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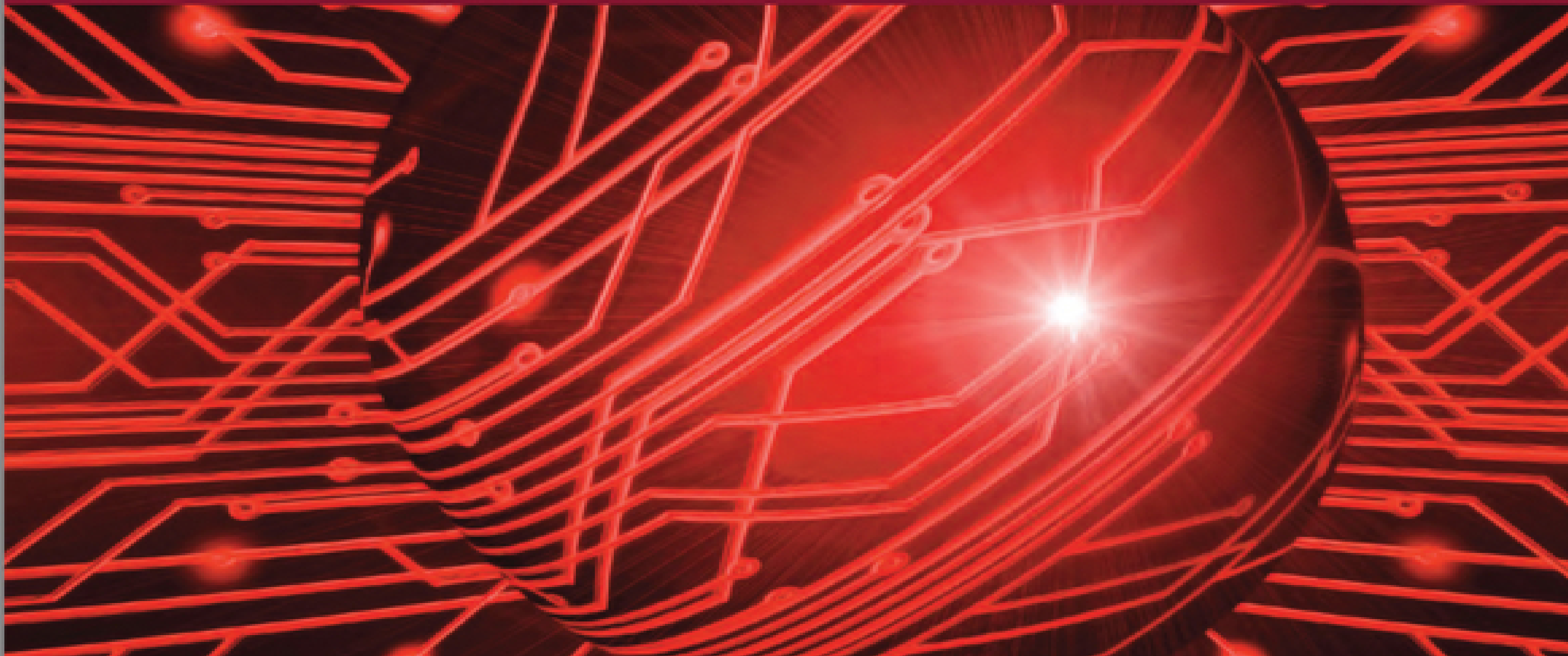

Electromagnetic Compatibility in Power Electronics

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Chapter 1

Phenomena of Perturbation in Electrical Systems

1.1. Electromagnetic perturbations in energy systems

1.1.1. *Introduction*

Power electronic systems are increasingly being used in every field; initially, they were used in the industrial sector and then used increasingly in transportation, services and housing sectors. The flexibility in the control of electrical energy explains this evolution well.

For the purposes of illustration, we estimate that the electrification of service or control functions in an aircraft offers the following gains[1]:

– 10% on the mass;

– 9% on fuel consumption;

– 13% on thrust from the engines;

– 15% on maintenance costs;

– 10% on the buying price.

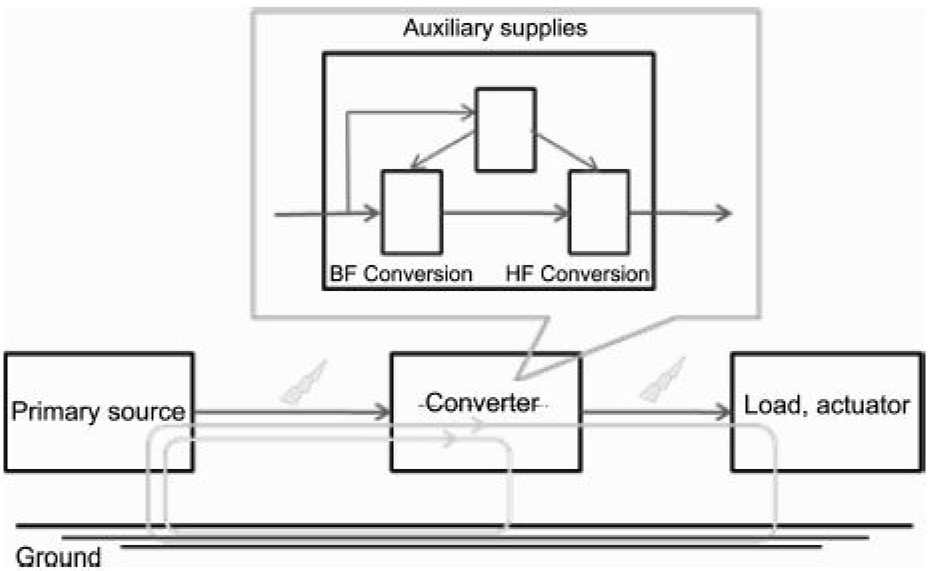
The field of automobiles is also subject to this evolution: the development of hybrid vehicles over the last 10 years and, more recently, the re-emergence of the fully electric car (while waiting for fuel cells vehicles) are evidence of this. Already, a large number of services have been electrified in thermal engine automobiles because of the flexibility of controls (speed variation) and high yield of the electrical systems: power steering, anti-blocking system (ABS), various pumps, window winders, air conditioning (to come).

