits every time there is an electrical connection, which is generally when there is a change in conductor cross-sectional area. The short-circuit current value must be calculated at every stage of installation for different possible network configurations. This is done to determine the characteristics of the equipment that must withstand or switch the fault current.

In order to choose the appropriate switching devices (circuit-breakers or fuses) and set the protection functions, three short-circuit values must be known:

- **the root mean square value of the maximum short-circuit current** (symmetrical three-phase short circuit)

  This determines:
  - the breaking capacity of the circuit-breakers and fuses
  - the thermal stress that the equipment must withstand.

  It corresponds to a short circuit in the immediate vicinity of the downstream terminals of the switching device. It must be calculated taking into account a good margin (maximum value).

- **the peak value of the maximum short-circuit current** (value of the first peak of the transient period)

  This determines:
  - the making capacity of the circuit-breakers and switches
  - the electrodynamic withstand of the wiring systems and switchgear.

- **the minimum short-circuit current**

  This must be known in order to choose the tripping curve of the circuit-breakers or fuses or set the thresholds of the overcurrent protections, especially when:
  - the cables are long or when the source has a relatively high internal impedance (e.g. generators or inverters)
  - protection of persons relies on the phase overcurrent protective devices operating. This is essentially the case in low voltage for TN or IT earthing systems.

  The use of calculating software programs* in compliance with IEC 909 is extremely advantageous as they both speed things up and provide reliable results.

(*) SELENA (Schneider ELEctrical Network Analysis)
13.3.7. Starting motors

Starting is a delicate part of using electric motors. The starting devices described in this paragraph should be able to solve most of the cases with which the installation designer is confronted:

- high load torque
- limited current inrush
- frequent starts.

On energization, the impedance of the motor is very low. A violent current inrush (4 to 10 times the nominal current) may follow if no specific device is provided to limit it.

Since the power supply network is never of infinite power, this current inrush may cause a drop in voltage on the network which is likely to disturb other users. This voltage drop may also cause the motor to operate in operating zones which are not recommended, due to the resulting excessive temperature rise, or a speed build-up of the machine which is too slow, or even a slowing down or stopping of the energized motor.

The network short-circuit power is a very important parameter. A motor starts more quickly, heats less and causes a smaller voltage drop if the short-circuit power at the connection point of the motor is high. We may consider that it is high if it is above 100 times the motor power.

Paragraph 3.3.4. explains the different motor starting methods and the current and torque characteristics.
13.3.8. Network dynamic stability study

The dynamic stability of a network is its ability to recover normal operation following a heavy disturbance.

The state of the network is determined by the spreading of loads and the current and voltage values in steady-state conditions.

This state is subject to variations following load fluctuations, electrical incidents and network configuration modifications. The progressive or sudden modification of one or several parameters changes the network state. It may then develop towards a new steady state or its behaviour may become unstable. It is then impossible for it to recover an acceptable steady state. This results in the loss of synchronous machine synchronism and the slowing down of the asynchronous motors to such a point that they may stop.

For example, when a short circuit occurs in a network having a more or less large amount of synchronous machines (alternators or motors) and asynchronous machines (generators or motors), all the machines supply this short circuit, the motors slow down and the generators accelerate (the generators no longer supply active power but remain nevertheless driven by the turbines or Diesel motors).

A stability study (see § 9) consists therefore in analysing the electrical and mechanical behaviour of the machines between the moment when the disturbance occurs and the moment when, once the disturbance has been cleared, the network either recovers or does not recover its normal operating state.

There are too many parameters involved for it to be possible to give an intuitive estimate of the influence of such and such a factor and roughly foresee the consequences of a variation in one of them.

The study is carried out by computer calculations as the number of calculations to be done is too great for them to be carried out “by hand”.

The MGSTAB software program developed by Schneider Electric to carry out calculations provides direct and economic processing of all industrial network cases, regardless of the number of cables and machines.
13.3.9. Reactive energy compensation (see § 7)
In general, electrical energy utilities charge consumers having a high $\tan \phi$ value.

For example, in France:

- customers subscribing to a power above 250 kVA pay for reactive energy above 40% of the active energy consumed (during certain periods).

- customers subscribing to a power between 36 and 250 kVA pay a standing charge which depends on the subscribed apparent power. Reactive energy compensation allows the standing charge to be reduced by decreasing the subscribed apparent power.

Thus, reactive power compensation enables savings to be made on the energy bill. Furthermore, it allows joule losses and voltage drops in conductors and transformers to be reduced.

### Search for optimum compensation

After having calculated the global reactive power to be installed (see § 7.6.), the optimum places to install the capacitors and the type of capacitor bank (fixed or automatic) must be determined in order to obtain as short a return on investment as possible.

First of all, it is necessary to determine the value of the reactive power and if possible the load curve for different places where the capacitors may be installed. Using these curves, information about the minimum, average and maximum reactive power required at these different places is obtained.

The compensation mode depends on the value of the minimum reactive power consumed by the installation compared with the global power to be installed.

#### Case where the minimum reactive power consumed by the installation is greater than the planned compensation power

Compensation may be global as there is no risk of overcompensating during normal operation, which would cause abnormal rises in voltage.

However, when the installation is stopped, the capacitors must be disconnected so that no steady-state overvoltages are caused on the public distribution network due to overcompensation.
case where the minimum reactive power consumed by the installation is lower than the planned compensation power

When the reactive power consumed is minimum, there would be overcompensation with global compensation which would cause an abnormal rise in voltage. For example, experience has shown that overcompensation at the terminals of a transformer must not exceed 15% of its nominal power.

