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Power Quality

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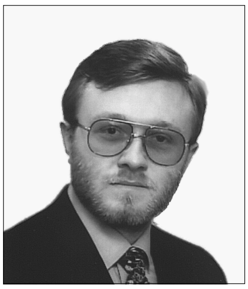
Foreword

no. 199

Power Quality



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Power Quality

One of the properties of electricity is that some of its characteristics depend not only on the electricity producer/distributor but also on the equipment manufacturers and the customer. The large number of players combined with the use of terminology and definitions which may sometimes be imprecise partly explain why this subject area is so complex.

This "Cahier Technique" aims to facilitate exchanges on this topic between specialists and non-specialists, as well as customers, manufacturers, installers, designers and distributors. The clear terminology used should help avoid confusion. It describes the main phenomena causing degradation in Power Quality (PQ), their origins, the consequences for equipment and the main solutions. It offers a methodology for measuring the PQ in accordance with differing aims. Illustrated with practical examples for the implementation of solutions, it shows that only by observing best practice and by applying strict methodology (diagnostics, research, solutions, implementation and preventive maintenance) can users obtain the right quality of power supply for their requirements.

Contents

1 Introduction

1.1 Context

The quality of electricity has become a strategic issue for electricity companies, the operating, maintenance and management personnel of service sector and industrial sites, as well as for equipment manufacturers, for the following main reasons:

- the economic necessity for businesses to increase their competitiveness,
- the widespread use of equipment which is sensitive to voltage disturbance and/or generates disturbance itself,
- the opening up of the electricity market.

The economic necessity for businesses to increase their competitiveness

- Reduction of costs linked to loss of supply continuity and problems of non-quality

The cost of disturbance (interruptions, voltage dips, harmonics, lightning overvoltages, etc.) is substantial. These costs must take into account losses in production and raw materials, restarting of production facilities, non-quality of production and delivery delays. The malfunction or shutdown of vital equipment such as computers, lighting and safety systems may put lives at risk (e.g. in hospitals, airport lighting systems, public and high-rise buildings, etc.).

Costs also include high quality, targeted preventive maintenance measures for anticipating possible problems. There is an increasing transfer of responsibility from the industrial user to the equipment manufacturer for the provision of site maintenance; manufacturers are now becoming electricity suppliers.

- Reduction of costs linked to oversized installations and energy bills

Other less obvious consequences of PQ degradation are:

- A reduction of installation energy efficiency, leading to higher energy bills
- Overloading of the installation, causing premature ageing and increasing the risk of breakdown, leading in turn to oversizing of distribution equipment

This is why professional users of electricity are keen to optimise the operation of their electrical installations.

The widespread use of equipment which is sensitive to voltage disturbance and/or generates disturbance itself

As a consequence of their numerous advantages (flexible operation, excellent efficiency, high performance levels, etc.), we have seen the development and widespread use of automated systems and adjustable speed drives in industry, information systems, and fluo-compact lighting in the service and domestic sectors. These types of equipment are both sensitive to voltage disturbance and generate disturbance themselves.

Their multiple use within individual processes requires an electrical power supply which can provide ever increasing performance in terms of continuity and quality. The temporary shutdown of just one element in the chain may interrupt the whole production facilities (manufacture of semi-conductors, cement works, water treatment, materials handling, printing, steelworks, petrochemicals, etc.) or services (data processing centres, banks, telecommunications, etc.).

Consequently, the work of the IEC on electromagnetic compatibility (EMC) has led to stricter and stricter standards and recommendations (limitations on disturbances emission levels, etc.).

The opening up of the electricity market

The rules governing the electricity sector are undergoing radical change: electricity production has opened up to competition, production is decentralised, and (large) electricity consumers now have the opportunity to choose their supplier.

In 1985, the Commission of the European Communities states (directive 85/374) that electricity is to be considered a product and as a consequence made it necessary to define its essential characteristics clearly.

In addition, in the context of liberalising energy markets, the search for competitiveness by electricity companies now means that quality has become a differentiating factor. A guarantee of quality is a potential criterion of choice for industrial users when looking for an energy supplier.

1.2 Objectives of Power Quality measurement

The measurement parameters and accuracy may differ depending on the application.

Contractual application

Within the context of a deregulated market, contractual relations may exist not only between the electricity supplier and the end user, but also between the power production company and transmission company or between the transmission company and distribution company. A contractual arrangement requires that terms are defined jointly and mutually agreed upon by all parties. The parameters for measuring quality must therefore be defined and the values compared with predefined, i.e. contractual limits.
This arrangement frequently requires the processing of significant quantities of data.

Corrective maintenance

Even where best practice is observed (single-line diagram, choice of protective devices and neutral point connection, application of appropriate solutions) right from the design phase, malfunctions may occur during operation:

- Disturbances may have been ignored or under-estimated.
- The installation may have changed (new loads and/or modification).

Troubleshooting is generally required as a consequence of problems of this nature.
The aim is frequently to get results as quickly as possible, which may lead to premature or unfounded conclusions.
Portable measurement systems (for limited periods) or fixed apparatus (for continuous monitoring) make it easier to carry out installation diagnostics (detection and archiving of disturbances and triggering of alarms).

Optimising the operation of electrical installations

To achieve productivity gains (operational economies and/or reduction of operating costs) correct operation of processes and sound energy management are required, both of which are factors dependent on PQ.
Operating, maintenance and management personnel of service sector and industrial sites all aim for a PQ which matches their requirements.
Complementary software tools to ensure control-command and continuous monitoring of the installation are thus required.

Statistical surveys

Such research requires a statistical approach on the basis of wide-ranging results from surveys generally carried out by the operators of transmission and distribution power systems.

- Benchmark the general performances of a power system

These can be used, for example, to:

- □ Plan and target preventive actions by mapping disturbance levels on a network. This helps reduce operating costs and improve control of disturbance. An abnormal situation with respect to an average level can be detected and correlated with the addition of new loads. Research can also be carried out into seasonal trends or excessive demand.
- □ Compare the PQ of various distribution companies in different geographical areas. Potential customers may request details of the reliability of the electricity supply before installing a new plant.

- Benchmark performances at individual points on the power system

These can be used to:

- □ Determine the electromagnetic environment in which a future installation or a new piece of equipment may have to operate. Preventive measures may then be taken to improve the distribution power system and/or desensitise the customer power system.
- □ Specify and verify the performance levels undertaken by the electricity supplier as part of the contract. This information on the electricity quality are of particular strategic importance for electricity companies who are seeking to improve competitiveness, satisfaction of needs and customer loyalty in the context of liberalising energy markets.

2 Degradation of PQ: origins - characteristics - definitions

2.1 General

Electromagnetic disturbances which are likely to disturb the correct operation of industrial equipment and processes is generally ranked in various classes relating to conducted and radiated disturbance:

- low frequency (< 9 kHz),
- high frequency (⩾ 9 kHz),
- electrostatic discharge.

Measurement of PQ usually involves characterising low frequency conducted electromagnetic disturbances (the range is widened to include transient overvoltages and transmission of signals on a power system):

- voltage dips and interruptions,
- harmonics and interharmonics,
- temporary overvoltages,
- swell,
- transient overvoltages,
- voltage fluctuations,
- voltage unbalance,
- power-frequency variations,
- DC in AC networks,
- signalling voltages.

It is not generally necessary to measure each type of disturbance.

The types can be placed in four categories, affecting the magnitude, waveform, frequency and symmetry of the voltage. Several of these characteristics may be modified simultaneously by any one type of disturbance. Disturbances can also be classified according to their permanent, semi-permanent or random nature (lightning, short-circuit, switching operations, etc.).

2.2 Voltage dips and interruptions

Definitions

A voltage dip is a sudden reduction of the voltage at a point in an electrical power system followed by voltage recovery after a short period of time from a few cycles to a few seconds (IEC 61050-161). A voltage dip is normally detected and characterised by the calculation of the root mean square value "rms (1/2)" over one cycle every half-cycle -each period overlaps the prior period by one half-cycle- (see **fig. 1**).

There is a dip to x % if the rms (1/2) value falls below the dip threshold x % of the reference value Uref. The threshold x is typically set below 90 (CENELEC EN 50160, IEEE 1159). The reference voltage Uref is generally the nominal voltage for LV power systems and the declared voltage for MV and HV power systems. A sliding reference voltage, equal to the voltage before the beginning of the disturbance is useful to study transference factor between different voltage systems.

A voltage dip is characterised by two parameters (see fig. 1b for x equal to 90):

- depth: ΔU (or its magnitude U),
- duration ΔT.

In case of a non-rectangular envelope, the duration is dependent on the selected dip threshold value (set by the user according to the objective). The duration is typically defined as the time interval during which the rms (1/2) is lower than 90 %. The shape of the envelope (for example in case of complex multi-step and not simple one step dip) may be assessed using several dip thresholds set and/or wave form capture. Time aggregation techniques may define an equivalent dip characterised by the smallest rms (1/2) value measured during the dip and the total duration of the dip. For three-phase systems phase aggregation techniques (mainly used for contractual applications) may define a single phase equivalent dip (characterised for example by the greatest depth on the three phases and the total duration).

Interruptions are a special type of voltage dip to a few percentage of Uref (typically within the range 1-10 %). They are characterised by one parameter only: the duration. Short interruptions last less than one minute (extended to three minutes depending on network operating conditions) and often result from tripping and automatic reclosure of a circuit breaker designed to avoid long interruptions which have longer duration. Short and long interruptions differ in both their origins and the solutions required to prevent or reduce their occurrence.

Voltage disturbances lasting less than a half-cycle T (ΔT < T/2) are regarded as transient. Different terms are used in the USA depending on the length of the dips (sags) and interruptions:

- instantaneous (T/2 < ΔT < 30 T),
- momentary (30 T < ΔT < 3 s),
- temporary (3 s < ΔT < 1 min),
- sustained interruption and undervoltage (ΔT > 1 min).

Depending on the context, the measured voltages may be between live conductors (between phases or between phase and neutral), between live conductors and earth (Ph/earth or neutral/earth), or between live conductors and the protective conductor.

In a 3-phase system, the characteristics ΔU and ΔT in general differ for each of the three phases. This is why a voltage dip must be detected and characterised separately on each phase.

A voltage dip is regarded as occurring on a 3-phase system if at least one phase is affected by the disturbance.

Origins

- Voltage dips and short interruptions are mainly caused by phenomena leading to high currents, which in turn cause a voltage drop across the network impedances with a magnitude which decreases in proportion to the electrical distance of the observation point from the source of the disturbance.

Voltage dips and short interruptions have various causes:

- Faults on the transmission (HV) or distribution (LV and MV) networks or on the installation itself

The occurrence of faults causes voltage dips for all users. The duration of a dip is usually conditioned by the operating time of the protective devices. The isolation of faults by protective devices (circuit breakers, fuses) will produce interruptions (long or short) for users feeded by the faulty section of the power system. Although the power source is no longer present, network voltage may be maintained by the residual voltage provided by asynchronous or synchronous motors as they slow down (0.3 to 1 s) or voltage due to the discharge of capacitor banks connected to the power system.

