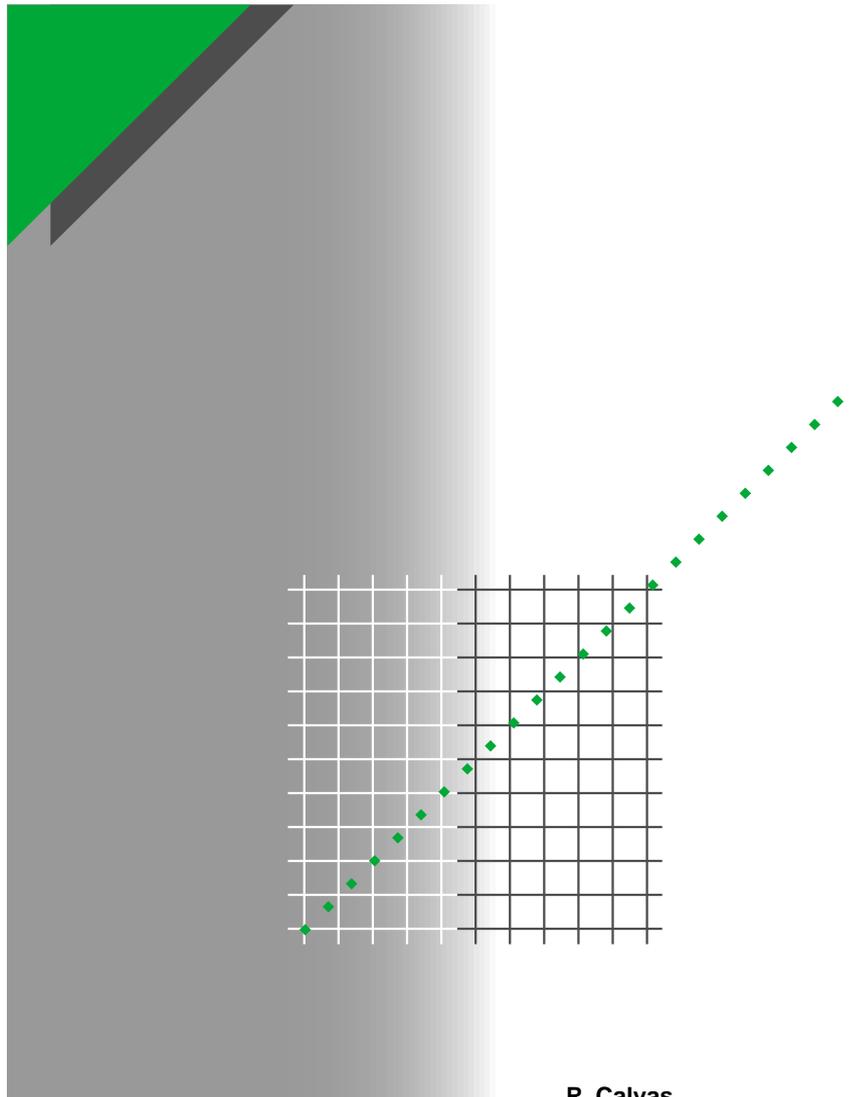


Cahier technique no. 141

Electrical disturbances in LV



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no. 141

Electrical disturbances in LV



Roland CALVAS

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During his career he has been sales manager, then marketing manager of the activity concerned with protection of people against electrical hazards.

Lexicon

Earthing systems:

Standard IEC 60364 (in France standard NF C 15-100) stipulates the three main official earthing systems defining the possible connections of the neutral, source and frames to the earth or neutral. The necessary electrical protection devices are defined according to the earthing system chosen for a network.

Electrical disturbance:

All disturbing phenomena that cause the mains voltage (or current) wave to depart from its nominal characteristics.

Electromagnetic disturbance:

All disturbing phenomena of an electrical, magnetic or electrostatic nature that may affect the mains and/or the operation of electric and electronic devices.

Impulse voltage:

Impulse lasting less than 10 ms superimposed on sinusoidal voltage.

Interruption:

Absence of voltage for a varying period of time.

Overvoltage:

Overshooting $U_n + 10\%$ for a varying period of time.

PWM: Pulse Width Modulation.

r.m.s. : root mean square.

Short overvoltage:

Transient voltage wave characterised by a rapid increase followed by a slower decrease, normally of a periodic nature.

Very short overvoltage:

Transient voltage wave characterised by a rapid increase followed by a slower decrease, normally of a periodic nature.

Voltage dip:

Voltage drop of more than 10% followed by a return to the normal variation range.

Electrical disturbances in LV

LV networks are highly polluted and subject to a large number of aggressions. Electrotechnical equipment and in particular electronic devices, that are increasingly numerous and process ever lower signals, must withstand a harsh electromagnetic environment. At the same time availability requirements, whether for production, management or commerce, are increasingly great.

To improve the quality of the “electricity product” and avoid malfunctioning and in some cases destruction of the components of the electrical network and/or sensitive loads, it is essential to understand the origin of the disturbances and evaluate their risks. This is the purpose of this “Cahier Technique”, which is an introduction to the vast field of electromagnetic compatibility and immunity from 50 Hz through to radioelectric frequencies. In this document the author deals with all parameters and their main “anomalies” used to characterise an electrical supply:

- amplitude: variations – interruptions – dips – overvoltages,
- frequency: variations,
- waveform: harmonics – transients – carrier currents,
- phase: unbalance,
- power: short-circuits – overloads (effects on voltage).

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1 LV industrial voltages

All networks undergo or create disturbances. However, loads, as well as control/monitoring and protection devices, are sensitive to the quality of the voltage applied to them. Knowledge and consideration of these electrical power supply requirements are thus justified:

- manufacturers of electrotechnical and electronic equipment designed for an international market must allow for tolerances that vary from country to country,

- electrical consultants and contractors must also take these phenomena into account right from the design stage of networks, and, according to their customers' needs, find technical solutions for distribution diagrams and switchgear.

Important reminder:

Low Voltage installations must comply with standard IEC 60364 (in France standard NF C 15-100).

1.1 Nominal voltages

The low voltage range concerns the following voltages:

- AC: $\leq 1,000$ V (frequency ≤ 10 kHz),

- DC: $\leq 1,500$ V

Also known as "rated voltages" they are defined in publication IEC 60038 of 1983. The most common LV voltage is "230/400 V" in France, made official by the decree of 29/05/86.

World-wide and up to 2003, various nominal voltages will continue to be found:

- European: 220/380 V, 50 Hz,

- English: 240/415, 50 Hz,

- USA: 120/240 V and 480 V, 60 Hz,

- Japan: 100/200 V, 50 and 60 Hz.

However, these voltages vary around nominal voltage according to structure and load of the

network (conductor length and load fluctuation) and the regulating systems of the public (or private) network.

In Europe, standard EN 50160 states that in normal operation, for each period in a week, 95% of r.m.s. values averaged out over 10 minutes must be included in the range $U_n \pm 10\%$. For example, in France, the Utility Company (EDF) announces a fluctuation of $\pm 10\%$ but accepts that, temporarily, voltages may depart from nominal voltage by more than 20%.

Furthermore, these fluctuations must be associated with the notion of time, e.g.:

- Permanent $U_n \pm 10\%$.

- Five minutes $U_n \pm 20\%$.

In developing countries, fluctuations in excess of $\pm 20\%$ can be frequently observed.

1.2 Frequency

With respect to frequency, slow fluctuations around the nominal value of 50 or 60 Hz are normally small.

In European countries, whose networks are interconnected, standard EN 50160 specifies

50 Hz $\pm 1\%$ for 95% of the week, and [+4%, - 6%] in the event of major disturbances. These fluctuations may be far greater for autonomous networks, for example on an island.

2 Amplitude disturbances

Networks are disturbed not only by load fluctuations in normal operation, but also and above all by random phenomena of accidental origin, for example short-circuits. A LV network is subjected to these two causes of disturbances

whatever their origin (LV, MV or HV). The two main amplitude disturbances are:

- voltage dips and short interruptions,
- overvoltages.

2.1 Voltage dips and short interruptions

A voltage dip is normally defined as a drop from 10% to nearly 100% of the nominal voltage value for a time lasting between 10 ms and a few seconds (see **fig. 1**). When power is off (100 % voltage drop), for 1 s to 1 min, we talk of a “short interruption”, and of a “very short interruption” between 10 ms and 1 s. When duration is ≤ 10 ms, the interruption is normally due to “transient” or voluntary phenomena, such as use of dimmers.

Disturbances due to operation of HV and MV networks

- Deliberate modification of network geometry causes short interruptions of up to several seconds. However meshed distribution networks are less sensitive to this phenomenon.

- Energisation of large transformers causes developing voltage dips due to inrush current. The table in **figure 2** gives, by way of an example, the energisation current of MV/LV transformers.

The same applies on energisation of MV capacitors and large motors: for capacitors the inrush current may reach 100 times their nominal current (as per IEC 60831-1) and up to 8 I_n for a few dozen seconds for motors.

- Disturbances due to faults on HV and MV networks (short-circuit and insulation fault). Phenomena such as: equipment insulation fault, lightning stroke, damage to an underground cable, earthing of an overhead conductor, cause short-circuits that generate high voltage drops in an area of varying size around the origin of the fault, prior to disconnection of the faulty device by the protection devices. At the same time users directly serviced by the faulty device have their power supply permanently or temporarily cut off. These phenomena affect all voltage levels, but particularly the MV networks (20 kV). For each fault, the number and type of voltage dips and short interruptions depend on the protection devices and reclosers used.

