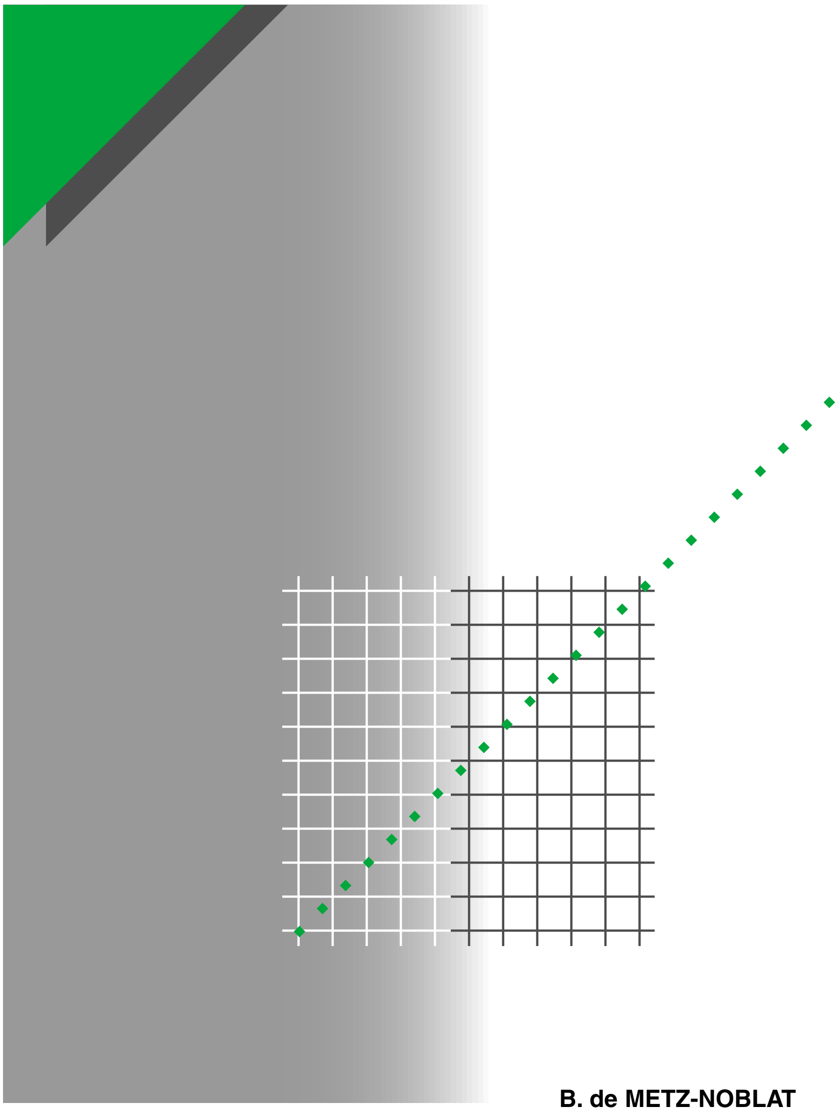
Cahier technique no. 213

Calculations for LV and HV networks



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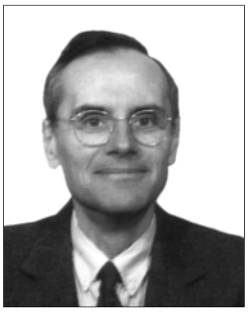
Foreword

no. 213

Calculations for LV and HV networks



Benoît de METZ-NOBLAT

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He is a member of the Electrical Network competence group that studies electrical phenomena concerning the operation of networks and their interaction with devices and equipment.

ECT 213 first issue, December 2004

Calculations for LV and HV networks

This Cahier Technique publication is intended to provide a general overview of the main electrotechnical calculations carried out in engineering studies on electrical systems at all voltage levels.

It is complementary to other Cahier Technique publications that deal more with the operation of devices and installations in electrical systems. This document will help owners, designers and operators understand the importance of these calculations in ensuring correct use of the electrical network and their impact on the total cost of ownership.

Contents

1 Introduction

Electrical networks have long been studied to ensure effective supply of electricity to processes. The main aspects studied are design, operation and upgrades.

Note that, in this document, the term "process" refers to all applications of electricity users (commercial, infrastructure, industry, distribution-system manager).

Given the recent worldwide context, the importance of electrical network studies is growing continuously.

■ Over the past few years, the electrical world and its organisational modes have undergone rapid change.

□ With deregulation of the electric market, the economic rules have changed. Consumers can take advantage of the competition between suppliers and utilities can extend their markets.

□ Users are refocusing on their core business and divesting secondary activities such as those required to run electrical networks. Examples are subcontracting of maintenance or operation of installations to specialised service companies.

□ Technological progress has also had a number of effects.
First of all, digital electronics and computer networks have opened new horizons, but also imposed new constraints. They have improved electric system instrumentation and control, including remote control, but at the same time have made processes more sensitive to energy quality.
Secondly, the trend toward multiple energy sources (combined heat and power - CHP, renewable energy) and the widespread use of non-linear loads can, over time, have major impact on network architecture and operating modes, due to voltage disturbances, protection needs and regulations.

■ Electricity is now considered a product like any other, which implies a need for quality.
Consumers want access to electrical energy suited to their needs. Given the extremely diverse requirements of processes in terms of safety and quality, the electricity supplied must meet the stipulated specifications.
At every level in the electrical supply chain (production, transmission, distribution), energy suppliers must satisfy customers and users in line with personalised contractual clauses.

■ Environmental protection criteria have become obligatory in terms of the selection and consumption of materials (minimum environmental impact) and energy (maximum efficiency).

■ More than ever, economic aspects are a crucial factor.

Users must optimise the total cost of ownership (TCO) of the electrical network. The TCO includes all expenditures required to use electrical energy, i.e. investments, operation, maintenance and the purchase of energy.

To demonstrate the importance of calculations in engineering studies, this Cahier Technique publication will successively discuss:

□ aspects pertaining to the life of an electrical network;

□ calculation methods;

□ the main calculations required according to the type of network and the applications involved.

Note that the calculations presented here represent only one element in the overall electrical-engineering process.

2 Life of an electrical network

A number of aspects concerning the life of an electrical network are discussed in this section, so that the readers can gain a better grasp on their own installations and take action at the correct level in terms of the subject presented here:

- life cycle, i.e. the successive phases in the life of an electrical network from its design on through to upgrades (see **Fig. 1**);
- electrical phenomena encountered in system operation;
- types of networks and their operation, which directly determine the impact of events on electrical components;
- finally, the calculations required to develop economically and technically viable solutions, and which constitute one of the final selection criteria of the user.

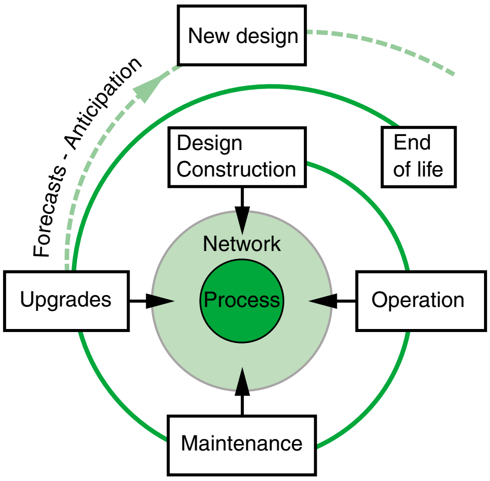


***Fig. 1**: Life cycle of an electrical network.*

2.1 Life cycle of an electrical network

The life cycle of an electrical network (see **Fig. 1**) comprises four typical phases primarily concerned by the calculations presented in this document.

- Design and installation

These are all the operations leading up to an installation that is ready to supply electrical power to processes. Various studies determine the basic choices, including the network architecture, sizing of equipment, protection, etc.

During this phase, it is important to carry out calculations that assist in making the decisions and determine future performance.

- Operation

This is the operational phase of installations, involving the supply of electrical power to processes and during which various events, normal and abnormal, occur on the network leading to operation in normal, downgraded or safe modes.

The protection and automation systems step in to deal with disturbances and critical situations. They are defined by calculations, taking into account all possible serious problems that can occur.

- Maintenance

Network performance levels are maintained by maintenance operations that can be preventive (before problems occur) or corrective (following a problem).

At times, additional measures and calculations are required to solve unforeseen difficulties.

- Upgrades

Adaptation of electrical installations to the changing needs of processes generally results in major work to renovate, modify and expand the system. This step requires calculations for the planned modifications, taking into account all acquired experience.

Correct execution of the calculations required during the various phases of the life cycle requires a good understanding of the electrical phenomena likely to occur in the network.

2.2 Electrical phenomena in networks

An electrical network is made up of different parts (components, devices and equipment) that mutually influence each other. System operation over time and on a given site is the result of this interaction, in compliance with the laws of electricity expressed by a set of equations establishing relations between values such as voltage, current, impedance, time, etc.

The classification of electrical phenomena according to the response time of the system (time constants) defines typical behaviour that must be handled on a case by case basis:

- discontinuous phenomena - temporary interruption of the supply;
- slow phenomena - standard changes in operating conditions;
- stable phenomena - steady-state conditions;
- fast phenomena - influence of the variable effects of rotating machines;
- conducted electromagnetic phenomena - influence of waves propagated by cables;
- radiated electromagnetic phenomena - radiation.

The main events associated with the above classes of phenomena produce very diverse effects on the distribution system and processes:

- interruption and breaks in the supply of electricity;
- voltage sags and variations;
- transient currents;
- harmonics;
- short-circuits;
- electromechanical oscillations;
- overvoltages due to switching, arcs and recovery transients;
- overvoltages caused by lightning;
- coupling between power and control currents.

The magnitudes of the effects listed above depend on the types of networks and operating requirements.

2.3 Types of networks and their operation

Certain parameters specific to the electrical installation in question determine the necessary calculations.

- Type of source
  - ☐ short-circuit power;
  - ☐ speed and voltage regulators;
  - ☐ harmonic pollution;
  - ☐ normal or replacement.
- Type of load
  - ☐ power (active/reactive, installed/drawn);
  - ☐ operating characteristics (commissioning, sensitivity to disturbances);
  - ☐ phase unbalance;
  - ☐ harmonic loads;
  - ☐ priorities of different loads for the process (normal / essential / vital).
- Network diagram
  - ☐ voltage levels;
  - ☐ structure (radial, loop, double/single supplies, double/single busbars);
  - ☐ configuration (normal/back-up, redundant);
  - ☐ system earthing arrangements (SEA);
  - ☐ line lengths;
  - ☐ power-factor correction;
  - ☐ types of switching devices;
  - ☐ maintenance requirements.
- Standards, regulations and local work habits

Analysis of the above parameters determines the types of studies capable of providing quantitative solutions for the problems at hand.

2.4 Necessary calculations

The purpose of the calculations is to analyse and foresee system responses to various situations. The results impact on network architecture, selection of device and equipment characteristics, and operating rules.

The following sections cover:

- dependability;
- steady-state conditions;
- short-circuits;
- protection;
- stability;
- harmonics;
- overvoltages;
- electromagnetic compatibility (EMC);
- measurements for evaluations and audits.

2.5 Summary table

The table (**Figure 2**) presents along a double scale (time and frequency) the information discussed above:

- classes of phenomena;
- electrical events;
- network types and operation;
- types of calculation.

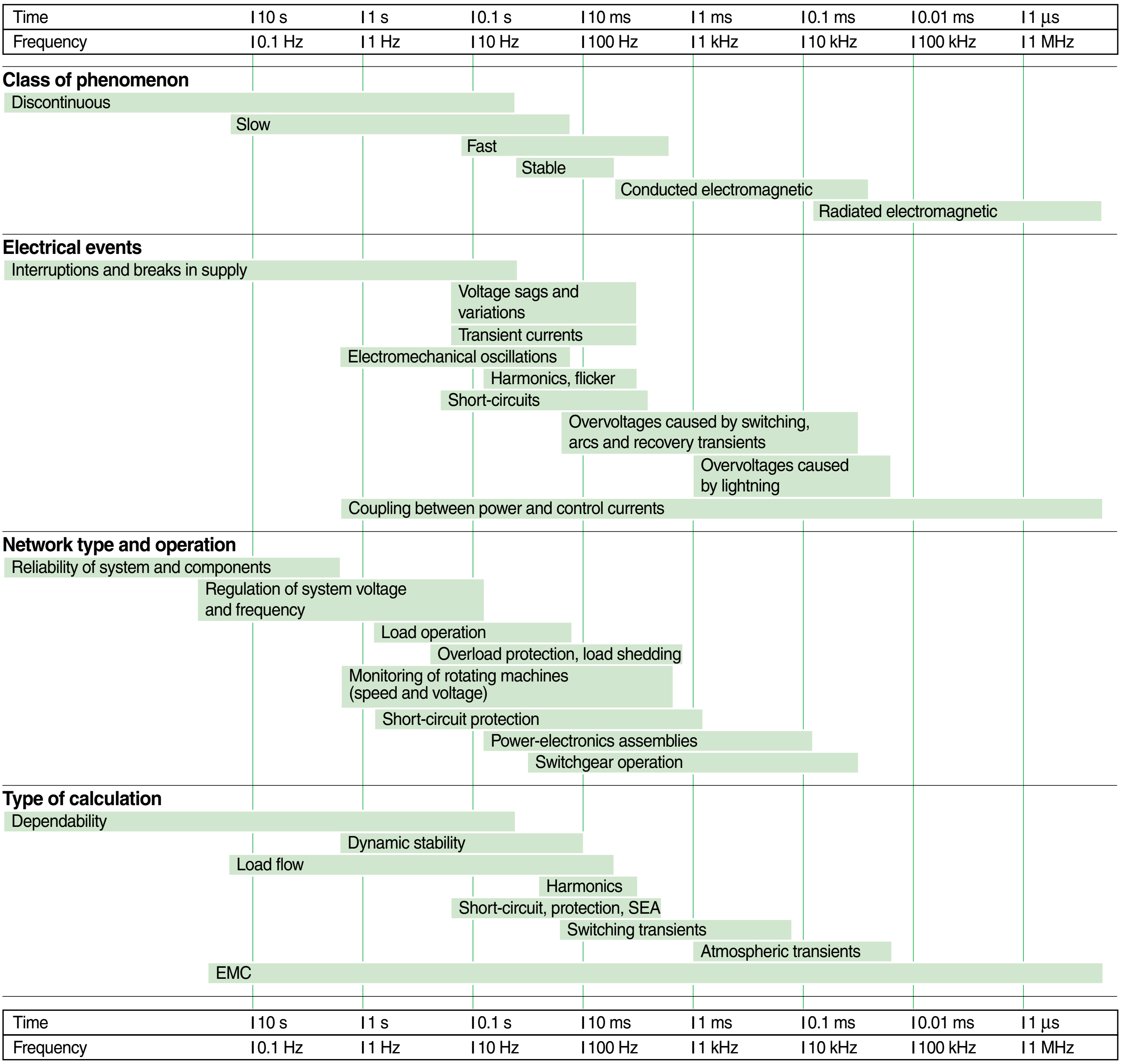


Fig. 2: Summary of electrical-network operation.

