5

Power Quality Phenomena and Indicators

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It is increasingly being accepted that the impact of poor power quality (PQ) on effective electric power utilization is significant and disruptive; it is also being ever more clearly understood that technical and financial impacts, where relevant, are far greater than had previously been recognized.

The true economic value of PQ is linked to the effects that electromagnetic disturbances have on equipment and other loads on the system. In the industrial sector, for example, the economic value of disturbances is actually increasing due to the extensive detrimental effects they can cause in modern, automated plants in which sensitive equipment and devices are integral components of highly complex processes. For such processes a PQ disturbance can cause downtime that can be directly correlated with lost production and, therefore, lost revenue and profits. The consequences are not limited only to electrical systems in non-residential environments, but can harm domestic systems and appliances as well as mainly introducing electrical danger into the home [1].

On the other hand, a poor power quality may increase power and energy losses in different components of power systems (electric lines, power transformers, etc.) or customers' receivers (mainly induction motors, power electronics, capacitor banks for power factor correction, etc.). These supplementary losses will diminish the energy efficiency for both utility and final users, increasing the customers' energy bills.

The economic impacts of power quality are usually divided into three broad categories:

- *direct economic impacts*: e.g. loss of production; unrecoverable downtime and resources (e.g. raw material, labour, capital); process restart costs; spoilage of (semi-) finished production; equipment damage; direct costs associated with human health and safety; financial penalties incurred through non-fulfilment of contract; environmental financial penalties; utility costs associated with the interruption; supplementary energy losses in the electric supply system;

Electrical Energy Efficiency: Technologies and Applications, First Edition. Andreas Sumper and Angelo Baggini.

- *indirect economic impacts*: e.g. the costs to an organization of revenue/income being postponed; the financial cost of loss of market share; the cost of restoring brand equity;
- *social-economic impacts*: e.g. uncomfortable building temperatures as relating to reduction in efficient working/health and safety; personal injury or fear, also as related to reduction in efficiency and health and safety.

It is an important part of the end users' armoury to arrive at the correct balance between what the organization's poor PQ costs are, the investment required for any PQ solution, as well as to assess whether unmitigated poor PQ can be tolerated. The power sector and equipment manufacturers also need to assess how great an effort to place behind helping end users to reduce the impacts of poor PQ.

The methods available in the specialized literature for the economic evaluation of PQ disturbances refer mainly to voltage dips and short or long interruptions, but also to harmonics [2]. The effects of other disturbances such as voltage level and fluctuations and unbalance are seldom considered. Their consequences and economic impact are that the *indirect* and *social* impacts often fail to be recognized and go unaddressed.

5.1 RMS Voltage Level

The complex value of the voltage in various characteristic points of the electric network represents one of the main parameters of the operation state of power systems.

Slow voltage variations are usually quantified by calculation of the rms value of the supply voltage. In assessing this parameter, measurement has to take place over a relatively long period of time to avoid the instantaneous effect on the measurement caused by individual load switching (e.g. motor starting or inrush currents) and faults. Standard EN 50160: 2009 quantifies slow voltage variations using the 10-minute mean rms value and considering a week as the minimum measurement period; in particular, the 99th percentile of the 10-minute mean rms values over one week is considered as the site index.

The voltage variation limits in different European countries are presented in [3] and [4]: (i) for the Norwegian PQ directives, variations in the voltage rms value, measured as a mean value over one minute, shall be within an interval of $\pm 10\%$ of the nominal voltage; (ii) in France, for MV customers, the supply contracts contain the voltage variation limit U_C $\pm 5\%$ of the nominal voltage for 100% of the time, where U_C must be in the range of $\pm 5\%$ around the nominal voltage; (iii) the regulation in Hungary contains three different objectives: (a) 100% of the 10-minute rms voltage shall be between 85% and 110% of the nominal voltage; (b) 95% of the 10-minute rms voltage shall be between 92.5% and 107.5% of the nominal voltage; (c) 100% of the 1-minute rms voltage shall be less than 115% of the nominal voltage.

The regulation in Spain fixes the following limit: the 95th percentile of the 10-minute mean rms value over one week shall be between 93% and 107% of the declared disturbance description.

The supply voltage amplitude can have slow variations, especially due to voltage drops on lines and transformers, produced by the variation of electric load at consumers. The voltage variations can also be produced by changes in the electric configuration scheme of the grid, as well as by changes in the operation stage of reactive power sources.

The calculation of the voltage drops has been presented in [1, 2, 5, 6].

The slow voltage variations can be characterized by the relative voltage deviation from the nominal value at a certain point of the grid and at a certain moment:

$$\varepsilon_{\mathrm{U}}\,[\%] = \frac{\Delta U}{U_{\mathrm{N}}}.100\,[\%] = \frac{U_{\mathrm{S}} - U_{\mathrm{N}}}{U_{\mathrm{N}}} \cdot 100\,[\%] \tag{5.1}$$

where U_{S} is the line voltage of the electric grid at a certain point and at a certain moment (the operating voltage) and U_{N} represents the nominal voltage. The ratio $U_{\mathrm{S}}/U_{\mathrm{N}}$ is called the voltage level.

The permitted variation limits depend on the voltage level with which the consumer is supplied. According to today's standards, the relative deviations for the voltage in the PCC in the case of grids with nominal values up to 220 kV must not be more than 10%.

Equipment manufacturers have to mention the immunity levels to voltage variations for each category of load and, generally, these values are within the interval ($\pm$5–$\pm$10)%. For example, the relative admissible deviation is: (i) $\pm$5% for electric motors; (ii) $\pm$10% for welding machines and (iii) $\pm$5% for electric lamps.

For a better characterization of the voltage variation from the nominal values, the following indices are defined:

- *The average value for the voltage relative deviation* from the nominal value in a T time interval [7]:

$$\varepsilon_{\mathrm{Umed}} = \frac{1}{T}\int_0^T \varepsilon_{\mathrm{U}} \cdot \mathrm{d}t \tag{5.2}$$

  The $\varepsilon_{\mathrm{Umed}}$ index is a measure for the mean voltage in the supply bus bars and gives indications on the accurate choice of the position of the transformer tap-changer.

- *The rms value of the voltage deviations* is given by the relation [7]:

$$\varepsilon_{\mathrm{q}}^2 = \frac{1}{T}\int_0^T \varepsilon_{\mathrm{U}}^2 \cdot \mathrm{d}t \tag{5.3}$$

  This index offers an evaluation of power quality from the point of view of slow voltage variations, as follows:
  - $\varepsilon_{\mathrm{q}}^2 \le 10\%$ very good quality
  - $10\% \le \varepsilon_{\mathrm{q}}^2 \le 20\%$ good quality
  - $20\% \le \varepsilon_{\mathrm{q}}^2 \le 50\%$ poor quality
  - $\varepsilon_{\mathrm{q}}^2 \ge 100\%$ inappropriate quality.

5.1.1 Sources

Voltage varies at different points of a power system, the voltage value being influenced by different factors occurring in the generating, transmission and distribution processes. The main factor that determines the voltage variation is load variation. Another factor that influences voltage is the balance between the reactive power consumed and that generated [2].

5.1.2 Effects on Energy Efficiency

Voltage deviation from the nominal value has various consequences according to the load characteristics and the position of the connecting point of the consumers to the grid. It is generally admitted that the optimal supply voltage for every load is its nominal voltage; any deviation from this value influences the operation of various loads [8].

5.1.2.1 Lighting Systems

Incandescent lamps are very sensitive to changes in the supply voltage. These characteristics are of great practical and economic importance as the voltage deviation influences the absorbed power P_n, the luminous flux Φ, the luminous efficacy η, the average lifetime T and the colour temperature. Due to its reduced luminous efficiency, the usage of such lamps will be limited in the near future according to the Directive 2006/32/EC of the European Union [9].

Fluorescent lamps are less sensitive to voltage variations; thus, a voltage variation of 1% changes the lumen output of the lamp by an average 1.25%. These lamps can actually function even if the voltage is at 90% of the nominal value.

5.1.2.2 Electric Motors

In the case of asynchronous motors, the main power load in industrialized countries, a decrease of voltage will increase the rotor slip, will reduce the speed and, implicitly, the productivity of the driven equipment will decrease. The active torque of asynchronous motors is proportional to the square voltage and this is why, when the voltage drops, the starting conditions become more difficult, sometimes even leading to a full stop of the motor (the maximum torque of the motor C_M is below the resistant static torque C_s of the working machine). Thus, when the voltage drops by 10%, the active torque of the asynchronous motor decreases by 19%, the rotor slip increases by 27.5%, the rotor current increases by 14% and that of the stator increases by 10% [10]. The direct consequence is the increase of power losses, reducing the motor's energy efficiency; due to this supplementary heating of the motor, the insulating layer will wear about twice as quickly as in the case of a nominal voltage. With an increase in voltage of 10%, the active torque increases by 21%, the rotor slip drops by 20%, the current in the rotor decreases by 18% and that in the stator by 10%. Figure 5.1 presents the variation in the motor speed of rotation Ω according to the variation of supply voltage U (p is the number of pairs of poles in the machine) [7].

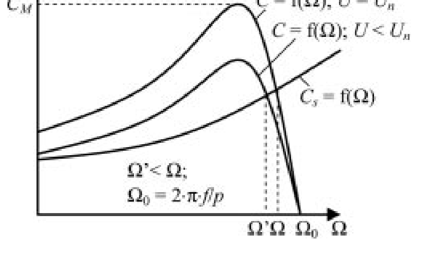


Figure 5.1 Variations in the characteristics of the asynchronous motor according to the power voltage

5.1.2.3 Electric Ovens

In the case of electric ovens with resistors, reducing the power voltage has negative effects on energy efficiency and the technological process, while increasing the supply voltage leads to the reduction of the heating elements' lifetimes. The lifetime of the heating elements of electric ovens with resistors depends on the operating temperature, material characteristics, the construction specifications of the element, etc. The reduction of the lifetime is determined by the acceleration of the oxidation processes of the resistive material and thus by the gradual alteration of the mechanical and electrical parameters.