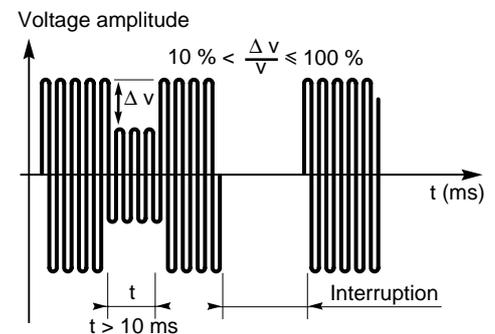


Fig. 1 : voltage dip (Δv) and interruption.

P (kVA)	$ne = \frac{I_{\text{peak energis.}}}{I_n \text{ transformer}}$	Time constant (s)
50	15	0.1
100	14	0.15
160	12	0.2
250	12	0.22
400	12	0.25
630	11	0.3
800	10	0.3
1000	10	0.35
1250	9	0.35
1600	9	0.4
2000	8	0.45

Fig. 2 : value of the energising currents and time constant of the MV/LV transformers on energisation on the MV side (on energisation on the LV side, “ne” is twice as high).

In France

□ On EHV networks (400 and 225 kV), various reclosers are used:

- slow single-phase reclosers tripping in event of single-phase faults: breaking time is around 1.5 to 2 s,
- slow three-phase reclosers (multiphase faults), whose operation depends on voltage synchronisation check: breaking time is around 5 s. These reclosers are also used on HV networks (90 and 63 kV).

□ On overhead MV networks (5 to 20 kV) for which the neutral is earthed by an impedance limiting the earth fault current to 300 A in the primary substation, "shunt circuit-breakers" eliminate intermittent single-phase faults (contacts with branches) without affecting LV users (see **fig. 3**).

However, multiphase faults are treated by rapid and slow reclosers that cause voltage dips on LV (see **fig. 4**). Roughly 75% of faults are eliminated after rapid reclosing that corresponds to the conventional short 300 ms interruption.

□ On underground MV networks (5 to 20 kV). In theory there are no intermittent faults, thus all faults result in "permanent" de-energisation of the faulty part of the network. Consequently underground networks (town) are organised either in "double shunt" (see **fig. 5**) or, in most cases, in an open ring (see **fig. 6**).

Automated systems restore supply to fault-free HV/LV substations in less than one minute.

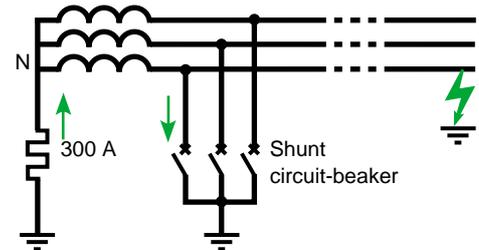


Fig. 3 : elimination of a single-phase fault by a shunt circuit-breaker which short-circuits the fault, thus quenching the arc.

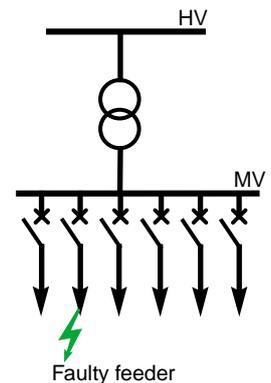
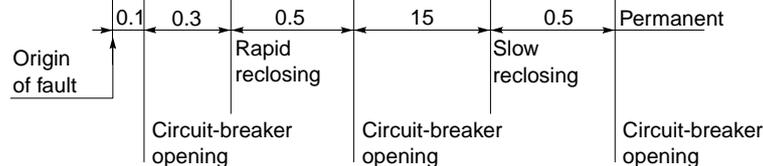
a - Current inrush by the faulty feeder



b - Voltage on the faulty feeder



c - Voltage on the other feeders



Principle: On an overhead MV network, most faults are intermittent. Thus, the incoming circuit-breaker on each feeder is equipped with an automated system that attempts two reclosings (sometimes three):

- the first instantaneously (opening + closing time: 0.3 s),
- the second after roughly 15 s.

Fig. 4 : voltage fluctuations on rapid and slow reclosing on a MV distribution network.

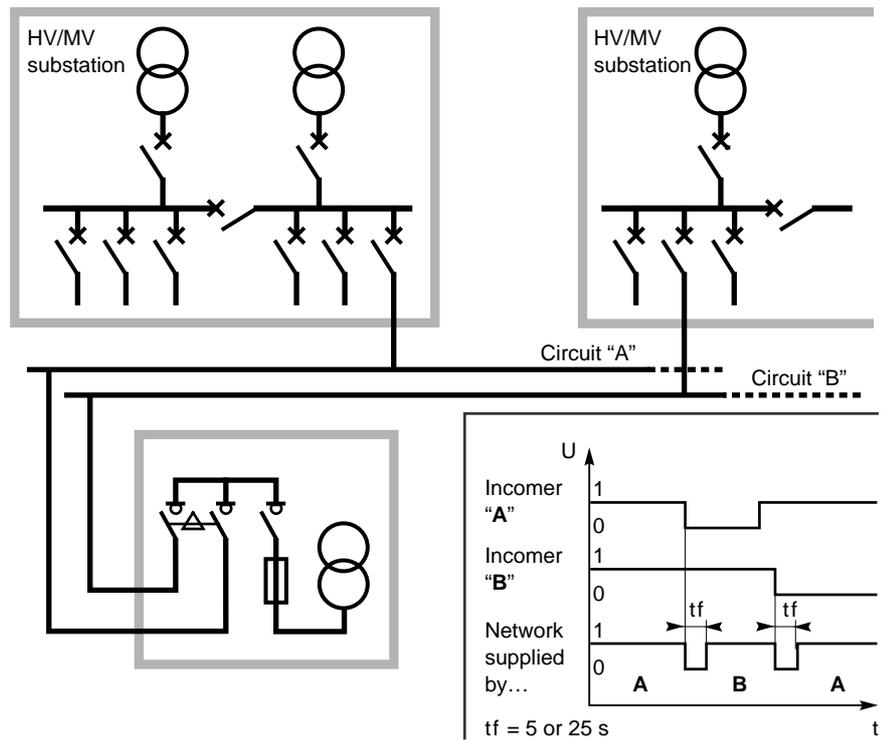


Fig. 5 : double shunt MV power supply. In the box, automated system sequence for a Merlin Gerin changeover switch conform to EDF specifications (France).

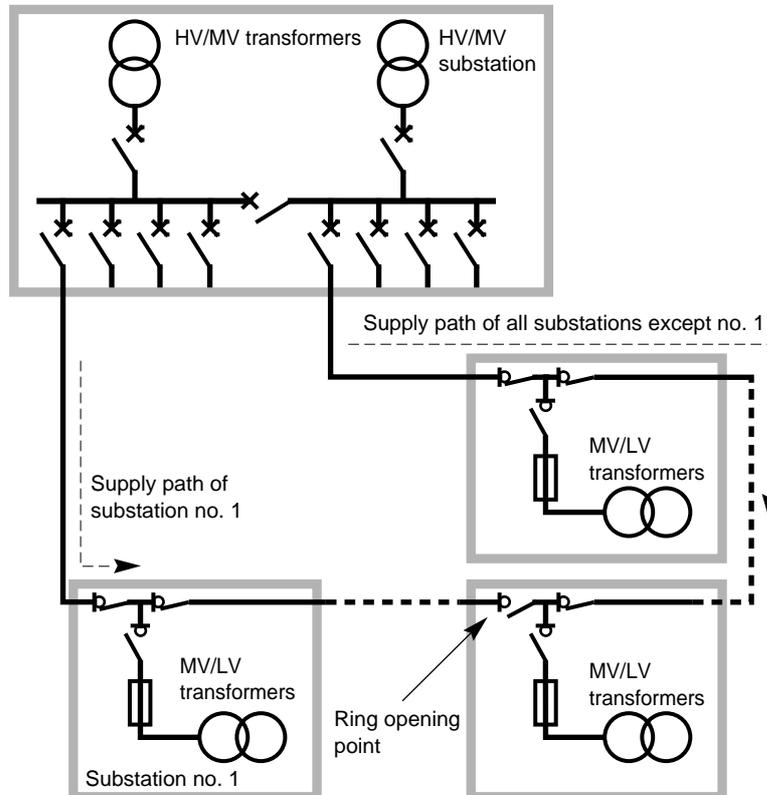


Fig. 6 : open ring MV power supply (main feeder interruption).

Disturbances due to operation of LV networks

The voltage dips observed on LV networks, due to their operation, are caused by:

- activation of capacitors (possibly placed at the supply end of the network) that causes, just as in MV, a very short voltage dip or a transient phenomenon of the oscillating kind;
- direct on line starting of large motors, directly supplied by the main LV board, that causes a voltage dip or whose catching a spinning load (resumption of supply after a short interruption) results in an inrush current that may be high (up to twice the I_n of an across the line start).

Disturbances due to faults on LV networks

Short-circuits on the main LV distribution, between two live conductors or between a live conductor and a frame in the TN earthing system (see "Cahier Technique" no. 172) are also responsible for voltage dips and interruptions.

These short-circuits eliminated by circuit-breakers, selective or otherwise, cause a voltage dip that is particularly "deep" if the faulty feeder is important for source power, and that can last from 50 to 500 ms. The shape of some voltage dips and interruptions is given in the table in **figure 7**.