3 Study prerequisites

In addition to the necessary know-how, the means implemented for network calculations constitute an essential aspect for studies, for a number of reasons:

- complete approach in terms of the method, to ensure valid final results;
- adaptation of tools to needs which can vary depending on the types of calculation and the applications;
- investment in tools and their maintenance, at the lowest possible cost.

In appendix 1, a rapid historical presentation shows the radical changes in the means used, from the origins to present day, due to the new technologies available and their decreasing cost.

This section presents the approach used for calculations and the digital tools currently employed, then discusses the importance of the expert's role in the calculations.

3.1 Method

The overall calculation procedure follows a standard scientific approach, i.e. simple in its principle, but precise and rigorous in its execution. This section discusses the steps in the method, then the currently used digital simulation tools.

Steps

Figure 3 shows the different steps in calculating electrical systems.

- Need

The overall purpose of calculations is to foresee the quantitative behaviour of a real system in order to size it, understand its operation or control it.

- Qualitative analysis

Preliminary analysis, based on experience and know-how, makes it possible to draft a qualitative list of the important phenomena for an application.

- Phenomena and events studied

This step consists in selecting, on the basis of the above analysis, the phenomena for which calculations will be run.

- Quantitative analysis

Use of the digital quantification tool comprises:

☐ Modelling

Modelling an electrical network means representing each element and all the interconnections between elements by equations expressing the electrical, magnetic and mechanical behaviour. The equations must be adapted to the phenomena studied.

☐ Simulation

Simulation of an electrical network means simultaneously solving all the equations in the

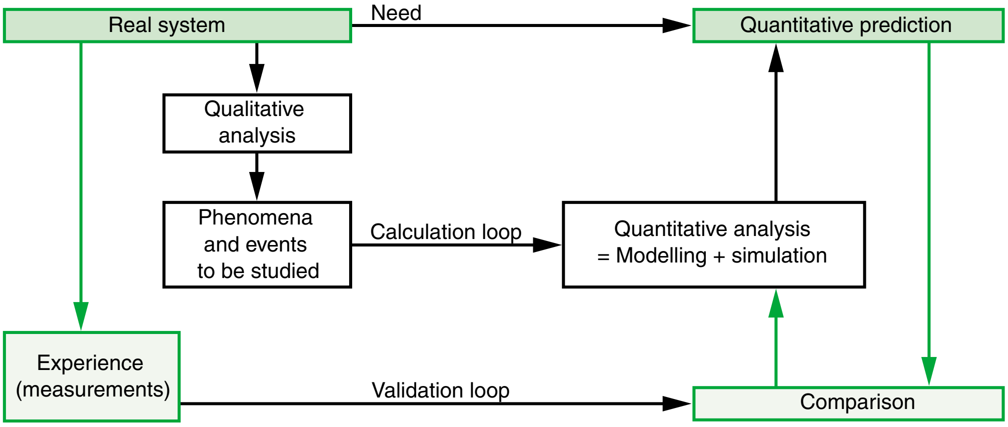


Fig. 3: The various steps in calculating electrical systems.

model. The main variable can be space, time or frequency. Simulation on a computer requires calculation software.

- Quantitative prediction
The simulations cover the possible situations and relevant parameters. Processing and formatting of the results produces the desired prediction.

- Experience, measurements and validation
This step checks that quantification was correctly carried out, i.e. that the models and digital processing produced significant results. Comparison of the prediction with measurements is a validation technique that justifies the selected method. It may be requested to guarantee the announced results.

Digital means

Digital calculation is now widely used and comprises a number of elements.

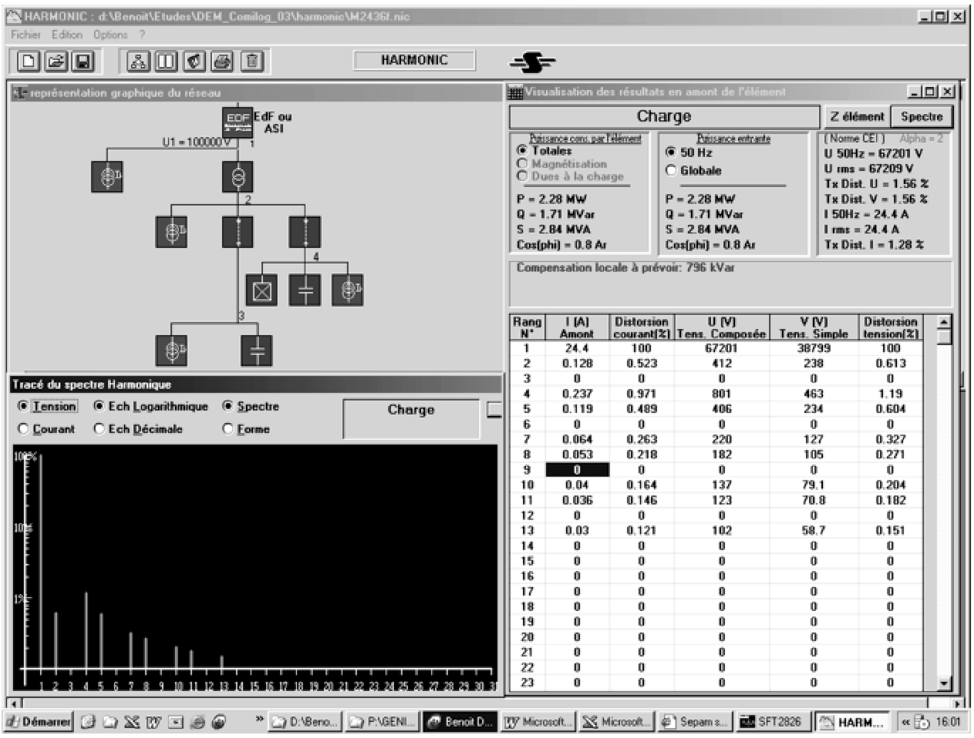
- Hardware
The calculation device is a computer, generally a PC, which now offers sufficient memory and calculating speed.

- Software
All system equations are processed by a special program. The user-machine interface (UMI) can be used to add data to the models, start the calculation and present the results in the form of values, tables and curves (see **Fig. 4**).
The table in appendix 2 lists the software suitable for the different calculations.

- Data bank
Each electrotechnical element is described by the models and the characteristic physical values. All of this data is stored in a data bank. Appendix 3 list the main data required for calculations.
The investment consists essentially of the software and its maintenance because the cost of hardware has become negligible due to widespread use of PCs.
Most software programs are available on the market, supplied by utilities, equipment manufacturers, electrical consulting firms, schools and universities.

Evaluation

This method is the means to confirm and quantify the phenomena foreseen by the theory. Under certain circumstances, it also reveals poorly identified phenomena.
A particularly difficult aspect is the experimental validation of the results which requires experience and know-how. For example, the necessary measures depend on the type of study and disturbance monitoring (with interpretation of the results) may be required.



● Tension ○ Courant
● Ech Logarithmique ○ Ech Décimale
● Spectre ○ Forme

Puissance cons. par l'élément
● Totales
○ Magnétisation
○ Dues à la charge
P = 2.28 MW
Q = 1.71 MVar
S = 2.84 MVA
Cos(phi) = 0.8 Ar

Puissance entrante
● 50 Hz
○ Globale
P = 2.28 MW
Q = 1.71 MVar
S = 2.84 MVA
Cos(phi) = 0.8 Ar

(Norme CEI) Alpha = 2
U 50Hz = 67201 V
U rms = 67209 V
Tx Dist. U = 1.56 %
Tx Dist. V = 1.56 %
I 50Hz = 24.4 A
I rms = 24.4 A
Tx Dist. I = 1.28 %

Compensation locale à prévoir: 796 kVar

Rang N°	I (A) Amont	Distorsion courant(%)	U (V) Tens. Composée	V (V) Tens. Simple	Distorsion tension(%)
1	24.4	100	67201	38799	100
2	0.128	0.523	412	238	0.613
3	0	0	0	0	0
4	0.237	0.971	801	463	1.19
5	0.119	0.489	406	234	0.604
6	0	0	0	0	0
7	0.064	0.263	220	127	0.327
8	0.053	0.218	182	105	0.271
9	0	0	0	0	0
10	0.04	0.164	137	79.1	0.204
11	0.036	0.146	123	70.8	0.182
12	0	0	0	0	0
13	0.03	0.121	102	58.7	0.151
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0
21	0	0	0	0	0
22	0	0	0	0	0
23	0	0	0	0	0

Fig 4: UMI screen for data entry and the display of the results (source - Schneider Electric).

3.2 Role of the expert

The above method has been proven by many years of practical experience.

But though it provides reliable results for the purpose to which it is put, correct results nonetheless require the knowledge, know-how and experience of specialised engineers.

These experts are in a position to:

- sift through all the available data and retain only the relevant information;
- recognise the orders of magnitude and detect any inconsistencies;
- evaluate the tools and models to select the most suitable;
- make the necessary approximations to simplify the calculations without altering the results;
- check and interpret the results to propose effective solutions.

4 Electrical-network calculations

This Cahier Technique publication covers all electrical networks and consequently all applications:

- on public, industrial, commercial and residential networks;
- from low to high voltages.

This section describes the studies listed above, systematically taking into account the following points:

- the purpose of the study;
- the concerned electrical phenomena and their origin;
- their effects and the proposed solutions;
- the contribution of the study and its deliverables;
- an example of an application drawn from real studies carried out by Schneider Electric.

The overall goal is simply to briefly inform the reader and the scope of each example is therefore necessarily limited. For more detailed technical information, consult the bibliography and particularly the Cahier Technique publications addressing the various points.

The risks run by users and the answers provided by the studies are then summarised in the following section.

4.1 Dependability

Over the course of the years, dependability is a need that has spread to all processes that are vulnerable to energy outages.

The notion of dependability is defined by the values for:

- energy availability;
- the annual rate of outages;
- maintainability.

Goals

The purpose of an operating-dependability study on network behaviour is to:

- design the optimum network architecture in view of meeting the energy needs of the loads in the installation, as defined by the continuity of service requirements imposed by the process, through:
  - ☐ better control over the risks caused by outages;
  - ☐ enhancement of the decision-aid criteria in order to make a selection between a number of solutions;
- plan for downgraded operating situations, quantify their probability and define a level of confidence attributed to the supply of electrical energy.

Phenomena and origins

The presence of electrical energy is generally characterised by:

- reliability for a time interval DT, expressed as the mean time between failures (MTBF) or the mean time to (the first) failure (MTTF);
- availability at time T;
- the mean time to repair (MTTR) a failure.

The supply of electrical energy depends essentially on:

- the topological structure of the electrical network for all the possible operating modes and during their changes in status condition (normal, downgraded and safe modes);
- normal operation of the system when the various operating scenarios run correctly;
- the organisation of maintenance;
- forecasts concerning accidental disturbances.

Effects and solutions

Electrically speaking, operating failures in a network manifest themselves in the manners presented below.

- Energy outages of the utility. The distribution networks themselves fail or are disturbed (device failure, atmospheric disturbances, etc.). The results are voltage sags and more or less long outages for the incoming substations. Depending on the network topology and the means implemented, these disturbances may be propagated down to the load level.
- Insulation faults. The resulting short-circuits provoke for the loads voltage sags or outages that depend on:
  - ☐ the protection devices installed and their level of discrimination;
  - ☐ the "electrical" distance between the load and the fault;
  - ☐ the network topology which may offer the means to reconfigure the system through active or passive redundancy.
- Nuisance tripping which provokes a break in the supply of power to the downstream loads.

- Switching faults when the switchgear does not carry out the expected change in status (requested opening or closing of a circuit). These failures are generally not a direct cause of disturbances for the loads. However, they are often not detected and subsequently cause network malfunctions when other phenomena occur such as:
  - ☐ loss of protection and/or discrimination;
  - ☐ loss of reconfiguration or backup means.

The effects of voltage sags or outages depend on the sensitivity of the load.