The introduction of this technology, as a consequence, must take into consideration its implementation constraints; electromagnetic compatibility (EMC) in particular. Indeed, static converters based on power electronics are important sources of electromagnetic perturbations that can occasionally cause malfunctions in their local or distant electronic environment: avionics, navigation systems, reception antennae, etc. Thus, it is important to understand the origin of these phenomena, their mode of propagation and the effects on their potential "victims" in order to optimize the essential reduction or protection devices necessary to conform to the standards of EMC.

A chain of management of the electrical energy is generally organized according to the diagram in Figure 1.1: a primary electrical source powers the energy conversion system (distributed control), which itself powers one or more passive loads or actuators. The link between these components is achieved through conductors or power cables. The converter can itself be a complex device with different levels of conversion and have auxiliary supplies.

The converters carrying out the *processing of electrical energy* (conditioning, control) are based on the use of power electronics in the same manner as microelectronics and *signal processing*. It is noteworthy to observe that these two fields are based on the switching of semiconductors. In the first case, this involves power components (insulated grid bipolar transistor (IGBT), metal oxide silicon field effect transistor (MOSFET, diodes, etc.)) operating with vertical conduction which, in a switching system, confer a very high efficiency to the static converters where they are used; in the other case, this involves heavily integrated lateral components that enable the increase in speed of information processing. In each case, the high-frequency operation of these systems causes electromagnetic perturbations, the disturbance frequencies of which get closer and closer.

Figure 1.1. *Organization of an power electronics management system*

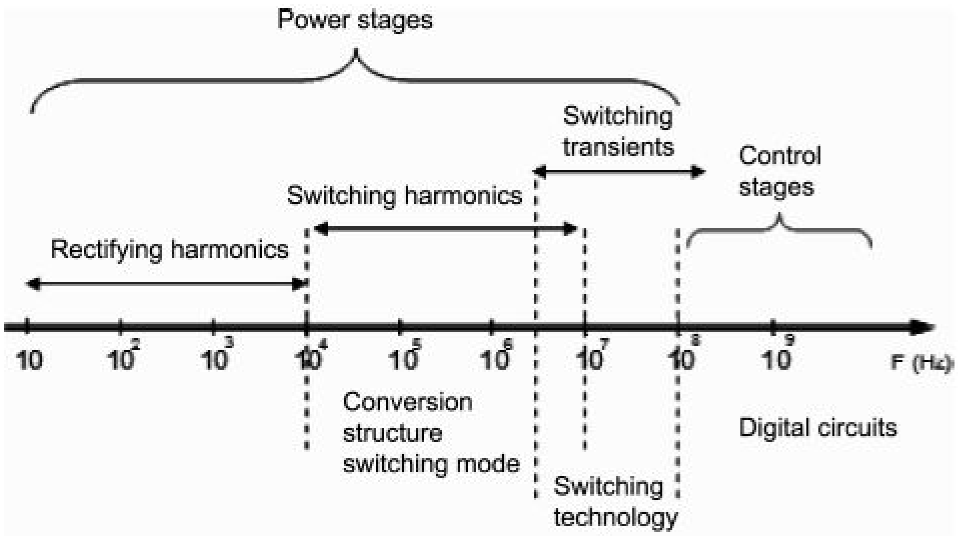


The consequences of the perturbations emitted by the power devices can be very serious in terms of the reliability and/or security of systems: in an airplane where security depends on electronic localization, communication and flight control systems, the introduction of electrical energy control systems based on power electronics must not threaten the current level of security; a good knowledge of these phenomena is therefore essential in this field.

Near-field or radiative couplings are proportional to the temporal derivative of the electrical quantities: Mdi/dt, CdV/dt; therefore, as their importance increases, these quantities are naturally bigger and the harmonics of the commuted electrical quantities are of a higher frequency.

Thus, the switching of power semiconductors can cause conducted and emitted electromagnetic perturbations that cover a very large frequency range as shown in Figure 1.2.

Figure 1.2. *Frequency range of power electronics perturbations*



– At low frequency from the network frequency of 50 Hz: the direct switching of diode or thyristor rectifiers, of triac dimmers, in synchronization with the network frequency, generates perturbations observable up to a few tens of kilohertz. This range is known as the “power grid harmonics”.

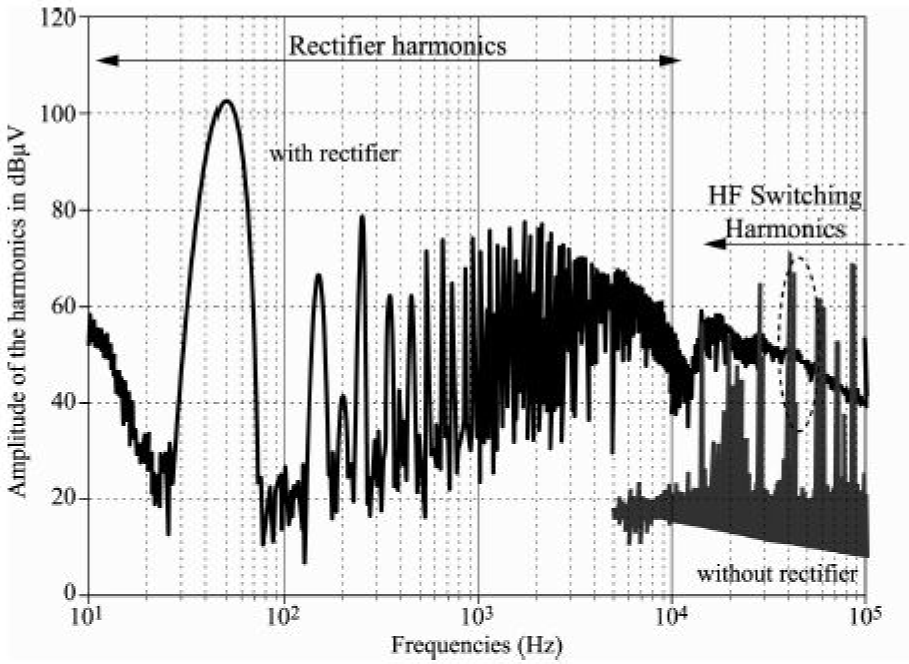
– At medium frequency (ranging from 10 kHz to 10 MHz): the switching of controlled semiconductors (MOSFET, IGBT) is performed in this range for switched-mode power supplies, choppers and power inverters. The commuted quantities show very quick temporal variations (of the order of a few 10 kV/μs and a few 100 A/μs) with extremely large spectral contents observed over at least four frequency decades: from 10^4 to 10^8 Hz.