Note that LV networks backed up by rotating sets and source changeover switches (main/standby) may not be powered for several seconds (see "Cahier Technique" no. 161):

Breaking time = $T_1 + T_d + T$, where:

T_1 = unit starting time delay (0.4 to 10 s),

T_d = unit starting time (a few seconds),

T = changeover time (< 0.4 s).

Orders of magnitude of voltage dips according to various switching types are given in the table in **figure 8**.

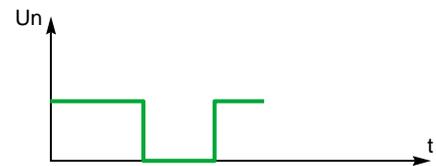
Conclusion concerning voltage dips and short interruptions

Statistically we observe interruptions and voltage dips, at the supply end of a LV network, at a frequency of once a month to 10 times a day. They are mainly found in medium and high voltage, and in 80% of cases last between 20 and 350 ms.

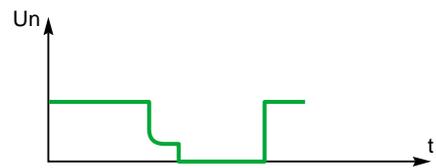
Electrotechnical switchgear is normally unaffected by these phenomena, except for contactors and relays whose nuisance "tripping" and "switching" may be a source of major problems in industrial processes.

With the growth of distributed intelligence and micro-PLCs, sensors, intelligent pre-actuators, etc. great attention should be paid to equipment immunity to voltage dips and supply interruptions. As a matter of fact, switchgear using electronic components must not give incorrect indications or untimely orders.

- Voluntary source switching
Duration: a few milliseconds to several minutes.



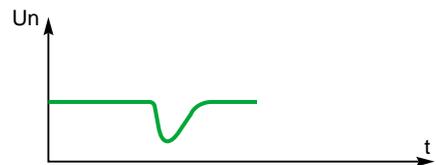
- Automatic source switching further to an external fault
Duration: a few milliseconds to 10 s.



- External short-circuit
Duration: 10 ms to more than 100 ms.



- Energisation of a large unit
Duration: depends on network power.



- Short interruptions with large motor and catching a spinning load.

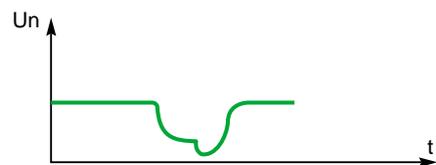


Fig. 7 : main types of interruptions and voltage dips.

	Type of switching			Pseudosynchronous
	Synchronous	Idle time		
		LV	MV	
Application examples	<ul style="list-style-type: none"> ■ Busbar switching ■ Substitution of one generator for another ■ Switching between a UPS and the mains 	<ul style="list-style-type: none"> ■ Pump supply ■ Supply of auxiliary circuits of a transformer substation ■ Supply of supermarkets ■ Etc. 	<ul style="list-style-type: none"> ■ Supply by two switchable MV incomers ■ Supply by one main source and one replacement source 	<ul style="list-style-type: none"> ■ Catching a spinning load of asynchronous motors
Switching duration	None	0.5 to 10 s	1 to 30 s	0.06 to 0.3 s
Devices used	<ul style="list-style-type: none"> ■ Coupler ■ Synchrocoupler ■ UPS assembly with static switch 	<ul style="list-style-type: none"> ■ Automatic source changeover switch with circuit-breakers 	<ul style="list-style-type: none"> ■ Set of MV cubicles with changeover switch 	<ul style="list-style-type: none"> ■ Rapid HV circuit-breakers associated with an ultra-rapid changeover switch and a phase controller
Observations	Switching must be performed before all power is cut to the main source	The changeover devices mentioned above are normally factory-assembled, cabled and adjusted assemblies (see for example the Schneider Electric catalogue)		Problems in preparing the switching order (residual voltage present)

Fig. 8 : various types of switching and their duration.

2.2 Overvoltages

Except for accidental voltage rises, for example connection of a 230 V transformer to a 400 V line, the only voltage rises that may exceed the nominal variation range of $U_n + 10\%$ are observed when the LV network is not on-load. However, the transformers of primary substations are normally equipped with on-load tap changers that enable the electrical utility to maintain MV within the range $U_n \pm 7\%$.

Impulse overvoltages are mainly due to switching operations on the network and to lightning. While without major risk for conventional LV switchgear built to manufacturing standards, they can affect devices containing electronic components (voltage withstand reduced to 1,500 V).

Switching on the MV network

- Energisation of MV capacitor banks without a blocking reactor: peak value may reach $2 U_n$ (see fig. 9).

- De-energisation of MV/LV transformers: peak value may reach $3 U_n$: it considerably depends on the current "chopped" by the MV breaking device (see fig. 10).

These overvoltages are transmitted to the LV by the MV/LV transformer according to its inductive and capacitive ratios (see appendix 2). They must not be ignored as they represent a risk for LV switchgear particularly when the LV circuit is weakly capacitive, i.e. small. This is particularly the case on commissioning of an installation.

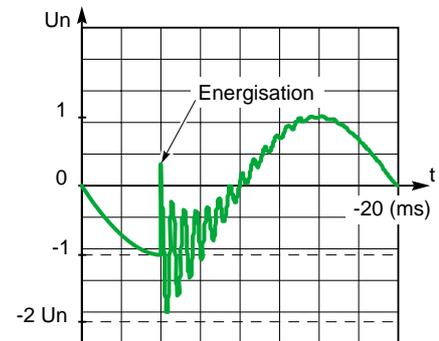


Fig. 9 : voltage wave on energisation of a MV capacitor bank.

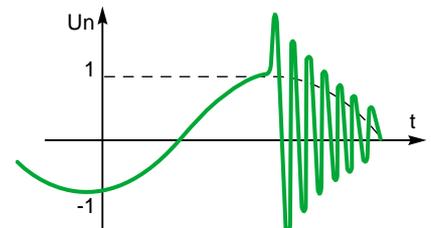


Fig. 10 : voltage wave on tripping of a MV/LV transformer.

Lightning

Lightning directly affects overhead networks. Many studies deal with this subject.

Not all regions are equally exposed: we talk of lightning density level.

Likewise, not all installations are equally exposed. Extreme exposure applies to very long overhead lines in regions that are particularly affected by storms. **Figure 11** shows the number and level of overvoltages that can be expected to be observed over one year. These are statistical values and there is always the risk of a direct lightning stroke of a far higher value.

Standards concerning insulation co-ordination and electromagnetic compatibility (EMC) take account of this natural phenomenon that develops a considerable impulse energy transmitted to LV networks by the MV/LV transformers.

Switchgear standards increasingly make provision for withstand to voltage and current waves representative of lightning.

In addition to these steep front "waves", lightning has a perverse effect due to the spark-gaps and surge arresters placed upstream of MV/LV substations.

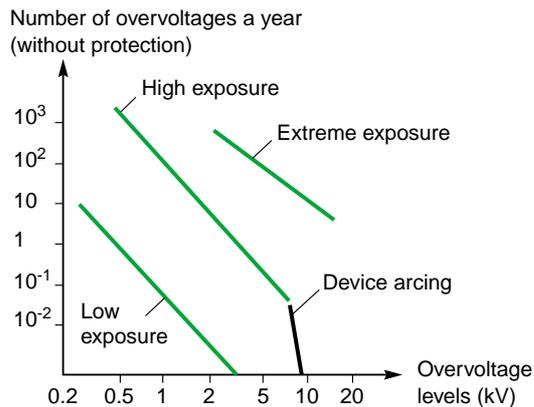


Fig. 11 : number and value of overvoltages statistically possible according to the level of exposure to lightning.

The importance of the risk depends on the earthing system (see standard NF C 13-100).

Take the case of the TTN earthing system (see **fig. 12**).

When lightning strikes the MV line, it causes arcing in the spark-gap or surge arrester, which lets through part of the impulse wave, that may be amplified by the wave reflection phenomenon (see "Cahier Technique" no. 168).

This spark-gap arcing results in a 50 Hz current, from the faulty phase to the Rpn earthing connection. This current, limited by the Z impedance (at 300 A in France) is maintained until the protection devices in the primary substation trip. When it flows through Rpn it results in a potential increase of the entire LV network with respect to the deep earth to which the LV equipment is connected by Ra.

There is then a risk of "return breakdown" of the LV equipment which is concretised when the "Current x Rpn" product is greater than insulation voltage with respect to the equipment frame. Thus, with a 300 A current and a 2500 V insulation voltage, Rpn must not exceed 8 W, a value that can be exceeded according to the hydraulicity and nature of the land!

Note that the problem is the same for an earth fault of an MV device in the substation. In this case, the underground MV networks present the greatest risk as this current is either limited to a higher value (1000 A in France) or not limited as is the case in some countries.

The 2 U + 1000 test at 50 Hz for 1 min enables the voltage withstand of LV equipment to be checked.

Finally, the substation earthing system plays an important role with respect to transmission of the impulse wave to the LV. As a matter of fact, in addition to the overvoltage due to capacitive transmission through the transformer, the lightning current wave develops a voltage U_l in the earthing connection impedance, as high as the earthing connection is inductive (see **fig. 12**).

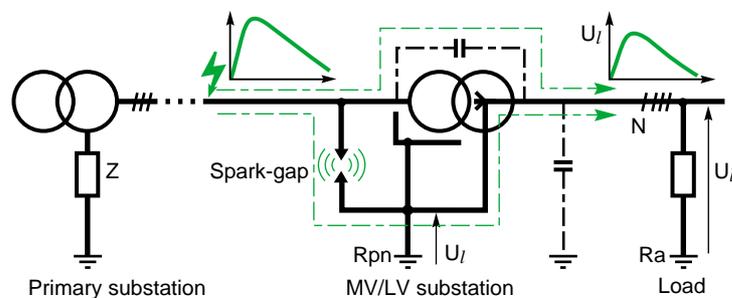


Fig. 12 : TTN earthing system of a MV/LV substation (common earthing of the spark-gap, transformer frame and LV neutral), and transmission of the lightning wave to the LV network.