To avoid overcompensation, it is possible to:

- install an automatically-controlled stepped capacitor bank which enables the load curve to be respected
- install, at the origin of the installation, compensation equal to the minimum power consumed and locally compensate loads or sectors consuming a large amount of reactive power, as long as capacitor switching is controlled by the load or sector.
- in the case of an installation containing several MV/LV transformers, transfer part of the compensation of a transformer to another transformer.

 selection criteria

Compensation may be:

- carried out in MV and/or in LV; it is more economical to install medium voltage capacitors for power greater than roughly 800 kvar.
- global, by sector, individual.
- carried out by fixed bank or automatically-controlled stepped capacitor bank; in the case where the stepped bank is selected, it may be preferable to install sections of different powers in order to obtain better adjustment. For example, with sections of 800, 400, 200 and 100 kvar, it is possible to obtain all powers from 0 to 1500 kvar in steps of 100 kvar.

To determine the optimum solution, the following criteria must be taken into account:

- avoidance of reactive energy costs or reduction of subscribed power
- reduction of Joule losses in conductors and in transformers
- regular voltage at any point of the installation
- cost of investment, installation and maintenance of every solution.
energization of capacitor banks and protections

Energizing capacitor banks causes considerable overcurrents and overvoltages in the network. These pose a problem for capacitor switching devices and for protections (especially in MV).

These problems are studied in paragraph 10.6. of the Protection guide.

problems relating to capacitors in the presence of harmonics

In the presence of harmonics, installing capacitors is likely to cause an amplification of harmonic currents and voltages and related problems. In this case, it is necessary to carry out an analysis.

These problems are studied in paragraph 8.
13.3.10. **Study of harmonics** (see § 8)

Non-linear loads such as arc furnaces, lighting systems, convertors, rectifiers, etc., absorb non-sinusoidal currents which flow through the network impedances and hence cause deformation of the supply voltage sinusoid. The wave form deformation is characterised by the occurrence of harmonic voltage frequencies.

The disturbances generally observed are:

- heating or breakdown of capacitors
- heating of motors or transformers
- abnormal operation of regulators, convertors, permanent insulation monitors, protective relays, etc.

The purpose of a harmonic study is to define the means enabling disturbances to be reduced to an acceptable level:

- for site equipment, an overall distortion rate < 5 to 10 %
- for the public distribution network (see table 8-23 for the case of France).

The means generally implemented are:

- installation of capacitor banks with antiharmonic inductors which reduce resonance phenomena between the capacitors and the power supply inductance
- installation of shunt filters which reduce harmonic voltages by "trapping" harmonic currents
- increase of short-circuit power at the location of disturbing loads
- electrically moving away disturbing loads from sensitive equipment
- installation of active filters
- restricting the generation of harmonics.

A harmonic study is generally essential in the presence of capacitors which amplify the distortion rate through resonance phenomena.

The harmonic study consists in:

- determining pre-existing voltage harmonics on the utility network
- defining powers and harmonic current values for each non-linear load
- calculating the voltage distortion rate, at different points of the installation and for all possible network configurations
- simulating possible solutions where the acceptable limits for equipment or the utility network are overstepped.
13.3.11. Insulation co-ordination in an industrial electrical installation

Co-ordinating the insulation of an installation consists in determining the insulation characteristics necessary for the various network elements, in view to obtaining a withstand level that matches the normal voltages, as well as the different overvoltages (see § 5).

Its ultimate purpose is to provide dependable and optimised energy distribution.

Optimal insulation co-ordination gives the best cost-effective ratio between the different parameters depending on it:

- cost of equipment insulation
- cost of overvoltage protections
- cost of failures (loss of operation and destruction of equipment), taking into account their probability of occurrence.

With the cost of overinsulating equipment being very high, the insulation cannot be rated to withstand the stress of all the overvoltages studied in paragraph 5.2.

Overcoming the damaging effects of overvoltages supposes an initial approach which consists in dealing with the phenomena that generate them, which is not always very easy. Indeed, although switchgear switching overvoltages can be limited using the appropriate arc interruption techniques, it is impossible to prevent lightning strikes.

Reducing the risks of overvoltages, and thus the danger that they represent for persons and equipment, is all the better if certain protection measures are respected:

- limitation of substation earth electrode resistances in order to reduce overvoltages on occurrence of an earth fault
- reduction of switching overvoltages by choosing the appropriate switching devices
- running lightning impulses to earth by a first clipping device (surge arrester or spark-gap at the substation entrance) with limitation of the earth electrode resistances and pylon impedances
- limiting the residual voltage of the first clipping carried out by the HV surge arrester which is transferred to the downstream network, with a second protection level being provided on the transformer secondary
- protection of sensitive equipment in LV (computer systems, telecommunications, automatic devices, etc.) by adding series filters and/or overvoltage limiters to them.
13.3.12. Dependability study

Owing to the increase in costs generated by a loss of supply, designers and users of electrical networks need a set of qualitative and quantitative network dependability evaluation methods (see § 10).

When designing, it is important to have methods enabling:

- dependability to be assessed in order to meet specifications
- suitable solutions to be chosen
- service continuity for the least cost to be guaranteed
- the optimum maintenance policy to be determined.

Schneider Electric has developed two software programs designed to carry out dependability studies.

- **Adélia**
  
  This is an expert system able to **construct an electrical network failure tree using the diagram** and carry out qualitative and quantitative analyses on it.

- **Micro Markov**
  
  This is a software program which determines the reliability of an electrical network **using the Markov graph method**.

The dependability study of an electrical network allows:

- **service continuity to be quantified** by the network's unavailability being calculated.
- **the cost of a production loss to be estimated** (to be compared with the investment costs).
13.4. **Choice of equipment** (stage 4)

Once the network structure has been chosen and validated, the electrical equipment selected must comply with the following constraints.

- **standards in force**
- **network characteristics**

These concern notably:

- duty voltages which must be compatible with the highest voltage for the equipment
- overvoltages likely to occur in the network and which must be compatible with the equipment withstand voltages (power frequency, switching impulse, lightning impulse)
- nominal currents
- short-circuit currents which must be compatible with the breaking capacity, the making capacity and the thermal and electrodynamic withstand of the equipment.