– At high frequency: the transients in switching of semiconductors excite the normal modes of very low resistance electrical circuits (necessary for small losses). Thus, very high frequency resonances appear (10 MHz–1 GHz) during each switching between the parasitic inductances of connections (or of magnetic components) and the structural capacitances of the semiconductors.

The reality is more complex than this first classification because in an electronic power device, there are generally several stages of conversion operating at different frequencies (rectifier, high frequency (HF) switch-mode for auxiliary power supplies, medium frequency (MF) switch-mode for power, etc.) that interfere or intermodulate. For illustrative purposes, Figure 1.3 shows the spectrum of the current measured at the input of an upstream switch-mode power supply (black curve) and at the input of a downstream rectifier (gray curve). We can clearly see the contribution of the rectifier starting from 50 Hz and the multiple harmonic peaks that it generates until approximately 10 kHz. Beyond that, we observe (black curve) multiple 15 kHz peaks (switch-mode frequency) that are modulated by the operation of the rectifier and are not modulated on the gray line: the effect of modulation is represented by a certain level of noise at the bottom of the switch-mode harmonic peaks (area circled in dotted line).

These observations show that the electromagnetic perturbations caused by the static converters are not only conducted in the electrical networks and in the cables linking the loads, but are also very easily transmitted by direct radiation, taking into account the amplitudes of the currents and voltages that are in play as well as their frequencies (see Figure 1.1).

Figure 1.3. *Spectrum of parasite input current of a power supply modulated or not by the input rectifier*



1.2. Power grid harmonics

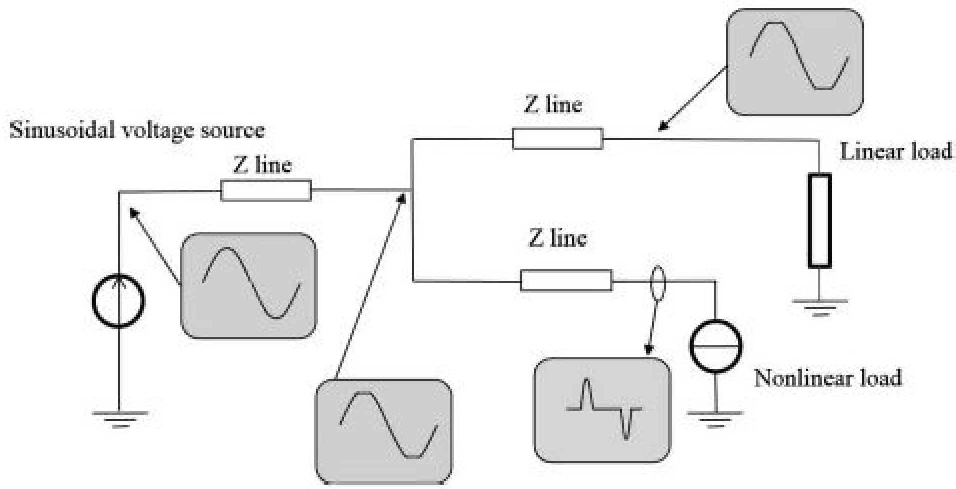
1.2.1 *Presentation*

In land-based or on-board (aircraft, vessels, etc.) electrical networks, the real shape of the current or voltage wave is never perfectly sinusoidal; real waves include harmonics caused by connected devices and present nonlinear features: diode rectifiers, inductive loads whose magnetic material is saturated over the course of its operation cycle (ballast of fluorescent tubes for example). They therefore summon non-sinusoidal currents which create deformations in the voltage which will, all the while remaining periodic, be deformed by harmonics, generally of odd order.

Figure 1.4 illustrates the propagation mechanism of harmonics in a grid: a nonlinear load creates harmonic currents that, while they travel through the branches of an impedant network, create harmonic voltage drops. The voltage wave is therefore deformed at the observed points.

This deformation is evidently bigger as the impedance of the network is also bigger.

Figure 1.4. *Propagation of harmonics in a network and its consequences on the voltage waveforms*



In addition to the effects resulting from the flow of harmonic currents in the lines of non-zero impedance, the voltage harmonics originate from small imperfections of construction (asymmetries) in the winding of equipment, in other words, rotating machines (motors and alternators) and transformers. These third-order harmonic voltages play a small part, and with low rates, in the origin of the overall harmonic distortions.

For household appliances, it is the accumulation of devices, all in phase and connected to an insufficiently small line impedance, that creates a major harmonic pollution of the network. We can cite, for example, the simultaneous operation of multimedia devices (and of their switch-mode power supply), the constant connection of computers as well as the general use of fluorescent lamps.