To allow for this phenomenon, “pole-top” substations in France are installed (see **fig. 13**) with separate substation, neutral and LV load earthing connections (this is known as a separate earthing connection diagram, TTS as per NF C 13-103).

This arrangement avoids potential increase of the LV installation and thus prevents the risk of return breakdown of switchgear and LV loads (see **fig. 14**).

Their manufacturing standards mean that MV equipment can withstand these overvoltages (125 kV impulse wave withstand for a device with a specified voltage of 24 kV). On an HV/LV breakdown in the transformer, it is the value of R_n or R_{pn} that prevents return breakdowns in the LV equipment.

Readings, mainly made in Switzerland by Landis & Gyr, and mainly published by the I.E.E.E., show that transient overvoltages in excess of 1 kV are observed several times a year at various points of a LV distribution network (see **fig. 15**).

It is relatively exceptional to detect overvoltages greater than 6 or 7 kV as, at these levels, arcing occurs in the air or in the cabling that acts as a spark-gap. Such arcing or dielectric breakdown clips overvoltages to a level that is particularly low for a careless wiring. Such a “protection” damages the installation and may in time lead to serious safety problems by piercing, bypassing and carbonising of insulators. The solution for exposed sites is to use surge arresters between the live conductors and the earth. For more details refer to “Cahier Technique” no. 179.

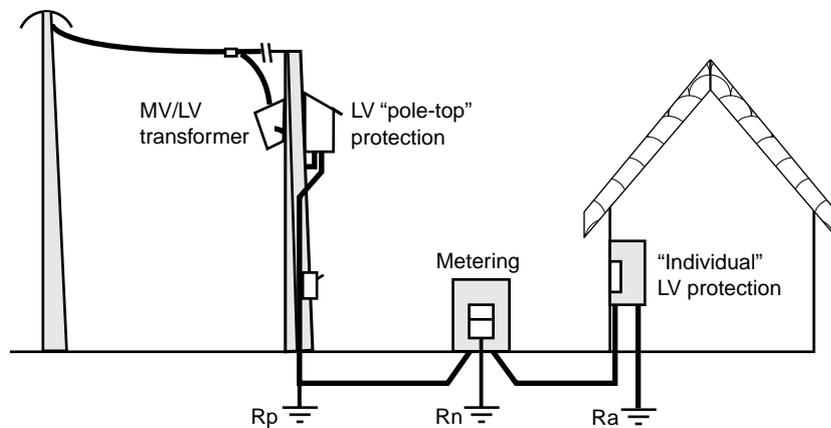


Fig. 13 : MV/LV “pole-top” substation. TTS earthing system of a MV/LV substation (separate earthing of the spark-gap, transformer frame and LV neutral). This earthing system is ITS if a surge limiter is inserted in the LV neutral earthing connection.

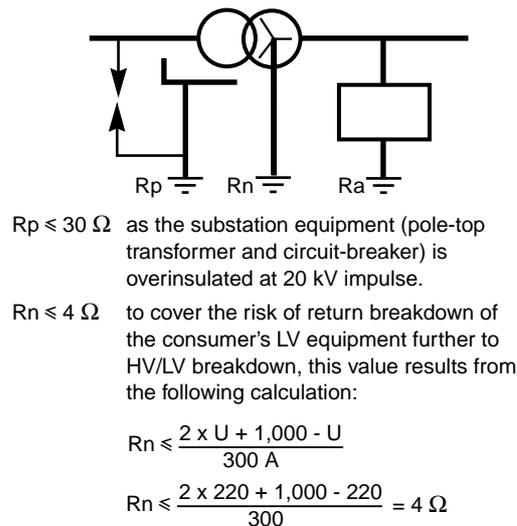


Fig. 14 : earthing connections of a MV/LV substation supplied by overhead lines.

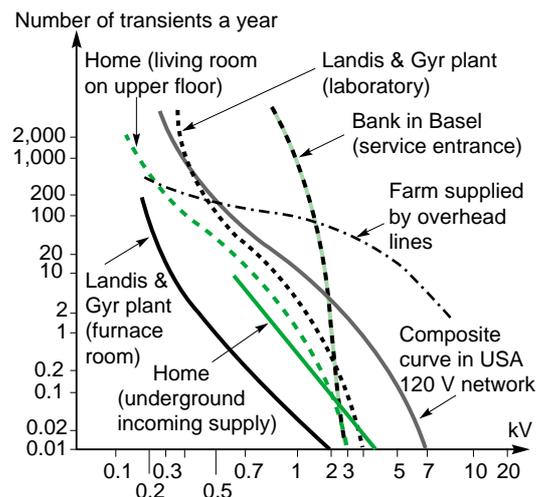


Fig. 15 : frequencies and peak values of overvoltages due to lightning on LV installations (source: Landis & Gyr).

Switchgear operations and operation of the LV protection devices

■ Relay and contactor coils have an inductive impedance. Breaking of an “inductive current” nearly always results in high overvoltages. In the case of a relay (see **fig. 16**), when the current is suddenly broken by the switch K, the energy $1/2 Li^2$ is converted into energy $1/2 CV^2$, hence an overvoltage:

$$V = i \sqrt{\frac{L}{C}} = 0.15 \sqrt{\frac{10^{-1}}{0.25 \times 10^{-9}}} = 3,000 \text{ V}$$

The overvoltages observed may reach nearly 10 kV on a 230 V circuit.

Interference must be suppressed on these control auxiliaries by their manufacturers, or a RC network or a varistor, connected in parallel on their coil, enables overvoltage to be absorbed.

■ On LV and HV networks, no-load or only on minimum load, breaking a low inductive current is not easy and results in creation of overvoltages that are frequently multiple (wave trains). On the single-phase circuit in **figure 17**, taken as an example, when switch K is opened, current continues to flow in L_2 with, at the terminals of C_2 , the voltage V_{BN} :

$$V_{BN} = i \sqrt{\frac{L_2}{C_2}} \sin \omega_2 t$$

The same applies to the upstream network with at the terminals of C_1 the voltage:

$$V_{AN} = i \sqrt{\frac{L_1}{C_1}} \sin \omega_1 t$$

On opening, voltages V_{BN} and V_{AN} evolve in opposition, and voltage V_{AB} quickly becomes high enough to cause arc re-arcing (re-arcing between the contacts of breaking device K).

The current to be broken is small, the contacts move apart, and the interference between the two voltages V_{BN} and V_{AN} are elements that extinguish the arc. Then the voltages begin to rise again and the phenomenon is repeated... Several cycles known as re-arcing can thus occur until the energy lost by the arc and the increasing distance between contacts interrupt the phenomenon.

The result is the appearance of wave trains,

of high voltage and frequency ($\omega = \frac{1}{\sqrt{LC}}$),

that are genuine interference generators.

The presence of different no-load circuits with reactor or transformer, and of slow opening

breaking devices, means that this phenomenon is fairly frequent. It is even observed on short-circuit current breaking, when at the end of breaking the current becomes sufficiently small to be “chopped”.

■ Breaking a short-circuit current can also present a risk of overvoltage as:

- rapid action must be taken, before the current reaches prospective short-circuit current,
- and “insert” in the circuit an arcing voltage that is not always easy to control according to the breaking conditions, as this voltage constitutes an overvoltage of several hundred volts for circuit-breakers and sometimes several kV for fuses (see **fig. 18**).

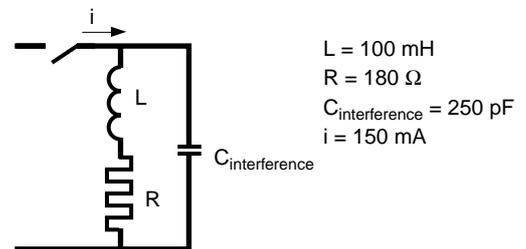
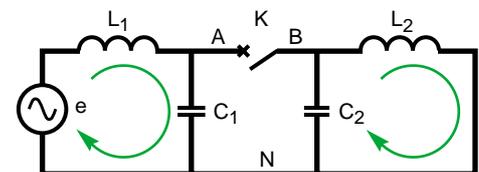


Fig. 16 : equivalent diagram of a network.



L_1, C_1 = inductance and capacitance of the upstream network
 L_2, C_2 = inductance and capacitance of the downstream network

Fig. 17 : equivalent diagram of a single-phase circuit.

	C32L circuit-breaker	GL fuse 20A
Prospective I_{sc} (kA)	11	4
$\cos \varphi$	0.25	0.3
U (V)	380 + 10 %	380 + 10 %
Overvoltage (V) $U + \Delta U$	400 to 650	2,100 to 2,650

Fig. 18 : overvoltages recorded with two protection devices tested on the same test installation.

With respect to this last point, note that:
 □ the closer the short-circuit occurs to the downstream terminals of the breaking device, the higher and shorter the overvoltage. Thus the results presented in **figure 19** were read for a fault observed on a 1.5 mm² diameter cable downstream of a 10 A fuse:

where **L = 0**

$$\frac{\Delta U + U}{U} = \frac{1700 + 220\sqrt{2}}{220\sqrt{2}} = 6.4 \text{ and } T = 50 \mu\text{s}$$

where **L = 20 m**

$$\frac{\Delta U + U}{U} = 2 \text{ and } T = 200 \mu\text{s}$$

□ generally, the higher the feeder protection rating (and thus the greater the cross-section of its conductors) with respect to the short-circuit power of the "busbar", the longer and lower the overvoltage.