- **functions associated with each piece of equipment**
  - short-circuit interruption (by circuit-breaker or fuse)
  - switching operation during nominal state (switch)
  - frequent switching operations (contactors, etc.)
  - off-load switching (isolators).

- **service continuity requirements**

This determines the choice of equipment type:

- fixed device
- drawout device to facilitate maintenance or replacement.

- **personnel qualifications**

The qualification level of operator and maintenance personnel determines:

- whether or not it is necessary to have interlocking devices to prevent erroneous switching operations
- the choice of equipment which is or is not maintenance-free.

- **requirements relating to future extensions**
This determines the reserves to be provided and may lead to the choice of modular equipment.
13.5. **Determining the protection system** (stage 5)

The basic role of the protections of an industrial electrical network is to ensure the safety of persons and equipment and improve continuity of supply to loads.

The normal operation of an installation may be disturbed by a certain number of incidents:

- overloads
- short circuits
- erroneous switching operations
- deterioration of insulating materials.

It is the purpose of the protections to prevent the consequences of these incidents, allowing:

- thermal and mechanical stress to which equipment is subject to be limited
- network stability to be preserved
- the duration of electromagnetic disturbances caused to neighbouring circuits to be reduced.

The protection system is a coherent assembly which depends on the network structure and the earthing system. It must ensure selectivity by isolating the faulty part of the network as quickly as possible while preventing the healthy parts from deteriorating (see *Industrial network protection guide*).
13.6. **Choice of a control and monitoring system** (stage 6)

To guarantee energy availability and reduce energy bills, industrial installations require optimal management of their electrical networks.

A control and monitoring system (see § 12) enables optimisation of network management through the use of automatic functions such as:

- supply changeover
- loop reconfiguration
- load-shedding/restoration
- time-dependent programming and tariff management
- management of internal generator sets, etc.

Furthermore, it offers network supervision, remote control of equipment and maintenance planning.

**network remote control and monitoring**

Remotely monitoring and controlling the network allows operators to:

- display the state of the electrical installation
- monitor the different measurements
- carry out remote control of equipment
- be informed of any incidents on the electrical installation.

**improving the speed and effectiveness of network diagnosis and intervention**

The speed and effectiveness of network diagnosis and intervention are improved through the following functions:

- automatic load-shedding/restoration and supply changeover management
- management of automatic restarting of medium voltage motors
- management of internal generator sets
- fine time stamping
- fault recording.
optimising energy costs

The following functions enable electrical energy costs to be optimised:

- tariff management
- time-dependent programming
- internal generator set management
- reactive energy compensation
- energy metering and sub-metering.

optimising maintenance

Using the system's recorded count of switching device operations and equipment operating times, maintenance can be optimised.
13.7. **Application example**

Let us now study the electrical supply of an industrial production installation whose layout plan is given in figure 13-1.

An analysis of the specifications sheet and the project technical file shows the constraints and basic data necessary for the design study.

The aim is not to present a detailed study, but to underline the methods for resolving problems relating to design.

This is the reason why certain stages are not dealt with in detail.

13.7.1. **Description of the installation**

The industrial installation to be supplied is a production plant which is spread over a surface area of 26 hectares and is made up of several buildings:

- a reception-preparation unit
- a production process
- a storage unit
- a dispatch unit
- a repairs workshop
- a water purification unit
- an administrative building

located inside the site and two buildings located outside the site:

- an extraction unit
- a waterworks.
Figure 13-1: installation layout plan
13.7.2. Collection of data

Only data useful to the parts being studied has been given.

- load power

A power analysis has been carried out and the results are given in table 13-3.

The characteristics of **MV motors** are given in table 13-1:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Number</th>
<th>Efficiency</th>
<th>( \cos \varphi )</th>
<th>( P_m ) (kW) ( (1) )</th>
<th>( P ) (kW) ( (1) )</th>
<th>( Q ) (kvar)</th>
<th>( S ) (kVA)</th>
<th>( \frac{T_{\text{max}}}{T_N} )</th>
<th>( \frac{I_{\text{st}}}{I_n} )</th>
<th>( \frac{T_{\text{st}}}{T_N} )</th>
<th>( \frac{T_{\text{max}}}{T_N} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>2</td>
<td>0.95</td>
<td>0.9</td>
<td>450</td>
<td>474</td>
<td>229</td>
<td>526</td>
<td>2.4</td>
<td>5.7</td>
<td>0.75</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.93</td>
<td>0.78</td>
<td>165</td>
<td>177</td>
<td>142</td>
<td>227</td>
<td>2.3</td>
<td>5.0</td>
<td>1.25</td>
<td>2.3</td>
</tr>
<tr>
<td>Reception-preparation</td>
<td>1</td>
<td>0.93</td>
<td>0.78</td>
<td>165</td>
<td>177</td>
<td>142</td>
<td>227</td>
<td>2.3</td>
<td>5.0</td>
<td>1.25</td>
<td>2.3</td>
</tr>
<tr>
<td>Storage</td>
<td>1</td>
<td>0.93</td>
<td>0.78</td>
<td>165</td>
<td>177</td>
<td>142</td>
<td>227</td>
<td>2.3</td>
<td>5.0</td>
<td>1.25</td>
<td>2.3</td>
</tr>
</tbody>
</table>

(1) \( P_m \) : mechanical power  
\( P \) : electrical power

**Table 13-1: MV motor characteristics**

- equipment causing disturbance

Two speed variators for asynchronous motors are installed at the location of the production unit and their characteristics are given in table 13-2.