In the case of three-phase electric arc furnaces, one of the main consumers of electricity in the industry, the deviation of the power quality indices from the contracted values determines – most of the time – an increase in the operating expenses. Thus, in the case of voltage value deviations from the contracted value, determining damage is done based on the extra amount of electric energy needed in order to bring the material to the temperature required by the technological process.

Changing the supply voltage determines a change in the duration of processing of the material. In the usual case of electric arc furnaces used to process steel, a reduction of supply voltage at the bus bars by 8% leads to an increase in the electricity consumption by about 7% and a decrease in productivity of about 6%.

In the case of electromagnetic induction ovens, which are supplied with an industrial frequency, a voltage reduction of 5% shows a productivity reduction of about 10% and a specific consumption increase of about 8%.

Modern installations used for metal processing in electromagnetic induction ovens are powered by means of a frequency converter, so that the reduction of supply voltage by 10% determines an increase in the supply voltage frequency by about 2% and the specific power consumption increases by about 5%.

5.1.2.4 Other Consumers

In the case of resistance welding equipment (spot, seam or butt welding), the variation in the supply voltage within an interval of ± 10%, in the case of regular types of steel, has consequences only on the duration of the technological process, without affecting the quality of the product. Voltage deviations of over 10% lead to the reject of the operation in most cases.

In the case of special types of steel, experimental results show the need to maintain the supply voltage within the interval $(0.95\dots1.05)U_{\mathrm{c}}$, where U_{c} is the contracted voltage, generally equal to the nominal voltage of the welding machine.

An increase of voltage on the supply rods determines the overcharge of the electric insulation and thus a reduction in its lifespan.

5.1.2.5 Cost

Establishing an optimal variation interval for the supply voltage of the consumers connected to a grid is both a technical and economic issue and its solutions should take into account both the expenses that are needed to reach a certain voltage quality benchmark, as well as the economic damage that can occur to the consumers and the grid placed upstream of the point where the voltage is regulated; this must be done according to the variation affecting the voltage in the electric network located before that specific point.

In most practical cases, the damage D, determined by the supply voltage deviation U from the rated voltage U_r of the loads can be expressed in the form of a second degree polynomial [7]:

$$D = a \cdot (U - U_r) + b \cdot (U - U_r)^2, \tag{5.4}$$

where the a and b values are specific to any technological process. Undoubtedly the relation, (5.4), can be applied only for a relatively narrow range of supply voltage variations. Reducing the supply voltage to below a critical value U_{cr1}, as well as increasing it above a value U_{cr2} can lead to significant damages.

The deviation in the supply voltage from the loads rated voltage leads, most of the time, to a reduction in the absorbed power and, subsequently, to a reduction in the productivity of the working equipment and to a reduction in the quality of the manufactured products.

5.1.3 Mitigation Methods

Maintaining the voltage within permitted values at the terminals of all the consumers can be accomplished only by combining centralized control activity (at a level of the whole power system) with local voltage controls. The central control maintains the voltage at a certain average level in the grid, while the local control systems continuously monitor the voltage levels at various points in the grid and brings them back to within established limits, if necessary.

Central control consists of regulating the voltage at the level of the generators' terminals by means of variations in the excitation current. This control can be achieved both automatically and manually. Thus, the automatic control maintains the voltages at an approximately constant value at the terminals of the generators, irrespective of the variation of the charge, while the manual control allows the increase or decrease of voltages at the generators' terminals according to the charge of the system.

Securing a certain value of the voltage with the help of central control is necessary but not sufficient to ensure admissible voltage at the connection point of all consumers. It is possible that the average level is acceptable, and yet the voltage at the connection point of the consumers is very different, some higher and some lower than the admissible values, hence the need for a local control in order to maintain the voltage values.

5.1.3.1 Voltage Control by Introducing Additional Voltage

Controlling the voltage from a point on the grid can be done by introducing additional voltage, for example by changing the transformation ratio. The devices used for the introduction of additional voltages in the electric grids are [2, 6, 7]:

Static Equipments with Adjustable Taps

- On-load or off-voltage ratio transformers and autotransformers. They are used for the direct control.
- Static boost and buck devices, transformers and autotransformers especially designed for additional voltage. They are used for indirect, longitudinal and transversal control.

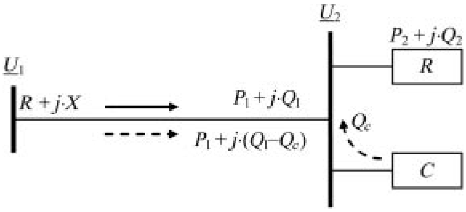


Figure 5.2 Line diagram of an electric network with a controllable installation C capable of absorbing or supplying reactive power

Static Equipments with Slow Control without Taps

- Autotransformers with a short-circuited coil
- Transformers and autotransformers with pre-magnetization
- Transformers with a control coil core

These devices can be used for consumers with high demands in terms of voltage quality.

Induction controllers – this category comprises widely spread direct or indirect controlling devices with on-load tap-changers.

5.1.3.2 Controlling Voltage by Changing the Reactive Power Flow

Figure 5.2 takes into account an electric network for energy transmission. If at the end of the line there is a controllable installation C, capable of absorbing or supplying reactive power, then, based on the relation:

$$\underline{U}_1 = U_2 + \frac{P_2 \cdot R + Q_2 \cdot X}{U_2} + j \cdot \frac{P_2 \cdot X - Q_2 \cdot R}{U_2} = U_2 + \Delta U + j \cdot \delta U \qquad (5.5)$$

it is possible to control the voltage U_2 at the end of the line for any load variation. The flow of the reactive power through the lines is accompanied by power losses, so that the choice of controlling method by modifying reactive power flow must be coordinated with the general issue of balancing reactive powers and energy losses.

The methods used to regulate the voltage by changing the reactive power flow are divided into two main categories (presented in Chapter 13):

1. rotating compensators: synchronous and asynchronous compensators, synchronous generators; and
2. static compensators.

5.1.3.3 Controlling Voltage by Changing the Impedance of the Grid

The inductive reactance of the lines can be reduced by a series connection of a capacitor bank, as presented in Figure 5.3. Reducing the inductive reactance of the grid greatly improves the voltage regime by decreasing voltage drops. If $X_L = \omega \cdot L$ is the inductive reactance of the

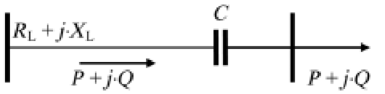


Figure 5.3 Compensating the inductive reactance of a line by placing a series capacitor bank on that line

line, then by placing a capacitor of capacitance C on the line, the resultant reactance of the line becomes:

$$X = X_L - X_c = \omega \cdot L - \frac{1}{\omega \cdot C} \tag{5.6}$$

According to the value of the reactance X_C or of the ratio $\lambda = X_C/X_L$, also called the compensation degree, the following situations are possible:

- partial compensation $X_C < X_L$, $\lambda < 1$;
- total compensation $X_C = X_L$, $\lambda = 1$;
- overcompensation $X_C > X_L$, $\lambda > 1$.

The voltage on the series capacitors is $U_C = I{\cdot}X_C$ and does not go beyond 10% of the phase voltage of the grid. This fact allows the usage, in the case of longitudinal compensation, of a capacitor with a rated voltage much smaller than the nominal voltage of the line. For example, for 110 kV, 6–10 kV capacitors are used, and in the case of 35 kV, the required range is 1–3 kV. Longitudinal compensation is not considered as a means of controlling the voltage because it is difficult to control the value of the capacitance of the capacitors installed in series according to voltage variations. Occasionally, connecting capacitors in series in the lines can lead to resonance phenomena, to self-excitation of electrical machines, or sub-harmonic oscillations. There is also an increase in possibility of resonance phenomena on the higher harmonics.

5.2 Voltage Fluctuations

Voltage fluctuation is a series of the rms voltage value changes or a cyclic variation of the voltage waveform envelope (Figure 5.4) [2]. In the case of this disturbance we can use the terms: *voltage fluctuation waveform* (the voltage peak value envelope represented as a function of time – periodic or non-periodic, determinate (seldom) or random (more often)), the *amplitude of voltage changes* (difference of the maximum and minimum rms or peak voltage values occurring during the disturbance) and the *voltage changes rate* (the number of voltage changes per unit of time) or *frequency* (for periodic waveforms).

5.2.1 Disturbance Description

Two basic methods for voltage fluctuations evaluation can be identified. The *first method* consists of the quantitative assessment of the phenomenon, based on the variation of rms value over time. In this case voltage fluctuations are represented as points in the coordinate system: relative voltage change ($\Delta U(t)/U$)-number of voltage changes per unit of time (Figure 5.5).

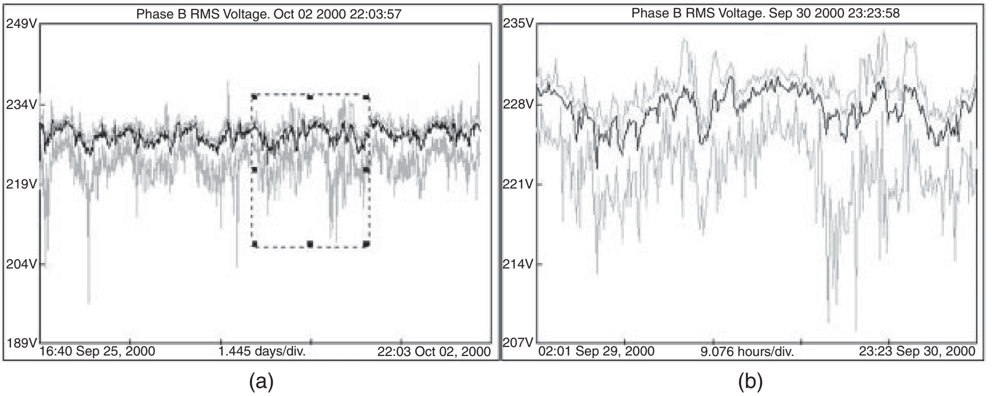


Figure 5.4 Example of (a) rms voltage fluctuation and (b) selected fragment of the waveform

Research on the visual perception of flicker caused by periodic voltage fluctuations resulted in evaluating the borderline curve of flicker severity (irritability) due to luminous flux changes.