Certain loads, such as computer equipment, are sensitive to voltage sags and very short outages (a few dozen milliseconds), whereas other devices can handle longer outages without disturbing the process.

It is therefore important to characterise devices by their degree of sensitivity.

What is more, the actual down time of a load or a process does not depend necessarily on the duration of the outage. In certain cases, the return to normal operation can depend on much more than the simple return of electrical energy (e.g. preparation of clean rooms, set-up of machine tools, chemical processes, etc.).

From it above, it is clear that it is necessary to determine the criticality of loads based on the consequences of a shutdown.

The traditional means implemented to prevent these disturbances are:

- autonomous sources (gensets, gas turbines, etc.);
- multiple incomers from the distribution network, as independent as possible;
- installation of power interfaces (UPSs, no-break power supplies, etc.);
- systems used to resupply loads via either network reconfiguration (source-changeover systems, loops, etc.) or an alternate source located as close as possible to the load;
- installation of devices to detect failures as fast as possible (short intervals between preventive maintenance work, automatic tests, etc.).

The contribution of a study

An operating-dependability study is the means to manage the risks of negative events during design of the network architecture by:

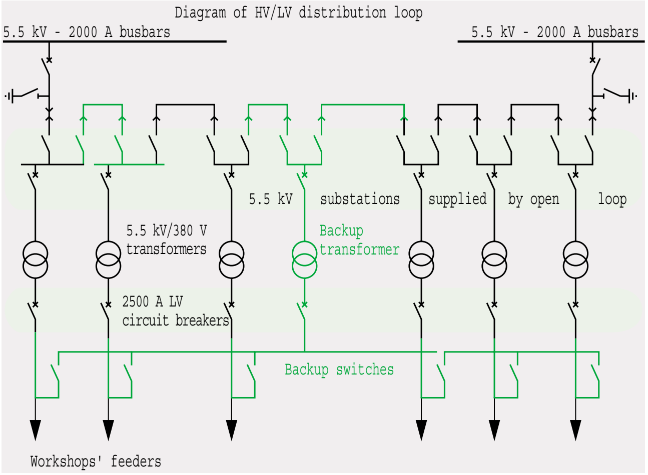
- determining the criticality of loads and, depending on their degree of sensitivity, the possible negative events for the electrical installation. The goal is to identify the critical points in the network and to determine their performance criteria in terms of dependability;
- running quantitative analysis of one or more basic architectures according to dependability factors;
- finally, justifying the decisions made concerning backup and/or interface systems, redundancy, preventive maintenance, given the customer's needs.

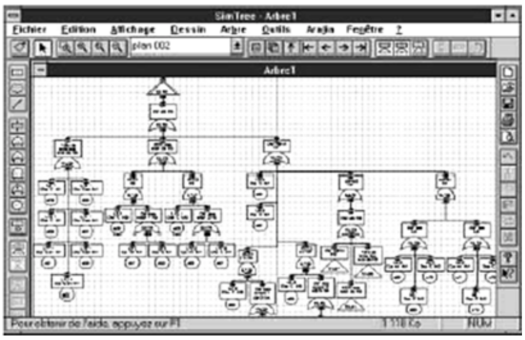
Example

This case is drawn from a study to improve the electrical network of an automobile factory (see **Fig. 5**). The goal was to reduce the number and duration of outages due to failures and maintenance activities.

- Purpose of the calculations

Implement criticality analysis, quantify the existing system, then propose improvements.





Fault-tree analysis

Parameter	Current	Future	Gain
Non-availability of electrical energy in hours per year	6.9	0.7	90 %

Fig. 5: Recommended modifications (in green) carried out on the electrical network of an automobile factory, diagram and results (source Schneider Electric).

- Results of the calculations

The calculations provided the data required to determine modifications in the topology that produced the desired increase in dependability (see the diagram in Figure 5).

Annual lack of energy availability of less than one hour was obtained and the maintenance of electrical equipment no longer results in interrupting the supply of power to the process.

4.2 Steady-state conditions

Correct operation of an electrical network during normal, stable operating conditions results from good overall design of the system.

The notion of steady-state conditions is defined in the installation and supply standards by:

- the rated frequency of the electrical signals, called the power frequency;
- the amplitude and phase of the voltage and current waves, and their changes over time;
- the active and reactive power levels (supplied, drawn, lost) and the corresponding energy.

Goals

The purpose of studying the behaviour under steady-state conditions is to:

- design networks (basic sizing of installations and equipment, system control and management);
- take into account risk situations caused by installation malfunctions or problems inherent in the electrical devices (wear, ageing).

Phenomena and origins

The phenomena requiring analysis are all the normal exchanges of active and reactive energy at power frequencies between the sources and loads, via electrical connectors, under the foreseeable operating conditions of the supplied process and the electrical system:

- flow of currents;
- distribution of voltages;
- corresponding active and reactive power.

Correct operation of networks under steady-state conditions depends on:

- normal use of the system, a consequence of the operation and requirements of the process and the network, i.e. the sources and loads in use, variations in supply voltages, downgraded and emergency modes;
- the structure of the electrical network for the various operating modes, in terms of topology, length of lines, voltage levels).

Effects and solutions

Electrically speaking, malfunctions occur in one of the three forms presented below.

- Supply voltages outside tolerances

The voltage of supply networks is standardised. For example, standard EN50160 authorises tolerances of ± 10% above and below the rated voltage. The entire network is subjected to the consequences of these variations (within ± 10%).

Calculation of steady-state conditions must therefore take into account the combinations of extreme voltage and consumption values.

- Voltage drops on lines or transformers

Drops are due to the currents and depend on the active (P) and reactive (Q) power levels, and the impedance, resistive (R) and inductive (X), according to the law on relative variation $\Delta U/U = (R\ P + X\ Q)/U^2$.

A voltage drop produces various disturbances:

- voltage variations within the ± 10% limits of the rated value, depending on the changes in the connected loads and sources;
- voltage fluctuations, due to voltage variations at frequencies that cause lights to flicker. These fluctuations are provoked by certain typical high-power variable loads, such as welding machines or arc furnaces;
- a voltage unbalance in the three-phase system due to large single-phase or two-phase loads.

Voltage drops provoke:

- additional temperature rise in electric circuits and thus greater losses;
- tripping of circuit breakers and slowing of machines;
- malfunctions of sensitive loads and protection devices;
- bothersome flicker effect in lighting.

Voltage drops can be limited in a number of manners.

- Reduction of R and X, by modifying the short-circuit voltage of transformers, the size of lines or their length (layout of loads).
- Increase of the rated voltage with a corresponding reduction of current, which provokes a significant reduction in losses (quadratic law).

- Instantaneous propagation throughout the network of the source voltage level and of voltage drops.

This effect impacts on each element to a different degree (quantitatively), depending on the system topology.

Calculation of the steady-state conditions is the means to foresee the distribution of voltages and to propose solutions in view of limiting propagation by:

- □ increasing the short-circuit power of the sources;
- □ using regulators for the transformers (load and no-load conditions);
- □ power-factor correction equipment, which corresponds to a negative voltage drop (capacitors, electromechanical conditioners in the form of synchronous machines or static systems such as static Var compensators);
- □ rebalancing of the single-phase loads on the three phases.

The contribution of a study

The purpose of this study is to ensure correct design of the electrical installation, taking into account future changes and all process operating modes through:

- ■ thoughtful evaluation of the basic decisions;
- ■ calculation of the power sums of the steady-state conditions;
- ■ taking into account the different operating configurations of the electrical network, including the emergency and backup structures;
- ■ economic optimisation (balance between investment and energy losses).

Example

This case is drawn from a study on the design of a commercial site, using the dedicated ECODIAL software program developed by Schneider Electric, in compliance with the UTE 15-500 guide.

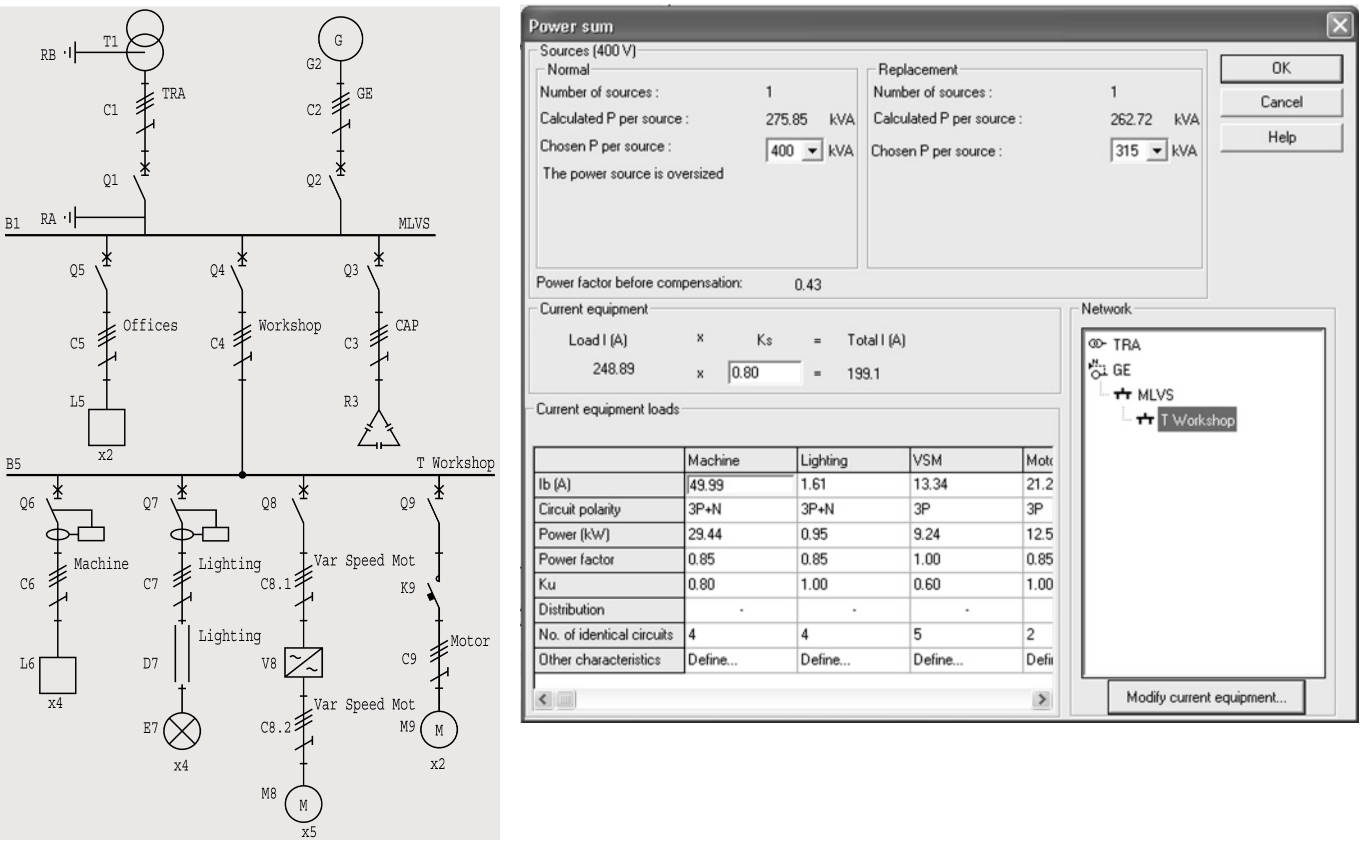
■ Purpose of the calculations

Only the first step in this study is presented here. It deals with the power sum of the installation, required to size the supply sources.

Note that for a low-voltage installation, the apparent-power values, after weighting by application of the load and diversity factors, are summed algebraically, conductor losses are neglected and the nodes are at the rated voltage.

■ Results of the calculations

Figure 6 shows the analysed single-line diagram with the screen for the data and the results (the



Power sum

Sources (400 V)

Normal

Number of sources : 1

Calculated P per source : 275.85 kVA

Chosen P per source : 400 kVA

The power source is oversized

Replacement

Number of sources : 1

Calculated P per source : 262.72 kVA

Chosen P per source : 315 kVA

Power factor before compensation: 0.43

Current equipment

Load I (A)	×	Ks	=	Total I (A)
248.89	x	0.80	=	199.1

Current equipment loads

	Machine	Lighting	VSM	Moto
Ib (A)	49.99	1.61	13.34	21.2
Circuit polarity	3P+N	3P+N	3P	3P
Power (kW)	29.44	0.95	9.24	12.5
Power factor	0.85	0.85	1.00	0.85
Ku	0.80	1.00	0.60	1.00
Distribution	-	-	-	
No. of identical circuits	4	4	5	2
Other characteristics	Define...	Define...	Define...	Defi

Network

- TRA
- GE
  - MLVS
    - T Workshop

Fig. 6: Design of a commercial site using the dedicated ECODIAL software, showing the single-line diagram and the power-sum screen (source Merlin Gerin - Schneider Electric).

characteristics of individual loads may be accessed for each switchboard), where the calculated total power for the source is 275 kVA.

This power sum is used to select the correct power ratings for the source transformer and the backup genset.

The values of the currents in lines are stored in memory for later use in sizing the devices.

4.3 Short-circuit

Operation of an electrical network may result in faults in the form of high short-circuit currents producing serious consequences that must be managed as best possible.

A short-circuit is an accidental contact between conductors, determined by:

- its type, which indicates the elements involved, i.e. single-phase (between a phase and earth or neutral), three-phase (between three phases), phase-to-phase clear of earth (between two phases), two-phase-to-earth (between two phases and earth),
- its initiation characteristics, i.e. the waveform of the current over time,
- its amperage (minimum and maximum values),
- its duration which is variable because the fault can be transient or continuous,
- its origin, internal (within a device) or external (between connectors).