<table>
<thead>
<tr>
<th>Type</th>
<th>( P ) (kW)</th>
<th>( \cos \varphi )</th>
<th>( S ) (kVA)</th>
<th>( F_p )</th>
<th>( Q ) (kvar)</th>
<th>( F_h )</th>
<th>( U_n ) (V)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATV-52 V</td>
<td>110</td>
<td>0.85</td>
<td>204</td>
<td>0.54</td>
<td>68</td>
<td>0.63</td>
<td>400</td>
<td>2</td>
</tr>
</tbody>
</table>

**Tableau 13-2: speed variator characteristics**
■ requirements imposed by the industrial process

□ interruption time tolerated

The interruption time tolerated is defined as follows:

- no interruption is tolerated for process control and emergency lighting; i.e. a total power of 250 kVA
- the production unit tolerates an interruption of 10 s
- the plant has an autonomy in raw materials and storage capacity of 8 hours, a long supply interruption is thus authorised on the reception-preparation, storage and dispatch units.

□ sheddable load

Loads which can be shed in the event of the public network failing, without this incurring any production problems, represent:

- 60 % of the reception-preparation unit
- 50 % of the storage unit
- 50 % of the dispatch unit.

■ utility network constraints

- short-circuit power equal to 200 MVA on a 20 kV overhead network
- earth fault current limited to 300 A
- average service continuity:
  . short interruptions : 50 to 100 per year
  . long interruptions : 10 to 20 per year.
- the other characteristics comply with European standard EN 50160 (see table 4-1).
13.7.3. Preparation of a preliminary single-line diagram

**Power Analysis** (see table 13-3)

The analysis of active and reactive powers is given for each unit on the basis of the installed power after the utilisation and coincidence factors have been applied. To determine the installation’s total power, a total coincidence factor of 0.9 is applied to the sum of powers of each unit.

<table>
<thead>
<tr>
<th>Production process</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variators</td>
<td>220</td>
<td>136</td>
<td>408</td>
<td>0.85</td>
</tr>
<tr>
<td>Motors</td>
<td>300</td>
<td>225</td>
<td>375</td>
<td>0.80</td>
</tr>
<tr>
<td>Lighting</td>
<td>30</td>
<td>69</td>
<td>75</td>
<td>0.40</td>
</tr>
<tr>
<td>Heating</td>
<td>300</td>
<td>0</td>
<td>300</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>850</td>
<td>430</td>
<td>953</td>
<td>0.89</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reception Preparation</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>150</td>
<td>113</td>
<td>188</td>
<td>0.80</td>
</tr>
<tr>
<td>Lighting</td>
<td>30</td>
<td>69</td>
<td>75</td>
<td>0.40</td>
</tr>
<tr>
<td>Heating</td>
<td>150</td>
<td>0</td>
<td>150</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>330</td>
<td>182</td>
<td>377</td>
<td>0.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>120</td>
<td>90</td>
<td>150</td>
<td>0.80</td>
</tr>
<tr>
<td>Lighting</td>
<td>45</td>
<td>103</td>
<td>113</td>
<td>0.40</td>
</tr>
<tr>
<td>Heating</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>265</td>
<td>193</td>
<td>328</td>
<td>0.81</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dispatch</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>192</td>
<td>144</td>
<td>240</td>
<td>0.80</td>
</tr>
<tr>
<td>Lighting</td>
<td>24</td>
<td>55</td>
<td>60</td>
<td>0.40</td>
</tr>
<tr>
<td>Heating</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>316</td>
<td>199</td>
<td>373</td>
<td>0.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Administrative building</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>30</td>
<td>69</td>
<td>75</td>
<td>0.40</td>
</tr>
<tr>
<td>Heating</td>
<td>300</td>
<td>0</td>
<td>300</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>330</td>
<td>69</td>
<td>337</td>
<td>0.98</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Repairs workshop</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>80</td>
<td>60</td>
<td>100</td>
<td>0.80</td>
</tr>
<tr>
<td>Lighting</td>
<td>20</td>
<td>46</td>
<td>50</td>
<td>0.40</td>
</tr>
<tr>
<td>Heating</td>
<td>60</td>
<td>0</td>
<td>60</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>160</td>
<td>106</td>
<td>192</td>
<td>0.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water purification</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>80</td>
<td>60</td>
<td>100</td>
<td>0.80</td>
</tr>
<tr>
<td>Lighting</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>0.40</td>
</tr>
<tr>
<td>Heating</td>
<td>90</td>
<td>0</td>
<td>90</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>173</td>
<td>67</td>
<td>186</td>
<td>0.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extraction</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>128</td>
<td>96</td>
<td>160</td>
<td>0.80</td>
</tr>
<tr>
<td>Lighting</td>
<td>6</td>
<td>14</td>
<td>15</td>
<td>0.40</td>
</tr>
<tr>
<td>Heating</td>
<td>50</td>
<td>0</td>
<td>50</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>184</td>
<td>110</td>
<td>214</td>
<td>0.86</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waterworks</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>160</td>
<td>120</td>
<td>200</td>
<td>0.80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MV motors</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1 656</td>
<td>1 026</td>
<td>1 948</td>
<td>0.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Installation total</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>cosφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>4 424</td>
<td>2 502</td>
<td>5 082</td>
<td>0.87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Utility takeover point balance</th>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3 982</td>
<td>2 252</td>
<td>4 575</td>
</tr>
</tbody>
</table>

Table 13-3: Plant power analysis
■ choice of voltages

□ utility supply voltage

The public distribution network 20 kV voltage is suitable for the power required by the plant which is roughly 5 MVA. The 200 MVA short-circuit power is equal to 400 times the power of the largest load. Possible disturbances generated by the loads probably do not disturb the public distribution network.

□ distribution voltages

The choice of a 5.5 kV MV distribution voltage is due to:

- the presence of 6 MV motors spread over the site (see table 13-2)
- the power required by each unit
- the size of the site, including distances varying between 300 m and 1 000 m.

With regard to low voltage, a three-phase voltage of 400 V is sufficient for the supply to the largest loads.

■ energy sources

□ main source

The plant power supply will be ensured by 2 mains/standby 20 kV lines coming from two different sources (from the same utility substation but from separate transformers).

□ replacement source

In case the public network fails, the plant power supply will be ensured by a replacement source connected to the utility substation 5.5 kV busbar. Disconnected from the public network, this source will supply loads which cannot be shed during storms or when the 20 kV lines are unavailable.