The characteristics in Figure 5.5, prepared for different supply voltages of a light source, divide the plane into two parts. The area above the curve defines the unacceptable level of voltage fluctuation, whereas the area below the curve is relevant to acceptable levels of voltage fluctuation.

The *second method* consists of indirect measurement, i.e. measuring the phenomenon of flicker by means of a flickermeter. This instrument, where the input signal are voltage changes, instead of actual changes in the luminous flux, uses a model of the incandescent light source

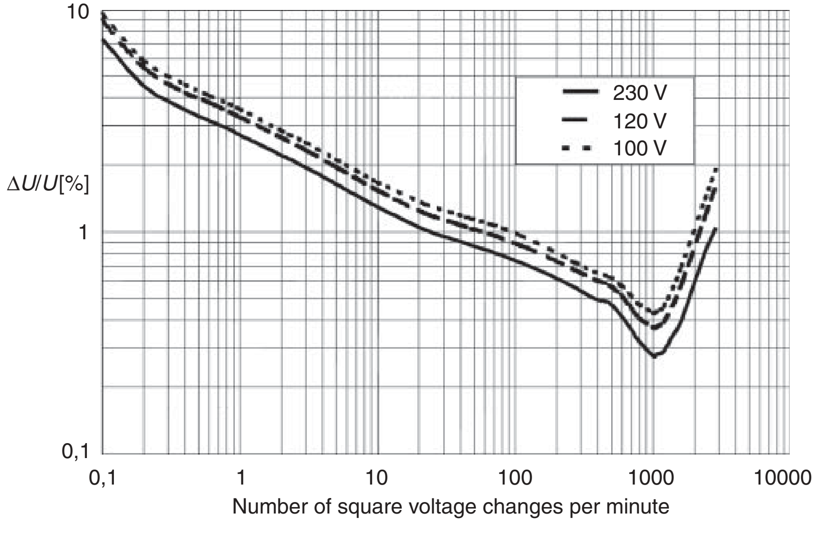


Figure 5.5 Flicker perception borderline characteristic for square-shaped, equidistant voltage changes applied to a 60 W incandescent lamp ($P_{st} = 1$)

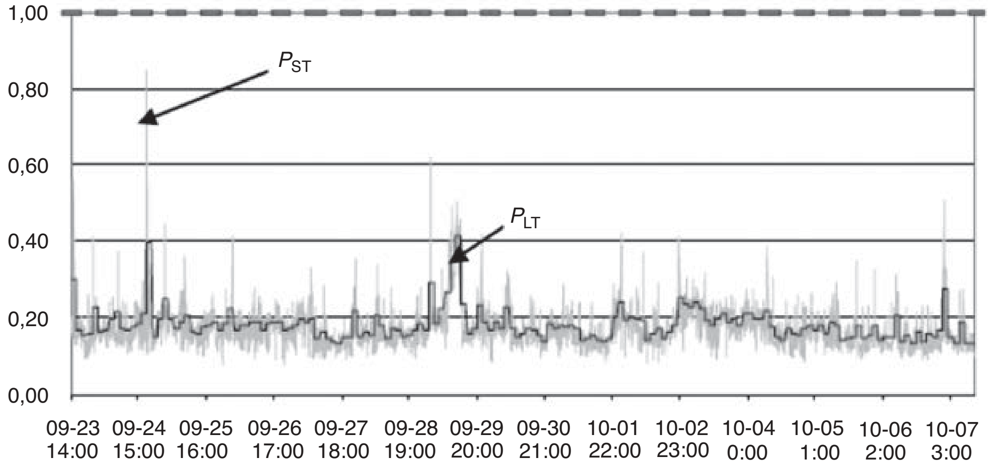


Figure 5.6 Example characteristics of P_{ST} and P_{LT} indices measured over seven days in an LV (low voltage) network

(60 W, 230 V tungsten bulb) and a model of the human reaction to light stimulus. The aim of the measurement is the evaluation of an observer's reaction – a discomfort or annoyance – to disturbance in visual perception. Two dimensionless numerical measures of voltage fluctuation are obtained at the instrument output: the short-term flicker severity index (P_{ST}) refreshed every 10 minutes and the long-term flicker severity index (P_{LT}) refreshed every 2 hours (Figure 5.6).

From at least seven-day measurements of these indices, particularly the P_{LT}, it is determined the value that has not been exceeded during a specified period of time, e.g. 95% or 99% of the measurement time (the so-called CP95 or CP99 percentile) and this value is compared with the limit value specified in standards or guides. In most European countries this value in LV networks equals one.

5.2.2 *Sources of Voltage Fluctuations*

The primary cause of voltage changes, including fluctuation, as follows from formula (5.5), is the time-variability of the load power. Such loads are mainly, but not exclusively, industrial loads with large individually rated power, particularly arc furnaces, rolling mill drives, mains' winders, welding equipment, etc. The cause of voltage fluctuation can also be frequent starts of electric motors, spot welders, boilers, power controllers, electric hammers, lifts, hoists, capacitor switching, etc. – in general, variable load whose power is large with respect to the short-circuit capacity at the point of connection to the supply. Similar influences are, e.g., X-ray equipment and large-power photocopiers used for commercial purposes.

Sources of voltage fluctuation in residential LV distribution networks can be loads whose operation implies cyclic switching on and off, like: refrigerators, washing machines, cookers, air conditioners, etc. Because of small individual powers their influence is limited only to the consumers/loads that are connected to the supply system not far from the terminals of fluctuating equipment, e.g. in one flat or house. Their adverse impact is, however, increased due to the simultaneous operation of many small loads, e.g. electric water heaters, during evening hours.

A particular source of voltage fluctuation can be mutually coupled data transmission and remote control signals (interlocks, protection systems, etc.) that occur in power networks, which are a source of interharmonics modulating the supply voltage waveform.

Voltage fluctuations occur also as the effect of switching processes in the power system (e.g. improper operation of transformer tap-changers) and operation of certain distributed energy sources, e.g. wind turbines.

A symmetrical generator with a constant load, excitation current and rotational speed, produces a constant voltage at its output terminals. If any of these quantities becomes disturbed, voltage fluctuations may occur. The rotational speed changes are dominant because the time constant of the generator excitation circuit effectively reduces the influence of the generator's flux variations on voltage changes.

In reciprocating engine-driven generators poor quality fuel or inadequate maintenance may lead to the engine's erratic ignition and, consequently, to changes in the output power.

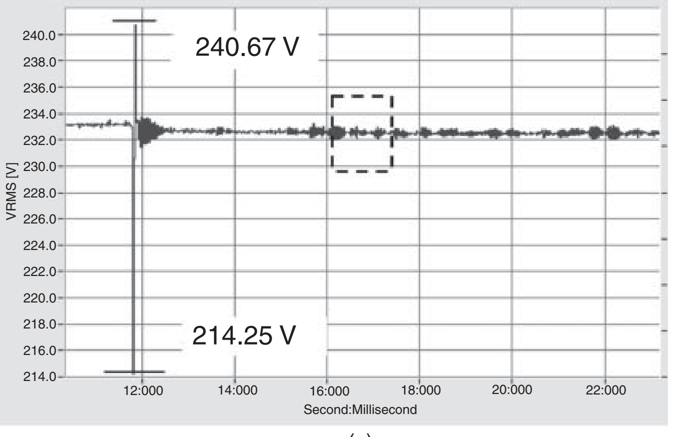
In very large, low-speed engines output torque fluctuations occur even during normal operation. The frequency of the generator output power changes with the reciprocating engine pistons strokes as: $f_F = (Nn/25k)$ Hz, where: N is the number of cylinders; n is the generator rotational speed in revolutions per minute, coefficient k takes the value of 2 for two-stroke engines and 4 for four-stroke engines [11]. During the proper operation of a reciprocating engine, even in the case of low-speed generators, the change in the output power due to the engine pistons' strokes is sufficiently fast and fluctuations do not occur. If a misfire occurs in a cylinder(s) the frequency of voltage changes in Hz can be expressed as: $f_F = (n/25k)$. In many, commonly used generators the frequency of voltage changes coincides exactly with the most unfavourable area. For instance, a four-cylinder, 900-rpm engine produces fluctuations with frequency 7.5 Hz. At 1800 rpm the situation is better – the fluctuation frequency is 15 Hz, i.e. it is located within the area of lower sensitivity of the human eye to flicker. The basic way of preventing this effect is to maintain fuel quality control and proper engine maintenance [11].

Figure 5.7 shows the waveforms of the chosen phase voltage at the output of a rotating UPS supplying an air-conditioning system. A switching process (from power network supply to UPS) and the voltage fluctuations during steady-state operation are noticeable in both the signal waveform and spectrum.

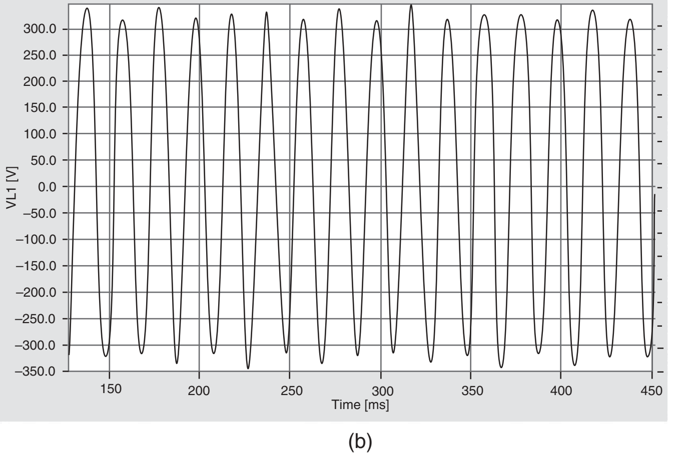
5.2.3 Effects and Cost

5.2.3.1 Light Sources

A change in the supply voltage causes a change in the luminous flux of a light source, known as the flicker effect. It is a subjective impression of the luminous flux variation whose luminance or spectral distribution undergoes changes with time [12]. This phenomenon occurs in both incandescent and fluorescent light sources, though its mechanism and frequency range, as well as the limit values of disturbing components, are different. The rectifiers in electronic



(a)