Goals

The purpose of studying a network subjected to a short-circuit is to:

- identify risk situations that can possibly cause:
  - danger for persons,
  - destruction of devices due to electrodynamic forces, excessive temperature rise and overvoltages,
  - malfunctions that can result in total loss of the network due to voltage sags and outages,
- assist in making basic design decisions to limit the effects of faults, concerning:
  - system earthing arrangements (SEA),
  - suitable sizing of devices,
  - protection settings, determined on the basis of the fault-current calculations.

Phenomena and origins

The phenomenon requiring analysis is a sudden unbalance in the initial steady-state conditions:

- due to the appearance of high currents and voltage drops at the fault points,
- extension of the unbalance to the entire network,
- resulting in a new balance rendering the system unusable in part or whole, more vulnerable and disturbed.

The origins of short-circuits in networks are accidental disturbances caused by undesired contacts between conductors, dielectric breakdown of insulation due to overvoltages, mechanical events (breaking of cable, falling tree, animal) or human errors. The effects depend on the structure of the network, including the SEA, distant sources (distribution network) or near sources (nearby genset).

Effects and solutions

Electrically speaking, short-circuits produce a direct effect in the form of an overcurrent and an indirect effect in the form of voltage variations.

- The direct effect is produced on the installation components according to the successive phases of the initiation of the current:
  - peak value of the first half period, which is the maximum instantaneous peak,
  - rms value of the AC component,
  - value of the non-periodic (DC) component, which depends on when the fault occurs and the network characteristics. If the value is equal to zero, the operating mode is said to be symmetrical, otherwise it is asymmetrical.
The DC component adds to the AC component.

The effects impacting on equipment are:

- the electrodynamic forces exerted on the busbars and along cables,
- the temperature rise due to the flow of current in lines and switchgear,
- the operating capability (C+O) of a device on a shorted circuit.

These effects are managed by selecting sufficiently sized devices and equipment:

- electrodynamic withstand of lines, which characterises their mechanical strength,
- the current vs. permissible duration characteristics, which represent the thermal withstand capacity,
- the short-circuit breaking and making capacities which define the capacity of circuit breakers to handle the forces brought into play.

- The indirect effect is produced by voltage sags or outages and by the increased potential of the exposed conductive parts (ECP), with as a result:
    - malfunctions of sensitive devices, opening of contacts, locking of variable-speed drives,
    - disturbances in the transient behaviour of rotating machines (see section 4.5),
    - dielectric destruction of devices (see section 4.5),
    - touch voltages for persons.

These effects are countered by controlling:

- the transient conditions (see section 4.5),
- overvoltages (see section 4.7),
- clearing of faults by implementing a suitable protection system (see section 4.4).

The contribution of a study

The purpose of this study is to foresee the constraints inherent in faults:

- calculation of currents and voltages,
- for the various types of faults,
- and for the operating configurations, providing minimum and maximum values.

These results are then used to design the electrical lines (e.g. the size of busbars and their fixing system).

Example

This case is drawn from a study on the design of a power station, where it was necessary to size the devices in the substation.

- Purpose of the calculations

Check that the protection circuit breaker has the capacity to break the short-circuit current produced by a fault close to the generator, for example on the substation busbars. The problem lies in determining the most unfavourable current initiation conditions (moment of the initial zero crossing time).

- Results of the calculations

Them three-phase current is asymmetrical (see **Fig. 7**) with the superposition of a damped

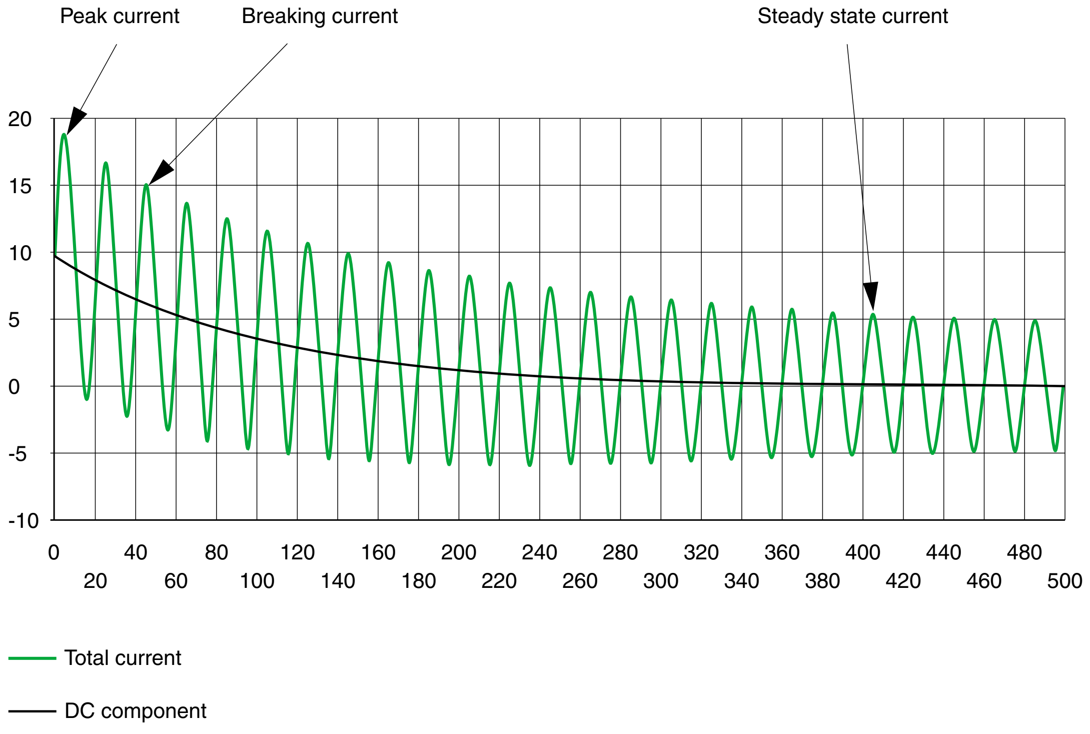


***Fig. 7**: Study on the substation of a power station, simulation of the asymmetrical three-phase short-circuit current produced by a fault near the generator.*

sinusoidal and a non-periodic current, hence the characteristic currents (peak, interrupted, continuous).

The maximum constraints exerted on the installation are used to select the circuit breaker in compliance with standard IEC 62271-100.

4.4 Protection

An electrical network that malfunctions must not endanger life and property.
Network protection is a set of devices that detect abnormal situations and react in a reliable, discriminate and rapid manner.
The main malfunctions were described in the previous sections.

Goals

The purpose of calculating the protection system is to:

- identify abnormal operating situations that may result in accidents for humans, destruction of devices or the loss of supply for consumers,
- determine the necessary measures to ensure the protection of life and property, and the availability of electrical energy. These measures result in the following necessary operations:
  - definition of the protection system,
  - selection, installation and combination of the breaking and protection devices,
  - determining the settings of protection devices.

Phenomena and origins

The electrical phenomena that must be studied are those present:

- during operation at power frequency, when operating malfunctions occur affecting the rated values, e.g. power (overload), current, voltage, frequency, etc.,
- during faults, short-circuits and overvoltages.

Protection devices must be suited to:

- normal system operation which may drift toward abnormal conditions (overloads, voltage sags, etc.),
- foreseeable accidental disturbances, including short-circuits, human errors,
- network architecture (radial, open or closed loop).

Effects and solutions

A faulty protection system is manifested, electrically speaking, by voltage drops throughout the network, overvoltages, overloads, short-circuit currents, where the main effects are:

- accidents for persons,
- destruction of devices and equipment,
- malfunctions of the electrical network and, consequently, of the process.

These effects can be avoided by:

- first, fundamental decisions concerning:
  - the SEA: isolated (IT), earthed (TT or TN), impedant, compensated,
  - the breaking devices: circuit breaker, fuse, disconnector-fuse, disconnector,
  - the discrimination system: current, time, energy, ZSI, directional, differential,
- then, by coordinating the protection devices based on the results of the short-circuit study (settings of relays and trip units, cascading between LV circuit breakers).
Practically speaking, this means:
  - de-energising the faulty section of the network as fast as possible,
  - maintaining energised the non-faulty sections and, if possible,
  - backup protection by the upstream device,

where the general idea behind the protection settings is to trip for the smallest fault current and not to trip for the highest normal current.

The contribution of a study

The purpose of this study is to ensure correct operation of the electrical installation, where the major parameters are:

- faults on the distribution network (phase faults, earth leakage and faults, overloads),
- faults in the machines operating on the site (rotating machines, computer equipment, etc.),
- the operating configurations, i.e. the sources, loads, emergency modes, future extensions,
- the devices in the protection system: sensors, relays/trip units, breaking devices,
- the protection plan and the settings of the protection devices.

Example

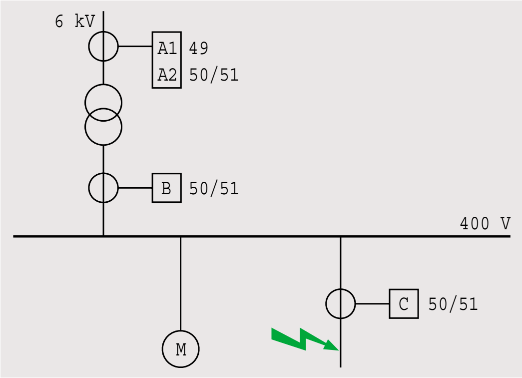
This case is drawn from a study on the design of the network for a petrochemical site.

- Purpose of the calculations

Select the protection functions for one of the HV/LV transformers in the installation and determine the settings for a maximum three-phase short-circuit on the LV side.

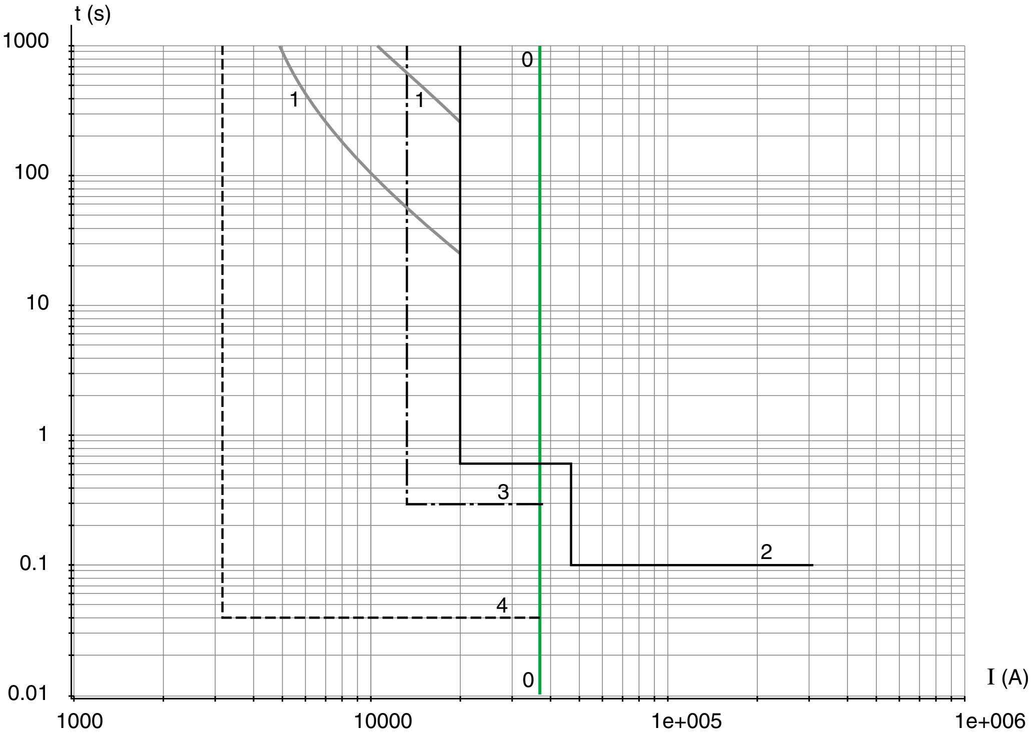
■ Results of the calculations

The part of the installation in question is shown with its protection system and the table lists the recommended settings for the protection functions (see **Fig. 8**). The time/LV current curves in **Figure 9** show that discrimination is ensured between the sections upstream and downstream of the transformer.



Relay	ANSI code	Type	Setting	Delay
A1	49	Thermal	120%	105 min
A2	50/51	Overcurrent Definite time	1400 A	0.5 s
A2	50/51	Overcurrent Definite time	3300 A	0.1 s
B	50/51	Overcurrent Definite time	12000 A	0.25 s
C	50/51	Overcurrent Definite time	3200 A	0.04 s

Fig. 8: Discrimination study for a petrochemical site, diagram and types of protection relays selected for a HV/LV transformer.



(O) : Fault current on LV outgoer: maximum three-phase

A1(1): thermal, **A2(2)**: overcurrent, **B(3)**: overcurrent, **C(4)**: overcurrent on LV outgoer

Fig. 9: Discrimination diagram for protection devices placed upstream and downstream of the transformer.

4.5 Stability

Stability concerns essentially high-power networks, with high voltages and generally a wide-area and complex topological structure, possibly with one or more energy-production sites.
Correct operation of an AC electrical network is the result of continuous adjustments in the balance (hence stability) between energy production and consumption over time and space.