Figure 20 shows a graphic summary of several tests.

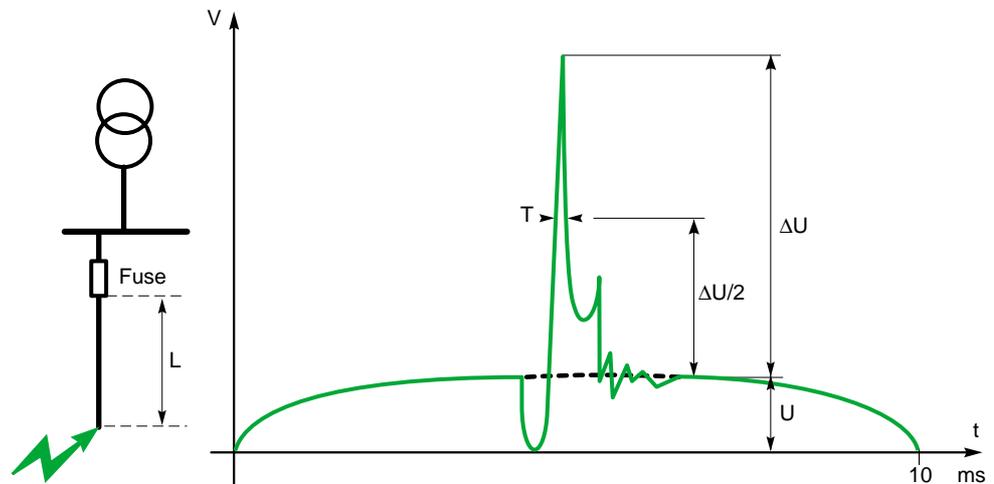


Fig. 19 : overvoltage depends on the distance separating the fault from the protection device.

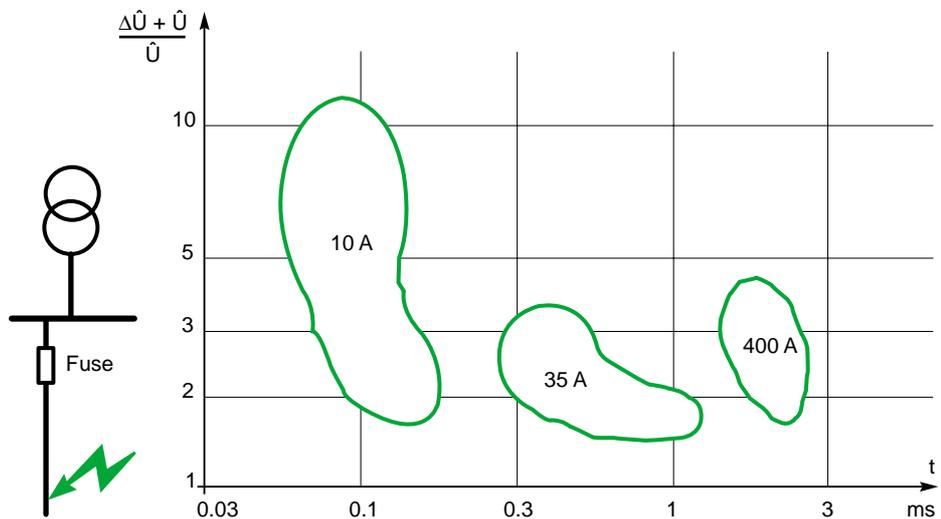


Fig. 20 : with the same upstream short-circuit power, overvoltage levels and durations on a feeder depend on the rating of its protection device and the cross-section of its conductors.

Ferroresonance

This phenomenon may occur on no-load and slightly loaded networks, particularly in high voltage, as well as behind small transformers and in the presence of filters.

Readers wishing to know more can consult appendix 3 and read "Cahier Technique" no. 190.

Overvoltage tests and solutions

The impulse overvoltages transmitted by conduction, with an inductive or capacitive effect,

are very dangerous in particular for electronic devices. In this area, experience has enabled tests to be defined.

■ Standardised waves for equipment testing

These are mostly (see **fig. 21**) dealt with in the IEC 61000 publications, particularly 61000-4-4, 61000-4-5 and 61000-4-12 (see appendix 3). In addition to waveforms, standards stipulate levels corresponding to conditions of use and to test voltages for equipment manufacturers. For example, **figure 22** gives, for the various

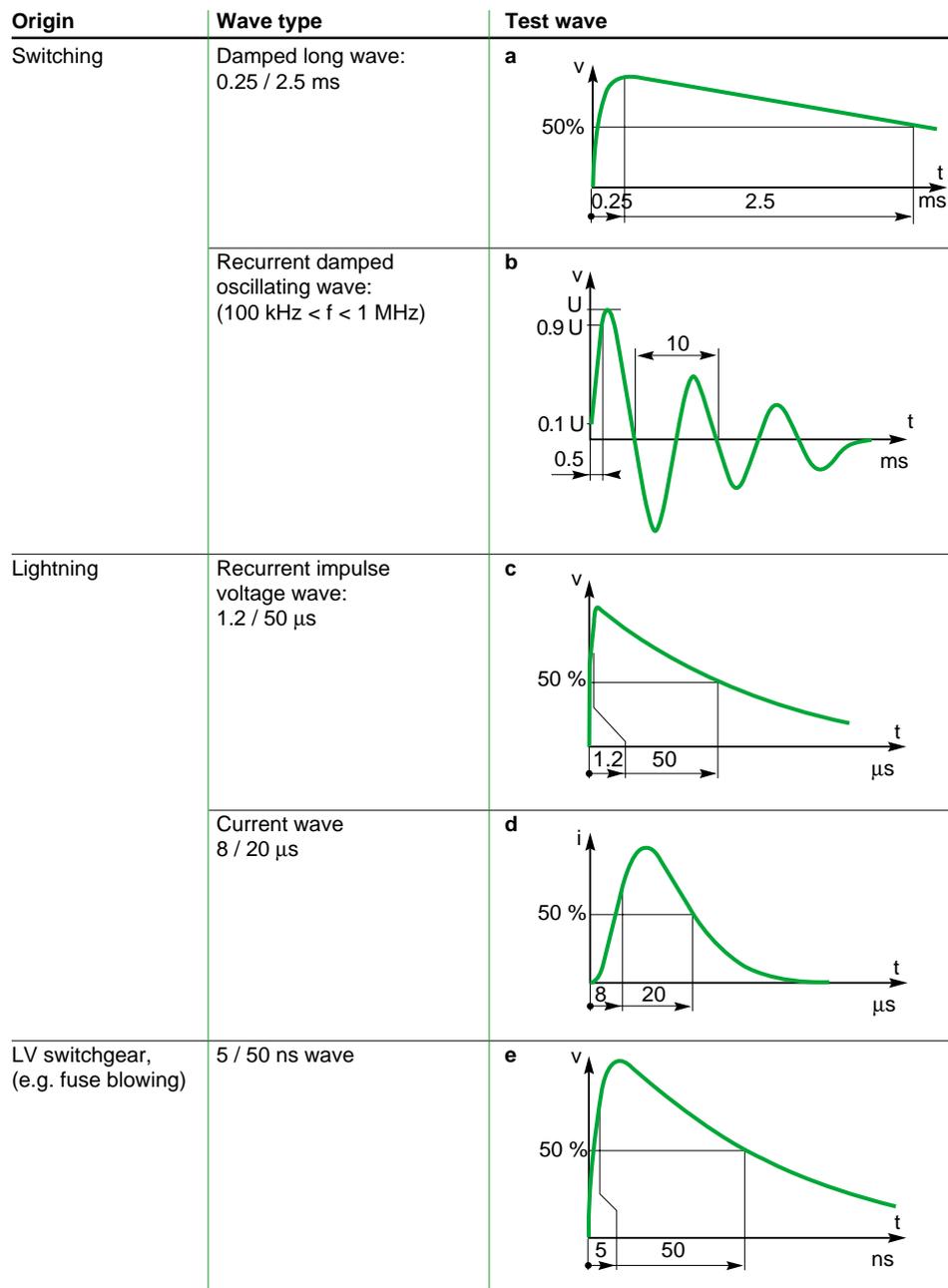


Fig. 21 : the main standardised test waveforms.

levels, the voltages for the impulse voltage wave test (see curve **d** on figure 21).

■ **Overvoltage solutions**

These are applied both when equipment is implemented and chosen:

- on installation, it is advisable to remove overvoltage sources away from the most sensitive items of equipment and to monitor equipment equipotentiality;
- when choosing, it may prove useful to provide:
 - electrostatic shielding or capacitors (see appendix 3),
 - screen transformers,
 - filters,
 - surge limiters (see **fig. 23**).

Low voltage surge limiters are also available designed for installations with an IT earthing system (with unearthed neutral). Defined in France by standard NF C 61-740, they are intended to prevent all voltage rises due to a MV fault: "Cahier Technique" no. 179 describes their implementation.

Level	Test voltage ± 1 % (kV)
1	0,5
2	1
3	2
4	4
x	Special

Level "x" is open: it must be defined for special equipment specifications.

Fig. 22 : test voltages according to standard IEC 61000-4-5.