It will be connected to the public network during peak tariff periods in order to make savings on the energy bill.

□ safety source

To ensure the safety of persons and equipment, an uninterruptible power supply (UPS) will be provided for the following vital loads:

- 200 kVA for the production control and monitoring system
- 50 kVA of emergency lighting.
The power supply to this UPS will be backed up by a 250 kVA generator set which supplies the production plant LV switchboard in order to overcome the limited autonomy of the storage batteries (10 to 30 min.).

- **choice of earthing systems**

  - **in medium voltage**

    The presence of MV motors requires the earth fault current to be limited to 30 A on the 5.5 kV network. Limiting resistance earthing is chosen.

  - **in low voltage**

    - production process: the service continuity requirements mean that the un earthed neutral system must be chosen. For lighting, an LV/LV transformer is used to change to the TT earthing system.

    - for the remainder of the installation the TT system is chosen, notably so as not to damage the motors in the event of an earth fault.

- **network structure**

  The previously determined data and elements are used to draw up a preliminary single-line diagram of the network (see fig. 13-2).

  - **utility substation**

    The utility substation is fed by 2 x 20 kV lines connected to two 20 kV/5.5 kV transformers supplying the 5.5 kV busbar with coupler.

  - **internal network**

    - production process: this part of the installation will be dual fed with couplers on the MV and LV sides

    - the reception-preparation, storage and dispatch units will be single fed

    - the rest of the units will have an open loop supply owing to the considerable distances.
Figure 13-2: installation single-line wiring diagram
13.7.4. Technical studies and single-line diagram validation

### choice of transformers

If the installation load curves are not known, the transformers are chosen in relation to the installation’s power analysis.

The characteristics of the transformers are given in figure 13-2.

### choice of generators

The power to be backed up is determined by the power analysis at the utility take-over point from which loads that can be shed are subtracted by applying the total coincidence factor:

\[
\begin{align*}
P &= 3\,982 - 0.9 \times (330 \times 0.6 + 265 \times 0.5 + 316 \times 0.5) = 3542 \, kW \\
Q &= 2\,252 - 0.9 \times (182 \times 0.6 + 193 \times 0.5 + 199 \times 0.5) = 1977 \, kvar \\
S &= 4\,575 - 0.9 \times (377 \times 0.6 + 328 \times 0.5 + 373 \times 0.5) = 4056 \, kVA
\end{align*}
\]

Three 1 500 kVA generators having the characteristics given in table 13-4 are chosen:

<table>
<thead>
<tr>
<th>Type</th>
<th>(U_n) (V)</th>
<th>(P) (kW)</th>
<th>(Q) (kvar)</th>
<th>(S) (kVA)</th>
<th>(X_d'') (%)</th>
<th>(\cos \varphi_n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSA 545A</td>
<td>5500</td>
<td>3 x 1200 = 3600</td>
<td>3 x 900 = 2700</td>
<td>3 x 1500 = 4500</td>
<td>18.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*Table 13-4: generator characteristics*

### short-circuit current calculation

The short-circuit current calculations are carried out using the Schneider SELENA software program for different source configurations:

- network fed by the utility only
- network fed by the generators only
- network fed by the generators connected to the utility.

The calculating method used complies with IEC standard 909.
■ determining conductor cross-sectional areas

The study is limited to 5.5 kV wiring systems.

□ wiring system characteristics

The wiring systems are made up of 3 XLPE-insulated copper 6/10 (12) kV single-core cables installed directly in enclosed channels at a temperature of 30°C. The wiring systems do not comprise groupings of several circuits.

The wiring system corresponds to the L4 installation method (see table 6-23).

Column (3) in the current-carrying capacity tables must be used.

The correction factors to be applied are:

- installation method $f_0 = 0.8$
- ambient temperature (see table 6-24): $f_1 = 1$
- group of several circuits (see table 6-28): $f_5 = 1$.

The total correction factor is: $f = 0.8$.

□ production unit: W01 and W02 wiring systems

• determining the maximum design current $I_B$

The W01 and W02 wiring systems can back each other up and they must therefore be able to supply the entire busbar BB2. Table 13-5 gives the power analysis on BB2 assuming that the transformer has a $\cos \varphi = 0.85$.

<table>
<thead>
<tr>
<th></th>
<th>$P$ (kW)</th>
<th>$Q$ (kvar)</th>
<th>$S$ (kVA)</th>
<th>$\cos \varphi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 kW motor</td>
<td>2 x 474</td>
<td>2 x 229</td>
<td>2 x 526</td>
<td>0.9</td>
</tr>
<tr>
<td>165 kW motor</td>
<td>2 x 177</td>
<td>2 x 142</td>
<td>2 x 227</td>
<td>0.78</td>
</tr>
<tr>
<td>1 250 kVA transformer</td>
<td>2 x 1 063</td>
<td>2 x 658</td>
<td>2 x 1 250</td>
<td>0.85</td>
</tr>
<tr>
<td>BB2 total</td>
<td>3 428</td>
<td>2 058</td>
<td>3 998</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 13-5: power analysis on BB2 busbar
The maximum design current is therefore:

\[ I_B = \frac{3998}{\sqrt{3 \times 5500}} = 420 \text{ A} \]

The equivalent current that the cable must be able to carry in standard installation conditions is:

\[ I_z = \frac{I_B}{f} = 525 \text{ A} \]

Table 6-31 (column (3), XLPE, copper) gives a minimum cross-sectional area of \( S_1 = 180 \text{ mm}^2 \) which has a current-carrying capacity of \( I_0 = 550 \text{ A} \).

**checking thermal withstand**

The calculations carried out by the SELENA software give us the maximum short-circuit current for BB1:

\[ I_{sc} = 8.77 \text{ kA} \]

We assume that the maximum short-circuit clearance time is \( t = 1 \text{ second} \).