The notion of network stability is characterised by:

- steady-state stability (minor changes) where the system returns to its initial status following a normal, low-amplitude disturbance,
- transient stability/instability, where the system shifts from one stable state to another, or diverges, following a sudden disturbance (loss of load or source, start of a high-power motor),
- dynamic stability, where system operation is controlled by limiting the negative effects of disturbances (e.g. protection of vital loads) using appropriate solutions (e.g. load shedding).

Goals

The purpose of studying the dynamic behaviour of a network is to identify risk situations that may result in transient instability and to determine the necessary counter-measures in view of maintaining dynamic stability. These measures deal with:

- clearing electrical faults within acceptable time limits, by the protection system,
- optimising operating modes,
- suitable sizing of the installation.

Phenomena and origins

Instability phenomena occur throughout the network in the form of:

- electromechanical oscillations of machines around their position of synchronous balance, resulting in variations in speed and the rated power frequency (50 or 60 Hz),
- oscillations in current flows in the lines between sources and/or loads, producing exchanges of active and reactive power and resulting in voltage drops.

Instability has three possible origins.

- Accidental disturbances
This category includes short-circuits, voltage sags, outages and failure of sources, nuisance tripping, device failure, human errors, etc.
- Normal network operation
This category includes the consequences of operation and the requirements of processes such as load variations, start of large motors, load switching and busbar management, etc.
- Structure of the electrical network
This category includes the topology, source regulations (generators and transformers) and the protection and automation systems in the electrical network.

Effects and solutions

Instability is manifested, electrically speaking, by the main types of malfunctions listed below.

- Frequency variations
An unbalance in the active power between the production centre and the loads results in a frequency variation throughout the system. The variation may exceed the permissible limits (e.g. ± 2%) beyond which the production centres are disconnected from the network. This situation can degenerate to the point where the entire system fails.

This problem can be avoided by automatically and gradually shedding loads, as well as by calling on reserve power (genset startup and regulation at maximum power).

- Voltage variations
Voltage drops are due to power flows (primarily reactive) in lines and transformers, or to very high currents.

This cumulative phenomenon (a drop in voltage produces an increase in the current and vice versa) can result in system failure or malfunctions.

This risk is limited by making available sufficient and well distributed reactive power (regulation of source reactive power, compensation capacitors, transformer load regulators, position of reactive sources), by load shedding and changes in motor start modes.

- Cascading overloads
The elimination of circuits due to temperature rise or damage results in load transfers to other circuits, again with the risk of a cumulative effect.

That is why systems are normally designed to accept the loss of a line (N-1 operating situation) by modifying the network operating topology or the overload protection devices, or by starting up new sources.

- Loss of synchronisation
Short-circuits result in desynchronisation between generators, which may make it necessary to disconnect certain machines. The resulting current and voltage oscillations in the network and the loss of elements (loads or sources) disconnected by their protection systems can lead to the failure of the entire network.

This situation is avoided by correct monitoring of generator settings, an effective protection plan and a well thought out load-shedding plan.

The contribution of a study

A study systematically covers the main phenomena presenting a risk and adapts to the particular aspects of each situation requiring analysis by taking into account the responses of the process:

- three-phase short-circuit (two-phase or single-phase where applicable),
- loss of lines, sources or loads,
- motor start-up,
- sharing, shedding and connection of loads,
- source electromechanical regulation modes and coupling (public networks, turbines and generators).

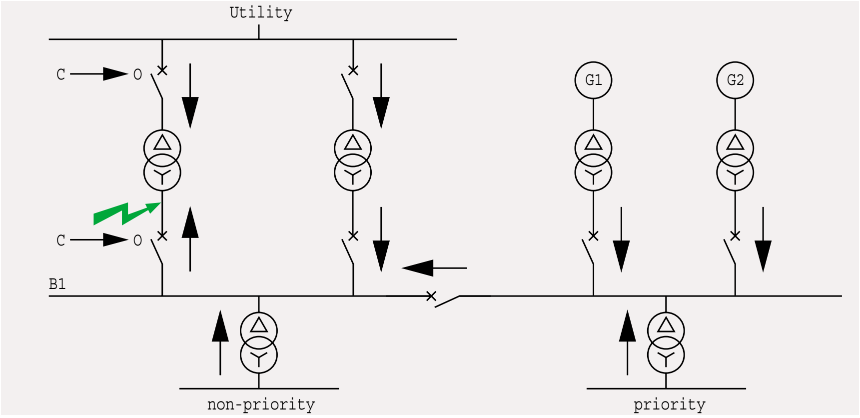
To be complete, the study must include:

- contingency analysis taking into account standard operating problems (e.g. the N+1 rule, short-circuits at different voltage levels, etc.) and even exceptional problems,
- simulation of the operation of protection devices and automation systems (actions and chronology),
- analysis of sensitivity to the decisive parameters (e.g. fault clearing time, motor characteristics, setting coefficients for generator regulators, etc.).

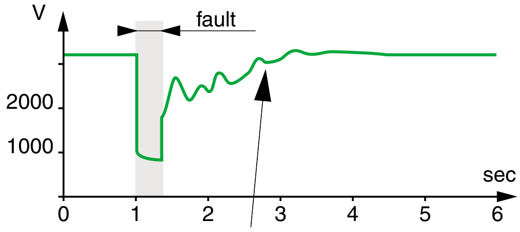
Example

This case is drawn from design study for a heavy-industry production site.

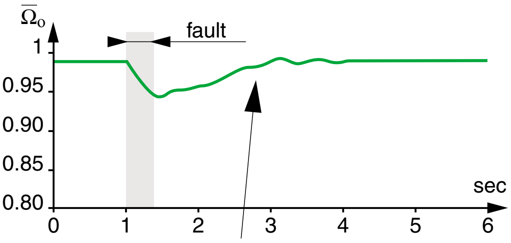
The installation comprises a number of sources supplying the loads (motors and passive loads) via two sets of busbars (priority and non-priority) (see **Fig. 10**).



Tripping in less than 300 ms

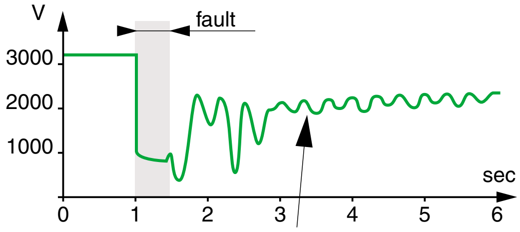


The voltage returns to normal.
The process is correctly resupplied.

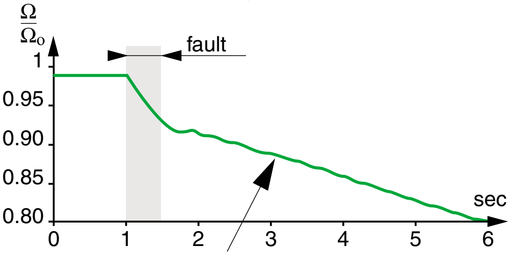


The pump reaccelerates. The process continues.

Tripping in 350 ms



The voltage does not return to normal.
The process is not correctly resupplied.



The pump stalls. The process shuts down.

***Fig. 10**: Stability study on a heavy-industry production site. Diagram and significant curves following tripping.*

The following was noted during a short-circuit on the secondary of a transformer connected to the public utility:

- a voltage drop that provoked, among other problems, a slowing of the motors,
- when the fault was cleared, the current drawn by the motors rose to the in-rush level, producing considerable voltage drops and insufficient reacceleration torques for certain motors that stalled or crawled.

The motors can reaccelerate only if the fault is sufficiently short.

- Purpose of the study

The short-circuit is normally cleared by the transformer protection devices (opening of the upstream and downstream circuit breakers). The goal is to determine the maximum clearing time that ensures the dynamic stability of the network.

- Results of the study

The voltage and speed curves show that network stability is ensured, for a three-phase short-circuit on the secondary of the transformer, when the protection devices are set to less than 300 ms.

4.6 Harmonics

Harmonics concern essentially electrical networks supplying non-linear loads representing a high power level with respect to the source and capacitors.

All AC networks encounter some distortion of the current and voltage sinusoidal waveforms due to the types of loads and/or the sources.

Harmonic pollution of a network is quantified by the signal distortion transformed into a spectrum (amplitude and phase) with the fundamental (50 or 60 Hz) and the harmonic orders (successive whole number orders), from which it is possible to deduce:

- the total harmonic distortion (THD) of the current and voltage, which measures the rms value of the distortion with respect to the fundamental,
- the laws governing the combination of harmonic values with respect to the amplitude and phase.

Goals

The purpose of studying the response of a network to harmonics is to:

- identify risk situations which may cause malfunctions or temperature rise in certain devices, premature ageing, electromagnetic or mechanical disturbances,
- then determine the precautions required to control the situations, maintaining pollution at acceptable levels with respect to standards (devices, installation, supply).

These precautions cover:

- identification of the polluting loads,
- estimation of filtering solutions,
- suitable sizing of installations,
- optimisation of operating architectures.

Phenomena and origins

The different electrical phenomena related to the presence of harmonics occur throughout the network, via interdependent mechanisms:

- generation of harmonic current or voltage sources by the polluting loads,
- effects of the pollution in the immediate vicinity of the polluting sources,
- propagation of the harmonics to the entire network with effects produced on all loads,
- composition of the pollution at all points in the network at each instant,
- possible amplification of the pollution through resonance (plug circuit) when capacitors are present (long lines, power-factor correction).

Harmonics have a number of causes:

- normal operation of the network, due to process operation and requirements, including operation of polluting loads at different speeds, starting or stopping of other loads,
- the structure of the electrical network, including the voltage levels, separation of polluting and vulnerable loads, the relative power of sources, polluting loads and capacitors.

Effects and solutions

This pollution is manifested, electrically speaking, by the main types of malfunctions listed below.

- Direct sources of pollution

The loads distorting the current represent the vast majority of the devices causing harmonics. They are said to be "non linear" because the current drawn does not have the same waveform as the supply voltage. Each type of load has a specific harmonic spectrum.

There are passive loads (welding machines, arc furnaces, lamps) and power-electronic loads that are increasingly used (variable-speed drives, rectifiers and dimmers, UPSs and devices with switch-mode power supplies).

The voltage and power ranges of these devices are very wide, ranging from small household appliances (LV, a few dozen Watts) up to large industrial loads (HV, dozens of MW).

Voltage pollution is due to the design of coils and magnetic circuits of devices (rotating machines, transformers).

The limitation of harmonics caused by loads is possible, to a certain extent, by 12-pulse bridges, converters drawing a sinusoidal signal, smoothing inductors and built-in filters.

■ Direct effects of pollution on loads

□ Harmonic currents cause stray power phenomena resulting in additional temperature rise and energy losses.
This can be avoided by oversizing devices according to derating coefficients defined by equipment standards.

□ Voltage distortion caused by harmonics disturbs operation of electronic devices (e.g. shift in zero crossing time of the reference wave).

□ Harmonics also product mechanical (noise, vibrations) and electromagnetic (low currents affected by high currents) effects (electromagnetic compatibility - EMC).

■ Transmission results in harmonic propagation, amplification and addition.

□ The loads drawing harmonic currents inject the disturbances into the entire network, as a function of the impedances encountered. The result is voltage distortion supplied to the loads throughout the network.

□ In addition, the presence of capacitors can amplify the pollution due to resonance (plug circuit) made up of the capacitor in parallel with the network inductors).

□ In its own immediate vicinity, each polluting load suffers the negative effects of its own harmonics.

Finally, at each point in the network, the vector composition of the various harmonics also produces its effect at all times. Practically speaking, the harmonics are summed using a standardised method that takes into account a non-simultaneity factor (IEC 60871).

■ The risk criteria are quantified by standards and regulations based on the distortion levels. Generally speaking, a situation is considered serious when the THDU reaches 5% and difficulties are certain to occur above 10%. That is why utilities contractually undertake to supply voltage under a given level of THD and users must limit the harmonic currents injected. Practically speaking, risk situations are evaluated according to power criteria applied to polluting loads and capacitors.

■ A number of methods exist to limit risks:

□ increase the short-circuit power of sources,

□ separate sensitive loads from polluters,

□ install antiharmonic inductors (capacitors are protected against harmonic overloads),

□ install passive filters (harmonics are trapped in circuits with a low inductance),

□ install active filters (harmonics are neutralised by harmonic injection in phase opposition).