Short interruptions are often the result of the operation of automated systems on the network such as fast and/or slow automatic reclosers, or changeover of transformers or lines. Users are subjected to a succession of voltage dips and/or short interruptions caused by intermittent arc faults, sequence of automatic reclosing (on overhead or mixed radial networks) intended to extinguish transient and semi-permanent faults or voltage feedback intended to locate the fault.

- Switching of large loads (asynchronous motors, arc furnaces, welding machines, boilers, etc.) compared to the short-circuit power.

- Long interruptions are the result of the definitive isolation of a permanent fault (requiring to repair or to replace any component before re-energising) by means of protective devices or by the intentional or unintentional opening of a device.

Voltage dips and interruptions are propagated to lower voltage levels via transformers. The number of phases affected and the depth of the voltage dips depend on the type of fault and the transformer coupling.

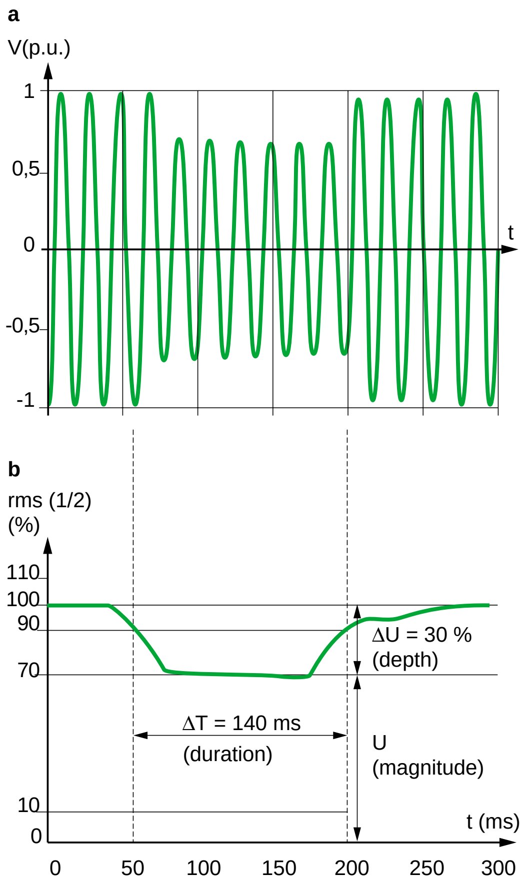


*Fig. 1: Characteristic parameters of a voltage dip **[a]** waveform **[b]** rms (1/2).*

Overhead networks, which are exposed to bad weather, are subject to more voltage dips and interruptions than underground networks. However, an underground feeder connected to the same busbar system as overhead or mixed networks will suffer voltage dips which are due to the faults affecting overhead lines.

■ Transients ($\Delta T < T/2$) are caused, for example, by the energisation of capacitor banks, the isolation of a fault by a fuse or a fast LV circuit breaker, or by commutation notches from polyphase converters.

2.3 Harmonics and interharmonics

Summary:

All periodic functions (of frequency f) can be broken down into a sum of sinusoidal waves of frequency h x f (h is an integer). h is the harmonic order (h > 1). The first order component is the fundamental component.

$$y(t) = Y_0 + \sum_{h=1}^{\infty} Y_h \sqrt{2} \sin(2 \pi h f + \varphi_h)$$

The rms is:

$$Y_{eff} = \sqrt{Y_0^2 + Y_1^2 + Y_2^2 + Y_h^2 + \ldots}$$

The THD (Total Harmonic Distortion) factor measures the signal distortion:

$$THD = \sqrt{\sum_{h=2}^{\infty} \left(\frac{Y_h}{Y_1} \right)^2}$$

Harmonics are mainly produced by non-linear loads which draw current of a different wave form from the supply voltage (see **fig. 2**). The spectrum of the harmonics depends on the nature of the load. Harmonic voltages occur across network impedances resulting distorted voltages which can disturb the operation of other users connected to the same supply. The value of the supply impedance at different harmonic frequencies thus has a vital role in limiting the voltage distortion. Note that if the source impedance is low (Scc is high), voltage distortion is low.

Main sources of harmonics

These are loads which can be distinguished according to their domain, i.e. industrial or domestic.

■ Industrial loads

□ Power electronic equipment: drives, rectifiers (diode or thyristor), inverters or switching power supplies;

□ Loads using electric arcs: arc furnaces, welding machines, lighting (discharge lamps, fluorescent tubes). Starting motors using electronic starters and power transformers energisation also generates (temporary) harmonics.

Note that because of its multiple advantages (operating flexibility, excellent energy efficiency, high performance levels, etc.), the use of power electronic equipment is becoming more widespread.

■ Domestic loads with power inverters or switching power supplies such as television, microwave ovens, induction hotplates, computers, printers, photocopiers, dimmer switches, electrodomestic equipments, fluorescent lamps.

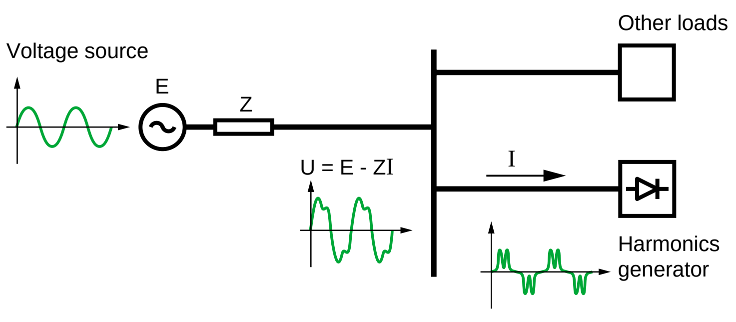


Fig. 2: Degradation of network voltage caused by a non-linear load.

Although their individual power ratings are much less than for industrial loads, the combination of large numbers and simultaneous use over long periods creates significant sources of harmonic distortion. Note that the use of this type of equipment is increasing, as in some cases is the power rating.

Harmonic levels

These generally vary according to the operating mode of the device, the hour and the season (heating and air conditioning).
The sources usually generate odd harmonic components (see **fig. 3**). Power transformer energisation, polarised loads (half-wave rectifiers) and arc furnaces generate even harmonics in addition to odd harmonics components.

Interharmonics are sinusoid components with frequencies which are not integer multiples of the fundamental component (they are located between harmonics). They are due to periodic or random variations in the power drawn by various devices such as arc furnaces, welding machines and frequency inverters (drives, cycloconverters). The remote control frequencies used by the power distributor are also interharmonics.

The spectrum may be discrete or continuous and vary randomly (arc furnaces) or intermittently (welding machines).
To study the short, medium and long term effects, the various parameters must be measured at time intervals which are compatible with the thermal time constant of the devices.

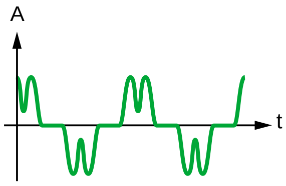
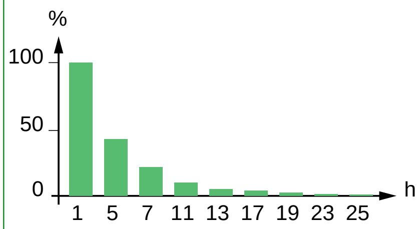
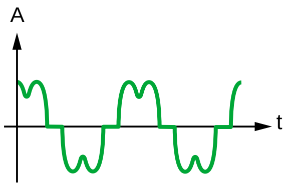
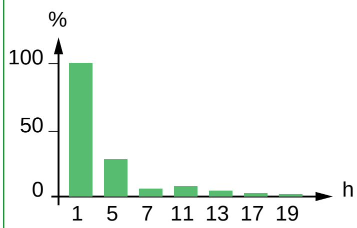
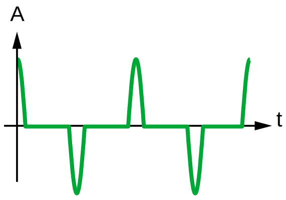
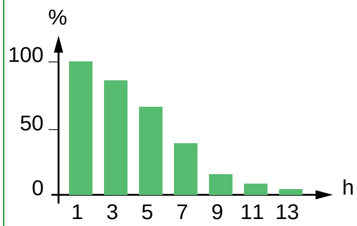
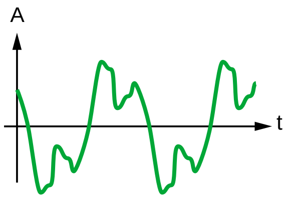
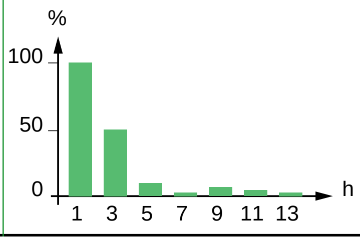
Non-linear loads	Current waveform	Spectrum	THD
Adjustable speed drive			44 %
Rectifier/charger			28 %
Data processing load			115 %
Fluorescent lighting			53 %

***Fig. 3**: Characteristics of certain harmonics generators.*

2.4 Overvoltages

Where voltage is applied to a device and the peak value exceeds the limits defined in a standard or specification, this is an overvoltage (see "Cahiers Techniques" nos. 141, 151 and 179).

Overvoltages are of three types:

- temporary,
- switching,
- lightning.

They can appear:

- in differential mode (between live conductors: ph/ph – ph/neutral),
- in common mode (between live conductors and the exposed-conductive-part or earth).

Temporary overvoltages

By definition, these occur at power frequency (50/60 Hz). They have various origins:

- An insulation fault

When an insulation fault occurs between phase and earth in an isolated neutral system or impedance earthed neutral system, the voltage of the healthy phases to earth may reach the phase to phase voltage. Overvoltages on LV installations may come from HV installations via the earth of the HV/LV station.

- Ferroresonance

This is a rare non-linear oscillatory phenomenon which can often be dangerous for equipment and which is produced in a circuit containing a capacitor and a saturable inductance. Ferroresonance is often the apparent cause of malfunctions or the destruction of devices (see "Cahier Technique" no. 190).

- Break of the neutral conductor

Devices powered by the phase with the least load witness an increase in voltage (sometimes up to the phase to phase voltage).

- Faults on alternator regulators or tap changer transformer

- Overcompensation of reactive power

Shunt capacitors produce an increase in voltage from the source to their location.
This voltage is especially high during periods of low load.

Switching overvoltages

These are produced by rapid modifications in the network structure (opening of protective devices, etc.). The following distinctions are made:

- switching overvoltages at normal load,
- overvoltages produced by the switching on and off of low inductive currents,
- overvoltages produced by the switching of capacitive circuits (no-load lines or cables, capacitor banks). For example, the energisation of a capacitor bank produces a transient overvoltage in which the first peak may reach $2\sqrt{2}$ times the rms value of the nominal voltage and a transient overcurrent with a peak value of up to 100 times the rated current of the capacitor (see "Cahier Technique" no. 142).