The conductor cross-sectional area meeting this short-circuit requirement is:

\[ S_2 \geq \frac{I_{sc} \sqrt{t}}{k} \]

\[ k = 143 \quad : \text{value of the coefficient corresponding to a XLPE-insulated copper conductor (see table 6-35)} \]

whence \( S_2 \geq 61 \text{ mm}^2 \)

The minimum cross-sectional area is therefore \( S_2 = 70 \text{ mm}^2 \).

**cross-sectional area to be chosen**

\[ S = 180 \text{ mm}^2 \]
reception-preparation unit: W05 wiring system

- determining the maximum design current

Table 13-6 gives the power analysis on the BB22 busbar assuming that the transformer has a \( \cos \varphi = 0.85 \).

<table>
<thead>
<tr>
<th>P (kW)</th>
<th>Q (kvar)</th>
<th>S (kVA)</th>
<th>( \cos \varphi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>165 kW motor</td>
<td>177</td>
<td>142</td>
<td>227</td>
</tr>
<tr>
<td>400 kVA transformer</td>
<td>340</td>
<td>210</td>
<td>400</td>
</tr>
<tr>
<td>BB22 total</td>
<td>517</td>
<td>352</td>
<td>625</td>
</tr>
</tbody>
</table>

Table 13-6: power analysis on BB22 busbar

The maximum design current is therefore:

\[
I_B = \frac{625}{\sqrt{3} \times 5000} = 66 \, A
\]

The equivalent current that the cable must be able to carry in standard installation conditions is:

\[
I_f = 83 \, A
\]

Table 6-31 (column (3), XLPE, copper) gives a minimum cross-sectional area of \( S_1 = 10 \, mm^2 \) which has a current carrying capacity of \( I_0 = 93 \, A \).

- checking thermal withstand

We assume that the maximum short-circuit clearance time is the same as for wiring systems W01 and W02 (\( t = 1 \) second), the minimum cross-sectional area adapted to the thermal stress is thus \( S_2 = 70 \, mm^2 \).

- cross-sectional area to be chosen

\[ S_2 = 70 \, mm^2 \]
**other 5.5 kV wiring systems**

The maximum design currents of other 5.5 kV wiring systems are lower than or equal to that of wiring system W05. The cross-sectional area is thus imposed by the thermal stress in the event of a short circuit. The values of the maximum short-circuit currents of all the 5.5 kV cables are identical as they are attached to the same busbar. Furthermore, it is assumed that the maximum short-circuit clearance time is the same for each cable, i.e. 1 second. The cross-sectional areas to be chosen are therefore: \( S = 70 \text{ mm}^2 \).

**voltage drops**

Voltage drops during normal operating conditions are lower than 1 %, at any point of the 5.5 kV network. They are not therefore restrictive.

**thermal withstand of cable screens**

The earth fault current is limited to 30 A, which does not impose any restriction (see table 6-37 to 6-39).

**reactive energy compensation**

The reactive energy to be compensated is calculated so as to limit it to \( \tan \varphi_0 = 0.4 \) at the take-over point.

**determining the total reactive power to be compensated**

The power analysis in table 13-3 gives the following total powers:

\[
P = 3982 \text{ kW}
\]

\[
Q = 2252 \text{ kvar}
\]

\[
S = 4575 \text{ kVA}
\]

\[
\cos \varphi = 0.87 \rightarrow \tan \varphi = 0.567
\]

We can deduce from this:

\[
Q_C = P \left( \tan \varphi - \tan \varphi_0 \right) = 3982 \left( 0.567 - 0.4 \right)
\]

\[
Q_C = 665 \text{ kvar}
\]
choice of capacitor location

We assume that the minimum reactive energy required by the plant is 120 kvar; this power will be installed on the 5.5 kV side of the supply substation, on BB1.

The production unit consumes the most amount of energy and the MV and LV motors have a highly irregular load curve. Stepped capacitor banks are therefore installed on the busbars supplying the motors, which will be controlled by a varmeter relay so that they match the load curve:

- 6 x 50 = 300 kvar on BB 2
- 4 x 30 = 120 kvar on BB3.

The remaining compensation is carried out by fixed banks:

- 50 kvar on the reception-preparation unit
- 50 kvar on the storage unit.

Table 13-7 provides a recap on capacitor bank location.

<table>
<thead>
<tr>
<th>Location</th>
<th>Supply substation</th>
<th>Production unit</th>
<th>Reception-preparation</th>
<th>Storage</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MV</td>
<td>LV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_C \ (kvar)$</td>
<td>150</td>
<td>300</td>
<td>120</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 13-7: location of capacitor banks

The power to be compensated is not very high and is essentially located on the MV side. With the MV cables not being very long, joule losses due to reactive power are almost negligible. It is therefore not useful to carry out an economic optimisation calculation.
**harmonic study**

The 250 kVA uninterruptible power supply is fitted with an input filter that reduces the harmonic current values enough for them to be negligible.

The study consists in determining the distortion rates of current and voltage generated by the speed variators for different network configurations and determining the means of reducing them to an acceptable level.

We will concentrate on the network branches connecting the utility substation to the speed variators; a model of the rest of the network is made using loads \((P,Q)\) connected to busbars BB1, BB2 and BB3 (see fig. 13-3).

The two speed variators are identical and are connected to busbar BB3. The values of the harmonic currents which they generate are given in table 13-8.