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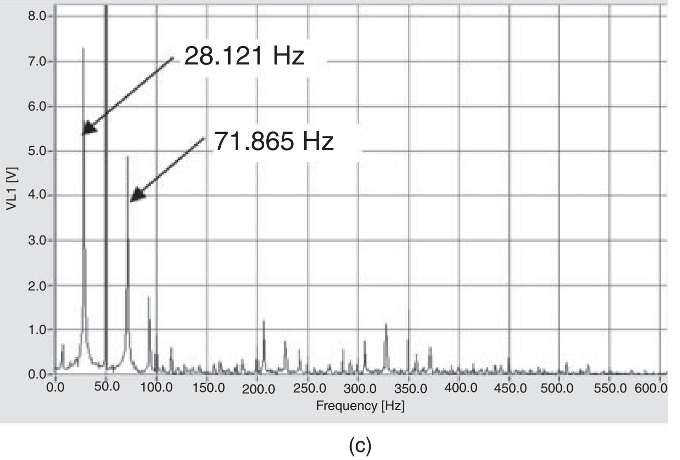


(c)

Figure 5.7 The waveforms of: (a) the chosen phase voltage rms value, (b) the instantaneous value at the output of a rotating UPS supplying an air-conditioning system and (c) the voltage spectrum

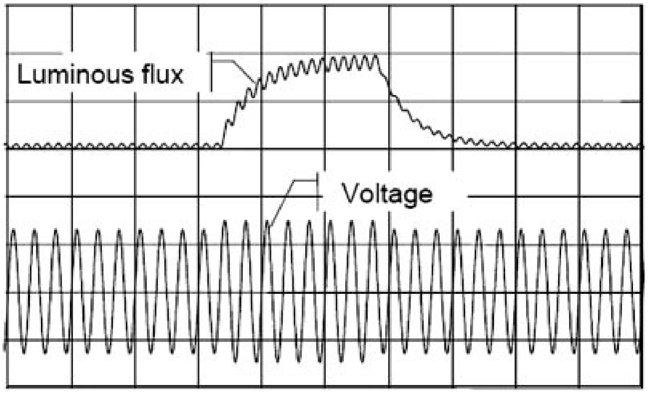


Figure 5.8 The effect of a voltage change on the luminous flux of an incandescent lamp [13]

starters transfer the instantaneous voltage value changes to the DC side, thereby changing the discharge conditions in a lamp and causing the flicker effect.

The luminous flux of an incandescent light source is proportional to the voltage according to $\Phi \sim U^{\gamma}$, where the exponent γ takes values in the interval 3.1–3.7 [12]. The exponent value for fluorescent lamps is: 1.5–1.8 [12].

Figure 5.8 shows an example of the change in luminous flux of an incandescent lamp in response to a temporary change in the supply voltage.

In low power incandescent lamps the filament temperature drops faster due to a smaller time constant, therefore such lamps are more prone to flickering (Figure 5.8).

Fluorescent lamps and present-day energy-efficient light sources are generally less sensitive to voltage fluctuation, though it is not a general rule. In this case the voltage peak value has a stronger influence on the luminous flux change than the rms value [13]. Certain solutions of electronic dimmers increase the flicker effect [14], though this rule also has its exceptions [15].

The flicker significantly impairs vision, causes general discomfort and fatigue, and deterioration in work quality. It considerably hampers reading and watching TV. Affecting the perception process and the human brain reactions, it can be the cause of work accidents and epileptic seizures. The psychophysical nature of the disturbance is complex [12].

5.2.3.2 Electric Machines

Voltage fluctuations at the terminals of an induction motor cause changes in torque and thereby in slip and, consequently, affect the production process. In the extreme case they may lead to excessive vibration, a reduction in mechanical strength and a shortening of the motor service life.

5.2.3.3 Static Converters

The supply voltage change in phase-controlled converters with DC side parameter control usually results in a reduction in the power factor and is a cause of non-characteristic harmonics and interharmonics generation. In the event of drive braking in an inverter mode, it can result in a commutation failure.

5.2.3.4 Electrolysers and Electro-Heat Equipment

In the presence of voltage fluctuations both the useful life of electrolyser equipment and the efficiency of technological process can be reduced. Elements of the high-current line become significantly degraded, increasing maintenance and/or repair costs. The efficiency of electro-heat equipment is reduced in every case – in an arc furnace as the result of a longer melt time, but generally these effects are noticeable only when voltage fluctuation amplitude is considerably large.

5.2.4 Mitigation Methods

The effects of voltage fluctuations depend first on their amplitude and their rate of occurrence. Whereas the amplitude is influenced, among other things, by the power system supplying fluctuating loads, the rate of changes depends upon the load type and its mode of operation. The rate of their occurrence is determined by the technological process. So far mitigation measures are focused on limiting the amplitude of voltage fluctuations; the technological process is influenced to a lesser extent. Example of these measures, in the case of an arc furnace, can be: a series reactor (also a controlled saturable reactor), proper functioning of the electrode control system, segregation and initial preparation of charge, admixing electrode material, etc. – methods well known to the steel-making process engineers. In the case of wind turbines it is a reduction of the number of switchings by keeping the turbine in standstill condition until the wind reaches a steady speed that is greater than the turbine start-up speed.

As follows from (5.5), the amplitude of voltage fluctuations – after modifications to the technological process (if possible) – can be limited in two ways:

1. *increasing the short-circuit power* (with respect to the load power) at the point of a fluctuating load coupling; practical means include: (a) connecting the load to higher nominal voltage system bus bars; (b) supplying this category of loads directly from a high voltage system through dedicated lines, supplying fluctuating loads and steady loads from either separate windings of a three-winding transformer or from separate two-winding transformers (separation of a fluctuating load); (c) supplying the fluctuating load from a transformer of a larger rated power or/and lower short-circuit voltage; (d) installing series capacitors, etc.;
2. *reducing reactive power changes* in the supply network by means of the so-called dynamic voltage compensator/stabilizer (Chapter 13).

A separate category of measures is the improvement of the loads' immunity to voltage fluctuations [16].

5.3 Voltage and Current Unbalance

Synchronous generators are the sources of a three-phase voltage in a power system. The voltages at the generator phase terminals are equal in magnitude and displaced from each other by 120°. This vector system is called symmetrical. If individual phases of the system are equally loaded the currents also form a symmetrical vector system. In such conditions, if the components of the power system are linear and symmetrical, the voltages measured at load buses during normal system operation remain symmetrical.

5.3.1 Disturbance Description

In practice, it is not possible to obtain the full symmetry at all nodes of the power system. A condition in which the three-phase voltages in three-phase systems are not equal in magnitude and/or the displacement angles between them are different from 120° is defined as voltage unbalance. The analogous definition is applied to currents.

For the analysis of unbalance the method of symmetrical components is commonly applied. The method was introduced to calculations of electric power systems at the beginning of the 20th century. The main idea of it consists in the substitution of any three-phase unsymmetrical vector system of currents or voltages with the sum of three three-phase positive-, negative- and zero-sequence symmetrical systems. The equations for the respective symmetrical sets of voltage may be written as follows:

$$\text{positive-sequence system (1) } \underline{U}_{1A} = \underline{U}_{1A} \quad \underline{U}_{1B} = a^2\underline{U}_{1A} \quad \underline{U}_{1C} = a\underline{U}_{1A} \tag{5.7a}$$

$$\text{negative-sequence system (2) } \underline{U}_{2A} = \underline{U}_{2A} \quad \underline{U}_{2B} = a\underline{U}_{2A} \quad \underline{U}_{2C} = a^2\underline{U}_{2A} \tag{5.7b}$$

$$\text{zero-sequence system (0) } \underline{U}_{0A} = \underline{U}_{0B} = \underline{U}_{0C}, \tag{5.7c}$$

where a is the rotational operator: $a = \exp(j2\pi/3) = -0.5 + j\sqrt{3}/2$. The respective phase voltage is the sum of relevant components:

$$\begin{aligned} \underline{U}_A &= \underline{U}_{1A} + \underline{U}_{2A} + \underline{U}_{0A} \\ \underline{U}_B &= \underline{U}_{1B} + \underline{U}_{2B} + \underline{U}_{0B} = a^2\underline{U}_{1A} + a\underline{U}_{2A} + \underline{U}_{0A} \\ \underline{U}_C &= \underline{U}_{1C} + \underline{U}_{2C} + \underline{U}_{0C} = a\underline{U}_{1A} + a^2\underline{U}_{2A} + \underline{U}_{0A}. \end{aligned} \tag{5.8}$$

The symmetrical component method, when applied to describe a three-phase circuit, allows the diagonalizing of the impedance matrix, which eliminates the couplings between phases and significantly simplifies the analysis of the circuit. A detailed description of the method is given in [2].

The unbalance factor K is commonly taken as a measure of unbalance. It is the ratio of the negative- and/or zero-sequence component to the positive-sequence component of voltage (current) of any phase:

$$K_{2U} = \frac{U_{2(1)}}{U_{1(1)}}100\% \quad K_{0U} = \frac{U_{0(1)}}{U_{1(1)}}100\% \qquad \left(K_{21} = \frac{I_{2(1)}}{I_{1(1)}}100\% \quad K_{01} = \frac{I_{0(1)}}{I_{1(1)}}100\%\right). \tag{5.9}$$

The subscript (1) in the formulae above denotes that definitions are referred to the first harmonic.

The negative-sequence component generated by multi-phase loads is very important for the description of unbalance. It is transformed by a transformer irrespective of a windings connection, similarly to that in the case of the positive-sequence component. The zero-sequence component is normally present only in low-voltage (LV) networks, and the delta-connected transformer prevents it from transferring to the network of a higher voltage.

According to the definition, the amplitudes of the positive and negative-sequence voltage components must be known for determination of the unbalance factor. In [17–20] the relations are given that allow the calculation of the unbalance factor making use of measurements of rms values of line and phase voltages.

Most international standards and documents are in agreement on the definition of the unbalance phenomenon and its parameters. The compatibility level for LV and MV systems is 2%, and under special conditions 3% [18, 21–23].

5.3.2 Sources

Unbalanced operating conditions in an electric power system are mainly caused by the operation of unbalanced loads. Most low-voltage loads and certain medium-voltage ones, e.g. an electric traction, are single-phase appliances. The operation of such equipment in a three-phase system results in unbalance of load currents. Consequently, unsymmetrical voltage drops in individual phases of the supply system are produced, thus the voltage at nodes of the network becomes unbalanced.