The harmonics, being caused by nonlinear loads, are therefore preferentially propagated between phase and neutral on a single-phase network or between the phases of a three-phase network (supposing the load does not have a neutral connection). This is called differential-mode propagation.

1.2.2. *Characterization of the quality of electrical energy*

This pollution is characterized by the *total harmonic distortion* defined either by its relation to the voltage fundamental or by its relation to its root mean square (RMS), as such:

[1.1] $$TDH_{fund} = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^{\ 2}}}{U_1} \qquad TDH_{RMS} = \frac{\sqrt{\sum_{n=2}^{\infty} U_{n_{eff}}^{\ 2}}}{U_{eff}}$$

Thus, it is appropriate to be vigilant with the adopted definition when we want to quantify these effects.

Currently in France, the distortion rate, except in certain rare cases, is between:

– 5% and 8% in the low-voltage grid;

– 5% and 7% in the medium-voltage grid;

– 2% and 3% in the high-voltage grid.

The current absorbed by a nonlinear load is defined in the same way by its current distortion rate (we can also find the definition relative to the total RMS value):

[1.2] $$TDH_{fund} = \frac{\sqrt{I_2^{\ 2} + I_3^{\ 2} + \ldots}}{I_1}$$

Therefore, we acknowledge that the presence of harmonics contributes to the augmentation of the RMS current, which generally increases losses (joules) in powered loads and in power lines:

[1.3] $$I = \sqrt{I_1^{\ 2} + I_2^{\ 2} + I_3^{\ 2} + \ldots} = I_1 \sqrt{1 + TDH_{fund}^{\ 2}}$$

The quality of the electrical energy is characterized by the *power factor,* defined as the relation between the active power provided to a load and the apparent power, the product of the RMS of voltage and current. In a pure sinusoidal system, ideally the power factor tends toward 1. If we take the case of equipment powered by a purely sinusoidal single-phase voltage and absorbing a non-sinusoidal current, the power factor (per phase) in this scenario is equal to:

$$\lambda = \frac{P}{S} = \frac{V\, I_1 \cos\varphi_1}{V\, \mathrm{I}} = \frac{1}{\sqrt{1 + \mathrm{TDH}_{\mathrm{fund}}^{\;2}}} \cos\varphi_1 \qquad [1.4]$$

where cos φ_1 represents the *displacement factor,* in other words the phase shift between the current fundamental and the voltage.

We can therefore see that the presence of harmonics increases the apparent power of a certain appliance or piece of equipment. This influence can equally be rendered as a power balance showing the apparent power, active power, reactive power and deforming power (showing the harmonic distortion). This relation for a grid with q phases is of the form:

$$S^2 = P^2 + Q^2 + D^2 \qquad [1.5]$$

with:

Simple voltage: V

RMS current per phase: I

Current fundamental: I_1

Apparent power: $S = q\, \mathrm{V}\, \mathrm{I}$

Active power: $P = q\, \mathrm{V}\, \mathrm{I}_1 \cos\varphi_1$

Reactive power: $Q = q\, \mathrm{V}\, \mathrm{I}_1 \sin\varphi_1$

Deforming power: $D = q\ \mathrm{V} \sqrt{\mathrm{I}_2^{\;2} + \mathrm{I}_3^{\;2} + \dots} = q\ \mathrm{V}\ \mathrm{I}_1\ \mathrm{TDH}_{\mathrm{fund}}$

Thus, the presence of harmonics degrades the quality of the electrical energy; it leads to additional losses, vibrations in rotating machines that contribute to the decrease in their longevity.

1.2.3. *Relevant standards for harmonic emissions*

The standard EN 61000-2-2 defines the levels of compatibility for low-voltage public networks and the standard 61000-2-4 defines them for medium- and high-voltage industrial applications. These levels are defined with regard to the network voltage deformations common to different kinds of equipment. We acknowledge that the number of harmonic sources will increase and that the proportion of purely resistive loads (electrical heating), which have a damping effect, will decrease relative to the total consumption. The levels of compatibility for individual harmonics in low-voltage grids are given in Table 1.1.

When several harmonics appear simultaneously, we can express their combined effect by the total harmonic distortion rate (THD_{fund}). Taking into account the levels given in Table 1.1 and that the individual harmonics do not simultaneously reach their level of compatibility, the compatibility level for the global harmonic distortion rate must be limited to 0.08.

Table 1.1. *Compatibility levels for individual harmonic voltages in low-voltage grids*

Odd harmonics not including multiples of 3		Odd harmonics that are multiples of 3		Even harmonics	
Harmonic order (n)	Harmonic voltage (%)	Harmonic order (n)	Harmonic voltage (%)	Harmonic order (n)	Harmonic voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.3	6	0.5
13	3	21	0.2	8	0.5
17	2	>21	0.2	10	0.5
19	1.5			12	0.2
23	1.5			>12	0.2
25	1.5				
>25	$0.2 + 0.5 \times 25/n$				

As we saw previously, the majority of low-frequency perturbations generated and endured by low-voltage equipment are linked to harmonic perturbations. These perturbations are therefore subject to international and European regulations. We will provide the content of the European regulations regarding the limitations of harmonic currents injected into the public power supply network (current used by appliances ≤ 16 A per phase). This standard is referred to as EN 61000-3-2.

1.2.4. *Classification of appliances*

Concerning the limitation of the harmonic voltage, appliances are classified in the following way:

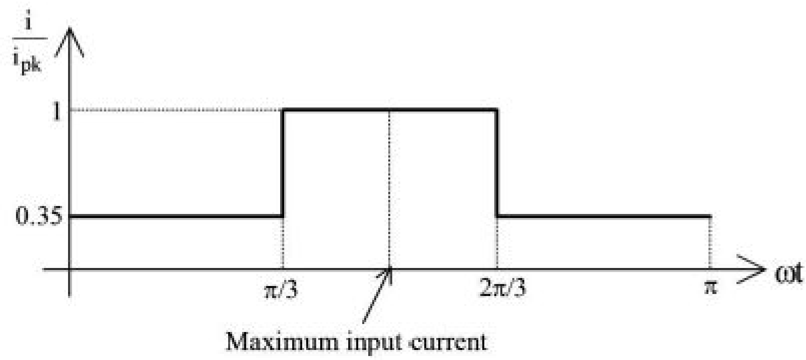
Class A: balanced three-phase appliances and all other appliances with the exception of those that are labeled as being in one of the following classes.