	Limited U (kV)	I max (kA) (8/20 wave)
Varistors	14 to 1,200	10 to 5,000
Rectifier diode	5 to 400	10 to 1,000

Fig. 23 : characteristics of the various surge limiter types.

3 Sine wave disturbances

Voltages (waves) observed, permanently or temporarily, on networks are never completely sinusoidal. This is because:

- generators are more or less perfect,

- transformers are also imperfect,
- loads generate or absorb harmonics,
- the network conveys various signals (carrier currents).

3.1 Generators

Inexpensive devices, normally low power, are often harmonic-generators (see **fig. 24**).

3.2 Transformers

When they are calculated improperly, they begin to saturate as soon as voltage exceeds their nominal value. They then absorb a non-sinusoidal current (see **fig. 25**).

3.3 Loads

Capacitors

Harmonic currents are particularly well absorbed by capacitors when their frequency is high. The current absorbed by the capacitors is thus a caricature of the voltage of the network on which they are placed. Associated with inductances, they form network cleaning filters and then absorb a non-sinusoidal current (see "Cahier Technique" no. 152).

Fluorescent tubes

Electric arcs absorb non-sinusoidal currents particularly harmonic-loaded. "Tandem" mounting and compensation do not prevent fluorescent tubes from generating harmonics.

Phase control rectifiers

In most cases, they are connected to an inductive circuit and successively absorb a rectangular current on each phase. At each semiconductor switching, the sine wave of the supply voltage is briefly interrupted. **Figure 26** provides a representation of the voltage and current waves.

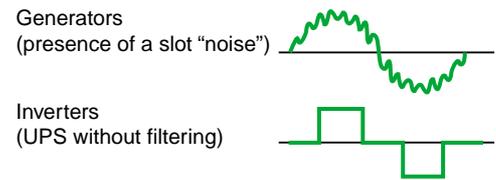


Fig. 24 : example of a voltage wave delivered by "inexpensive" generators.

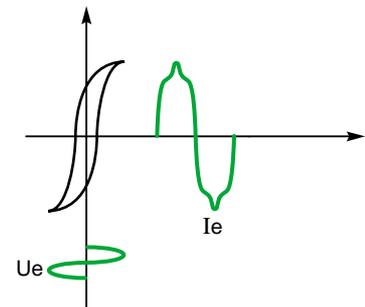


Fig. 25 : off-load current wave absorbed by a transformer with an insufficiently large power rating.

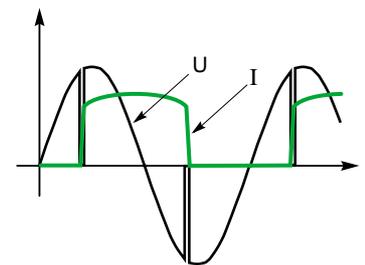


Fig. 26 : voltage and current waves distorted by a phase control rectifier.

As regards phase controlled heating dimmers, each thyristor firing results in a supply voltage dip due to its inductive component followed by a slight voltage drop linked to the internal resistance of the power supply (see **fig. 27**).

3.4 Switch mode power supplies

Very common (microcomputers, TV sets, electrical household appliances, etc.), they use at the input circuit a diode bridge followed by a filtering capacitor that generates high harmonic currents.

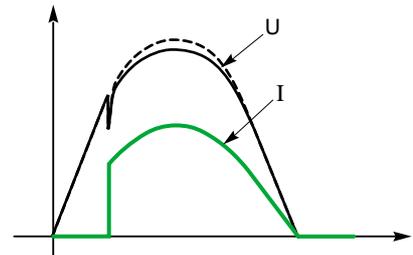


Fig. 27 : voltage and current waves distorted by a heating dimmer.

3.5 Industrial furnaces

These are real network polluters:

- arc furnaces produce a genuine electric noise containing all the frequencies, whose amplitude decreases with frequency,

- HF induction furnaces are narrow-band interference generators centred on a few dozen kilohertz.

3.6 Carrier currents

These are additional signals that are deliberately injected on the network by the electrical utility, for example to remotely control Day/Night tariff changes, such as the Pulsadix system (175 Hz) used in France.

These signals are audible with a car radio when the car passes under an HV line. Their frequency varies from country to country:

110 Hz, 175 Hz, 183 Hz, 217 Hz, 283 Hz, 317 Hz, 600 Hz, 1050 Hz, 1350 Hz.

The signals are made up of pulse trains of the chosen frequency, injected according to a certain code. Their voltage is around 10 V.

Other signals conveyed by the network can also disturb the mains at a LV consumer:

- digital communications, such as those used for Building Management Systems (BMS),
- intercom transmissions (a few dozen kilohertz),
- remote control orders (50 to 150 kHz).

3.7 Effects of disturbances

All periodic signals, whatever their waveform, can be considered as the sum of alternating signals of a frequency equal to that of the signal, "The fundamental", and multiples of that of the signal, "The harmonics".

The harmonics and the special frequencies injected on the network produce harmful and in some cases dangerous effects. Thus harmonics:

- increase iron losses and eddy currents in motors and transformers,
- jeopardise capacitor bank service life, whose long time protection has to take harmonic currents into account,

- jeopardise service life of filtering capacitors of electronic circuit power supplies,

- can cause temperature rise of the neutral conductor (3rd order harmonic currents and multiples generated by switch mode power supplies and fluorescent tubes, are added up and return to the source by the neutral).

To avoid these risks, "long time" or "overload" overcurrent electronic protection devices (equivalent to electromechanical releases said to be "thermal") must contain a circuit measuring the total root mean square value of the current.

Standard EN 50160 indicates, for public distribution networks, that "...for each period of a week, 95% of r.m.s values of each harmonic voltage averaged out over 10 minutes must not exceed the values stated in the table in **figure 28** . Higher voltages for a given harmonic can be due to resonance.

Moreover, the total harmonic distortion provided (including all harmonics up to the 40th order) must not exceed 8%".

To reduce harmonic currents and voltages, passive filters or active compensators can be used (see "Cahier Technique" no. 183).

Odd harmonics				Even harmonics	
Multiples of 3		Non multiples of 3			
Order	Relative voltage (% Un)	Order	Relative voltage (% Un)	Order	Relative voltage (% Un)
3	5	5	6	2	2
9	1.5	7	5	4	1
15	0.5	11	3.5	6 to 24	0.5
21	0.5	13	3		
		17	2		
		19	1.5		
		23	1.5		

Fig. 28 : values of harmonic voltages at the supply points (source: EN 50160).

4 Disturbances specific to multiphase systems

4.1 Current and voltage unbalance

Electrical networks are normally three-phase. They supply three-phase loads but also a large number of single-phase loads. The currents absorbed on the three phases are thus of different amplitude, which results in voltage unbalances.

These voltage unbalances generate negative sequence components (see **fig. 29**) that mainly lead to unwanted braking torques and temperature rises in AC motors.

In Europe, standard EN 50160 specifies "In normal operating conditions, for each period of a week, 95% of rms values calculated over 10 minutes of the negative sequence component of the supply voltage must fall between 0 and 2% of the direct component.

In some regions, unbalance may reach 3%".

In France, EDF estimates that for LV networks

(at the customer's), the unbalance ratio $\left(\frac{V_i}{V_d}\right)$

although fluctuating for the most part, is between 0.5 and 2% on average.

The highest ratios are observed on LV networks supplied by a low power transformer with a majority of single-phase connections... This is the case of pole-top substations that supply few LV consumers with single-phase.

In difficult cases, "Zig-Zag" connection is a means of attenuating unbalance for the upstream network.

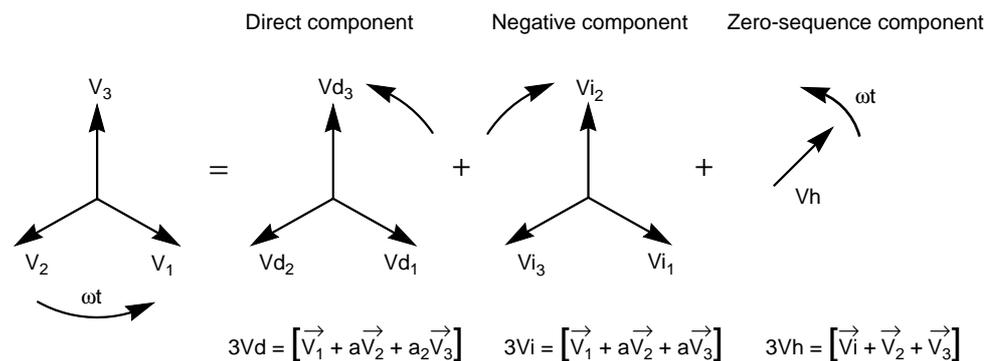


Fig. 29 : reminder of the various components, direct, negative and zero-sequence of the three-phase system.

4.2 Phase unbalance

Besides the effects of negative sequence components on motors, unbalance of three-phase voltages disturbs the operation of phase control thyristor devices (see **fig. 30**). Furthermore, harmonics, which modify the zero passage of voltages, can interfere with thyristor ignition synchronisation.

As concerns protection against electrical hazards, this type of disturbance is also a nuisance as current unbalance limits use of the Nicholson set-up (pooling four current transformers) to detect residual currents due to an insulation fault (see "Cahier Technique" no. 114).