Three-phase loads that may introduce unbalance to the power system are arc furnaces. The disturbance results from different impedances of high-current paths of the furnace and not equal phase loads, this being the effect of the physical nature of the melting process, i.e. variations of the arc impedance.

As arc furnaces are devices of relatively large power (tens or even hundreds MVA), the furnace load unbalance may result in significant voltage unbalance in the supply system.

The sources of unbalance can also be the three-phase components of the transmission system, in particular, overhead lines. Owing to different towers geometries, the conductors of individual phases are not simultaneously at the same location to each other and to earth. Following this, the line has different values of phase parameters, so the values of a voltage loss in individual phases are also different.

5.3.3 Effect and Cost

5.3.3.1 Power System

The negative-sequence and zero-sequence currents flowing in an electric power system result in technical and economical effects:

- additional losses of power and energy;
- additional heating, the consequence of which is the limitation of line transmission – capability for positive-sequence currents;
- voltage unbalance at nodes of the network that affects the operation of equipment.

Additional power and energy losses are the main effects of current unbalance in three-phase four-wire LV grids where the number of single-phase loads is significant. Under unbalance conditions the sum of the phase current vectors is not equal to zero and the resultant current flows through neutral wire. Active power losses are then expressed by:

$$\Delta P_{\mathrm{un}} = \left(I_{\mathrm{A}}^2 + I_{\mathrm{B}}^2 + I_{\mathrm{C}}^2\right) R_{\mathrm{L}} + I_{\mathrm{N}}^2 R_{\mathrm{N}}, \tag{5.10}$$

where I_{A}, I_{B}, I_{C} are phase currents, I_{N} is the current flowing through neutral, R_{L} and R_{N} are phase and neutral wire resistances, respectively. Additional losses are proportional to the neutral current I_{N}.

As an example, let us consider the current unbalance caused by the difference in current amplitudes in one phase, phase C. Assuming, that $\underline{I}_A = I$, $\underline{I}_B = a^2\underline{I}_A = a^2 I$ and $\underline{I}_C = ak\underline{I} = akI$, where $0 < k < 1$, it can be easily proved that the neutral current $I_N = (1-k)I$. The unsymmetrical current vector system can be substituted by symmetrical components:

$$\underline{I}_1 = \frac{1}{3}\left(\underline{I}_A + aI_B + a^2\underline{I}_C\right) = \frac{1}{3}(2+k)\underline{I} \quad I_2 = \frac{1}{3}\left(\underline{I}_A + a^2\underline{I}_B + a\underline{I}_C\right) = \frac{1}{3}(k-1)a^2 I$$

$$\underline{I}_0 = \frac{1}{3}(\underline{I}_A + \underline{I}_B + \underline{I}_C) = \frac{1}{3}(k-1)aI. \tag{5.11}$$

The active power losses in the line wires can be calculated using sequence components according to (5.12):

$$\Delta P = 3I_1^2 R_P + 3I_2^2 R_P + 3I_0^2 R_P + 91_0^2 R_N, \tag{5.12}$$

where R_p and R_N are the resistances of the phase and neutral wire, respectively. Taking into account (5.11) and assuming that $R_p = R$ one can obtain

$$\Delta P = I^2 R(2k^2 - 2k + 3) \tag{5.13}$$

To analyse the impact of unbalance, power losses are compared with the losses calculated for positive-sequence currents:

$$\Delta P_1 = I^2 R\left(\frac{1}{3}k^2 + \frac{4}{3}k + \frac{4}{3}\right) \tag{5.14}$$

Figure 5.9 shows the losses ΔP in relation to ΔP_1 as a function of ratio I_N/I_1 for different ratios of phase wire cross-section to neutral wire cross-section s_p/s_n. This simple example illustrates

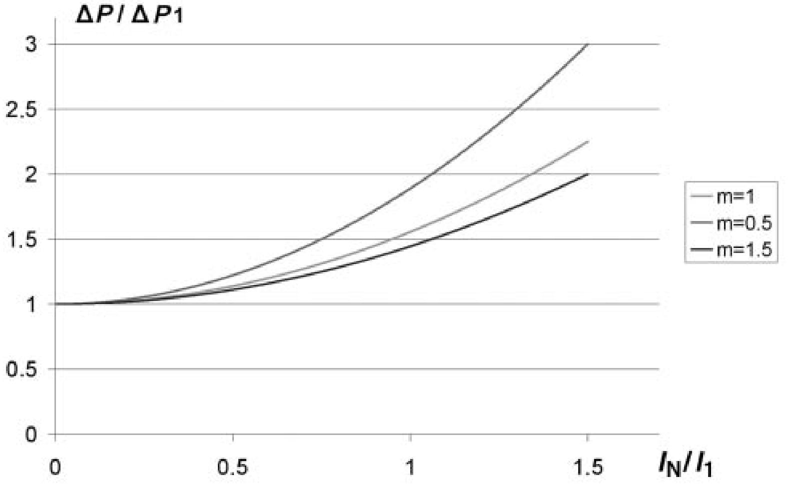


Figure 5.9 Increasing active power losses in three-phase four-wire line as a result of current unbalance, where $m = s_P/s_n$

the negative impact of unbalance on power and energy losses and thus on the efficiency of power delivery. Increasing neutral cross-section can be a means for the losses' reduction.

5.3.3.2 Asynchronous Motors

Asynchronous motors have their windings connected usually in a delta or star with an isolated star point. For this reason the operation of a motor is affected only by the positive-sequence and the negative-sequence component. The negative-sequence currents create a flux rotating in the direction opposite to the rotor. This flux causes:

- increased heating of the stator windings;
- additional losses of active power in the stator;
- additional torque operating in the opposite direction to the torque produced by the positive-sequence flux;
- inducting additional currents in the windings and rotor iron of a motor, and thereby additional power losses in the rotor.

The motor current under unbalance conditions can be several times higher than the rated current. Long-lasting unbalance can cause the motor insulation to deteriorate more quickly and its life shortened. Motors may be equipped with protections, which detect an overcurrent and can cause them to switch off.

Additional power losses due to the unbalance of a supply voltage reduce the maximum power of the motor to an extent that is dependent on the degree of unbalance, the type of the motor, and its construction.

A negative-sequence torque causes a reduction of the useful torque of the motor. Moreover, in the case of unbalance of the supply voltage, additional vibrations of the motor are produced, also resulting in a shortening of its service life.

Laboratory tests have shown that most asynchronous motors are not affected by a supply voltage unbalance of 2%, which is accepted as the limit value.

5.3.3.3 Synchronous Generators

Load unbalance mainly affects the operation of generators in industrial heat and power stations supplying distribution grids. Generators of commercial power stations are located at some distance from unbalanced loads and thus, in this case, a load unbalance is of no importance.

Analysis of the effects of a load unbalance for synchronous generators can be limited to the negative-sequence component, because generators are connected to a system through transformers, in which on one side the windings are connected in delta preventing zero-sequence currents from entering the generator.

Negative-sequence currents generate a magnetic flux in the machine, rotating in the direction opposite to the rotational direction of a flux generated by positive-sequence currents. Similarly to the asynchronous motors, this flux affects the rotor and the stator of a generator; it induces eddy currents, increases heating and power losses. The negative-sequence flux also produces additional mechanical forces acting on the rotor and the stator of a generator, which are hazardous to the strength of structural components.

The fundamental criterion for evaluating the permissible operation of a generator under unbalanced conditions is the additional heating of the rotor.

In general, unbalanced loads are not a great problem for the operation of synchronous generators; unbalance may cause more severe hazard during disturbances, for example, during unsymmetrical short-circuits.

5.3.3.4 Static Rectifiers

Converter equipment in most cases is supplied from a three-phase three-wire system, thus its operation can be affected only by the negative-sequence component of the voltage. It generates:

- an additional variable component of a rectified voltage (current) whose amplitude depends on the unbalance factor,
- harmonics that are non-characteristic for the given topology of a converter and interharmonics [24].

5.3.3.5 Other Loads

Unbalance can also affect the operation of other three-phase loads, changing the electric power, exploitative characteristics and their service life. Moreover, voltage unbalance associated with the change of voltage magnitude has an effect on the operation of single-phase loads. Some of them may be under the influence of a supply voltage that is too high or too low. Disturbances can also occur in the functioning of control systems, resulting in a disturbance and even an interruption of the operation of equipment.

5.3.4 Mitigation Methods

The unbalance of power system components is eliminated by a suitable design thereof. In the case of overhead lines, a transposition of conductors is applied for this purpose. The line is divided into sections, the number of which is divisible by 3, with three sections forming one transposition cycle. In each section the conductor of a given phase is routed at a different position to the other phases, which causes the line, taken as a whole, can be considered as a symmetrical one.

The methods for unbalance mitigation primarily concern balancing the load. The traditional approach to load balancing is to connect nominal loads evenly to each phase. Normally this is sufficient, so that severe unbalance of voltage does not appear very frequently. Where significant load unbalance is unavoidable, particularly in the case of large single-phase loads, special balancing equipment for disturbance compensation should be applied. The purpose of this is usually the elimination or limitation of the negative-sequence and zero-sequence components of the load currents. This process is called balancing.

5.3.4.1 Principle of Balancing

In three-phase medium-voltage (MV) systems, which usually operate as isolated or compensated ones, unbalanced loads are connected to a line voltage. In this case, there is no zero-sequence component of currents, so the balancing resolves itself into the elimination or limitation of the negative-sequence component. LV grids are four-wire earthed neutral systems, so there the negative-sequence as well as the zero-sequence component is present.

A balancing device (BD) is connected in parallel with the unbalanced load (UL) (Figure 5.10). This equipment causes the currents $\underline{I}_{Ak,}$ $\underline{I}_{Bk}$, $\underline{I}_{Ck}$ to flow, which added to the load currents $\underline{I}_{Al}$, $\underline{I}_{Bl}$, $\underline{I}_{Cl}$ result in the symmetrical set of the source currents $\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$.