Class B: portable tools (short-term use).

Class C: lighting appliances including light dimming devices.

Class D: appliances with an input current such that its wave shape at each normalized half-period relative to its peak value is within the range defined in Figure 1.5 (in fact at least 95% of the time) and with an input power of less than 600 W.

Figure 1.5. *Shape of the current for class D of the EN 61000-3-2 standard*



Regardless of the shape of the input wave, the appliances in class B and class C and motorized phase control appliances are not considered class D appliances.

1.2.5. *The limits of harmonic currents*

They are given in RMS.

Class A appliances: the input current harmonics must not exceed the values indicated in Table 1.2.

Class B appliances: the input current harmonics must not exceed the values indicated in Table 1.2, multiplied by a factor of 1.5.

Class C equipment: we must differentiate lighting appliances and light dimmers. The limits of harmonic currents in lighting appliances must not exceed the limits indicated in Table 1.2.

Table 1.2. *Limits for class A appliances*

Harmonic order	Maximum authorized harmonic order (A)
Odd harmonics	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
$15 \leq n \leq 39$	0.15×15/n
Even harmonics	
2	1.08
4	0.43
6	0.30
$8 \leq n \leq 40$	0.23×8/n

For light dimmers that are either independent or incorporated into lamps, the following conditions must apply:

– For independent light dimmers, the values of the harmonic currents incorporated into incandescent lamps must not exceed the values in Table 1.2. When we use a phase-shift command, the firing angle must not exceed 145°.

– For discharge lamps in maximum charge conditions, the value of the harmonic current must not exceed the values defined in percentages in Table 1.2.

– For all positions of the light dimmer, the value of the harmonic currents must not exceed the limits defined in the case of a maximum charge.

Class D appliances: the limits of the harmonic currents are defined in the assigned load conditions. The input current harmonics must not exceed the limits in Table 1.4.

The limits given in Table 1.3 are valid for all appliances whose active input power is greater than 50 W. There are no limits for appliances with an active input power of less than 50 W.

Table 1.3. *Limits for class C appliances*

Harmonic order	Maximum authorized harmonic current expressed as a percentage of the fundamental input current of the lighting (%)
Odd harmonics	
3	30 λ (λ: power factor of the circuit)
5	10
7	7
9	5
$11 \leq n \leq 39$	3
Even harmonics	
2	2

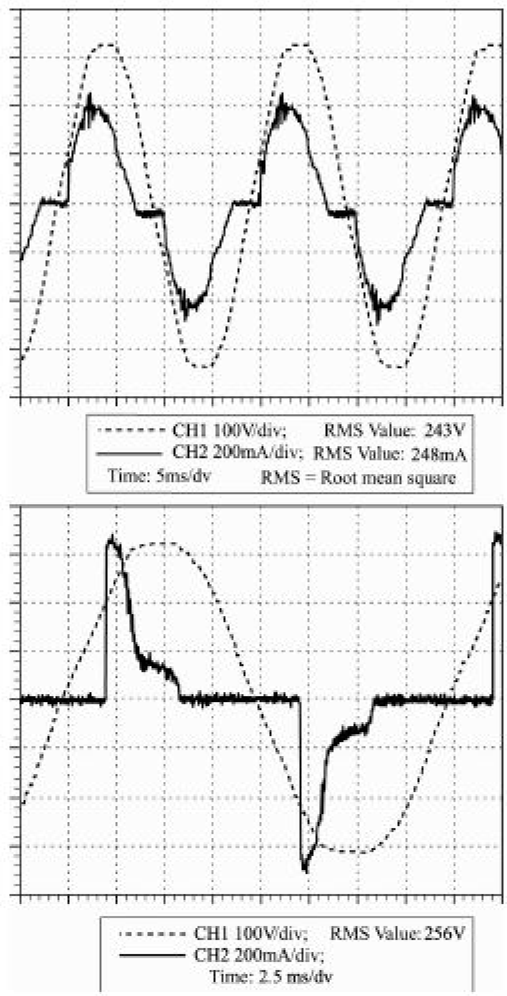
Table 1.4. *Limits for class D appliances*

Harmonic order	Maximum authorized harmonic current per watt (mA/W)	Maximum authorized harmonic current (A)
Odd harmonics		
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
$11 \leq n \leq 39$	$3.85/n$	0.15×15/n

1.2.6. *Examples of observations of harmonic currents*

Figure 1.6 shows the measurements[2] taken for several household appliances. We note that they have a high harmonic content. We also observe that the voltage waveform is clipped, so not perfectly sinusoidal, showing the consequences of current harmonics and of an insufficiently low impedance.

Figure 1.6. *Examples of current and household appliance voltage waveforms measurements highlighting the harmonic content*

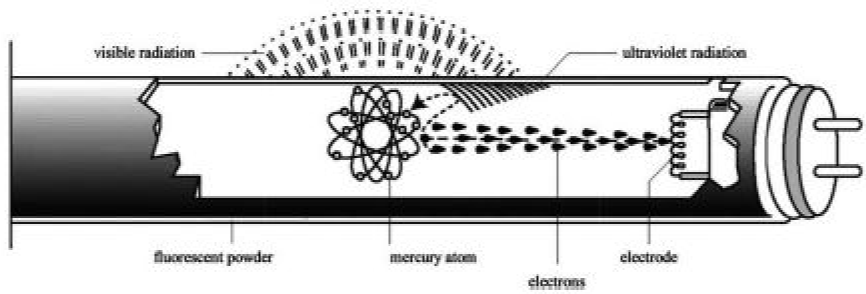


These appliances are produced in very high quantities and therefore contribute to a heavy pollution of distribution networks. We can see especially that energy saving lighting does not represent progress from this point of view; certain office buildings in which the consumption is determined by fluorescent lighting and computing appliances (PC, monitors, printers, etc.) generate a very high level of odd harmonics that require specific reduction methods or the resizing of neutral conductors.