Lightning overvoltages

Lightning is a natural phenomenon occurring during storms. A distinction is made between direct lightning strike (on a line or structure) and the indirect effects of lightning (induced overvoltages and increase in earth potential) (see "Cahiers Techniques" nos. 151 and 179).

2.5 Voltage variations and fluctuations

Voltage variations are variations in the rms value or the peak value with an amplitude of less than 10% of the nominal voltage.

Voltage fluctuations are a series of voltage changes or cyclical or random variations in the voltage envelope which are characterised by the frequency of variation and the magnitude.

- Slow voltage variations are caused by the slow variation of loads connected to the network.
- Voltage fluctuations are mainly due to rapidly varying industrial loads such as welding machines, arc furnaces or rolling mills.

2.6 Unbalance

A 3-phase system is unbalanced if the rms value of the phase voltages or the phase angles between consecutive phases are not equal. The degree of unbalance is defined using the Fortescue components, comparing the negative sequence component ($U1_i$) (or zero sequence component ($U1_o$)) of the fundamental to the positive sequence component ($U1_d$) of the fundamental.

$$\Delta Ui = \frac{\overline{|U1_i|}}{|U1_d|} \text{ and } \Delta Uo = \frac{\overline{|U1_o|}}{|U1_d|}$$

The following approximate formula can also be used: $\Delta Ui = \max_i \frac{V_i - Vavg}{Vavg}$

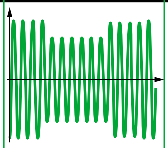
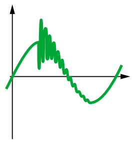
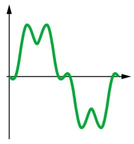
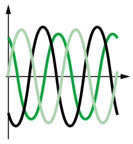
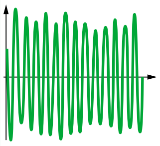
where Vi = phase voltage i and

$$Vavg = \frac{V1 + V2 + V3}{3}$$

The negative sequence (or zero sequence) voltage is produced by voltage drops along the network impedances due to negative sequence (or zero sequence) currents produced by unbalanced loads leading to non-identical currents on the three phases (LV loads connected between phase and neutral, or single-phase or 2-phase MV loads such as welding machines and induction furnaces).

Single-phase or 2-phase faults produce unbalance until tripping of the protective devices.

2.7 Summary

Disturbances	Voltage dips	Overvoltages	Harmonics	Unbalance	Voltage fluctuations
Characteristic waveforms					
Origin of disturbance					
■ **Power system**					
□ Insulation fault, break of the neutral conductor...	Occasional			Occasional	
□ Switching, ferroresonance		Occasional			
□ Lightning		Occasional			
■ **Equipment**					
□ Asynchronous motor	Occasional				
□ Synchronous motor	Occasional		Frequent		
□ Welding machine	Occasional		Frequent	Frequent	Frequent
□ Arc furnace	Occasional		Frequent	Frequent	Frequent
□ Converter		Frequent	Frequent		
□ Data processing loads			Frequent		
□ Lighting			Frequent		
□ Inverter			Frequent		
□ Capacitor bank	Occasional	Frequent	Frequent		Occasional

: Occasional phenomenon   : Frequent phenomenon

3 Effects of disturbance on loads and processes

Generally speaking, the effects of all disturbances can be classified in two ways:

■ Instantaneous effects: unwanted operation of contactors or protective devices, incorrect operation or shutdown of a machine. The financial impact of the disturbance can be estimated directly.

■ Deferred effects: energy losses, accelerated ageing of equipment due to overheating and additional electro-dynamic stress caused by the disturbance.
The financial impact (e.g. on productivity) is more difficult to quantify.

3.1 Voltage dips and interruptions

Voltage dips and interruptions disturb many types of devices connected to the network. They are the most frequent cause of Power Quality problems. A voltage dip or interruption of a few hundred milliseconds may have damaging consequences for several hours.

The most sensitive applications are:

■ complete continuous production lines where the process cannot tolerate any temporary shutdown of any element in the chain (printing, steelworks, paper mills, petrochemicals, etc.),

■ lighting and safety systems (hospitals, airport lighting systems, public and high-rise buildings, etc.),

■ computer equipment (data processing centres, banks, telecommunications, etc.),

■ essential auxiliary plant for power stations.

The paragraphs below cover the main consequences of voltage dips and interruptions on equipment used in the industrial, service and domestic sectors.

Asynchronous motors

When a voltage dip occurs, the torque of an asynchronous motor (proportional to the square of the voltage) drops suddenly which slowdowns the motor. This slowdown depends on the magnitude and duration of the dip, the inertia of the rotating masses and the torque-speed characteristics of the driven load. If the torque developed by the motor drops below the resistant torque, the motor stops (stalls). Following an interruption, at the time of voltage recovery, the motor tends to re-accelerate and absorb current whose value is nearly its starting current, the duration of which depends on the duration of the interruption. Where there are several motors in an installation, the simultaneous restarting may produce a voltage drop in the upstream impedances on the network which will increase the duration of the dip and may make restarting difficult (long restarts with overheating) or even impossible (motor torque lower than the resistive torque).

Rapidly reconnecting (~ 150 ms) the power to an asynchronous motor which is slowing down without precautionary measures may lead to reclosing in opposition to the phase between the source and the residual voltage in asynchronous motors. In this case the first current peak may reach three times the start-up current (15 to 20 In) (see "Cahier Technique" no. 161).
The overcurrents and consequent voltage drops have consequences for the motor (excessive overheating and electro-dynamic force in the coils, which may cause insulation failures and torque shocks with abnormal mechanical stress on the couplings and reducers, leading to premature wear or even breakage) as well as other equipment such as contactors (wear or even fusion of the contacts). Overcurrents may cause tripping of the main general protective devices of the installation causing the process to shutdown.

Synchronous motors

The effects are almost identical to those for asynchronous motors. Synchronous motors can however withstand deeper voltage dips (around 50 %) without stalling, owing to their generally greater inertia, the possibilities of overexcitation and the fact that their torque is proportional to the voltage. In the event of stalling, the motor stops and the entire complex start-up process must be repeated.

Actuators

The control devices (contactors, circuit breakers with voltage loss coils) powered directly from the network are sensitive to voltage dips whose depth exceeds 25 % of Un. Indeed, for a standard contactor, there is a minimum voltage value which must be observed (known as the drop-out voltage), otherwise the poles will separate and transform a voltage dip (lasting a few tens of milliseconds) or a short interruption into a long interruption until the contactor is reenergized.

Computer equipment

Computer equipment (computers, measurement apparatus) today occupy a dominant position in the monitoring and control-command of installations, management and production. All of this equipment is sensitive to voltage dips with depth greater than 10 % Un.

The ITIC (Information Technology Industry Council) curve – formerly CBEMA curve – shows on a duration-amplitude scale, the typical withstand of computer equipment to voltage dips, interruptions and overvoltages (see **fig. 4**).

Operation outside these limits leads to loss of data, incorrect commands, and shutdown or malfunction of equipment. The consequences of the loss of equipment functions depend in particular on the restart conditions when voltage is restored. Certain equipment, for example, has its own voltage dip detection devices which enable data to be backed up and ensure safety by interrupting calculation processes and any incorrect commands.

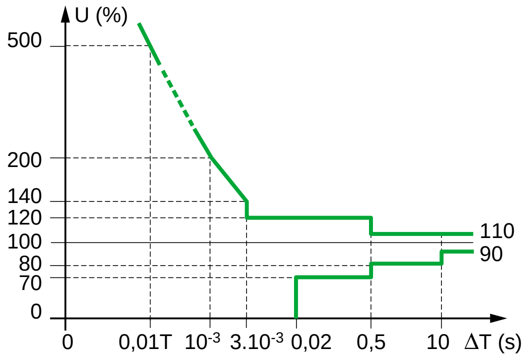


Fig. 4: Typical withstand as defined by the ITIC curve.

Adjustable speed machines

The problems of voltage dips applied to variable speed drives are:

■ It is not possible to supply sufficient voltage to the motor (loss of torque, slowdown).

■ The control circuits supplied directly by the network cannot function.

■ There is overcurrent when voltage recovers (the drive filter capacitor is recharged).

■ There is overcurrent and unbalanced current in the event of voltage dips on a single phase.

■ There is loss of control of DC drives functioning as inverters (regenerative braking).

Adjustable speed drives usually trip out when a voltage dip deeper than 15 % occurs.

Lighting

Voltage dips cause premature ageing of incandescent lamps and fluorescent tubes.

Voltage dips deeper than or equal to 50 % with a duration of around 50 ms will extinguish discharge lamps. The lamp must then be left off for several minutes to cool the bulb before it is turned on again.

3.2 Harmonics

The consequences of harmonics are linked to the increase in peak values (dielectric breakdown), rms values (excessive overheating) and to the frequency spectrum (vibration and mechanical stress) of voltages and currents.

The effects always have an economic impact resulting from the additional costs linked to:

■ degradation in the energy efficiency of the installation (energy loss),

■ oversizing of equipment,

■ loss of productivity (accelerated ageing of equipment, unwanted tripping).

Malfunctions are probable with a harmonic distortion factor of greater than 8 % of the voltage. Between 5 and 8 %, malfunctions are possible.

■ Instantaneous or short term effects

□ Unwanted operation of protective devices: harmonics have a harmful influence mainly on thermal control devices. Indeed, when protective devices of this type calculate the rms value of the current from the peak value, there is a risk of error and unwanted operation even during normal operation with no overload.

□ Disturbances induced by low current systems (remote control, telecommunications, hi-fi systems, computer screens, television sets).

□ Abnormal vibrations and acoustic noise (LV switchboards, motors, transformers).

□ Destruction of capacitors by thermal overload

If the actual frequency of the upstream capacitor-network system is similar to a harmonic order, this causes resonance and amplification of the corresponding harmonic.

□ Loss of accuracy of measurement instruments

A class 2 induction energy meter will produce in current and voltage, a 0.3 % additional error in the presence of 5 % of harmonic 5.

■ Long term effects

Current overload produces excessive overheating and leads to premature ageing of equipment:

□ Overheating of sources: transformers, alternators (through increased joule and iron losses).

- Mechanical stress (pulse torque in asynchronous machines).
- Overheating of equipment: phase and neutral conductors through increased joule and dielectric losses. Capacitors are especially sensitive to harmonics as their impedance decreases in proportion to the harmonic order.
- Destruction of equipment (capacitors, circuit breakers, etc.).