There are a variety of systems for balancing load currents that differ in the number and type of elements and the art of connection. Comprehensive information on this can be found in [25]. BDs accomplish their tasks at a constant value of loads. For time-varying loads, such as electric traction or arc furnaces, a follow-up compensation is necessary. This kind of compensation is implemented through:

- *Shunt compensators* (**s**tatic **V**Ar **c**ompensators – SVC e.g. TCR, FC/TCR, STATCOM, Chapter 13). Connected to a node of an electric power network, they may be considered as a controlled parallel susceptance. Balancing is one of the tasks that can be accomplished by these devices. They are usually also applied for the compensation of reactive power or the limitation of voltage fluctuations and a light flicker phenomenon. The idea of compensation is to control currents or voltages in such a way as to minimize the negative- and zero-sequence components.
- *Series connected compensators* applied for mitigation of the supply voltage unbalance. The purpose of the system is to generate, for instance by means of a PWM converter, the boosting voltage $\underline{U}_b$ whose value and phase in relation to the source voltage $\underline{U}_s$/current $\underline{I}$ are regulated. The converter can be considered as a voltage source represented on the *dq* plane by two orthogonal components with regulated values:
  - ○ component U_{bd} (in phase or in opposite phase in relation to a line current) decides the exchange of active power between a supply system and a compensator,
  - ○ component U_{bq} (orthogonal to a line current) decides the value (also the character) of a series compensator reactive power.

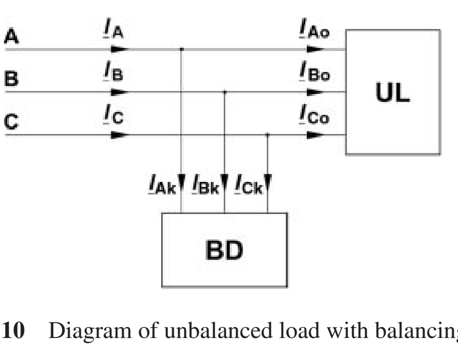


Figure 5.10 Diagram of unbalanced load with balancing device

5.4 Voltage and Current Distortion

The component parts of a power system are designed to work in a sinusoidal condition, where the curves of the voltage and electrical currents in the circuit have a sinusoidal waveform with the same frequency as the nominal frequency. In reality, nowadays in most of the nodes of the power system, the waveforms of currents and voltages present distortions from a sinusoidal curve [2, 7, 24].

The periodical deviation from the sinusoidal shape of the electric current or voltage waveforms is called distortion or deformation.

The distortion is produced by the non-linearity of the components of the power system. The nonlinear characteristics of the user's loads are the most frequent source of distortions in the curve of the electrical current; distorted currents lead to distortions in the curve of the power supply voltage. With the development of command and control systems using power semiconductors, the sources of distorted currents became widely spread; their presence in the power system led to supplementary actions to identify disturbance sources, to assess the disturbance levels and effects, and to implement actions that could limit the damages caused by them, both in the electrical grid, as well as in the case of consumers connected to a harmonic polluted grid.

In order to assess the effects of the distortion of both electrical currents and voltages, special attention should be paid to establishing suitable indices that define the distortion level and their admissible values.

5.4.1 Disturbance Description

According to the theory elaborated by Fourier, in the case of periodic signals, the distorted curves can be regarded as an overlapping of a number of sinusoidal oscillations with frequencies that are an integral multiple of the fundamental frequency. In such conditions, an analysis of the distorted curves can be done in the frequency area, by evaluating the characteristic values of the component oscillations. This evaluation method is nowadays widely used and is the basis for all methods used today in measuring, analysing and evaluating various methods of limiting the distortion level.

Figure 5.11 presents a distorted waveform and the harmonic spectrum that compose it. Using the Fourier series, any periodic distorted signal can be decomposed under the form:

$$u(t) = U_0 + \sum_{k=1}^{\infty} U_k \cdot \sqrt{2} \cdot \sin(k \cdot \omega_1 \cdot t + \alpha_k), \tag{5.15}$$

where U_0 is the constant component of the signal, U_k is the r.m.s. value of the k-th harmonic, and α_k is the phase angle of the k-th harmonic from a reference axis.

Taking into account the fact that, in an electrical grid, the condition for a phenomenon to become periodical is not always being met, the use of (5.15) is allowed only on such intervals in which the electric quantities can be regarded as periodic. Based on this decomposition, a series of indices are used to define the spectral components of the distorted curve. Any index on the frequency domain cannot unequivocally characterize a distorted curve, which means

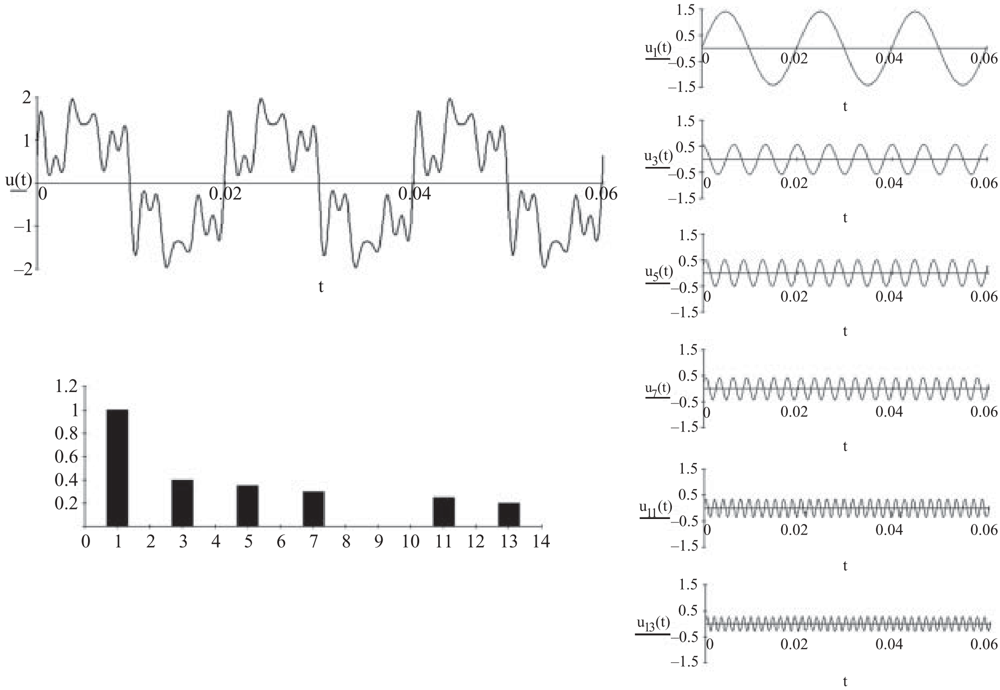


Figure 5.11 Distorted curve and the harmonic spectrum that comprises it

that several indices should be used. Table 5.1 presents the main indices used to characterize the distortion state [2,3,26,27].

The harmonics standardization process can be considered as quite complete since this problem has already been studied for several decades. On the other hand, the same cannot be said about the interharmonics standardization process, which is work in progress, with knowledge and measured data still being accumulated.

Standards prescriptions define the limits on voltage supply, measurement method and instruments, mitigation process, etc. The main IEC standards dealing with harmonics and interharmonics are presented in [2]. The essential standards regarding the harmonics are EN 50160 [21], IEEE 519-1992 [28] and IEEE 1159-2009 [29].

5.4.2 Sources

The presence of distortion sources in the power system determines the creation and distribution of deformed curves of voltages or electrical current into the electrical grids. In practice, most common distortions have frequencies from just a few hertz to almost 10 kHz.

Table 5.2 presents some of the most important distortion sources for power systems, their ranks and the amplitude of harmonics that they generate [3,26,30].

Table 5.1 The main indices of the distortion state

Index	Calculation	Observations
R.m.s. value	$U = \sqrt{\frac{1}{T} \cdot \int_0^T u^2 \cdot \mathrm{d}t}$	u defines the voltage variation in time, and T the integration interval.
Average value for half a period	$U_{med1/2} = \frac{2}{T} \cdot \int_0^{T/2} u \cdot \mathrm{d}t$	This expresses the DC voltage that can be obtained after the rectification of an alternative signal during a period T.
Peak factor	$k_v = \frac{u_M}{U}$	u_M is the maximum value of the periodical non-sinusoidal curve. The peak factor can have the following values: • in the case of a sinusoidal curve, $k_v = \sqrt{2}$; • in the case of a sharp curve, $k_v > \sqrt{2}$; • in the case of a flattened curve, $k_v < \sqrt{2}$. The voltage curves characterized by a peak factor $k_v > \sqrt{2}$ can determine dangerous overloads for the electrical equipment insulation.
Form factor	$k_f = \frac{U}{U_{med1/2}}$	The form factor can have the following values: • for a sinusoidal curve, $k_f = 1.11$; • for a periodical curve more pointed than a sinusoidal form, $k_f > 1.11$; • for a periodical curve more flattened than a sinusoidal form, $k_f < 1.11$.
Harmonic level	$\gamma_k = \frac{U_k}{U_1}$	The harmonic level is an important index when evaluating the distortion level, the norms giving the maximal admissible values for the voltage curve within the nodes of the power system.
Distortion (harmonic) content	$U_d = \sqrt{u^2 - U_1^2} \cong \cong \sqrt{U_0^2 + U_2^2 + Y_3^2 + \ldots}$	The distortion content is a measure of the thermal effect created by the harmonic components of the distorted signal.
Distortion factor	$THD = \frac{U_d}{U_1}$	The distortion factor, *THD*, is one of the indices used to evaluate the maximum level of distortion; its maximum allowed values in the nodes of power system are indicated by norms.

5.4.3 Effects and Cost

The greater importance of the nonlinear elements in the power systems, both in terms of installed capacity as well as in terms of types of equipment, leads to an increase in their harmonic pollution levels and to an increase of negative effects determined by the presence of harmonics in the electric grid. These effects can be classified into two main categories, according to the information presented in Table 5.3.