The contribution of a study

The purpose of this study is to ensure correct operation of the installation when the harmonic loads are turned on, by:

■ calculation of distortion, taking into account the spectrum of the polluters (amplitudes and phases, laws governing composition and propagation),

■ optimum calculation of filtering,

■ calculation of device oversizing (steady-state and transient harmonic constraints),

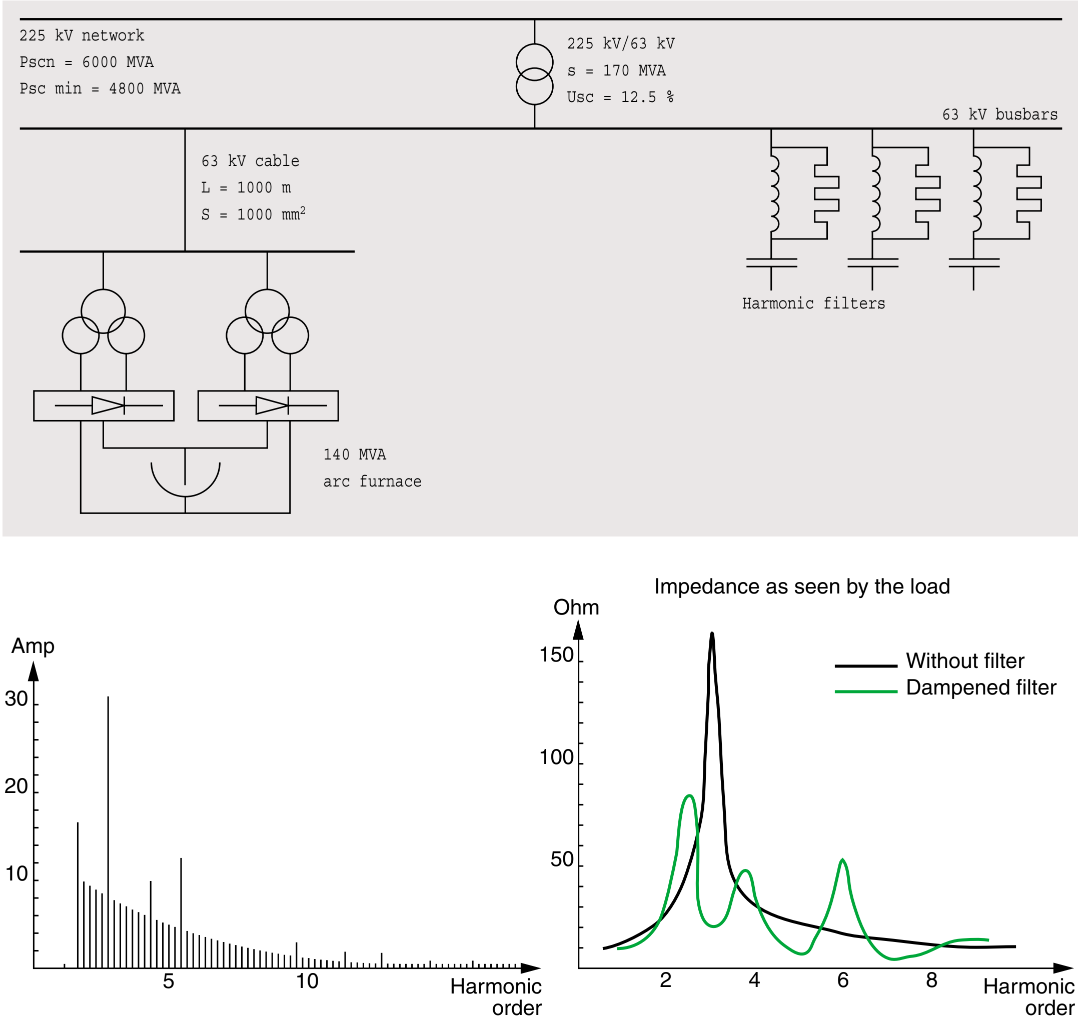
■ analysis of network operating diagrams in the various operating modes (normal and downgraded for connection of sources, polluters and loads),

■ analysis of sensitivity to important parameters (e.g. variation in the values of electrical elements in the network as a function of the accuracy, temperature, etc.).

Example

This case is drawn from a study on the design of a steel mill with a DC arc furnace and a capacitor bank for power-factor correction (see **Fig. 11**). The furnace draws whole-number harmonics (rectifier) superimposed on a DC spectrum (unstable arc).

■ Purpose of the study
The capacitor bank forms a plug circuit with the system inductors (antiresonant, third order), resulting in a prohibitively high level of THD (18.5%). It is necessary to calculate the filtering required to reduce the THD to an acceptable level.



Current spectrum of the furnace.

Impedance spectrum as seen from the 63 kV busbars.

Fig. 11: Study on harmonics for a steel mill (diagram and spectra).

- Results of the study

Mounting of the capacitors in three damped resonant filters (tuned to orders 3, 5, 7) modifies the network impedance spectrum and reduces the voltage THD to an acceptable value of 3%.

4.7 Overvoltages

Overvoltages concern all electrical networks, which however differ in vulnerability according to their topology, voltage level, types of devices employed and operating modes.

Operation of AC networks is always subject to voltage disturbances in the form of peak voltages beyond the limits stipulated by standards or specifications.

Overvoltages in a network are quantified by the amplitude and shape of the waveform and by the duration of the disturbance:

- overvoltage coefficient, ratio between the peak amplitude of the voltage and the rms value of the operating voltage,
- continuous sinusoidal overvoltage (at power frequency) for a long duration (over one hour),

- temporary sinusoidal overvoltage (near power frequency), for a relatively long duration (between 1.5 times the power frequency and one hour),
- transient overvoltage (oscillating or not), generally rapidly damped, very short (less than the power frequency). This category includes overvoltages with a slow front (e.g. switching impulses), a fast front (lightning strikes) and a very fast front.

Goals

The purpose of a network study on overvoltages is to:

- identify risk situations that may result in:
  - ☐ destruction of devices and equipment by dielectric breakdown, electrodynamic constraints and ageing,
  - ☐ malfunction of electronic devices,
- determine the measures required to limit their effects to a minimum, thus ensuring effective withstand of network devices and equipment.

These measures cover:

- installation design (SEA),
- estimation of protection devices (type, location and rating),
- correct sizing of devices and equipment,
- operating advice.

Phenomena and origins

The observed phenomena are damped oscillating exchanges of energy between circuits (inductors, capacitors, resistors) occurring instantaneously by local status changes (e.g. device switching). Depending on the type of overvoltage, they are manifested by:

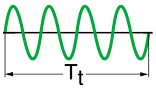
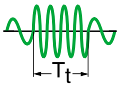
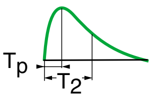
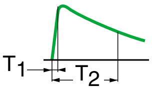
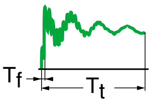
- their formation at the point of change,
- their propagation to the rest of the network, according to the laws of reflection, refraction and overlaying of the transmitted waves, with attenuation that is a function of the frequencies involved (the higher the frequency, the faster the damping),
- the possible combination of different types of overvoltage, likely to increase the constraints.

Overvoltages affecting networks have a number of origins:

- normal network operation, including load switching, switching on or off of inductive or capacitive circuits (cables, lines, capacitors, transformers, motors), the specific operation of protection devices,
- the structure of the electrical network, including the SEA, voltage levels, the length of lines,
- accidental disturbances, including faults and the measures to clear them, nuisance tripping, lightning strikes.

Electrically speaking, these overvoltages are grouped according to their main types (see **Fig. 12**):

- at power frequency, which may have different causes such as insulation faults, load unbalance, overcorrection of the power factor, etc.,
- switching impulses, due to connection or disconnection (common events during normal

Overvoltage class	**Low frequency**		**Transient**		
	Permanent	**Temporary**	**Slow front**	**Fast front**	**Very fast front**
Shape					
Shape range (frequency, rising front, term)	f = 50 or 60 Hz Tt ⩾ 3.600 s	10 < f < 500 Hz 3.600 ⩾ Tt ⩾ 0.03 s	5.000 > Tp > 20 µs 20 ms ⩾ T2	20 > T1 > 0,1 µs 300 µs ⩾ T2	100 > Tf > 3 ns 0.3 > f1 > 100 MHz 30 > f2 > 300 kHz 3 ms ⩾ Tt
Standardised shape	f = 50 or 60 Hz Tt (*)	48 ⩽ f ⩽ 62 Hz Tt = 60 s	Tp = 250 µs T2 = 2.500 µs	T1 = 1.2 µs T2 = 50 µs	(*)
Standardised withstand test	(*)	Short duration power frequency test	Switching impulse test	Lightning impulse test	(*)

(*) to be specified by the relevant product Committee

Fig. 12: The different types of overvoltage.

operation of the network) of a device, such as a transformer, motor, reactor, capacitor or cable/ line,

- resulting from faults or their clearing. The fault is considered an involuntary or inevitable switching operation, followed by a second operation when it is cleared,
- lightning impulses, following a lightning strike which is a sudden discharge of current that can reach several thousand amperes.

Effects and solutions

Depending on their type, overvoltages produce different effects and the solutions to avoid them must be suited to each type.

- Power frequency
  - An insulation fault in a network causes an overvoltage with a theoretical coefficient of up to 1.7 (single-phase fault with an isolated neutral).

Similarly, breaking of the neutral conductor causes overvoltages by displacing the neutral point.

  - A load unbalance in a three-phase network can unbalance the system to the point of saturating the transformers and disturbing operation of motors.
  - Overcorrection of the power factor due to shunt capacitors raises the voltage if the load level is low.
  - A line carrying no load behaves like a series of LC circuits with a gain greater than one (Ferranti effect), resulting in a continuous overvoltage at the end of the line with a non-negligible amplitude for distances greater than 300 km (factor of 1.05). This effect is even greater when a load is disconnected at the end of a long line.
  - Ferro-resonance, a non-linear oscillation between a capacitor and a saturable inductor, may result in overvoltages in some situations, e.g. a voltage transformer in series with an open circuit breaker or between a phase and the neutral in an IT system, etc.

All these risks can be limited by design and operating precautions. For example, correctly balanced loads, checks on initial energisation of capacitors, installation of voltage relays on incomers.

- Switching impulses

The resulting overvoltages depend on the load conditions (load or no load), with or without a residual load, according to a certain periodicity and taking into account the actual physical behaviour of the switching device in terms of pre-arcing, withstand to the transient recovery voltage (restrike/re-ignition) and current pinch-off.

  - When a capacitor is switched in at the maximum network voltage, the overvoltage coefficient can reach 2 and for disconnection the coefficient can reach 3.
  - During switching of a transformer or motor, the overvoltage coefficient can reach 2, in addition the steep front of the transients produces particularly high constraints on the initial spires of the windings of the devices.
  - During line switching, the overvoltage coefficient can reach 3. This is the case for reconnection of a long line with a trapped residual charge (capacitive load).

Switching overvoltages can cause dielectric breakdown in devices and system malfunction.

The recommended protection devices act by limiting and damping the energy oscillations between the circuits, through insertion resistors in circuit breakers and contactors, checks at the time of switching by a synchroniser, RC surge arrestor or even lightning arrestors.

- Impulses during faults (appearance and clearing).

The occurrence of a fault generally results in an overvoltage coefficient of less than 2 and it is more the overcurrents that are a problem (see section 4.3).

Fault clearing provokes an overvoltage with a coefficient of less than 2.5 (worst case of a single-phase fault with an isolated neutral). The transient is overlaid on the temporary situation caused by the fault.

- Lightning strikes

The sudden current discharge can reach several hundred kiloamperes, combined with a voltage that is a function of the network impedances. This current can discharge:

  - to a line or a metal structure. During propagation, the resulting voltage waves can cause insulator flash-over and overvoltages,
  - to earth causing an increase in the potential, which causes voltage increases in the earth electrodes of installations.

Lightning currents produce thermal and mechanical effects (electrodynamic forces), whereas lightning voltages cause dielectric breakdown of devices and system malfunctions.

Protection devices act in two manners:

  - first, they avoid direct lightning impacts on electrical systems and divert them to earth (lightning rods, lightning shields and earth electrodes),
  - secondly, they direct the lightning currents conducted in the network to earth to limit overvoltages and avoid dielectric breakdown

(spark gap units, lightning arrestors, varistors, high-quality earth electrodes, etc. in LV/MV/HV).

The contribution of a study

A study intended to prevent the negative effects of overvoltages in installations comprises the following steps:

- qualitative evaluation of the risk phenomena, which depend on the studied network,
- calculation of the generated overvoltages and study of their transmission to the system,
- analysis of sensitivity to important parameters,
- definition of the protection devices,
- determination of device and equipment insulation in compliance with the applicable standards.

Example

The selected case is drawn from a study on the design of a HV distribution substation that must be securely protected against overvoltages caused by lightning striking the incoming line.

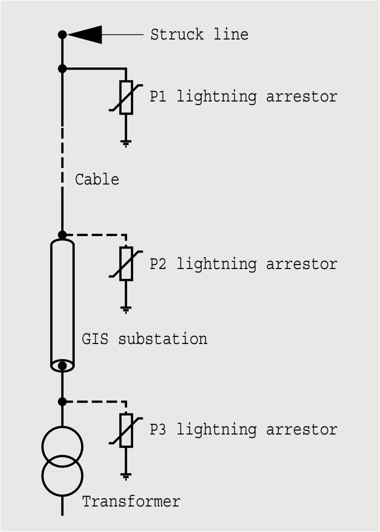
- Purpose of the calculations

The purpose is to size devices for lightning overvoltages taking into account the recommendations of standard IEC 60071-1 and 2 on insulation coordination, which quantifies the risk. The mean time between two destructive faults is between 250 and 1 000 years.

- Results of the calculations

Statistic simulation of lightning impacts on the line using the electrogeometric model indicates the distribution of the overvoltages propagated in the substation and is used to deduce the probability of the resulting risk (see table in **Figure 13**).

Optimum substation protection against lightning, quantified as per the insulation-coordination standard, consisted of lightning arrestors in the substation and the level of protection shown in figure 13.



	Risk for:		
Installed lightning arrestors	**Cable** (LIWL* 650 kV)	**GIS substation** (LIWL 650 kV)	**Transformer** (LIWL 650 kV)
P1	1454 years	425 years	299 years
P1+ P3	2053 years	812 years	592 years
P1+ P2 + P3	10^{E} 9 years	10^{E} 9 years	2.7 10^{E} 6 years

(*) LIWL: lightning impulse withstand level.

Fig. 13: Study on lightning overvoltages for the design of a HV distribution substation, diagram and risk estimates.