Overload and excessive overheating of the neutral conductor may result from the presence of third harmonic (and multiples of 3) currents in the phase conductors which add in the neutral. The TNC neutral earthing system uses the same conductor for neutral and protection purposes. This conductor interconnects the installation earth, including the metal structures of the building. Third harmonic (and multiples of 3) currents will flow through these circuits and produce variations in potential with the following results:

- corrosion of metal parts,
- overcurrent in the telecommunication links between the exposed-conductive-part of two devices (for example, printer and computer),
- electromagnetic radiation causing screen disturbance (computers, laboratory apparatus).

The table in **figure 5** summarises the main effects of harmonics and the normal permitted levels.

Interharmonics affect remotely-controlled devices and produce a phenomenon known as flicker.

Equipment	Effects	Limits
Power capacitors	Overheating, premature ageing (breakdown), resonance.	I < 1.3 In, (THD < 83 %) or U < 1.1 Un for 12 hrs/days at MV or 8 hrs/days at LV
Motors	Losses and excessive overheating. Reduction of capacity for use at full load. Pulse torque (vibrations, mechanical stress) Noise pollution.	HVF ⩽ 2 % for usual asynchronous motors
Transformers	Losses (ohmic-iron) and excessive overheating. Mechanical vibrations. Noise pollution.	
Circuit breakers	Unwanted tripping (exceeding voltage peak values, etc.).	$U_h / U_1 \leqslant$ 6 to 12 %
Cables	Additional dielectric and ohmic losses (especially in the neutral conductor if third harmonic currents present).	THD ⩽ 10 % $U_h / U_1 \leqslant 7$ %
Computers	Operating problems.	$U_h / U_1 \leqslant 5$ %
Power electronics	Problems related to waveform (commutation, synchronisation).	

$$HVF = \sqrt{\sum_{h=2}^{13} U_h^2 / h}$$ (Harmonic Variation Factor according to IEC892)

Fig. 5: Effects of harmonics and practical limits.

3.3 Overvoltages

The consequences are extremely varied according to the period of application, repetitivity, magnitude, mode (common or differential), gradient and frequency:

- Dielectric breakdown, causing significant permanent damage to equipment (electronic components, etc.).
- Degradation of equipment through ageing (repetitive rather than destructive overvoltages).
- Long interruptions caused by the destruction of equipment (loss of sales for distribution company, loss of production for industrial companies).
- Disturbance in control system and low current communication circuits (see "Cahier Technique" no. 187).
- Electrodynamic and thermal stress (fire) caused by:
  - Lightning (usually)

Overhead networks are most vulnerable to lightning, but installations supplied by underground networks may also be affected by stress due to high voltage if lightning strikes close to the site.

□ Switching overvoltages: these are repetitive and their probability of occurrence is considerably higher than that of lightning, with a longer duration.

They can lead to degradation as serious as that caused by lightning.

3.4 Voltage variations and fluctuations

As fluctuations have a magnitude no greater than ± 10 %, most equipment is not affected.
The main effect of voltage fluctuations is a fluctuation in the luminance of lamps (flicker).
The physiological strain (visual and nervous fatigue) depends on the magnitude of the fluctuations, the repetition rate of the variations, the composition of the spectrum and the duration of the disturbance.
There is however a perceptibility threshold (the amplitude as a function of the variation frequency) defined by the IEC below which flicker is no longer visible.

3.5 Unbalance

The main effect is the overheating of 3-phase asynchronous machines.
In fact, the zero sequence reactance of an asynchronous machine is equivalent to its reactance during the start-up phase. The current unbalance factor will thus be several times that of the supply voltage. Phase currents can thus differ considerably. This increases the overheating of the phase(s) which the highest current flows through and reduces the operating life of the machine.
In practice, a voltage unbalance factor of 1 % over a long period, and 1.5 % over a few minutes is acceptable.

3.6 Summary

Equipment	**Sensitivity to disturbance**					
	Voltage dips < 0.5 s	Voltage dips > 0.5 s	Overvoltages	Harmonics	Unbalance	Voltage fluctuation
■ Asynchronous motor		■		■	■	
■ Synchronous motor		■		■	■	
■ Actuator		■				
■ Speed drive	■	■	■	■	■	
■ Data processing load, numerical control	■	■	■	■	■	
■ Induction furnace			■			
■ Lighting			■	■		■
■ Capacitor bank			■	■		
■ Transformer			■	■		
■ Inverter	■	■			■	
■ Circuit breaker			■	■		
■ Cable			■	■		

4 Level of Power Quality

4.1 Evaluation methodology

Contractual application

The contract must state:

- Its duration.
- The parameters to be measured.
- The contractual values.
- The measurement point(s).
- The voltages measured: these voltages (between phases and/or between phase and neutral) must be the equipment supply voltages.
- For each parameter measured the choice of measurement method, the time interval, the measurement period (e.g. 10 minutes and 1 year for the voltage amplitude) and the reference values; for voltage dips and interruptions, for example, the reference voltage, detection thresholds and the distinction between long and short interruptions must be defined.
- The measurement accuracy.
- The method of determining penalties in the event of one party failing to honour the terms of the contract.
- Clauses in the event of disagreement concerning the interpretation of the measurements (intervention of third parties, etc.).
- Data access and confidentiality.

Corrective maintenance

This is generally the consequence of incidents or malfunctions during operation requiring troubleshooting in order to apply corrective measures.
The usual steps are:

- Data collection

This involves the collection of information such as the type of load, the age of the network components and the single-line diagram.

- Search for symptoms

This involves identifying and locating the equipment subject to disturbance, determining the time and date (fixed or random) when the problem occurred, any correlation with particular meteorological conditions (strong winds, rain, storm) or recent modification of the installation (installation of new machines, modification of the power system).

- Examination of the installation

This phase is sometimes sufficient for quickly determining the origin of the malfunction. Environmental conditions such as humidity, dust and temperature must not be overlooked.
The installation, especially the wiring, circuit breakers and fuses, have to be checked.

- Monitor the installation

This step consists in equipping the site with measurement apparatus to detect and record the event where the problem originated. It may be necessary to place instruments at several points in the installation, especially (where possible) close to the equipment subject to disturbance.

The apparatus detects events when the thresholds of the parameters used to measure the Power Quality are exceeded, and records the data characterising the event (for example date, time, depth of voltage dip, THD). The waveforms just before, during and after the disturbance can also be recorded. The threshold settings must match the sensitivity of the equipment.

When using portable apparatus, the duration of the measurements must be representative of the operating cycle of the factory in question (e.g. one week). It must always be assumed that the disturbance will recur.

Fixed apparatus can be used for continuous monitoring of the installation. If the apparatus settings are correct, it will carry out prevention and detection by recording each occurrence of disturbance. The data can be displayed locally or remotely via an Intranet or Internet connection. This can be used to diagnose events as well as to anticipate problems (preventive maintenance). This is the case with apparatus in the Power Logic System range (Circuit Monitor - Power Meter), Digipact and the latest generation of Masterpact circuit breakers fitted with Micrologic P trip release (see **fig. 6**).

Records of disturbance from the distributor's power system which have caused damage (destruction of equipment, production losses, etc.) may also prove useful when negotiating compensation claims.

■ Identification of origin

The signature (waveform, profile of rms value) of the disturbance can in general be used by experts to locate and identify the source of the problem (fault, motor starting, capacitor bank energisation, etc.).
The simultaneous recognition of the signature for the voltage and the current can be used to determine if the disturbance is sourced upstream or downstream of the measurement point. The disturbance may come from either the installation or the distribution power system.

■ Definition and choice of mitigation solutions

A list of solutions and costings is prepared. The choice of solution is often made by comparing the cost with the potential lost earnings in the event of disturbance.
After implementing a solution, it is important to verify, via measurement, that it is effective.

Optimising the operation of electrical installations

The operation of electrical installations can be optimised through three complementary actions:

■ Saving energy and reducing energy bills:

□ making users aware of costs,

□ assigning costs internally (by site, department or product line),

□ locating potential economies,

□ managing peaks in consumption (load shedding, standalone sources),

□ optimising the power contract (reduction in subscribed power demand),

□ improving the power factor (reduction in reactive power).

■ Ensuring the Power Quality:

□ displaying and monitoring the measurement parameters for Power Quality,

□ detecting problems in advance (monitoring of harmonics and neutral current, etc.) for preventive maintenance purposes.

■ Ensuring continuity of service:

□ optimising maintenance and operation,

□ becoming acquainted with the network in real time,

□ monitoring the protection plan,

□ diagnosing faults,

□ reconfiguring a network following a fault,

□ ensuring an automatic source transfer.

Software tools are used for the control-command and monitoring of the installation. They can be used for example to detect and archive events, monitor circuit breakers and protection relays in real time, control circuit breakers remotely, and generally make use of the possibilities of communicating devices (see fig. 6).

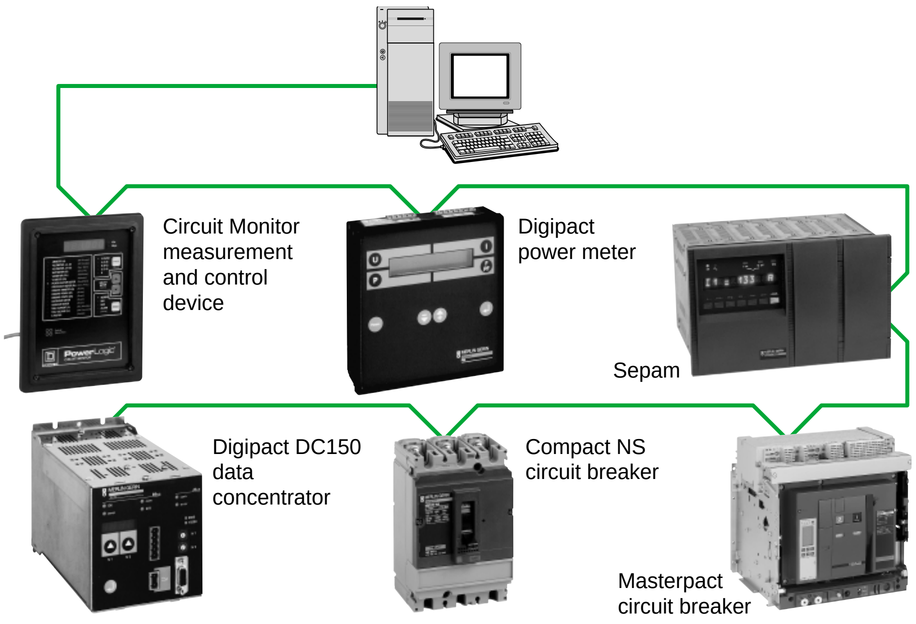


Fig. 6: Some communicating products (Merlin Gerin brand).

4.2 EMC and planning levels

Electromagnetic compatibility (EMC)

Electromagnetic compatibility is the ability of an equipment or system to fonction satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment (IEC 60050-161).