<table>
<thead>
<tr>
<th>order</th>
<th>1</th>
<th>5</th>
<th>7</th>
<th>11</th>
<th>13</th>
<th>17</th>
<th>19</th>
<th>23</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>current (%)</td>
<td>100</td>
<td>85</td>
<td>72</td>
<td>41</td>
<td>27</td>
<td>8</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

*Table 13-8: harmonic currents generated by the ATV-52V variators*

Simulations have been carried out using the Schneider "harmonic" software program for different source configurations:

- **UTILITY**, plant fed by the utility alone

- **GENERATORS**, plant fed by the replacement generator sets alone

- **UTILITY AND GENERATORS**, plant fed by both sources in parallel.
Figure 13-3: network model diagram
For each case, 4 different simulations have been carried out:

- **A**: network before compensation (without capacitors).
- **B**: network with compensation defined in table 13-7.
- **C**: network with modified compensation to move resonance to an order that is far away from the high value harmonic currents. To carry out this modification, 50 kvar is installed instead of 120 kvar on BB3; the difference is installed on BB1.
- **D**: network after an anti-harmonic inductor tuned to order 3.8 has been installed on capacitor $C_3$; compensation is as in case **B**.
- **E**: network after resonant shunts tuned to orders 5 and 7 have been installed.

The simulation results are presented in table 13-9.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type of simulation</th>
<th>voltage distortion (%)</th>
<th>capacitor load (%)</th>
<th>transformer derating (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BB 1</td>
<td>BB 2</td>
<td>BB 3</td>
</tr>
<tr>
<td><strong>UTILITY</strong></td>
<td>A</td>
<td>2.6</td>
<td>2.6</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>7.2</td>
<td>7.2</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>6.8</td>
<td>6.8</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>8.4</td>
<td>8.4</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>6.1</td>
<td>6.1</td>
<td>6.2</td>
</tr>
<tr>
<td><strong>GENERATORS</strong></td>
<td>A</td>
<td>4.3</td>
<td>4.3</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>13.8</td>
<td>14.1</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>10.8</td>
<td>11.0</td>
<td>16.3</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>6.8</td>
<td>6.8</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>3.5</td>
<td>3.5</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>GENERATORS &amp; UTILITY</strong></td>
<td>A</td>
<td>1.8</td>
<td>1.8</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>8.6</td>
<td>9.1</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>8.0</td>
<td>8.5</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>4.9</td>
<td>4.9</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>3.6</td>
<td>3.6</td>
<td>5.5</td>
</tr>
</tbody>
</table>

(*) both values correspond to order 5 and 7 filter capacitor loads respectively.

*Table 13-9: simulation results*
interpreting results

- the results obtained for the 3 source configurations without compensation underline the influence of the short-circuit impedance on the harmonic distortion rates

- installing capacitors increases the distortion rates owing to the harmonic resonances. They well exceed the compatibility levels of IEC 1000-4-2 (see table 8-20)

- installing an anti-harmonic inductor limits voltage distortions, capacitor overloads and transformer derating factors, but not enough.

- installing resonant shunts tuned to orders 5 and 7 greatly limits voltage distortions. The maximum rate (6.2% on BB3) is recorded on the utility and it remains acceptable. With the association of a third shunt tuned to order 11, we obtain very weak distortion rates (1.8 % on BB3), compatible with the use of very sensitive loads (class 1).

interpreting impedance curves

The curves in figures 13-4 to 13-8 represent the network impedance seen from the speed variator terminals in the case of generator supply (generally the most restrictive case). They illustrate the distortion rates obtained on the busbar supplying the variators (BB3).

Before compensation (case A), the network impedance is proportional to the harmonic order. Compensation (case B) causes resonance close to order 7, having a high harmonic current value. The distortion rate is thus high. Moving the capacitors (case C) reduces the resonance close to order 7, but not enough.

Installing an anti-harmonic inductor (case D) reduces the impedance on order 7. On the other hand, a resonance close to order 9 appears. This is due to resonance between the MV capacitors and the upstream network.

The order 5 and 7 resonant shunts (case E) decrease the resonance close to order 9. There is no high impedance on the harmonic orders supplied by the variators. The distortion rate is thus reduced to an acceptable value.
Figure 13-4: generator-fed network, case A

Figure 13-5: generator-fed network, case B
Figure 13-6: generator-fed network, case C

Figure 13-7: generator-fed network, case D
**Protection selectivity study**

We shall study the selectivity of overcurrent protections for three MV network elements (see fig. 13-9):

- production unit MV/LV transformer, TR22
- MV motor, ASM1
- MV cable, W01.

Obtaining selectivity whatever the source configuration (utility alone, generators alone, utility + generators) is sometimes difficult, if not impossible. In this case, two protection systems must be provided, one for the utility alone and the utility + generators, and another for the generators alone. A change in source configuration will cause, if necessary, the modification of the protection settings (the Sepam 2000 offers this possibility).

We will limit ourselves to studying the case of the network being supplied by the utility alone.

The short-circuit current calculations and selectivity curve simulations are carried out using the SELENA software program.
Figure 13-9: short-circuit current values

$I_{sc3\text{max}}$: maximum three-phase short circuit

$I_{sc2\text{min}}$: minimum two-phase short circuit
TR22 transformer protection

The transformer is protected by a primary side double threshold protection, the low threshold acting as back-up to the secondary side protection (see § 10.3.4.3.2 of the Protection guide).

See curve 1 in figure 13-10.

High threshold:
\[ I_{h,\text{set}} \geq 1.25 \times I_{sc\text{ max }LV} = 1.25 \times 1600 = 2000 \text{ A} \]
\[ I_{h,\text{set}} = 2 \text{ kA} \]
\[ t_{h,\text{set}} = 0.1 \text{ s} \]
\[ I_{sc\text{ max }LV} : \text{maximum current for a three-phase short circuit at the transformer secondary terminals} \]

Low threshold:
\[ I_{l,\text{set}} \leq 0.8 \times I_{sc\text{ min }LV} = 0.8 \times 1500 = 1200 \text{ A} \]
\[ I_{l,\text{set}} = 1.2 \text{ kA} \]
\[ t_{l,\text{set}} = 0.4 \text{ s} \]
\[ I_{sc\text{ min }LV} : \text{minimum current seen by the MV protection for a short circuit at the transformer secondary terminals} \]

The curves in figure 13-10 show that the protection is not activated when the transformer is energized.

ASM1 motor protection (see § 10.4.1 of the Protection guide)

See curve 1 in figure 13-11.