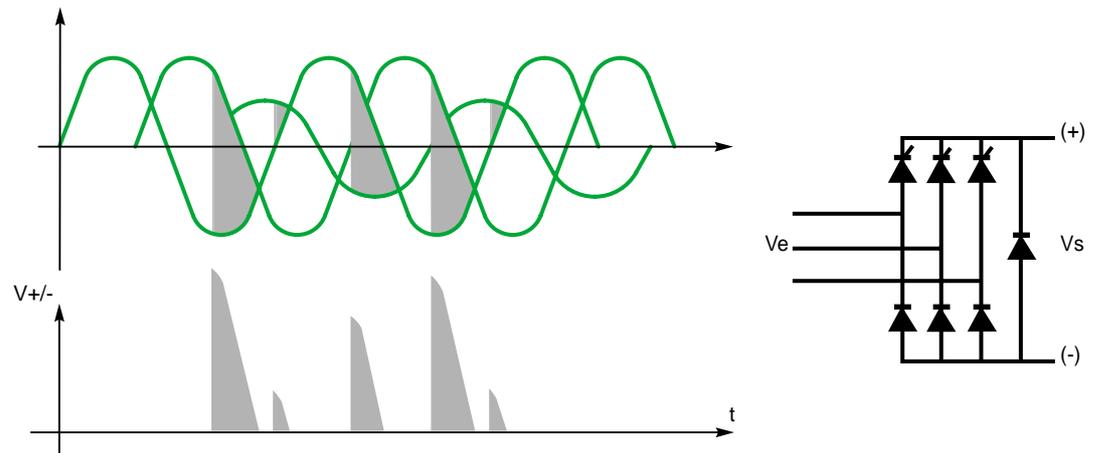


Fig. 30 : effect of a voltage unbalance on a rectifier in semi-controlled Graetz bridge.

5 Electromagnetic disturbances

5.1 Fields and radiations

The LV network disturbances dealt with in the earlier chapters are mainly of the “conduction” type, i.e. transmitted by conductors, transformers, stray capacitances, etc.

Electrical engineers know that a device placed near a conductor conveying a large 50 Hz current will collect an electromotive force by inductive coupling. This is true for all circuits placed in the magnetic field (see **fig. 31**). They also know that a device placed near an HV network will collect an induced voltage: this is true for all conductors placed in the electric field (see **fig. 32**).

A high current is said to “radiate” a low impedance magnetic field, and a high voltage to “radiate” a high impedance electric field. In point of fact, field impedance is equal to:

$$Z_c = \frac{E}{H}$$

In fact, all electromagnetic fields are characterised by the simultaneous presence of electrical and magnetic fields linked in what is known as the Poynting vector:

$$\vec{P}(\text{W/m}^2) = \vec{E}(\text{V/m}) \wedge \vec{H}(\text{A/m})$$

Impedance Z_c depends on distance and frequency (see **fig. 33**).

If for 50 Hz we can talk of a field E or H, high or low impedance, this is because:

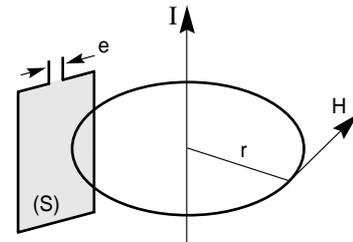
$$\frac{\lambda}{2\pi} = \frac{C}{2\pi f} = 1,000 \text{ km}$$

Around a conductor through which a high current flows, the magnetic field H decreases according to $1/r$ (r = radius) up to $\lambda/2\pi$.

Near an antenna (high impedance) it is field E that decreases as a function of distance in $1/r^3$. When distance exceeds $\lambda/2\pi$, the two fields E and H decrease according to $1/r$ and impedance is a constant that, in air, is equal to 377 W. When transmission of interference is, for example, due to fuse blowing, as wave rising edge is 5 ns, the equivalent frequency is 10^8 Hz. The transition distance is:

$$\frac{\lambda}{2\pi} = \frac{C}{2\pi f} = 5 \text{ cm, beyond this value the}$$

fields E and H decrease in $1/r$; we say we are in a “flat wave”.

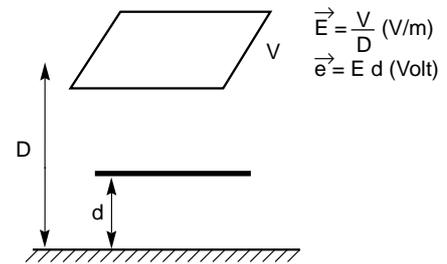


$$\vec{H} = \frac{I}{2\pi r} \text{ (A/m)}$$

$$\Phi_{(s)} = \int_{(s)} \mu H n \, ds \text{ (Weber)}$$

$$\vec{e} = - \frac{d\Phi}{dt} \text{ (Volt)}$$

Fig. 31 : voltage induced by a current.



$$\vec{E} = \frac{V}{D} \text{ (V/m)}$$

$$\vec{e} = E d \text{ (Volt)}$$

Fig. 32 : example of an electric field.

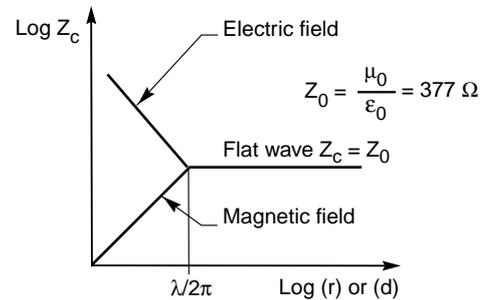


Fig. 33 : example of wave impedance for a bipole.

There is a large diversity of radiated disturbance sources, normally divided into two major families:

- those with a narrow spectrum: radio transmitters, radars, induction furnaces, microwaves, etc.

- those with a wide spectrum: lightning, electrostatic discharge, breaking devices, commutator motors, welding machines, arc furnaces, etc.

Note that some sources such as static converters and lightning are both conducted and radiated interference generators.

Electronic circuits are the main victims of electromagnetic disturbances since they process very low voltage signals and have large impedances (they consume less and less). Interference occurs on the "victim", mainly through the cables entering and leaving the box (by coupling in common mode – differential mode – common impedance – crosstalk). Also, the paths of printed circuits and components can and must be determined to ensure minimum electromagnetic susceptibility.

The most sensitive functions are:

- LF amplifiers (low-pass)
- Input circuits (integrators)
- Logic circuits (digital).

Furthermore, growth of digital communications is responsible for new difficulties as buses create, with the electrical network, loops that are sensitive to the magnetic fields developed by the high electric currents and close lightning strokes. Precautions must therefore be taken for the study and production of installations (see "Cahier Technique" no. 187).

In LV, immunity tests against radiated fields are defined in standard IEC 61000-4-3 and subsequent sections. Thus, the releases of the Compact circuit-breakers of Merlin Gerin brand are tested according to the maximum degree of severity of standard IEC 60947-2 referring to standards IEC 61000.

Finally, to better understand electromagnetic compatibility (EMC), readers can refer to "Cahier Technique" no. 149.

5.2 Electrostatic discharges

This type of disturbance affects and/or destroys electronic switchgear, but has no impact on electrical networks.

In point of fact, electronic components are particularly sensitive to these electrostatic discharges as they use increasingly more "low level" components with low consumption and high input impedance. Also, a part of these switchgear, e.g. indicator lights, potentiometers, is always accessible to touch.

People, depending on their footwear and the floor on which they walk, plus air humidity, can be "charged" with a potential of up to 15 kV (phenomenon modelled and represented on **figure 34**). In this case the discharge current can reach several dozen amperes (see **fig. 35**)!

It is thus necessary to immunise and test electronic apparatus for these discharges. This subject is described in standard IEC 61000-4-2.

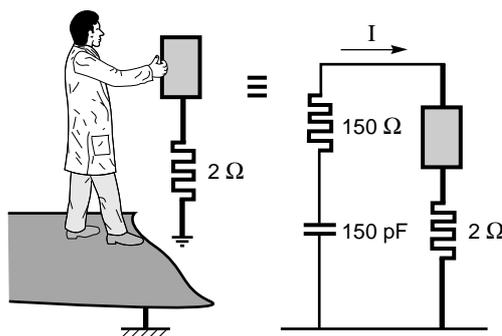


Fig. 34 : modelling the electrostatic load circuit of a person.

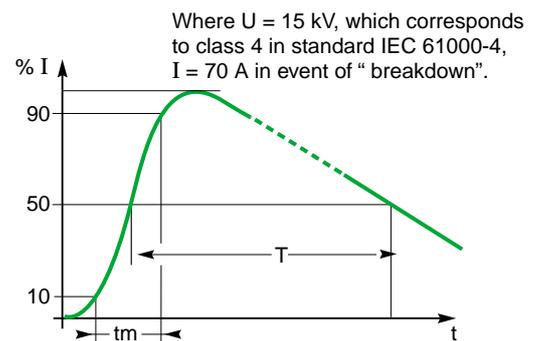


Fig. 35 : electrostatic discharge current ($t_m = 5 \text{ ns}$, $T = 30 \text{ ms}$).

6 Conclusion

LV networks are very polluted as they are subjected to numerous aggressions of varying origins: external (sources, MV networks, etc.), operation (elimination of faults, control by carrier current, etc.), applications (furnaces, electronic loads, etc.). At the same time, quality requirements of the “electricity” product as well as operating dependability of electrical and electronic equipment, whether for production, management or commerce, are increasingly great.

■ Users, aware of malfunctions and operating losses, are seeking to control their energy supply. They are increasingly measuring conventional values (voltage, current, power, $\cos \varphi$) and recording overvoltages, dips and power cuts, etc. For example they also want to know:

- total harmonic distortion,
- harmonic level,
- peak factor,
- voltage unbalance ratio.

■ Electrical utilities have to guarantee a certain level of quality of the “electricity” product they deliver (see appendix 3: standard EN 50160).