The aim of electromagnetic compatibility is to ensure that:

- The emission of disturbances from each separate source is such that the combined emission from all sources does not exceed the expected levels of disturbance in the environment.
- The immunity level of the equipment gives the appropriate level of performance for the expected disturbance in three classes of environment (see **fig. 7**).

Note that the environment is also determined by the characteristics specific to the user installation (single-line diagram, types of load, etc.) and by the characteristics of the supply voltage.

One way of ensuring compatibility levels is to specify the emission limits of user installations with a sufficient margin below the compatibility level. In practice this is possible for large installations (IEC 61000-3-6, IEC 61000-3-7). For other installations (e.g. LV) the "product" standards specify emission limits for families of equipment (e.g. standard IEC 61000-3-2 imposes emission limits on current harmonics for loads under 16 A).

In certain cases, technical solutions must be applied to keep the emission levels below the prescribed levels.

Voltage characteristics

The method used to evaluate the actual voltage characteristics at a given point on the network and to compare them to the predefined limits is based on a statistical calculation over a given measurement period. For example, for the harmonic voltage the measurement period is one week: 95 % of the rms values calculated over successive periods of 10 minutes must not exceed the specified limits.

Planning levels

These are the internal quality objectives specified by the network operator which are used to evaluate the impact of all disturbance-producing loads on the network. They are usually equal to or below the compatibility levels.

Summary

Figure 8 summarises the relations between the various levels of disturbance.

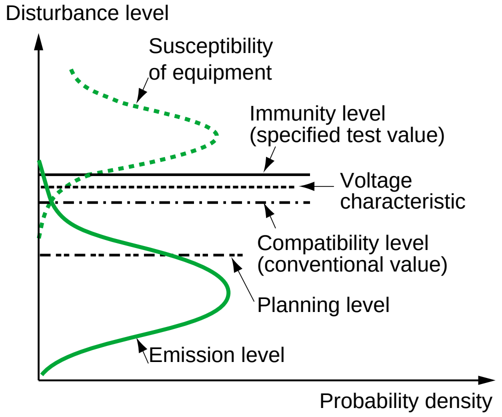


Fig. 8: Relations between the various levels of disturbance.

Disturbances	Class 1	Class 2	Class 3
Voltage variations $\Delta U/U_N$	± 8 %	± 10 %	+10 % -15 %
Voltage dips[(1)] $\Delta U / U_N$ ΔT (number of half-cycle)	 10 % to 100 % 1	 10 % to 100 % 1 to 300	 10 % to 100 % 1 to 300
Short interruption (s)	none	–	⩽ 60
Voltage unbalance U_i / U_d	2 %	2 %	3 %
Frequency variations $\Delta f / f_N$	± 1 %	± 1 %	± 2 %

(1) These values are not compatibility levels: they are given for indicative purposes only.

Fig. 7: Compatibility levels according to IEC 61000-2-4.

5 Solutions for improving PQ

A degradation of quality may lead to a change in behaviour, performance or even the destruction of equipment and dependent processes with possible consequences for the safety of personnel and additional economic costs.
This assumes three elements:

- one or more generators of disturbance,
- one or more loads sensitive to the disturbance,
- a channel for the disturbance to be propagated between them.

The solutions consist in taking action with regard to all or part of the three elements, either globally (the installation) or locally (one or more loads).
The solutions can be implemented to:

- correct a malfunction in an installation,
- take preventive action when polluting loads are to be connected,
- ensure the installation conforms to a standard or to the power distributor's recommendations,
- reduce energy bills (reduction of subscribed power in kVA, reduction in consumption).

Loads are not sensitive to the same disturbance and have different levels of sensitivity, the solution adopted, as well as being the best from a technical and economic point of view, must ensure an appropriate level of PQ which meets actual requirements.
It is vital that specialists carry out a prior diagnosis to determine the nature of the disturbance to be prevented (e.g. remedies may differ depending on the duration of an interruption). This determines the effectiveness of the chosen solution. The definition, choice, implementation and maintenance (to ensure long-term effectiveness) of solutions must also be carried out by specialists.
The value of the choice and implementation of a solution depends on:

- The required level of performance

Malfunction is not permitted if it would put lives at risk (e.g. in hospitals, airport lighting systems, lighting and safety systems in public buildings, auxiliary plant for power stations, etc.).

- The financial consequences of malfunction

Any unprogrammed stop, even when very short, of certain processes (manufacture of semi-conductors, steelworks, petrochemicals, etc.) results in loss or non-quality of production or even restarting of production facilities.

- The time required for a return on the investment

This is the ratio of financial losses (raw materials, production losses, etc.) caused by the non-quality of electrical power and the cost (research, implementation, operation, maintenance) of the solution.

Other criteria such as practices, regulation and the limits on disturbance imposed by the distributor must also be taken into account.

5.1 Voltage dips and interruptions

The network architecture, automated power restart systems, the reliability of equipment, the presence of a control-command system and maintenance policy all play an important role in the reduction and elimination of interruptions.

Correct diagnosis is vital before choosing an effective solution. For example, at the point of common coupling (the customer's electricity input), it is important to determine whether the voltage dip is coming from the customer's installation (with a corresponding increase in current) or from the distribution power system (no increase in current).
Different types of solution exist.

Reducing the number of voltage dips and interruptions

Distributors can take certain measures such as making their infrastructure more reliable (targeted preventive maintenance, modernisation, underground installation) or restructuring power systems (shortening feeders). For impedance earthed neutral power systems, they can also replace auto-reclosing circuit breakers with shunt circuit breakers which present the major advantage of not causing interruptions on a damaged feeder in the event of a transient earth fault (reducing the number of short interruptions).

These circuit breakers allow the extinction of transient earth faults by cancelling the voltage to the fault terminals for at least 300 ms by earthing the single faulty phase at the substation busbars. This does not alter the voltage between phases supplying the customer.

Reducing the duration and depth of voltage dips

- At power system level

- Increasing the possibilities of ring connections (new substations, ring closing switch)
- Improving the performance of electrical protective devices (selectivity, automatic power restart, remote control devices on the network, remote management, replacement of spark gaps with surge arresters, etc.)
- Increasing the network short-circuit power

- At equipment level

Decrease the power consumed by the switched large loads with real time reactive compensators and soft starters which limit current peaks (and mechanical stress).

Increasing immunity of industrial and service installations

The general principle for ensuring that equipment is immune to voltage dips and interruptions is to compensate for a lack of power with an energy storage device between the distribution power system and the installation. The availability of the storage device has to be greater than the duration of the disturbances to which the system has to be immune to.
The information required when choosing mitigation solutions is:

- the quality of the source (maximum level of existing disturbances),
- the load requirements (voltage sag ride-through capability in the duration-depth scale).

Only by careful analysis of the process and of the technical and financial consequences of disturbances can these two elements be reconciled. There are various possible solutions to provide immunity depending on the power required by the installation and the duration of the voltage dip or interruption. It may well be helpful to study solutions by making a distinction between power supplies for control systems and regulation systems and those for motors and large power consumers. Indeed, a voltage dip or interruption (even of short duration) may be sufficient to open all of the contactors whose coils are supplied by the power circuit. Loads controlled by the contactors are thus no longer supplied when the voltage is restored.

Increasing immunity of the control system

The increase of immunity of a process is in general based on providing immunity to the control system.
In general, the control system is not of high power and is thus extremely sensitive to disturbances. It is therefore often more economical to immunise only the control system rather than the equipment power supply.
Maintaining control of machines assumes:

- There will be no risk to the safety of personnel or equipment when the voltage is restored.
- The loads and processes tolerate a short interruption in the power circuit (high inertia or slowdown is tolerated) and can be restarted on the fly when the voltage is restored.
- The source can ensure that all of the equipment can be supplied simultaneously (in the case of a replacement source) and provide the inrush current caused by the simultaneous restart of several motors.

The solutions consist in powering all of the contactor coils from a reliable auxiliary source (battery or rotating set with flywheel), or in using an off-delay relay, or in using a rectifier and a capacitor connected in parallel with the coil.

Increasing immunity of the equipment power supply

Certain loads cannot withstand the expected disturbance levels, i.e. neither voltage dips nor interruptions. This is the case for "priority" loads such as computers, lighting and safety systems (hospitals, airport lighting systems, public buildings) and continuous production lines (manufacture of semi-conductors, data processing centres, cement works, water treatment, materials handling, paper industry, steelworks, petrochemicals, etc.).
The following different technical solutions are possible depending on the power required by the

installation and the duration of the voltage dip or interruption.

■ Solid state uninterruptible power supply (UPS)

A UPS consists of three main elements:

□ a rectifier-charger, powered from the main supply, to convert AC voltage to DC,

□ a flywheel and/or battery (kept charged) which on interruption provide the necessary power for the load via the inverter,

□ a DC-AC inverter.

Two technologies are currently in use: on-line and off-line.

□ On-line technology

During normal operation, power is supplied continuously via the inverter without drawing on the battery. This, for example, is the case for MGE-UPS brand Comet and Galaxy UPS units. They ensure continuity (no changeover delays) and quality (voltage and frequency regulation) of the power supply for sensitive loads ranging from a few hundred to several thousand kVA.

Several UPS can be connected in parallel to obtain more power or to provide redundancy.

In the event of overload, power is provided by the static contactor (see **fig. 9**) from network 2 (which may be combined with network 1).

Power is maintained without interruption via a maintenance by-pass.

□ Off-line (or stand-by) technology

This is used for applications of no more than a few kVA. During normal operation, power is supplied from the network. In the event of loss of network power or if the voltage exceeds the prescribed tolerances, use is transferred to the UPS. The changeover causes an interruption of 2 to 10 ms.

■ Sources transfer

A device is used to control transfer between the main source and a replacement source (and vice versa) for supply to priority loads and if necessary orders the shedding of non-priority loads.

There are three types of transfer depending on the duration of transfer (Δt):

□ synchronous ($\Delta t = 0$),

□ delayed ($\Delta t = 0.2$ to 30 s),

□ pseudo-synchronous (0.1 s $< \Delta t <$ 0.3 s).

The devices require special precautions (see "Cahier Technique" no. 161). For example, if there are several motors in the installation, simultaneous restart may produce a voltage drop which could prevent restart or lead to excessively long restarts (with the risk of overheating). It is therefore prudent to install a PLC which will restart the priority motors at intervals, especially with a replacement (backup) source with a low short-circuit power.