Table 5.2 Pollution sources for the energy systems

Distortion source	Rank and amplitude of harmonics they generate
• Controlled or semi-controlled single-phase rectifiers (full bridge) with resistive charge or filtered current, practically continuous when exiting the rectifier • AC power controller with resistive load • Home appliances.	• Odd rank harmonics • The amplitude of the harmonics decreases with the increase of their rank • The disappearance of certain frequencies for various values of the thyristor phase angle, in the case of semi-controlled or controlled rectifiers.
• Single-phase rectifiers (half-bridge) with a resistive charge or filtered current, basically continuous upon exit.	• Odd and even rank of harmonics • The amplitude of the harmonics decreases when the rank increases.
• p-pulse rectifiers	• $k = m \cdot p \pm 1$ ($m = 1, 2, 3 \ldots$) harmonics • the amplitude of harmonics decreases together with their rank, approximately according to the relation: $$I_k = \frac{I_1}{k^{1,2}},$$ where I_1 is the rms value of the fundamental and k is the harmonic rank • The disappearance of certain frequencies for various values of the thyristor phase angle in the case of semi-controlled converters.
• Saturated universal electrical motors • Fluorescent tubes	• Odd harmonics • The amplitude of the 3rd harmonic is below 15% of the fundamental one • The rapid decrease of the amplitude of the harmonics when their rank increases • The appearance of even harmonics during heating up.
• Automatic washing machines	• Odd harmonics • Even harmonics when rectifying only one half-wave • Decreasing amplitude when the rank of harmonic increases.
• Colour television sets	• Systems using the rectification for both half-waves ○ Odd harmonics ○ The amplitude of the 3rd current harmonic may reach 80% of the fundamental amplitude of the supply current ○ The amplitude of the harmonic decreases with the increase of its rank • Systems using rectification for a single half-wave: ○ Odd and even rank harmonics; ○ The amplitude of the 2^{nd} current harmonic is below 45% of the fundamental amplitude of the electric current; ○ The amplitude of harmonics decreases with the increase of their rank.

Table 5.2 (*Continued*)

Distortion source	Rank and amplitude of harmonics they generate
• Electric ovens	• Odd and even rank harmonics • The amplitude of the 2nd current harmonic, about 5% from the fundamental amplitude of the electric current • The amplitude of the harmonics decreases with the increase of their rank.
• Static compensators for electric arc furnaces	• harmonics of rank 5, 7, 11, 13, . . . • the amplitude of the 5th current harmonic is below 20% from the fundamental electric current amplitude • the amplitude of the harmonics decreases as their rank increases.
• Electric locomotives with single-phase rectifiers	• Odd harmonics • The amplitude of the 3rd current harmonic is below 20% from the fundamental electric current amplitude • The amplitude of the harmonics decreases as their rank increases.

5.4.3.1 The Decrease of Energy Efficiency in Power Systems

The flow of harmonic currents through the elements of the electric grid produces an increase of active power losses in the conductive, magnetic and dielectric materials [2]. The supplementary power losses in the conductor material are generated by the harmonic currents that pass through the elements of the electric grid, as well as by the increased electric resistance of these elements (the latter is influenced by the skin and the proximity effects).

Assuming continuous component neglect, these losses can be calculated from the equation [6, 7]:

$$\Delta P = 3 \cdot \sum_{k=1}^{\infty} R_k \cdot I_k^2, \tag{5.16}$$

Table 5.3 Classification of negative effects produced by the harmonic distortion

Technical point of view	Economic point of view
• The system components are sensitive either to the harmonic currents (Joule losses, disturbances in the audio frequency), or to the deformed voltages (losses in the magnetic circuits and dielectric materials; over-voltages that, in certain cases, can be above the permitted levels). • The proper operation of some equipment is affected by the presence of voltage and/or current harmonics (control systems, equipment that are synchronized with the voltage of the grid, etc.).	• There are increased manufacturing expenses in order to limit the specific non-linearity of various equipment or in order to increase the immunity levels to disturbances (the equipment should comply with imposed immunity norms). • There is an increase in operation expenses for preventive or corrective maintenance. • There is an increase in electric energy production costs and generally an increase in investments in the power systems due to the over-sizing of the grid elements.

where I_k is the rms value of range k harmonic current; R_k is the electrical resistance of the element, calculated for harmonic frequency of rank k. An element crossed by alternating current presents an electrical resistance, $R_{a.c.}$, calculated as:

$$R_{\text{a.c.}} = R_{\text{d.c.}} \cdot (1 + r_s + r_p), \tag{5.17}$$

where $R_{d.c.}$ is electrical resistance in DC; r_s is the factor taking into account the skin effect; r_p is the factor taking into account the proximity effect. Assuming that the resistance R does not vary with frequency and the DC component is zero:

$$\Delta P = 3 \cdot R \cdot \sum_{k=1}^{\infty} I_k^2 = 3 \cdot R \cdot I_1^2 \cdot \left(1 + THD_I^2\right), \tag{5.18}$$

where THD_I is the total harmonic distortion of the current.

Equation (5.18) shows that the active losses in conducting elements can greatly increase if the system is functioning in non-sinusoidal condition rather than the sinusoidal condition.

The losses in the magnetic materials are determined by the hysteresis phenomenon and/or eddy currents. The losses in the dielectric materials are mainly located in the dielectric of the capacitors and in the insulation of overhead and underground electric lines. Losses are produced by the active component of the electric current and by the insulation resistance of the dielectric material and their value depends on the value of the loss angle on the k-th harmonic.

5.4.3.2 Skin Effect

The skin effect is the tendency of alternating current to flow on the outer surface of a conductor. This effect is more pronounced at high frequencies; in fact it is normally ignored because it has very little effect at power supply frequencies, while above approximately 350 Hz (the seventh harmonic and above), it becomes significant, causing additional loss and heating. The AC resistance to DC resistance ratio is dependent on r/δ where r is the conductor radius and δ is the current penetration thickness, which can be expressed as $\delta = (2\rho/\omega\mu)^{1/2}$, where μ is the magnetic permeability (H/m); ω the frequency (rad/s); and ρ the resistivity (Ω mm^2/m). It is evident that δ is dependent on the frequency; in particular it decreases as frequency increases [2].

5.4.3.3 Over-Voltages in the Power Grid

The increase of voltage in the nodes of electric grids or at the terminals of various equipment can be determined by the resonance on a voltage harmonic or by the increase of the potential of the neutral point in the case of star-connected transformers or three-phase receivers.

5.4.3.4 The Increase of the Neutral Point Potential in the Case of Star Connections

A well balanced load or a downward three-phase transformer connected to a balanced three-phase electric grid, with sinusoidal voltages on a fundamental frequency, has the neutral point potential equal to zero with reference to the ground if it presents a star connection. If the electric grid is affected by a non-sinusoidal periodical state, the equipment terminals will receive a harmonic voltage, which determines on the neutral point a potential with reference to the ground and which has a value that depends on the ratio between the harmonic impedance of the active phase and that of the neutral circuit.

5.4.3.5 Overcharging the Neutral Circuit of Three-Phase Grids

In the case of balanced electric grids with four conductors, the existence of harmonic currents determines the flow of a harmonic current through the neutral conductor, obtained by summing up the triplen harmonics. The harmonic current $3k$ is placed over that determined by a likely current unbalance; as a result, an overheating of the conductor is possible, especially since its cross-section – in regular constructions – is inferior to that corresponding to the conductors on the active phases. The problem of the overheating of the neutral circuit appears especially in low-voltage distribution networks, where a large percentage of the consumers are computers and lighting installations with gas and metallic vapour discharge; they are characterized by a high value of the 3rd harmonic (its value may reach 80%), so that in the neutral conductor high current will flow. As this conductor has no protective devices, the risk of overheating and fire might prove to be important.

5.4.3.6 Effects on Three-Phase Transformers

The operation of three-phase transformers in harmonic polluted electric grids can have the following consequences [7]:

- an increase of the active power losses in the conductor materials due to the increase of the winding's electric resistance for different current harmonics;
- an increase in the losses of magnetic materials in the presence of higher harmonics due mainly to the increase of the losses through eddy currents;
- the increase in the electric stress of insulations, determined both by the maximal value of the terminal voltage and its variation speed;
- additional mechanical stresses;
- the increase in the value of the distortion factor of the electric current in case of operation in the nonlinear portion of the of the magnetization curve (due to overcharge, a state that can be determined just by the harmonic pollution; in this case it is possible that a reduced voltage harmonic level generates a high level of current harmonics).

The main effect of an electric transformer functioning in a non-sinusoidal state is represented by the increase in temperature due to the supplementary losses in the windings and core. To avoid heating above the maximum temperature allowed by the manufacturer, a reduction of charge is required, i.e., applying *a depreciation factor of the nominal power*:

$$S = k_t \cdot S_{\mathrm{N}} \tag{5.19}$$

where S is the apparent power in the non-sinusoidal state and S_N is the nominal power of the transformer. The depreciation factor k_t can be determined using the relation:

$$k_t = \frac{1}{\sqrt{1 + 0.1 \cdot \sum_{k=2}^{\infty} \left(\frac{I_k}{I_N}\right)^2 \cdot k^{1,6}}} \tag{5.20}$$

in which I_N is the rated current of the transformer and I_k is the rms value of the rank k harmonic.

5.4.3.7 The Effects on the Operation of Rotating Machines

The main negative effects that appear in the case of electric rotating machines, determined by the harmonic pollution of the grid to which they are connected, are:

- an increase in temperature of the windings and magnetic core due to additional losses in the conductive and magnetic materials;
- changes in the torque of the electric machine, leading to a reduction in its efficiency;
- the presence of oscillations of the running torque of the shaft of the electric machine, thus contributing to the ageing of the material and extra vibrations;
- changes in the magnetic induction in the machine gap due to the higher rank harmonics;
- interactions between the magnetic flux determined by the fundamental harmonic and the magnetic flux determined by the superior harmonics.

A specific problem appears in the case of variable speed drives (VSD), where the electric motors are fed by means of frequency static converters. They (except those that contain PWM controlled inverters) create a highly distorted voltage that can lead to heavy thermal and mechanical wear in the motor. All these cases require an analysis of the practical possibilities that can reduce the distortions and the motor wear.

5.4.3.8 The Effects of the Non-Sinusoidal Periodical State on Electronic Equipment

Electronic equipment used in control systems is generally powered by a sinusoidal voltage, but they themselves could represent distortion sources for the grid to which they are connected, due to the specific way in which they change the controlled values (phase control, time control, etc.). When a non-sinusoidal voltage is applied to the terminals of these devices, the technical characteristics of the installation are altered and this could lead to negative consequences on the control and operation of the equipment.