■ Electrical and electronic switchgear manufacturers are obliged to comply with the European directive on EMC as from design of their products that they then test according to the

specifications of standards such as IEC 61000 (see appendix 3). However they are increasingly offering new products able to meet users' expectations with respect to follow-up of energy quality and distribution reliability, for example:

□ control units placed in circuit-breakers are used to take all measurements (I, F, P, $\cos \varphi$, etc.),

□ switchboard centres are now used to know instantaneous, maximum and average reactive and apparent energies and powers over a specific period. They can also measure total harmonic distortion, the peak factor and phase unbalances (voltage and current).

■ Professional electricians (ranging from designers to cable layers) must study the main probable disturbances in order to find the most suitable solutions. For example designers have to provide emergency sources, Uninterruptible Power Supplies (UPS), surge arresters, filters and active harmonic compensators.

In this sense, for all people concerned with quality and availability of electrical power throughout the distribution process, this “Cahier Technique” forms an initial tool in so far as it explains the various disturbances that can affect electrical networks and equipment. Its purpose is to increase knowledge of these disturbances in order to combat them more effectively.

Appendix 1: transmission of overvoltages through transformers

Magnetic transfer

For an MV/LV transformer, no-load or on minimum load, lightning and switching overvoltages are transmitted to the secondary according to the ratio to which a corrective coefficient is applied.

This coefficient is normally less than 1.3 for the 1.2/50 μs lightning wave, and only rarely exceeds 1.8 for switching overvoltages according to the 250 / 2,500 μs wave specified by IEC 60060-2.

For example in the case of a 20 kV/410 V-Dyn 11 transformer, its ratio has the following value:

$$\frac{20,000}{410} = 48.8$$

■ a 1.2/50 μs wave of 125 kV applied on its primary winding gives its secondary a similar waveform of an amplitude equal to:

$$125 \text{ kV} \times \frac{1}{48.8} \times 1.3 = 3.3 \text{ kV peak}$$

■ a 250 / 2,500 μs wave of 90 kV gives:

$$90 \text{ kV} \times \frac{1}{48.8} \times 1.8 = 3.3 \text{ kV peak} .$$

Capacitive transfer

This depends on the arrangement of the primary and secondary windings with respect to the transformer frame.

Normally for each "column", the LV winding is close to the core and the MV winding is relatively far away, since it is placed around the LV winding (see **fig. 36**).

The overvoltage transmitted to the secondary, by the various "stray capacitances" of the transformer (see **fig. 37**) is calculated by the formula:

$$U_s = U_e \frac{C_{LV/Frame}}{C_{HV/Frame} + C_{LV/Frame}}$$

In the worst possible case, according to IEC 60071-2, it can reach 0.7 U_e.

In reality, the transmission coefficient is around 0.3 for a MV/LV transformer with no connection

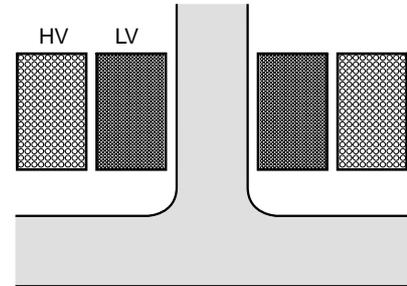


Fig. 36 : position of the windings on a MV/LV transformer column.

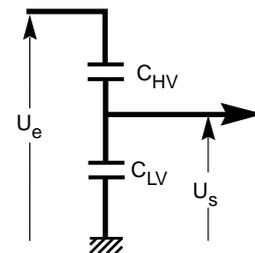


Fig. 37 : diagram of the capacitive transfers of overvoltages in a MV/LV transformer.

to the secondary. The presence of capacitances between the live conductors and the frame at the LV main switchboard considerably reduces these overvoltages.

It should be borne in mind that to avoid breakdown in the LV part of the "overhead" supplied substations, the switchgear installed must have reinforced insulation (10 kV / 50 Hz) and that it is strongly recommended to install surge arresters in the main LV board. Furthermore, if this board contains control and monitoring auxiliaries, they must be supplied by means of a shield LV/LV transformer.

Appendix 2: ferroresonance

In theory

The serial (and parallel) resonance phenomenon is well known.

When $\omega = \frac{1}{\sqrt{LC}}$, the voltages developed by L

and C are identical, opposed and in absolute value far higher than the voltage e (see **fig. 38**).

The serial (and parallel) ferroresonance phenomenon is a special case of the above that occurs when the reactor is iron and thus saturable.

If we plot the development of the absolute values of the various voltages for a specific frequency as a function of current (see **fig. 39**), two stable operating points A and B are observed on the curves. To move from A to B, all that is required is for a transient (interference) to temporarily increase the value of e and exceed the voltage limit at point E.

In practice

The voltages developed in L and C are then very high. There is a risk of dielectric breakdown and a high risk of a low power load parallel-connected on C being destroyed.

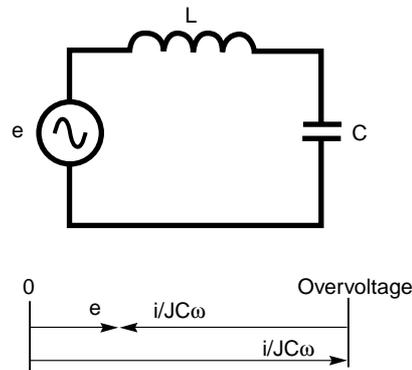


Fig. 38 : a resonant circuit.

Note that, as long as the curves

$\frac{i}{C\omega}$ and $L\omega i$ intersect, there is a risk of

ferroresonance, hence:

■ Ferroresonance can occur in a wide range of frequencies, including 50 Hz and its harmonics. In this case, the voltage wave at 50 Hz is overmodulated by a high voltage at 150 Hz for example,

■ To be certain of avoiding this, $\frac{1}{C\omega}$ must be greater than $L_0\omega$ ($L_0 = L$ with low induction) or the circuit must always be loaded (damped).

In conclusion

LV equipment designers must take the risk of ferroresonance into account. This risk is present on no-load “networks” with respect to:

- the dielectric phase/frame withstand of switchgear (≥ 8 to $10 U_n$),
- the supply voltage of very low power loads (e.g. own-voltage electronic protection devices). For more details on this phenomenon consult “Cahier Technique” no. 190.

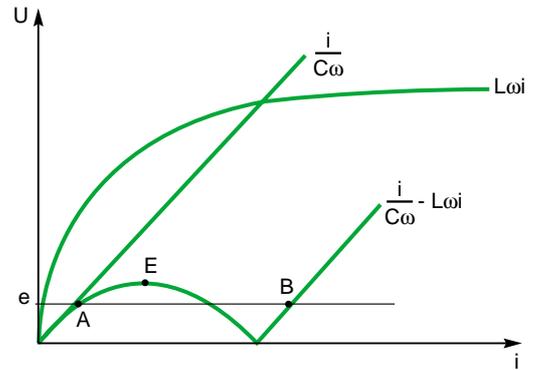


Fig. 39 : principle of ferroresonance.

Bibliography

Standards

■ EN 50160: Voltage characteristics of electricity supplied by public distribution systems. This standard specifies in MV and in LV:

- Frequency,
- Amplitude of the supplied voltage,
- Variation in the supplied voltage,
- Rapid voltage variation,
- Voltage dips,
- Short interruptions in the supplied voltage,
- Long interruptions in the supplied voltage,
- Temporary overvoltages on the network between phase and earth,
- Transient overvoltages between phase and earth,
- Unbalance of the supplied voltage,
- Harmonic voltages,
- Interharmonic voltages,
- Signalling on the network.

■ IEC 60038: IEC standard voltages.

■ IEC 60060-2: High-voltage test techniques – Part 2: Measuring systems.

■ IEC 60071-2, NF C 10-102: Insulation coordination – Part 2: Application guide.

■ IEC 60364, NF C 15-100: Electrical installations of buildings.

■ IEC 60664: Insulation co-ordination for equipment within low-voltage systems.

■ IEC 61000: Electromagnetic compatibility (EMC).

With hereafter a selection of most interesting parts for a first approach:

- 1.1: Fundamental definitions and terms.
- 2: Environment:
 - Electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems.
 - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems.
 - Radiated and non-network-frequency-related conducted phenomena.
 - Low frequency magnetic fields in various environments.
- 3: Limits:
 - Limits for harmonic current emissions (equipment input current 16 A per phase).
 - Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current 16 A.
 - Signalling on low-voltage electrical installations.

□ 4: Testing and measurement techniques:

- Electrostatic discharge immunity test.
- Radiated, radio-frequency, electromagnetic field immunity test.
- Electrical fast transient/burst immunity test.
- Surge immunity test.
- General guide on harmonics and interharmonics measurements.
- Power frequency magnetic field immunity test. Basic EMC publication.
- Pulse magnetic field immunity test.
- Damped oscillatory magnetic field immunity test.
- Voltage dips, short interruptions and voltage variations immunity tests.
- Oscillatory waves immunity test.
- Test for immunity to conducted, common mode disturbances in the frequency range 0 Hz to 150 kHz.

NB:

Readers wanting to know more about documents related to the standards may consult the internet sites:

■ For IEC: "<http://www.iec.com>",

■ For UTE: "<http://www.ute-fr.com>".

Schneider Electric "Cahiers Techniques"

■ Residual Current Devices in LV

R. CALVAS, Cahier Technique no. 114.

■ EMC: electromagnetic compatibility

J. DELABALLE, Cahier Technique no. 149.

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