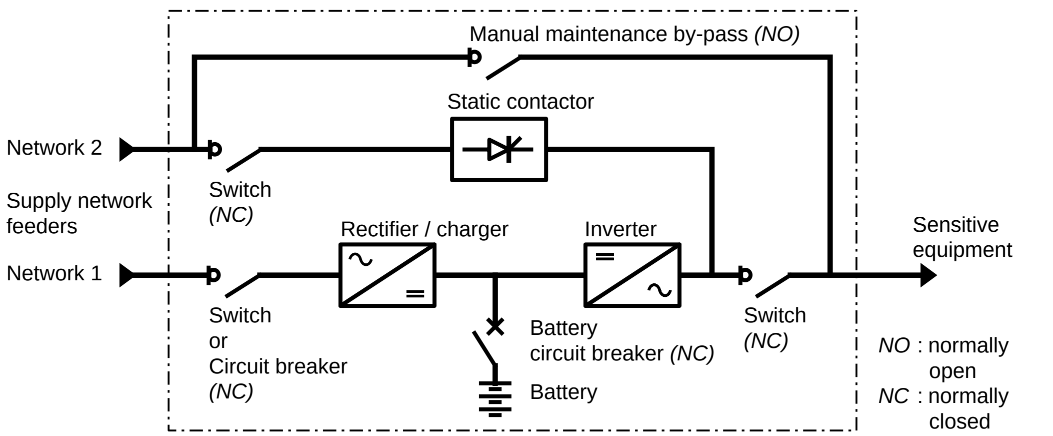


***Fig. 9**: Schematic diagram of an on-line uninterruptible power supply (UPS).*

This solution is selected where the installation cannot withstand a long interruption of more than a few minutes, and/or requires a large amount of power. It can also be used in conjunction with a UPS.

- Zero-time set

In certain installations, the autonomy required in the event of interruption makes it necessary to install a generating set (large batteries would be too expensive, or cause technical or installation problems). Here, in the event of any loss of power supply, the battery or flywheel is used to provide sufficient time for starting and running up the stand-by engine generator, load shedding (if necessary) and interruption-free coupling by means of an automatic source changeover.

- Electronic conditioners

These are modern electronic devices to compensate voltage dips and interruptions to a certain extent with a short response time: for example the real time reactive compensator compensates the reactive power in real time and is especially well suited to loads with rapid, large variations (welding machines, lifts, presses, crushers, motor starting, etc.).

Clean stop

If a stoppage is acceptable, it is especially advisable to prevent uncontrolled restarting if an unwanted restart would present a risk for the machine operator (circular saws, rotating electrical machines) or for the equipment (compression chambers while still under pressure, staggered restarts of air-conditioning compressors, heating pumps or refrigeration units) or for the application (necessity of controlling production restart). The process may be automatically restarted by a PLC using a predetermined restart sequence when conditions return to normal.

Summary (see table below)

Installation power	**Duration (indicative values) and technical requirements**						**Immunisation solution**
	0 to 100 ms	100 ms to 400 ms	400 ms to 1 s	1 s to 1 min	1 min to 3 min	> 3 min	
A few VA							Time-delayed contactors
							DC power with capacitor storage
< 500 kVA							Rotating set with flywheel
< 1 MVA							Transfer source with diesel set
< 300 kVA	Between 15 minutes and several hours depending on battery capacity						DC power with battery storage
< 500 kVA	Transfer time to a backup source may cause a short interruption						Rotating set with flywheel and thermal motor or backup source
< 500 kVA	Between 15 minutes and several hours depending on battery capacity						DC motor connected to battery and alternator
< 1 MVA (up to 4800 kVA with several UPS in parallel)	Between 10 minutes (standard) and several hours UPS depending on battery capacity						

Effective mitigation solution

Ineffective mitigation solution

5.2 Harmonics

There are three possible ways of suppressing or at least reducing the influence of harmonics. One section will examine the question of protective devices.

- Reducing generated harmonic currents

- Line choke

A 3-phase choke is connected in series with the power supply (or integrated into the DC bus for frequency inverters). It reduces the line current harmonics (especially high number harmonics) and therefore the rms value of the current consumption and the distortion at the inverter connection point.
It is possible to install the choke without affecting the harmonics generator and to use chokes for several drives.

- Using 12-phase rectifiers

Here, by combining currents, low-order harmonics such as 5 and 7 are eliminated upstream (these often cause the most disturbance owing to their large amplitude). This solution requires a transformer with two secondary windings (star and delta), and only generates harmonics numbered 12 k ± 1.

- Sinewave input current devices

(see "Cahier Technique" no. 183)
This method consists in using static converters where the rectifier uses PWM switching to absorb a sinusoidal current.

- Modifying the installation

- Immunise sensitive loads with filters
- Increase the short-circuit power of the installation
- Derate equipment
- Segregate polluting loads

As a first step, the sensitive equipment must be connected as close as possible to the power supply source.
Next, the polluting loads must be identified and separated from the sensitive loads, for example by powering them from separate sources or from dedicated transformers. These solutions involve work on the structure of the installation and are, of course, usually difficult and costly.

- Protective devices and oversizing of capacitors

The choice of solution depends on the installation characteristics. A simple rule is used to choose the type of equipment where Gh is the apparent power of all generators of harmonics supplied from the same busbar system as the capacitors, and Sn is the apparent power of the upstream transformer(s):

- If Gh/Sn ⩽ 15 %, standard equipment is suitable
- If Gh/Sn > 15 %, there are two possible solutions.

1 - For polluted networks
(15 % < Gh/Sn ⩽ 25 %): the current rating of the switchgear and in-series links must be oversized, as must the voltage rating of the capacitors.

2 - For very polluted networks
(25 % < Gh/Sn ⩽ 60 %): anti-harmonic chokes must be connected to the capacitors and set to a frequency lower than the frequency of the lowest harmonic (for example, 215 Hz for a 50 Hz network) (see **fig. 10**). This eliminates any risk of resonance and helps to reduce harmonics.

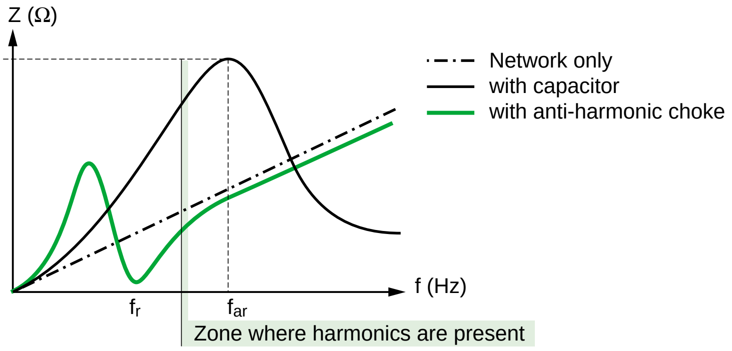


***Fig 10**: Effects of an anti-harmonic choke on network impedance*

■ Filtering

Where Gh/Sn > 60%, specialists must calculate and install the harmonics filter (see **fig. 11**).

□ Passive filtering (see "Cahier Technique" no. 152)

This involves connecting a low impedance by-pass to the frequencies to be attenuated using passive components (inductor, capacitor, resistor). Several passive filters connected in parallel may be necessary to eliminate several components. Careful attention must be paid to the sizing of harmonic filters: a poorly designed passive filter may lead to resonance and amplify frequencies which did not cause disturbance before installation of the filter.

□ Active filtering (see "Cahier Technique" no. 183)

This consists in neutralising the harmonics induced by the load. First an analysis of the current identifies them in amplitude and phase. Then the same but opposite harmonics are produced by the active filter. It is possible to connect several active filters in parallel. An active filter may for example be connected to a UPS to reduce harmonics which have been injected upstream.

□ Hybrid filtering

This consists of an active filter and a passive filter set to the order of the dominant harmonic (e.g. 5) which supplies the necessary reactive power.

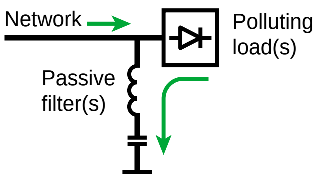
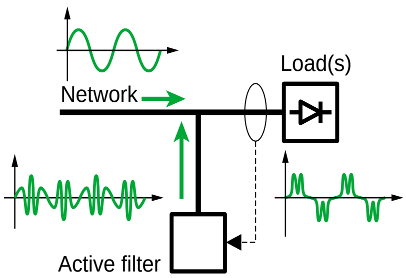
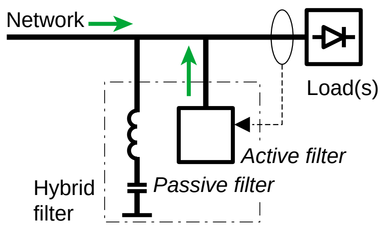
Filter	Principle	Characteristics
Passive	By-pass series LC circuit tuned to each harmonic frequency to be eliminated.  	■ No limits in harmonic current. ■ Compensation of reactive power. ■ Elimination of one or more harmonic orders (generally 5, 7, 11). One filter for one or two orders to be compensated. ■ Risk of amplification of harmonics in the event of network modification. ■ Risk of overload caused by external pollution. ■ "Network" filter (global). ■ Case by case engineering study.
Active	Generation of current cancelling out all harmonics created by the load.  	■ Solution particularly suited to "machine" filtering (local). ■ Filtering on a wide frequency band (elimination of harmonic orders 2 to 25). ■ Self-adapting: □ network modification has no effect, □ adapts to all variations in load and harmonic spectrum, □ open-ended, flexible solution for each type of load. ■ Simple engineering study.
Hybrid	 	Offers the advantages of passive and active filtering solutions and covers a wide range of power and performance: ■ filtering on a wide frequency band (elimination of harmonics numbered 2 to 25), ■ compensation of reactive power, ■ large capacity for current filtering, ■ good technical-economic solution for "network" filtering.

***Fig. 11**: Principles and characteristics of passive, active, and hybrid filtering.*

■ Special case: circuit breakers
(see "Cahier Technique" no. 182)

Harmonics may cause unwanted tripping of protective devices: care must be taken when choosing protective devices to avoid this.
Circuit breakers can be fitted with two types of trip device, thermal-magnetic or electronic.
The heat sensors of thermal-magnetic circuit breakers are particularly sensitive to harmonics and can identify the actual load on the conductors caused by the presence of harmonics. They are thus well suited to use on low current circuits, essentially in domestic or industrial applications.
The method used by electronic circuit breakers to calculate the current being carried may present a risk of unwanted tripping and care must therefore be taken when choosing these devices that the true rms value of the current is measured. These devices have the advantage of being better able to track changes in the temperature of cables, particularly in the case of cyclical loads, as their thermal memory is superior to that of indirectly heated bimetallic strips.

■ Derating

This solution is applicable to some equipment and is a simple and frequently adequate response to disturbance caused by harmonics.

5.3 Overvoltages

Correct insulation co-ordination involves ensuring the protection of personnel and equipment against overvoltages, with the best balance between technical and economic considerations.
This requires (see "Cahier Technique" no. 151):

■ knowledge of the level and energy of the overvoltages which may occur on the network,

■ selection of the level of overvoltage withstand of the power system components to meet constraints,

■ use of protective devices where necessary, in fact, the appropriate solutions depend on the type of overvoltage encountered.