The condition to be met for protection setting is:
\[ I_{m,\text{set}} = 1.3 I_{st} \]

The starting current is:
\[ I_{st} = 5.7 I_{n} = 315 \text{ A} \]

whence
\[ I_{m,\text{set}} = 410 \text{ A} \]

we will take a time delay of \[ t_{m,\text{set}} = 0.1 \text{ s} \]

Figure 13-11 shows that selectivity is ensured with the upstream part.
W01 wiring system protection

see curves in figures 13-10 and 13-11.

Selectivity with the TR22 transformer and ASM1 motor protections is of the time-graded type.

The conditions to be met for protection setting are:

\[
\begin{align*}
  - I_{w,\text{set}} & \leq 0.8 \times I_{sc,\text{min,BB2}} = 0.8 \times 4200 = 3.4 \text{ kA} \\
  - I_{w,\text{set}} & \geq 1.25 \times I_{h,\text{set}} = 2.5 \text{ kA} \quad \text{and} \quad I_{w,\text{set}} \geq 1.25 \times I_{m,\text{set}} = 0.51 \text{ kA} \\
  - t_{w,\text{set}} & \geq t_{h,\text{set}} + \Delta t = 0.4 \text{ s} \quad \text{and} \quad t_{w,\text{set}} \geq t_{m,\text{set}} + \Delta t = 0.4 \text{ s}
\end{align*}
\]

The following settings are therefore chosen:

\[
\begin{align*}
  - I_{w,\text{set}} & = 2.5 \text{ kA} \\
  - t_{w,\text{set}} & = 0.4 \text{ s}
\end{align*}
\]
Figure 13-10: transformer selectivity curves

- 0: W01 wiring system protection curve
- 1: TR22 transformer protection curve
- 2: TR22 transformer inrush current

Figure 13-11: motor selectivity curves

- 0: W01 wiring system protection curve
- 1: ASM1 motor protection curve
- 2: ASM1 motor starting current
study of motor starting

The study has been carried out using simulations on the Schneider "Start'n Go" software:

- for the installation's most powerful motor

- for the simultaneous starting of the production unit's 4 MV motors using an "equivalent" motor (the software allows only one motor to be studied at a time).

study of the 450 kW motor starting

- motor-load assembly characteristics (see table 13-10)

<table>
<thead>
<tr>
<th>Elements</th>
<th>( P_n ) (kW)</th>
<th>Efficiency</th>
<th>Speed ( \text{tr/min} )</th>
<th>Moment of inertia (kg m(^2))</th>
<th>( U_n ) (V)</th>
<th>( \cos \varphi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asynchronous motor</td>
<td>450</td>
<td>0.95</td>
<td>1485</td>
<td>135</td>
<td>5500</td>
<td>0.9</td>
</tr>
<tr>
<td>Compressor without sliding lock panels</td>
<td>300</td>
<td>--</td>
<td>1485</td>
<td>200</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 13-10: motor-load assembly characteristics

Note: the other motor characteristics are given in table 13-1.

starting diagnosis

- starting time: 8.9 s

- starting current: 296 A
  The starting current given by the manufacturer is determined for an infinite short-circuit power and its value of 315 A. The value determined by the software program is lower since it takes into account the voltage drop at the motor connection point.

- voltage drops:
  - 6.26% on busbar BB2
  - 5.93% on busbar BB1
  - 1.57% at the utility take-over point (20 kV)

  These values are acceptable for the motor and other loads fed by BB2 and BB1, and for the utility whose voltage variation must be lower than 4% (see table 4.1, EN 50 160).
- motor heating:

The software program has a database of starting withstands determined using motor heating characteristics. The database provides the withstands for our motor, i.e. $992 \text{kA}^2\text{\times s}$ when cold and $298 \text{kA}^2\text{\times s}$ when warm. The stress on starting is $602 \text{kA}^2\text{\times s}$. The motor will therefore be able to withstand cold starting, but not warm starting.

**study of simultaneous starting of the production unit's 4 MV motors**

The motor characteristics are given in table 13-1.

We assume that the values of the moments of inertia of each motor and each load are known.

We determine an equivalent $\cos\varphi$ by weighting the $\cos\varphi$ of each motor giving them a coefficient equal to the power:

$$\cos\varphi = \frac{\sum_{i=1}^{4} P_i \cos\varphi_i}{\sum_{i=1}^{4} P_i} = \frac{(474 \times 2 \times 0.9) + (177 \times 2 \times 0.78)}{2 \times 474 + 2 \times 177} = 0.87$$

In the same way we can determine the equivalent starting current:

$$\frac{I_{st}}{I_n} = \frac{(474 \times 2 \times 5.7) + (177 \times 2 \times 5)}{2 \times 474 + 2 \times 177} = 5.5$$

We can deduce from this the characteristics of the equivalent motor-load assembly (see table 13-11).

<table>
<thead>
<tr>
<th>Elements</th>
<th>$P_n$ (kW)</th>
<th>Efficiency</th>
<th>Speed (tr/min)</th>
<th>Moment of inertia (kg m²)</th>
<th>$U_n$ (V)</th>
<th>$\cos\varphi$</th>
<th>$\frac{I_{st}}{I_n}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent motor</td>
<td>1 230</td>
<td>0.95</td>
<td>1 485</td>
<td>370</td>
<td>5 500</td>
<td>0.87</td>
<td>5.5</td>
</tr>
<tr>
<td>Equivalent load</td>
<td>900</td>
<td>--</td>
<td>1 485</td>
<td>600</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

*Table 13-11: equivalent motor-load assembly characteristics*
• **starting diagnosis**

- starting time: 13.7 s
- starting current: 765 A
- voltage drops:
  
  16.2 % on busbar BB 2  
  15.4 % on busbar BB 1  

Voltage drops are considerable and they may disturb the network. Furthermore, the motors are subject to considerable heating when they are started since the voltage drop causes an increase in starting time. It will thus be preferable to start the motors one by one.
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