4.8 Electromagnetic compatibility

Electromagnetic compatibility (EMC) concerns all electric and electronic devices, systems and installations. The notion is defined in the international standards as the capacity of a device, system or installation to operate normally in its electromagnetic environment without causing disturbances.

Goals

The purpose of an EMC study is to:

- identify the situations likely to provoke and/or be subjected to system malfunctions during operation in view of evaluating the consequences,
- provide the suitable solutions based on the standards and good professional practices to limit the effects in installations.

Phenomena and origins

Studies cover all electromagnetic disturbances:

- resulting from interaction between various network elements, i.e. the source, coupling via the transmitter and the victim for which normal operation is disturbed,
- over a spectrum, depending on the waveform, ranging from continuous up to a GHz and higher,
- characterised by their amplitude and energy,

- according to the conduction and/or radiation modes.

Electromagnetic emissions have a number of origins:

- normal network operation, because voltages and currents can be natural sources of disturbances,
- the network structure and installation implementation, which can facilitate the transmission of disturbances.

Effects and solutions

Transmission of electromagnetic disturbances takes place via different types of coupling:

- capacitive (voltage) between nearby conductors, e.g. closely laid cables, etc.,
- inductive (current) between conductors, e.g. cables with high and low currents, etc.,
- antenna effect (electromagnetic radiation), e.g. output cable of an electronic device with HF chopping, etc.,
- galvanic due to the common impedance of circuits, e.g. a single conductor for the supply of a data-acquisition device and measurement acquisition.

The noted effects concern essentially:

- the malfunction of elements in the electrical system and the process controlled by sensitive devices,
- temperature rise and/or the destruction of electronic, analogue or digital components.

All these effects are managed by good professional practices in view of:

- reducing the level of disturbances emitted by the sources,
- reducing the coupling modes,
- reducing the vulnerability of the victims (hardening), by adapting, for the concerned frequency ranges:
  - □ the manner in which the SEA is taken into account,
  - □ wiring, e.g. cable selection, separation and running of power cables and low-current (signal) cables,
  - □ shielding, e.g. the types of screen (conducting or ferromagnetic), the connection mode of terminals, management of earth loops,
  - □ use of electrical filters tuned to the signals requiring attenuation.

The contribution of a study

Correct design of an electrical installation requires a study to:

- identify the sources of disturbances, the couplings and the victims,
- define the means required to obtain a system complying with standards.

Example

This case is drawn from a study on an industrial site where the measurement-acquisition and video systems were disturbed by operation of the process test facility.

- Purpose of the study

Determine the action required for normal operation of the metrology system.

- Results of the study

The SEAs of the test facility (TN-C) and the acquisition system (TN-C-S) are different (see **Fig. 14**). The 50 Hz leakage currents and the harmonics caused by the variable-speed

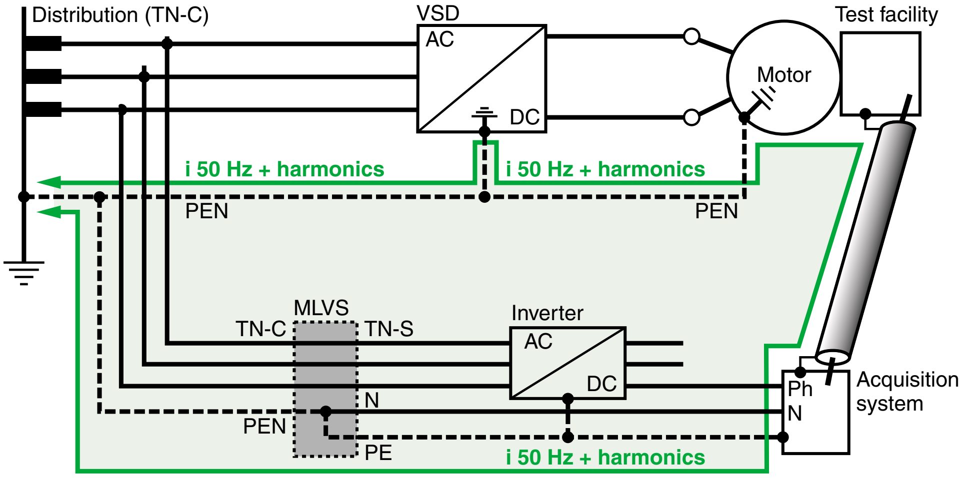


Fig. 14: EMC study for measurement-acquisition and video systems installed near a test facility, diagram showing the path of leakage currents and harmonics.

drive in the test facility loop back to the supply via two possible paths, the test bench and the acquisition system, with current levels proportional to the admittances.

The study recommended protecting the acquisition system from its environment using galvanic isolation for its lines, a practical, effective and inexpensive solution.

4.9 Measurements for audits

This section fills out the previous sections by highlighting the importance of measurements in monitoring an electrical network and improving its effectiveness.

Measurements are indispensable when an audit of the network is necessary:

- either during normal operation of the system, at start-up of the installation or during major modifications, to check that the network operates as planned during the design stage,
- or following unexplained problems such as the destruction of devices or the loss, in part or in whole, of power.

Even a well designed network can suffer problems or malfunctions that are difficult to understand, in which case measurements are a basic element in establishing a diagnosis.

Measurements for network audits

The purpose of measurements is to:

- check electrotechnical values following start-up of an installation,
- monitor consumption and energy quality,
- identify and explain major or reoccurring problems in the system,
- recommend solutions for problems,
- validate the models used in network simulations.

Phenomena studied

The phenomena studied, for which measurements are required, span all the elements discussed in the above sections.

The solutions decided in view of avoiding their effects result from:

- observations made during visits to the installation,
- processing of the electrical measurements made by permanent devices and devices temporarily installed,
- electrotechnical calculations,
- checks on compliance with standards and good professional practices.

The contribution of an audit

The purpose of an audit is to maintain or improve the operating conditions of an electrical network, with different levels of complexity and requirements, by:

- a general understanding of system based on essentially qualitative checks concerning the safety of life and property, the long-term operation of devices, power sums, the protection plan and the presence of the necessary instrumentation,
- achieving satisfactory system performance with respect to defined qualitative criteria, e.g. dependability analysis, analysis of electrotechnical risks, sizing of the network and of devices,
- overall optimisation of the system, e.g. energy quality, utility contract and consumption, maintenance and replacement parts, and ranking of the proposed action according to its importance,
- taking into account the existing system and any future changes.

Note. The development of data-exchange techniques (IT) has opened new horizons with, for example, disturbance monitoring (see **Fig. 15 and 16**) and remote diagnostics and monitoring of electrical networks in various fields (industrial and commercial) (see **Fig. 17**).

An audit example

This example is drawn from the audit on the electrical network of a micro-electronics industry, carried out to provide a general check-up after many years of operation.

- Purpose of the audit

The purpose of the audit is to detect any weak points in the electrical installation that could impact on the quality of the energy supply.

- Results of the audit

The aspects specific to the electrical network and its components made clear the need to make improvements on the network architecture, the protection plan and to take into account the ageing of the HV/LV transformers.
The table in **figure 18** (see page 30) sums up the results of the audit.

Fig. 15: SEPAM Series 40 digital protection relay (Merlin Gerin brand - Schneider Electric).

Fig. 17: PM70 remote metering device (Merlin Gerin brand - Schneider Electric).

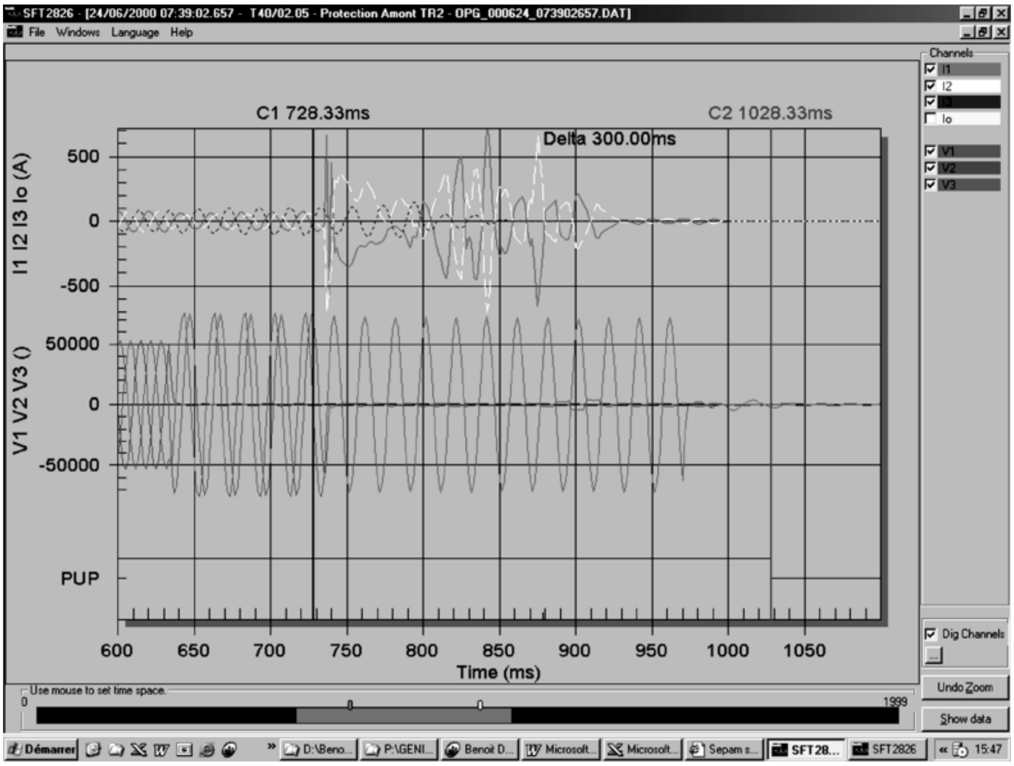


Fig. 16: Oscillogram of a fault recorded by a SEPAM relay.

Chapter	Item	Measurements	Diagnostic	Action required	Priority level
Network diagram	Network architecture	No	In a number of substations, for a fault on the LV busbars, no redundancy is available during repairs.	Run an availability study to improve the architecture.	Not urgent
	Major fault	No	After a fault on a HV loop, resupply of the substations requires manual operations. No LV gensets to supply critical switchboards.	Check the operating mode of the UPSs. Study the need for LV gensets.	Not urgent
	Earthing	No	The HV SEA is isolated to ensure good continuity of service, but the number of earth faults is on the rise with network ageing.	Study the possibility of an impedant SEA.	Must be studied
Protection plan	130 kV protection	No	In certain configurations, overcurrent protection can result in the total failure of the HV network.	Revise the protection plan implementing differential and directional functions. Check the discrimination offered by the protection devices between the utility and the factory.	Urgent
	15 kV protection	No	Discrimination is partial in the cases listed below: ■ insufficient time delay between upstream and downstream ends of lines, ■ in part of the network, the time required to clear an LV fault can reach several seconds.	Restudy the settings of the protection devices for the HV network, based on the calculation of the short-circuit currents. Study the possibility of logic-based discrimination.	Urgent
Dielectric characteristics of HV/LV transformers	Lightning impulse on HV side	No	Transformers equipped with lightning arrestors.	No action required.	
	Lightning impulse on LV side	No	No lightning arrestors on the LV loads.	Study lightning protection for the LV network.	Not urgent
	Switching impulse when HV CB opens	No	The setting for overcurrent protection accepts in-rush currents. No risk of nuisance tripping.	No action required.	
	Internal resonance at HF	Yes	No HF overvoltages measured.	No action required.	
	HV harmonics	Yes	Negligible THD.	No action required.	
	LV harmonics	Yes	Negligible THD.	No action required.	
	Switching impulse when capacitor bank opens	Yes	Capacitor contactors are not equipped with insertion resistors.	Study the possibility of insertion resistors to reduce the in-rush currents.	Not urgent
Thermal characteristics of HV/LV transformers	Overload and harmonic currents	Yes	No overloads. Negligible harmonic values.	No action required.	
	Continuous overvoltage (HV)	Yes	Negligible values.	No action required.	
	HV harmonics	Yes	Negligible values.	No action required.	
	DC current (LV)	No	Phenomenon not taken into account.		Must be checked

SEA: System earthing arrangement.

Fig. 18: Results of an audit on an electrical network in the micro-electronics industry

5 Summary - Main risks for users - Answers provided by studies

	Main risks for user	Answers provided by studies
Dependability See section 4.1	Accidents involving persons. Destruction of property. Production shutdown. Loss of information (computer systems, etc.). Additional costs, e.g. possible replacement of equipment, repairs, production shutdown (lost production and process restarts).	Quantify the frequency of problems. Quantify the availability of electrical energy. Determine the weak points in the solution which must be improved, if necessary. Determine any unnecessary redundancies. Compare different architectures. Recommend preventive maintenance. Recommend stocks of replacement parts.
Stmeady-state conditions See section 4.2	Operating disturbances (damage to sensitive loads, variation in motor torques, mechanical vibrations and even production shutdowns). Visual disturbances (flicker). Abnormal temperature rise in connections and magnetic circuits, resulting in energy losses and possible risk of fire and accelerated ageing. Additional costs, e.g. possible replacement of equipment (need to oversize), repairs, production shutdown (lost production and process restarts).	A check on system sizing in compliance with standards: ■ selection of voltage levels in the network structure, ■ short-circuit power and voltage tolerances ■ location and distribution on power-factor correction, ■ equipment: breaking devices, cable sizes, transformer and motor characteristics, etc. Calculation of system steady-state conditions (load-flows) in different operating situations: ■ distribution of voltages at nodes and of currents in the connectors, in amplitude and phase, ■ voltage drops, ■ power flows and the corresponding losses. Optimisation of energy contracts. Operating recommendations (selection of transformer voltage taps, load-shedding and reconnection plan, start-up of capacitors, etc.). Updating of network data.
Short-circuit See section 4.3	Dangerous touch voltages for persons. Damage to electrical equipment due to overcurrents (temperature rise and fire). Production shutdown. Disturbances due to voltage sags (malfunction of sensitive devices). Additional costs, e.g. (repairs, production shutdown, etc.).	Short-circuit currents calculated in compliance with the installation standards (IEC 60909 and UTE C15105 guide), required to calculate the protection devices. Sizing of devices and equipment (circuit breakers, fuses, transformers, switchboards, sensors, cables, wiring systems, earthing circuits) taking into account making and breaking capacities as well as short-circuit thermal and electrodynamic withstands.
Protection See section 4.4	Accidents involving persons. Damage to electrical equipment and machines. Shutdown of unaffected parts of the network. Production shutdown. Faulty sections of the network maintained in operation, resulting in system instability. Process malfunctions leading to production losses and repair costs.	A general definition of the protection system and its principles, e.g. SEA, protection and backup functions, selected discrimination, coordination between different voltage levels. Sensor characteristics: location, ratio, accuracy class. Breaking-device characteristics: type, location. Protection-device characteristics: settings of trip units and relays. Curves or tables showing effective discrimination between protection devices.