Temporary overvoltages

■ Switch off all or some of the capacitors during periods of low load.

■ Avoid configurations susceptible to ferroresonance or introduce losses (reducing resistors) to damp the phenomenon (see "Cahier Technique" no. 190).

Switching overvoltages

■ Limit the capacitors energisation transients by installing a fixed reactor and pre-insertion resistors. Static automatic reactive compensators which control closing instant are especially suitable for LV applications which cannot withstand transient overvoltages (PLCs, computer systems).

■ Connect line chokes upstream of the frequency inverters to limit the effects of transient overvoltages.

■ Use main residual current circuit breakers of discriminatory type (type "**S**") for LV and circuit breakers of type "**si**" ($I\Delta n$ = 30 mA and 300 mA). Their use avoids unwanted tripping due to transient leakage currents : lightning and switching overvoltages, energisation of circuits with a high capacitance to earth (capacitive filters connected to earth, extended cable networks, etc.) which flow through the network downstream of the RCD (residual current device) via the network capacitance to earth.

Lightning overvoltages

■ Primary protection

This protects the building and its structure from direct lightning strikes (lightning conductors, Faraday cages, overhead earth wire/earthing wire).

■ Secondary protection

This protects equipment against the overvoltages which follow lightning.
Surge arresters (spark gaps are now used less and less) are installed on the particularly exposed points of HV and MV networks and at the input to MV/LV installations (see "Cahier Technique" no. 151).
On LV installations, they are installed as far upstream as possible (to offer maximum protection) and as close as possible to the load. It is sometimes necessary to cascade surge arresters: one at the head of the installation, and one close to the load (see "Cahier Technique" no. 179). An LV surge arrester is always connected to a disconnection device. In addition, the use of main residual current circuit breakers of discriminatory type on LV installations avoids any current flow to earth via the surge arrester tripping the circuit breaker at the head of the installation, which would be incompatible with some equipment (freezers, controllers, etc.).
Note that overvoltages can be propagated to the equipment by other routes than the electrical power supply: telephone lines (telephone, fax), coaxial cables (computer links, TV aerials). Suitable protective devices are commercially available.

5.4 Voltage fluctuations

Fluctuations produced by industrial loads may affect a large number of consumers supplied from the same source. The fluctuation magnitude depends on the ratio between the impedance of the device generating the disturbance and the impedance of the power supply. The solutions are:

- Changing the type of lighting

Fluorescent lamps are less sensitive than incandescent lamps.

- Installing an uninterruptible power supply

This may be a cost-effective solution if users subject to disturbance are identified and grouped together.

- Modify the device generating the disturbance

Changing the starting mode of motors which have to start frequently, for example, can reduce overcurrents.

- Modify the network

□ Increase the short-circuit power by connecting lighting circuits to the nearest power supply point.

□ Increase the "electrical distance" between the disturbance-generating load and lighting circuits by powering the disturbance-generating load from an independent transformer.

- Use a reactive compensator

This device provides real time reactive compensation for each phase. Flicker can be reduced from 25 % to 50 %.

- Connect a reactance in series

By reducing the inrush current, a reactance downstream from the connection point of an arc furnace can reduce flicker by 30 %.

5.5 Unbalance

The solutions are:

- balancing single phase loads on all three phases,
- reducing the power system impedance upstream of the devices causing the unbalance by increasing the transformer rated power and the cable cross-section,
- fitting the appropriate protective device for the machines,
- using carefully connected LC loads (Steinmetz connection).

5.6 Summary

Type of disturbance	Origins	Consequences	Examples of mitigation solutions (special equipment and modifications)
Voltage variations and fluctuations	Large load variations (welding machines, arc furnaces, etc.).	Fluctuation in the luminance of lamps (flicker).	Electromechanical reactive power compensator, real time reactive compensator, series electronic conditioner, tap changer.
Voltage dips	Short-circuit, switching of large loads (motor starting, etc.).	Disturbance or shutdown of process: loss of data, incorrect data, opening of contactors, locking of drives, slowdown or stalling of motors, extinguishing of discharge lamps.	UPS, real time reactive compensator, dynamic electronic voltage regulator, soft starter, series electronic conditioner. Increase the short-circuit power (Scc). Modify the discrimination of protective devices.
Interruptions	Short-circuit, overloads, maintenance, unwanted tripping.		UPS, mechanical source transfer, static transfer swtich, zero-time set, shunt circuit breaker, remote management.
Harmonics	Non-linear loads (adjustable speed drives, arc furnaces, welding machines, discharge lamps, fluorescent tubes, etc.).	Overloads (of neutral conductor, sources, etc.), unwanted tripping, accelerated ageing, degradation of energy efficiency, loss of productivity.	Anti-harmonic choke, passive or active filter, hybrid filter, line choke. Increase the Scc. Contain polluting loads. Derate the equipment.
Inter-harmonics	Fluctuating loads (arc furnaces, welding machines, etc.), frequency inverters.	Interruption of metering signals, flicker.	Series reactance.
Transient overvoltages	Operation of switchgear and capacitors, lightning.	Locking of drives, unwanted tripping, destruction of switchgear, fire, operating losses.	Surge arrester, surge diverter, controlled switching, pre-insertion resistor, line chokes, static automatic compensator.
Voltage unbalance	Unbalanced loads (large single-phase loads, etc.).	Inverse motor torque (vibration) and overheating of asynchronous machines.	Balance the loads. Shunt electronic compensator, dynamic electronic voltage regulator. Increase the Scc.

6 Case studies

6.1 Hybrid filtering

Description of the installation

Ski-lifts are powered by an MV/LV transformer (800 kVA).
The connected loads are the chair lifts together with other loads such as payment booths, ski-pass validation systems, the official timing system for competitions and a telephone network.

Problems encountered

When the chair lifts are running, the low voltage network powered by the MV/LV transformer is subject to disturbance.
The measures taken at the site pinpointed a high pre-existing harmonic distortion factor in the voltage (THD ≈ 9 %) from the MV power system as well as harmonic pollution from the chair-lift feeder. The resulting distortion of the supply voltage (THD ≈ 12 %) disturbed sensitive equipment (payment booths, timing system, etc.).

Solutions

The aim of the device is to ensure the simultaneous reactive compensation when harmonics are present and neutralisation of harmonics likely to disturb the installation.
The solution chosen (see **fig. 12**) was to install a hybrid filter (see **fig. 13**) consisting of a passive filter tuned to the order of the dominant harmonic (H5) which provides the required reactive power (188 kvar), and an active filter rated at 20 A is dedicated to the elimination of all other harmonics.

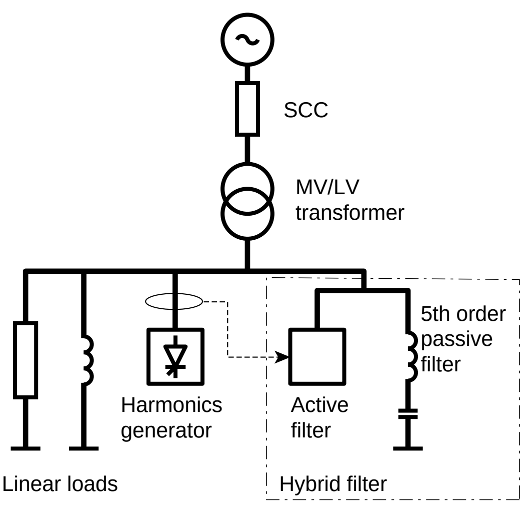


Fig. 12: Implementation of the solution.

After commissioning, measurements show that the device reduces the magnitude of the harmonics over a wide frequency spectrum in both current and voltage (see **fig. 14**) and reduced the voltage distortion factor from 12.6 % to 4.47 %. It also increased the power factor of the installation from 0.67 to 0.87. This solution solved all of the problems as no malfunction was subsequently detected.

Fig. 13: Rectiphase hybrid filter device (Merlin Gerin brand).

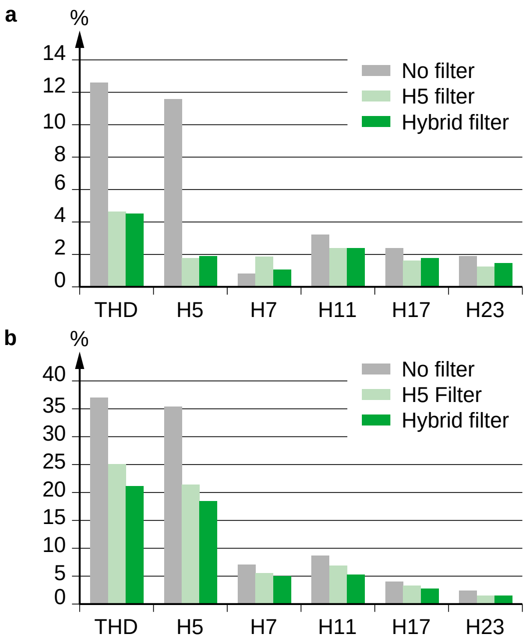


*Fig 14: Spectrums showing the effectiveness of a hybrid filter: **[a]** in voltage **[b]** in current.*

6.2 Real time reactive compensation

Description of the installation

A car equipment manufacturer's plant in Concord (Ontario - Canada) is supplied by a transformer rated at 2000 kVA - 27.6 kV / 600 V - Yy - Ucc = 5.23 %.
It manufactures exhaust assemblies from steel plate using spot welders and seam welders.

Problems encountered

- Visual and nervous fatigue in personnel, due to the fluctuation in brightness of lamps (flicker) when welding equipment was in operation.
- Noise pollution and premature mechanical ageing of equipment caused by vibrations mainly in the transformer and the main switchgear when welding equipment was in operation.
- Inability to add equipment for fear that the installation would be overloaded (peak currents when welders were fired were greater that the nominal current of the main circuit breaker). Expansion of the installation would thus require substantial investment, either to upgrade the existing installation or to build a new power supply facility.
- Annual penalties of 5 k€ for exceeding the reactive power consumption limit (0.75 power factor).
- Defective parts caused by welding faults appeared at the end of the manufacturing process when the tubes are bent into shape.

All these factors reduced company productivity.

Solutions

The measures taken during the operation of the welding equipment showed a nominal voltage of 584 V, voltage dips of 5.8 %, current peaks of 2000 A, and reactive power peaks of 1200 kvar (see **fig. 15**).

	Before	After
Voltage (V)	584	599
Voltage dip		
■ Depth (%):	5.8	3.2
■ Duration (cycle)	20 to 25	10 to 15
Current		
■ Average	1000	550
■ Peak	2000	1250
Reactive power (kvar)	600 to 1200	0 to 300
Power factor	0.75	> 0.92

Fig. 15: Improvements due to the real time reactive compensator.

The problems clearly stemmed from voltage fluctuations caused by the operation of welders with loads which vary rapidly and frequently and which consume significant reactive power.