1.2.7. *Fluorescent lighting scenario*

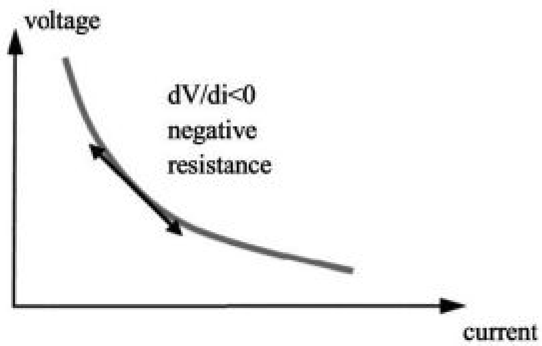
The principle of operation of a fluorescent tube is described in Figure 1.7. The tube has two electrodes at each extremity, and is filled with an inert gas and a small quantity of mercury (in liquid form and in gas form before ignition). The interior of the tube is lined with a mixture of different fluorescent powders. These powders allow the conversion of ultraviolet radiation into several rays situated in visible frequencies. Numerous different powders exist, which can give practically all color temperatures (from hot to cold colors).

Figure 1.7. *Principle of light emission of a fluorescent tube*



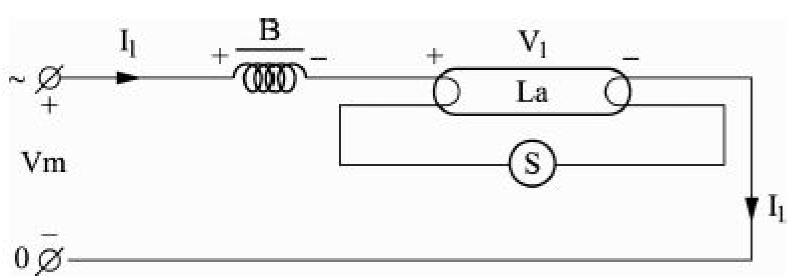
Nevertheless, these lamps have excellent luminous outputs that cannot, as opposed to traditional incandescent lamps, be placed directly on the electrical network. Indeed, the electrodes of the majority of these tubes must be preheated to facilitate ignition (vaporization of mercury). This means that a voltage dedicated to the preheating must be applied before executing the ignition. The ignition of the tube (ignition of the ionization process) is thus realized through the application of a high voltage at the ends of the two electrodes. Moreover, once it is ignited, its negative resistance (Figure 1.8) renders its direct connection to the network impossible. These lamps can therefore only work when combined with an electrical ballast (reactive impedance) allowing for control of the preheating and dimming, and for the limitation of the current circulating in the tube by ensuring stable operation. Indeed, we can observe that due to the distinctive negative resistance, any point of operation where constant voltage is imposed is instable.

Figure 1.8. *Distinctive negative resistance of a fluorescent tube*



The simplest ballast consists of an iron core inductance operating in tandem with a “starter” for the ignition. The corresponding diagram is shown in Figure 1.9. The combination of the ballast and the lamp acts as a complex form of impedance, but presents a partly positive impedance. This provides a stable operating point in a fixed-voltage grid on the condition that it is placed beyond a voltage limit V_{min}.

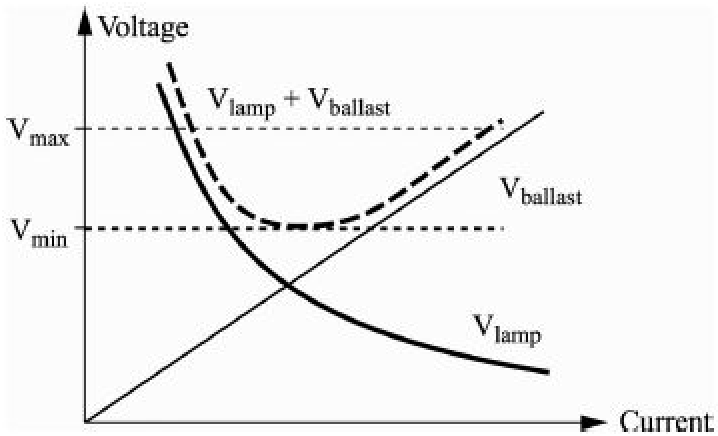
Figure 1.9. *Power supply of the tube through an intermediate ballast*



The curves shown in Figure 1.10 can be determined by only taking into account the fundamental components of the different quantities, particularly for the voltage at the terminals of the tube. The calculations enabling this construction are given below:

$$V_{ballast} = jL\omega I_l \qquad V_{lamp} = f(I_l)$$
$$V = V_{ballast} + V_{lamp} \qquad [1.6]$$

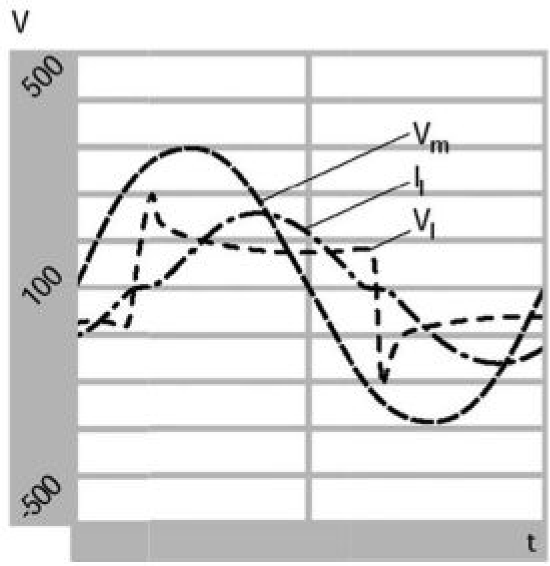
Figure 1.10. *Electrical characteristic of ballast+lamp*



Thus, the ballast can be resized in such a way that a correct operation of the lamp can be ensured in the possible variation range of the grid RMS voltage. Indeed, we must ensure that the minimum voltage is greater than V_{min} and that the maximum voltage V_{max} is compatible with the maximum power that the lamp can consume. This power is in fact limited by the temperature maintained by the electrodes.