	Main risks for user	Answers provided by studies
Stability See section 4.5	Mechanical failures (breaking of shafts of rotating machines and speed reducers, damage to coils) following heavy torque shifts. Destruction or premature wear of electrical equipment due to abnormal temperature rise caused by overcurrents (transformers and connections, motors when supply is unbalanced or motors that crawl during reacceleration). Malfunctions due to variations in voltage, in loads, notably for sensitive equipment such as variable-speed drives, computers, safety systems, measurement devices), control devices (contactors, circuit breakers) and lighting. Production shutdown. Additional costs, e.g. (repairs, production shutdown, etc.).	Validation of source short-circuit power. Optimum distribution of loads (operating diagrams). Improvement in the protection system (basic design, settings with critical fault-clearance times). Selection of the motor-start method. Plan for load shedding and source uncoupling. Definition of load reconnection sequences and/or load transfers. Automation of source transfers. Optimisation of regulation-device operation and settings.
Harmonics See section 4.6	Destruction or premature ageing of electrical equipment due to thermal overloads (temperature rise due to harmonic currents, to third-order harmonics in neutral conductors) or dielectric breakdown (overvoltages due to harmonic voltages). Harmonic mechanical disturbances, e.g. vibrations and motor fatigue, abnormal noise in transformers and switchboards. Malfunctions caused by current and voltage harmonics (equipment incorporating power electronics), nuisance tripping of protection devices, disturbances in low-current systems (telecom, measurement and metering systems). Additional costs: ■ reduced installation efficiency due to additional energy losses (Joule, iron, skin and proximity effects), ■ additional investment to oversize equipment (derating) or to install filters.	Identification of polluting loads. Evaluation of harmonic distortion levels (current and voltage THD) and of harmonic spectra. Validation of network structure, e.g. short-circuit power of sources, isolation of disturbing devices, separation of sensitive parts of the network, power-factor correction. Recommendations for direct action on polluting loads, e.g. by changing from a 6 to a 12-pulse bridge. Recommendations for action on the pollution, e.g. sizing of filters (type of filter, specifications on components). Recommendations on device derating.
Overvoltages See section 4.7	Operating disturbances (voltage sags and short outages). Destruction of equipment due to dielectric breakdown. Production shutdown. Accelerated ageing and temperature rise in equipment due to non-destructive, but repeated stresses. Malfunctions of sensitive equipment (power electronics, low-current systems). Additional costs, e.g. (repairs, production shutdown, etc.).	Definition of the optimum solutions to attenuate the problem, based on the selective, simultaneous and selective use of several protection systems, e.g. lightning rods, overhead earth wire, lightning arrestors, surge arrestors, spark gap units, varistors, diodes, choke coils, insertion resistors, synchronisers. Sizing and location of the recommended systems. Definition of equipment insulation in line with the protection systems, selection of dielectric withstand in compliance with insulation-coordination standards (IEC 60664 for LV and IEC 60071 for HV). Design of the SEA. Operating advice.
EMC See section 4.8	Damage to electrical and electronic equipment due to temperature rise or dielectric breakdown. Malfunctions of electrical components that may impact on the entire network. Malfunctions of process machines. Additional costs, e.g. (repairs, production shutdown, etc.).	An EMC audit (to understand how disturbances occur). Assistance in drafting technical specifications for electrical systems. Advice on installation configuration, e.g. running of different types of cables, SEA, ECPs, etc. Application of EMC standards.
Measurements for audits See section 4.9	Studies and calculations often require measurements carried out on site, either continuously (e.g. via a permanently installed remote-monitoring system) or by temporarily installed measurement devices.	

6 Conclusion

The optimum total cost of ownership (TCO) of a system is the result of the best compromise between the service obtained by the user for the needs of the process and the total outlay.

For an electrical network, the TCO takes into account the different phases in the life of the system, e.g. design, construction, operation, maintenance and upgrades.

For this reason, all participants (owners, designers and users) are involved in all phases of the project and the electrical engineering studies constitute an indispensable step in the overall process leading to effective use of electrical energy. These studies can also be considered a profitable investment in that the efficiency of the installation can be improved.

This Cahier Technique publication has demonstrated the wide range of calculations required in conducting these studies.

These studies concern all types of networks in the LV and HV fields, and applications in all domains (industrial, commercial, residential, distribution). They can be used to foresee the electrical phenomena occurring during operation of systems and to analyse their impact on installation sizing and network operation. They also take into account important events and parameters, in both the normal and downgraded operating modes.

The various summary tables show the importance of the necessary means and know-how (see the following appendices as well). Finally, the examples provided indicate that the relevance of the selected solutions is also the result of the vast experience gained through a large number of audits. Only very large electrical companies (energy distributors or device manufacturers) have the necessary experience.

N.B. More in-depth information is available in the collection of Cahier Technique publications dealing specifically with many of the topics covered in this document (see the bibliography).

Appendix 1. History

The physical laws governing the operation of electrical networks were established prior to the generalisation of networks and thus to the need for calculations.

The development over time of the tools used for predictive analysis of the behaviour of electrical networks can be broken down into four overlapping periods.

■ Calculations "by hand" from 1925 to 1960
During this period, the many aspects involved in the operation of electrical networks were discovered, based on the phenomena observed and measurements made in installations. Analytical methods were used, based on a priori ideas concerning the physical phenomena, i.e. solutions were calculated on the basis of electrical laws, using manual techniques (slide rules and tables), and hypotheses were confirmed by checking the calculations with the measurements made. Predictive extrapolation was widely used, thanks to nomographs in which the major parameters could be varied. In parallel, professional practices based on experience were improved.

■ Physical simulation models from 1950 to 1990
Due to their increasing size and complexity, networks became true electrical systems with extensive interaction between components. In addition, the notion of energy quality gradually appeared. The need for prediction became more pressing and more general, because it was necessary to foresee the many operating situations, both normal and disturbed, precisely and dependably.

Simulators met these requirements fairly well. They were laboratory instruments, expensive both to purchase and use, and thus limited to the major utilities. The idea behind a simulator is to create a scale model of the network, reproducing the behaviour of the system in real time.

Depending on the planned application, the simulator can analyse transients (e.g. wave propagation), constitute an artificial network (e.g. tests on protection systems) or a micro-network (e.g. tests on dynamic stability).

To enhance their capacity and performance levels, simulators were equipped with analogue simulators having the electronic devices required to model certain components (e.g. regulators), thus creating hybrid simulators.

■ Digital simulation models since 1970
At the time when optimisation of networks had started and major failures of large industrial and public-distribution networks occurred, needs in terms of calculations increased. Digital simulators were the answer with the coming of the computer age.

□ Initially, calculations were run on large mainframe computers. The programs were generally created by large companies for their own needs.

□ Around 1990, digital simulation and decentralisation spread with the progress achieved in PCs. Programs appeared on the market and, today, users have a wide selection for a number of applications.

Note. The idea behind a digital simulator is to set up a digital model based on the laws governing the network, then to simulate operation by solving the equations with the suitable program. The major advantage lies in its great flexibility in handling all types of networks and a wide range of phenomena, but it does not operate in real time.

■ Digital Case Tools since 1990
These software engineering tools represent the generalisation of computerised simulation as the universal means of calculation (virtual networks) with comprehensive data bases and real-time processing for product development, operator training, optimised management, etc.

Appendix 2. Software

The table below indicates the main software programs available on the market and the calculations for which they are used.

	Type of calculation							
Type of program	**Dependability**	**Steady-state conditions**	**Short-circuit**	**Protection**	**Dynamic stability**	**Harmonics**	**Overvoltages**	**EMC**
Functional analysis	■			■				
FMECA	■			■				
Fault tree	■							
Markoff graph	■							
Pétri network	■							
Load-flow		■			■	■		
Load-flow optimisation		■						
Cable sizing		■	■					
LV cable sizing and protection			■	■		■		
Earthing network calculations		■	■	■				■
Short-circuit			■	■	■			
Discrimination			■	■	■			
Steady-state stability		■			■			
Dynamic stability					■			
Motor starting		■		■	■			
Harmonics		■				■		■
Current/voltage transients			■	■		■	■	■
Lightning protection							■	■
EMC disturbances		■						■
EMTP general-purpose software		■	■		■	■	■	
Data acquisition (measurements)		■	■	■	■	■	■	■

Appendix 3. Necessary data

This table presents a general overview of the data required for the various calculations.

Type of calculation ▶ Necessary data ▼	Dependability	Steady-state conditions	Short-circuits	Protection	Stability	Harmonics	Overvoltages	EMC	Measurements
General data								■	■
☐ network single-line diagram	■	■	■	■	■	■	■		
☐ operating configurations	■	■	■	■	■	■	■		
☐ SEAs	■	■	■	■	■	■	■		
For all components								■	■
☐ rated voltage and power	■	■	■		■	■	■		
☐ impedances (positive, negative and zero sequence)			■		■	■	■		
☐ short-circuit withstand			■		■				
☐ transient-voltage withstand (switching and lightning)							■		
☐ types of protection				■	■				
Sources								■	■
☐ voltage and frequency (rated/min./max.)	■	■	■	■	■	■	■		
☐ short-circuit power (rated/min./max.)		■	■		■	■	■		
☐ existing harmonic voltages						■			
☐ protection settings				■	■				
Gensets								■	■
☐ voltage, power and power factor	■	■	■		■	■	■		
☐ impedances and time constants			■		■	■	■		
☐ mechanical characteristics (inertia, number of poles)					■				
☐ transfer functions, turbine regulation, excitation					■				
Lines, cables, busbars, GIS substations								■	■
☐ resistance, inductance, capacitance of lines		■	■		■	■	■		
☐ length, parallel elements, installation methods	■	■	■		■	■	■		
☐ geometric data on pylons and structures							■		
☐ characteristics of insulators, spark gap units, etc.							■		
Transformers								■	■
☐ voltages (primary, secondary, tertiary)	■	■	■		■	■	■		
☐ power, type of connection, taps	■	■	■		■	■	■		
☐ short-circuit voltages and losses		■	■		■	■	■		
Passive loads, capacitors, inductors								■	■
☐ rated voltage and power		■			■	■	■		
☐ power factor		■			■	■	■		
☐ type of load (constant impedance, current or power)		■			■	■	■		
☐ load and diversity factors		■			■	■	■		
Active loads								■	■
☐ rated voltage and power		■	■		■	■	■		
☐ power factor		■	■		■	■	■		
☐ motor characteristics (speed, inertia, slip, Tstart/Tn, Tmax/Tn, Istart/In, etc.)		■	■		■	■	■		
☐ characteristics of devices incorporating power electronics (type of assembly, etc.)		■			■	■	■		
☐ load and diversity factors		■	■		■	■	■		
Non-linear loads								■	■
☐ U, I (lightning arrestor) characteristics							■		
☐ current and voltage harmonic spectra						■			
Breaking devices								■	■
☐ fuse type and rating				■	■				
☐ circuit-breaker characteristics (making and breaking capacity, transient recovery voltage, etc.)			■	■	■		■		
Protection								■	■
☐ characteristics of current and voltage sensors				■					
☐ protection functions and setting ranges				■					

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Other publications

- Les Techniques de l’Ingénieur
- Les cahiers de l’ingénierie published by Electricité de France

Normes

- IEC 60071-1: Insulation coordination - part 1: definitions, principles and rules.
- IEC 60071-2: Insulation coordination - Part 2: Application guide.
- IEC 60364: Electrical installations of buildings - part 1: scope, object and fundamental principles.
- IEC 60871-1: Shunt capacitors for a.c. power systems having a rated voltage above 1000 V - Part 1: General - Performance, testing and rating - Safety requirements - Guide for installation and operation.
- IEC 62271-100: High-voltage switchgear and controlgear - Part 100: High-voltage alternating-current circuit-breakers
- NF C02-160 / NF EN 50160 : Caractéristiques de la tension fournie par les réseaux publics de distribution.
- UTE C15-500 : Guide pratique - Détermination des sections des conducteurs et choix des dispositifs de protection à l'aide de logiciels de calcul.

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DTP: SEDOC Meylan.
Transl.: Lloyd International - Tarporley - Cheshire - GB.
Editor: Schneider Electric
- 20 € -

12-04