A voltage dip of 6 % produces a reduction of 12 % ($1-0.94^2$) in the power available for welding. This was the reason for the large number of defective welds.

Standard devices for reactive power compensation use electromechanical contactors which cannot achieve the required response times; the operation of capacitor steps is deliberately time delayed to reduce the number of operations and avoid reducing the service life of the contactors through premature wear, as well as to enable the capacitors to discharge.

The solution chosen was to connect a real time reactive compensator (see **fig. 16**). This innovative device offers:

- ultra-rapid compensation of the variations in reactive power within one cycle (16.6 ms at 60 Hz), which is especially suitable for loads with rapid, large variations (welding machines, lifts, presses, crushers, motor starting, etc.);
- transient-free switch through controlled switching, which is especially useful with loads which cannot withstand transient overvoltages (PLCs, computer systems, etc.);
- increased service life of capacitors and contactors owing to the absence of moving mechanical parts and overvoltages

With compensation of 1200 kvar it would be possible to minimise voltage dips, but 800 kvar was deemed sufficient to maintain the voltage at

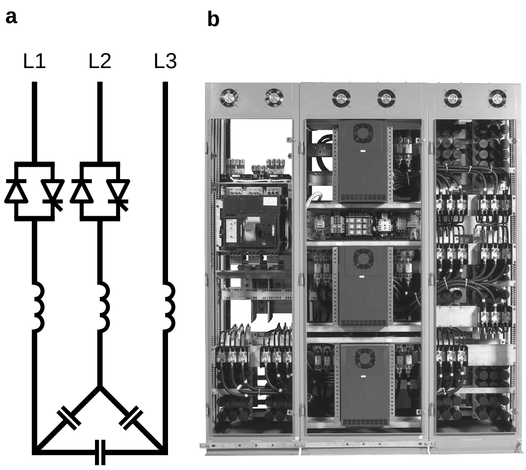


*Fig. 16: Real time reactive compensator **[a]** principle, **[b]** practical implementation.*

an acceptable level for all processes in the plant under all load conditions.
The results of implementing the solution are (see **fig. 17**):

- a reduction in current peaks to 1250 A and the addition of loads without modification of the installation, with improved installation efficiency through reduction of joule losses;
- a reduction in reactive power peaks to 300 kvar and an increase in the power factor to over 0.92, thus avoiding power factor penalties;
- an increase in the nominal voltage to 599 V and a reduction in voltage dips to 3.2 % (see fig. 16). This is a consequence of the increase in the power factor and reduction in the current amplitude (see **fig. 18**). Visual and nervous fatigue in personnel due to the flicker was also eliminated. Welding quality improved, as did productivity.

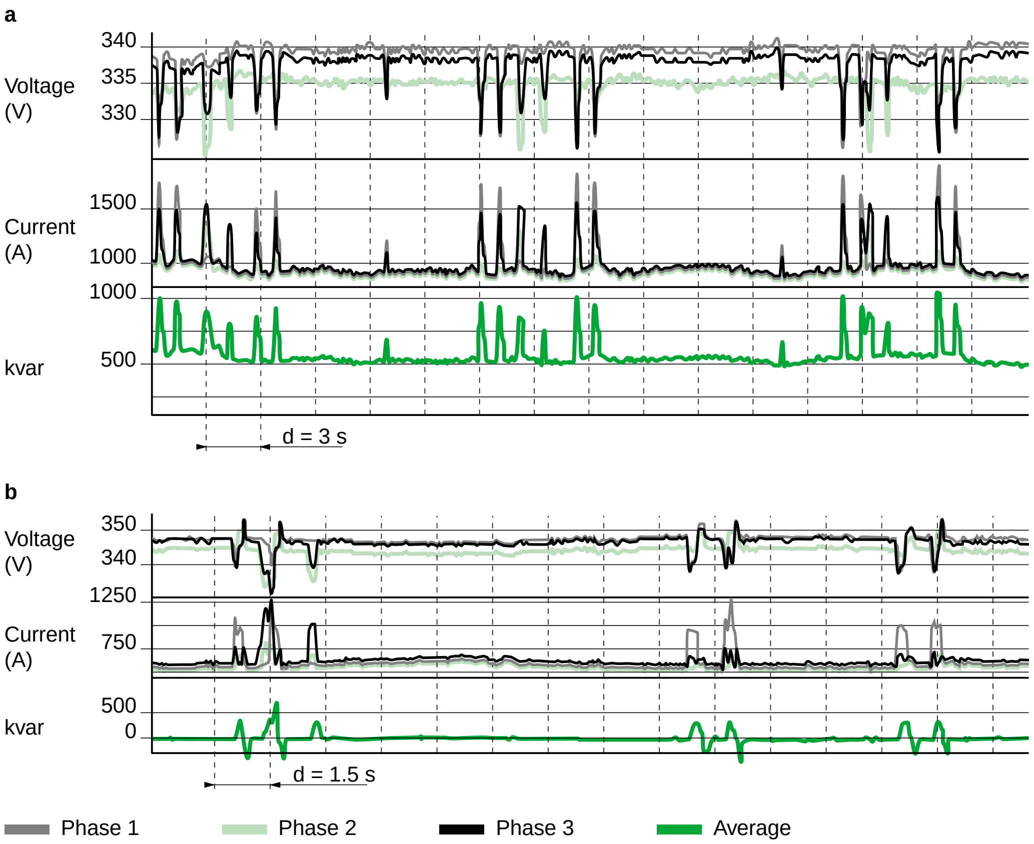


*Fig. 17: Measurement of current, voltage and reactive power: **[a]** without compensation **[b]** with compensation.*

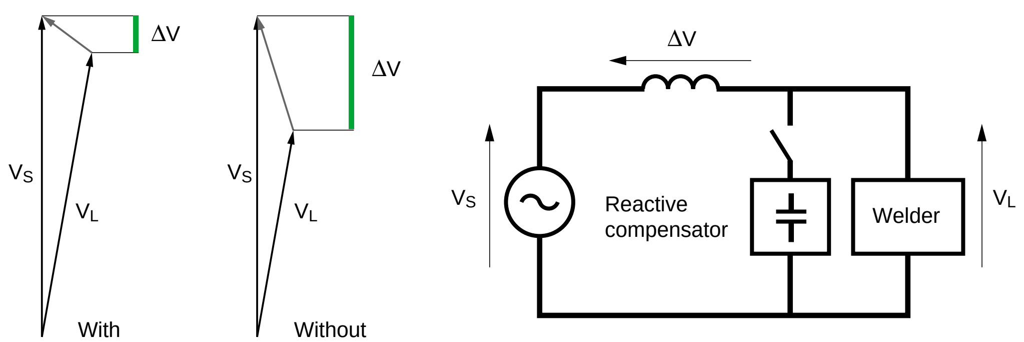


Fig. 18: Reduction in voltage drop obtained using a real time reactive compensator.

6.3 Protection against lightning

Description of the installation

The site consists of offices (computer hardware, lighting and heating unit), a security post (fire alarm, burglar alarm, access control, video surveillance) and three buildings for the manufacturing process on 10 hectares in the Avignon region of France (probability of lightning is 2 strikes per km^2 per year).
There are trees and metal structures (pylons) in the vicinity of the site. All of the buildings are fitted with lightning conductors. The MV and LV power supplies are underground.

Problems encountered

A storm struck the site, destroying the LV installation in the security post and causing 36.5 k€ of operating losses. The presence of lightning conductors prevented the structure from catching fire, but the electrical equipment which was destroyed was not protected by surge arresters, contrary to the recommendation in standards UTE C-15443 and IEC 61024.

Solutions

After analysing equipotentiality and earthing of the power system, followed by verification of the installation of lightning conductors and checking of the values of the earth electrodes, the decision was taken to install surge arresters.

Surge arresters were installed at the head of the installation (main LV distribution board) and in cascade in each manufacturing building (see **fig. 19**). As the neutral point connection was TNC, protection would only be provided in common mode (between phases and PEN).

In conformity with guide UTE C-15443 regarding operation in the presence of lightning conductors, the characteristics of the Merlin Gerin PF65 and PF8 surge arresters (see **fig. 20**) are as follows:

- At the head of the installation

In = 20 kA – Imax = 65 kA – Up = 2 kV

- In cascade (at least 10 m apart)

In = 2 kA – Imax = 8 kA – Up = 1.5 kV

In cascade, good protection is provided for the secondary distribution boards (offices and security post).

As the neutral point connection was converted to TNS, protection had to be provided in common mode (between phase and PE) and differential mode (between phases and neutral). The disconnection devices in this case are circuit breakers with a breaking capacity of 22 kA.

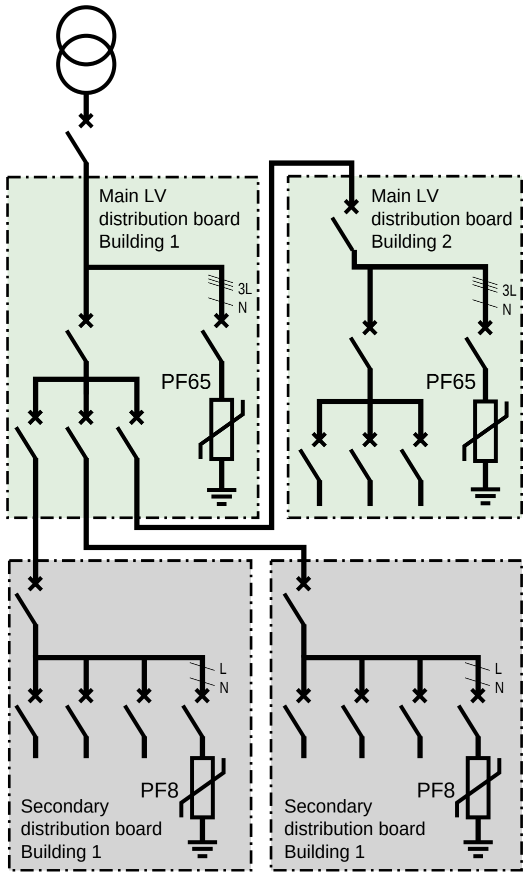


Fig. 19: Installation diagram for several surge arresters in cascade.

Fig. 20: Low voltage surge arresters (Merlin Gerin PF65 and PF8).

7 Conclusion

Electrical disturbance may originate in the distribution power system, in the installation of the user who is subject to disturbance or in the installation of a nearby user.

The consequences of the disturbance vary according to the economic context and the area of application: from inconvenience to shutdown of production facilities - it can even put lives at risk.

The search to improve company competitiveness and the deregulation of the electricity market mean that the quality of electricity has become a strategic issue for electricity companies, the operating, maintenance and management personnel of service sector and industrial sites, as well as for equipment manufacturers.

However, problems of disturbance should not be regarded as insurmountable, as solutions do exist. Employing specialists to define, implement and maintain these solutions while observing best practice will provide users with the right quality of power supply for their requirements.

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