When the lamps are powered by the 230 V/50 Hz electric network through a magnetic ballast (as in Figure 1.9), the voltage at the terminals of the lamp and the current that travels through it are not sinusoidal (see Figure 1.11). Each time the current passes through zero, the lamp is neutralized and requires a certain voltage in order to be reignited. The lamp being “hot”, this voltage is much weaker than that required for the initial ignition. This re-ignition phase is shown as a slight overvoltage appearing at the start of each half-period. The power factor of the lamp will therefore not exceed 0.8 due to the high deformation of the two quantities.

Figure 1.11. *Evolution of the electrical quantities in the fluorescent lamp*



As we can see from the shape of the current as shown in Figure 1.11, the current is not strictly sinusoidal. The deformation of the current is linked both to the square waveform of the voltage at the terminals of the lamp and also to the nonlinearity of the inductance making up the ballast (hysteresis). Measurements performed on tubes in a stabilized state give the following typical values:

Table 1.5. *Typical values of current harmonic rates for a fluorescent lamp*

Harmonic order	Amplitude (%)	NF EN 61000-3-2
Fundamental	100	100%
3	10	30%
5	3	10%
7	2	7%

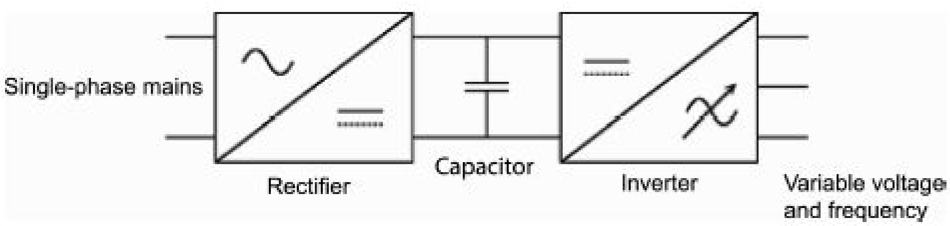
9	1	5%

Nevertheless, the power factor of the ballast/lamp combination is approximately 0.5. The total third-order harmonic distortion is thus limited to 15%. This equipment therefore conforms to the prescribed values.

1.2.8. *Practical scenario of the improvement of the total harmonic distortion generated by a variable-frequency drive*

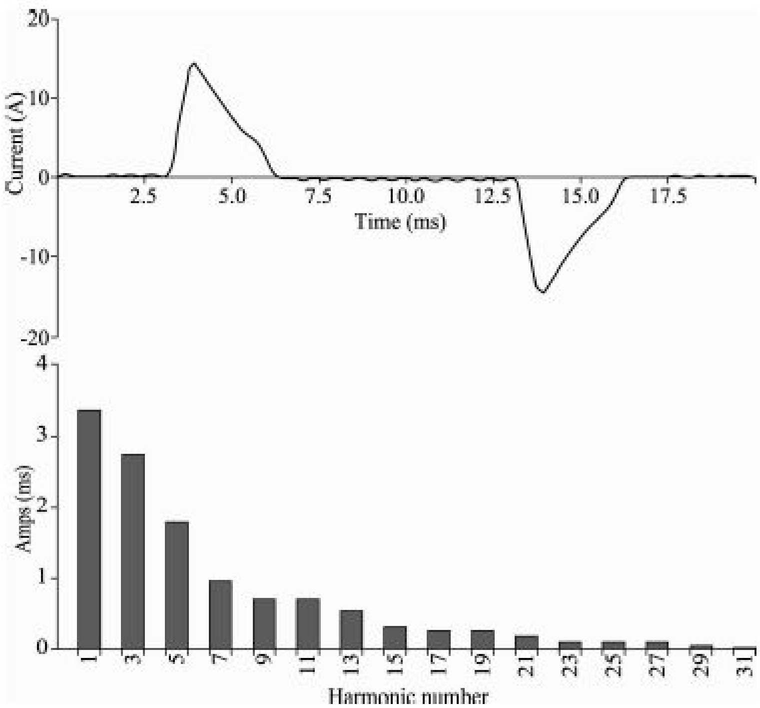
Let us consider the following case of a variable-frequency drive using the variable-frequency control of a three-phase induction motor starting from the single-phase electrical network. The principle of this power supply is illustrated in Figure 1.12. The temporal curves of the current and its measured harmonics in this type of equipment with the help of a network analyzer are shown in Figure 1.13.

Figure 1.12. *Structure of the variable-frequency drive*



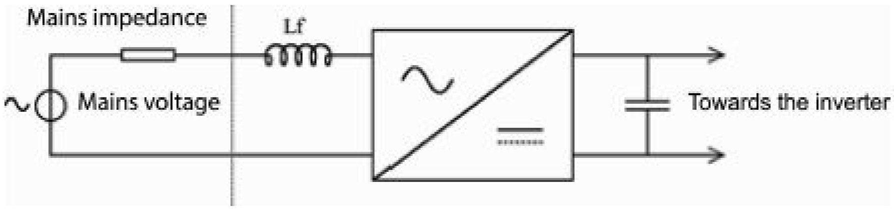
Since this equipment functions on the low-voltage mains and absorbs a current less than 16 A, we can refer to the NF EN 61000-3-2 standard in order to determine the permitted harmonic levels for it. The current absorbed by this equipment is such that it must be considered as a class D appliance. The limits for the permitted harmonic perturbations are given in Table 1.4. The values of these limits from the table can be calculated by using a nominal absorbed power of 750 W and a limit of 2.3 A for the third-order harmonic. It is obvious that in this configuration, the variable-frequency drive does not conform to the regulations. Indeed, if we were to only consider the third-order harmonic, we would obtain a value measured at 2.74 A. The variable-frequency drive therefore does not strictly conform to the regulations. Thus, it is necessary to reduce the harmonic currents.

Figure 1.13. *Current absorbed at the input of the variable-frequency drive as a function of time and representation of the harmonics*



One possible solution consists of adding an inductance in series with the variable-frequency drive. The corresponding diagram is given in Figure 1.14.

Figure 1.14. *Structure of the variable-frequency drive with an inductance in series*



The presence of an inductance in series helps to reduce the harmonic currents absorbed by the variable-frequency drive. Nevertheless, we note that its value is limited for two reasons: its presence damages the displacement factor of the system through the phase shift of the current fundamental in relation to the voltage. This inductance causes a voltage drop that results in a reduction of the voltage on the continuous bus. For these two reasons, the value of this inductance cannot exceed 10 mH in this example. The results from measurements and the wave shape of the absorbed current are given in Figure 1.15. We can verify that the equipment comprised of the variable-frequency drive/inductance combination now conforms to the EN 61000-3-2 standard.

The analytical calculation of this inductance is quite complex provided we take into account the different constraints we have mentioned (voltage drop, power factor). It is also preferable to resort to the computer simulation. This example has thus been modeled with the equivalent diagram in Figure 1.16 in order to precisely determine the value of L by paying particular attention to the impedance of the source. The values of the simulation components are indicated in the diagram, which help to find the observed electrical values, as shown in Figure 1.17.

Figure 1.15. *Current absorbed at the input of the variable-frequency drive as a function of time and representation of the harmonics*

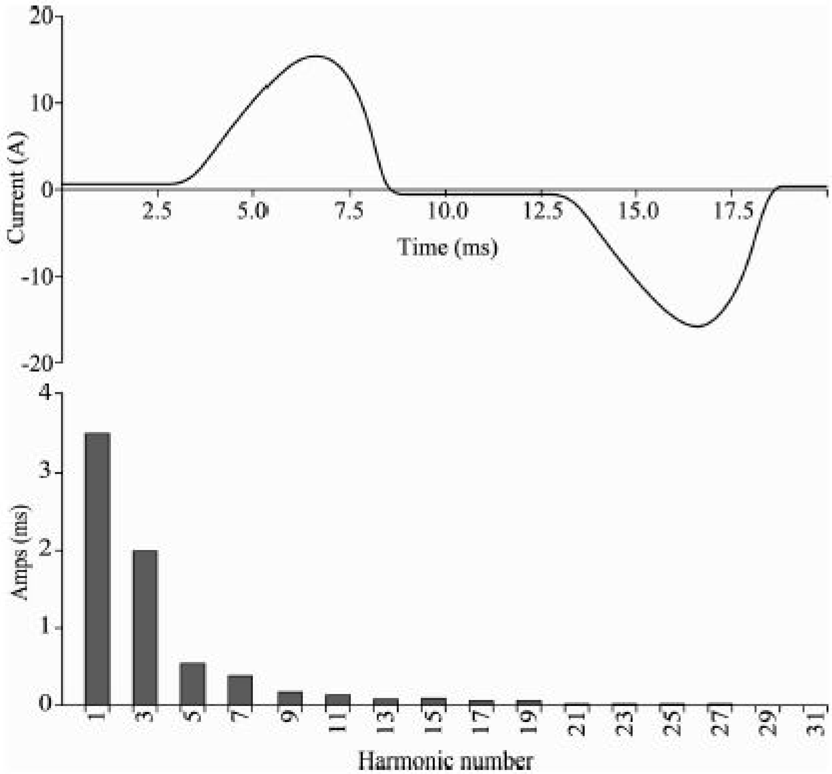


Figure 1.16. *Diagram of the simulation used to determine L*

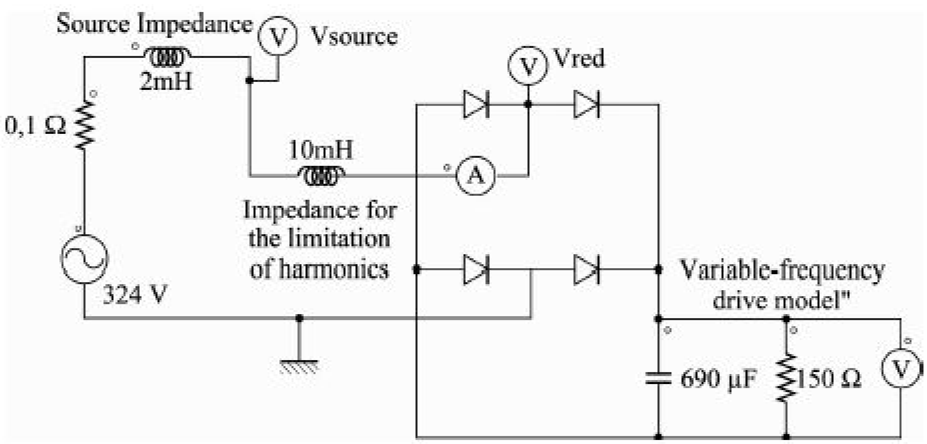


Figure 1.17. *Simulated waveforms*