Harmonic pollution affects electronic devices in several ways, the main ones being as follows:

- the possibility of multiple zero crossings of the voltage curve as a result of harmonic distortion represents a problem because a large number of electronic circuits are operated based on synchronization with the zero crossing of the grid voltage;
- the amplitude of the voltage curve and the value of its peak must be taken into account because some electronic sources use this information to charge the filter capacitor. However,

the presence of harmonics may determine the increase or reduction of the voltage in the grid; therefore, the voltage given by the source is modified, even if the rms value of the input voltage equals the rated value. The operation of the devices supplied by the source is affected starting from an increased sensitivity to voltage dips up to significant misoperation. In order to avoid such an effect, some computer manufacturers limit the peak values to $k_v = \sqrt{2} \pm 0.1$ and others demand that the total distortion factor should not be more than 5%;
- interharmonics and subharmonics can affect the operation of displays and television sets by modulating the amplitude of the fundamental frequency. In the case of such components, for levels above 0.5%, some periodic changes in the image may appear (for cathode tubes).

5.4.3.9 Effects on Capacitor Banks

In the case of three-phase electric grids, in which higher harmonics appear, the capacitor banks belonging to filters or installations used for power factor correction are subjected to the following overloads:

- extra heating due to dielectric losses;
- long-lasting overcharges due to the amplification of the pollution level;
- resonance phenomena (of voltage or current) that have an amplifying effect on already existing system harmonics: in the case of a series resonance, there is an increase in the value of the current on that particular harmonic and of voltages on the components of the resonant circuit; in the case of a parallel resonance, there are overcharges in the voltage in the system and high currents in the capacitors.

5.4.3.10 Economic Damages

The presence of harmonics in the electric grid causes damage due mainly to [7]:

- the increase in manufacturing costs in order to limit the non-linearity that is specific to various equipment or to increase the immunity level to distortions (by meeting the requirements of norms referring to immunity);
- the increase of operating expenses in the case of preventive or corrective maintenance;
- the increase of expense in the case of electric energy production and a general increase in investments in power systems due to over-sizing of the elements of the electric grid.

5.4.4 Mitigation Methods

Basically, the pollution of a power system becomes a problem if:

- the source of the harmonic currents is too strong;
- the part of the system that is traversed by the harmonics is too long (from an electric point of view), thus resulting either in an inadmissible distortion of the system voltage, or in unacceptable interferences with other systems (generally telecommunications interference);
- the frequency response of the system amplifies one or more harmonics.

Table 5.4 Solutions for the mitigation of the disturbed regime

Methods and means of limiting the disturbed state	Decreasing the generated harmonic currents	Rectifiers	Mounting AC line reactors at the converter input
			Increasing the value of the DC side reactors
			Using multi-pulse methods
		PWM invertors	Mounting AC line reactors on the input circuit
		Electric arc furnaces	Limiting reactors
			Decreasing short-circuit reactance
	Changing the frequency response of the power system	Increasing the power of the supply transformer	
		Mounting a series detuning reactor with the capacitor bank for power factor correction	
		Changing the placement of the capacitor bank for power factor correction	
		Splitting up the capacitor banks	
	Limiting the area where the harmonic currents can flow	Power supply using suitable insulating transformers	
		Using Y/Z transformers	
	Harmonic filters	Passive	With one step
			With several steps
		Active	Series
			Parallel
		Hybrid	

Taking into account these negative consequences of the presence of the disturbance, there is a need to initiate certain actions that can mitigate or remove this problem. The main options to achieve this are [2, 6, 7]:

- reducing the harmonic currents produced by the nonlinear loads;
- limiting the area crossed by the harmonic currents;
- changing the frequency response of the power system;
- mounting filters that could reduce the bidirectional flow of harmonic currents between the power system and the distribution installation of the consumer.

Nowadays there are many methods that are used. Table 5.4 gives an overview of these methods, giving examples for some of the disturbing receivers frequently encountered in industrial applications [7].

The classic solutions to reduce the distorted state are based on using passive components (inductors, capacitors and transformers) or on interventions on the configuration and/or the structure of the power supply system of the consumer in order to reduce the distortion level of the voltage at the heaviest charged point of common coupling. Developments in the technology of semiconductor devices – mostly achieved in the last decades – have made an important mark on the techniques and equipment used for reducing the distortions. Thus, the traditional methods have been completed by modern ways of removing harmonic pollution, based on devices and specialized highly performing semi-conductive circuits.

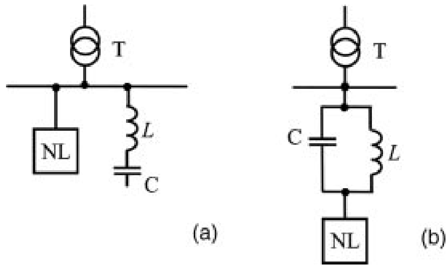


Figure 5.12 Suppressing filter (a) parallel; (b) series (NL – nonlinear load)

5.4.4.1 Passive Filters

Starting from the frequency analysis of the current distorted waveform, one of the most effective solutions to eliminate the harmonic currents is to use passive filters. Basically, a passive filter is composed of a number of *LC* series resonant circuits for the aimed harmonics, presenting a zero reactance for the rank *k* harmonics that are about to be filtered. These filters can be classified according to their application field [2, 27]:

- passive suppressing filters;
- passive absorber filters.

The first type of filters is used in already existing installations when a limit of the harmonic transfer due to nonlinear receivers should be obtained, Figure 5.12 [30]. Nonlinear consumers with a known steady state use passive absorber filters as one of the most effective means of limiting the harmonic transfer in the electric grid and of limiting the charge of the capacitors on the banks for power factor correction.

Absorber filters are formed of series circuits tuned on harmonic *k*, Figure 5.13. The filters are achieved in such a way that each of its resonant circuits has a capacitive character for the frequencies lower than the resonance frequency defined by the *k* harmonic and an inductive character for the frequencies higher than this value. Thus, for the fundamental frequency, each of the circuits generates reactive power that will be taken into account when sizing the power factor correction system. The presence of the absorber filter at the consumer power supply bus bars stops the harmonics and therefore the power voltage is free of distortions [7, 30].

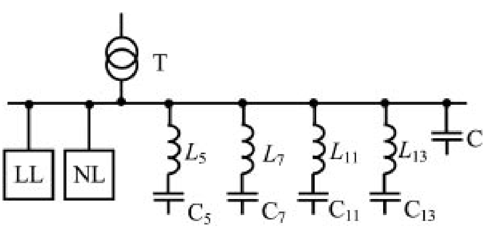


Figure 5.13 Connecting the absorber filter to the bars of the distortion consumer (LL – linear load, NL – nonlinear load)

Table 5.5 Classification of active filters

Classification criterion	Types of active filters
The type of circuit or electric grid for which the filter is designed	DC AC
Type of operation and connection to the grid	parallel series parallel–series
Static power converter configuration used to implement the filter	voltage source inverter current source inverter
Structure and technologies used for the implementation	active hybrid
Number of phases	single phase three phase

5.4.4.2 The Active Filter

An active filter basically represents a static power converter made in such a way that it synthesizes a current or voltage signal in the desired form; the signal is injected/applied in a certain point of an AC power grid, and simulates the desired impedance by meeting the specified values of the absolute value and argument.

The advantages of active filters over other conventional (passive) means used to reduce the harmonic pollution of electric grids are mainly:

- the high response speed;
- flexibility in defining and/or implementing the functions of the filter (modern active filters are capable of simultaneously executing several functions, which can easily be activated or deactivated and/or modified);
- elimination of the resonance problems of the compensating device – distribution grid assembly, specific to conventional solutions (passive filters, capacitor banks, transformers and specially designed transformers).

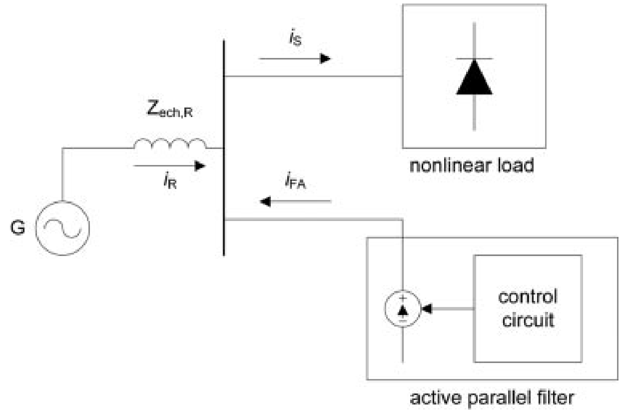
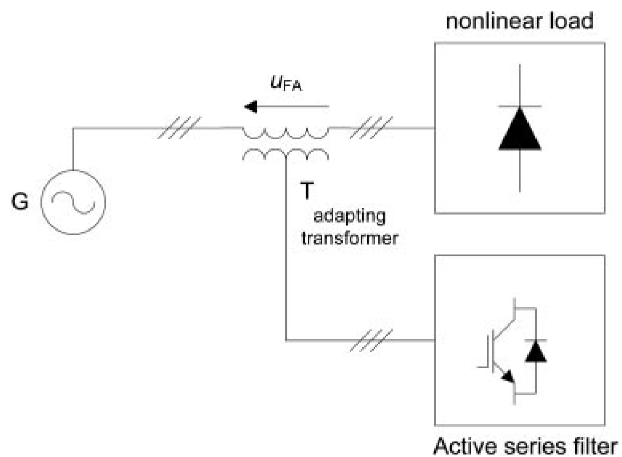
A classification of active filters is presented in Table 5.5.

According to the type of the synthesized signal (current or voltage), there are several ways of connecting the active filter to the grid – parallel or series, namely, active parallel filter (shunt) or series. In the context of the total power quality management concept, several designs of complex equipment that combine a structure of current source and one type of voltage source inverter have been designed and produced. These are called active parallel–series filters and they combine the functions and performances of both schemes. Table 5.6 shows the main types of active filters.

5.4.4.3 Hybrid Filters

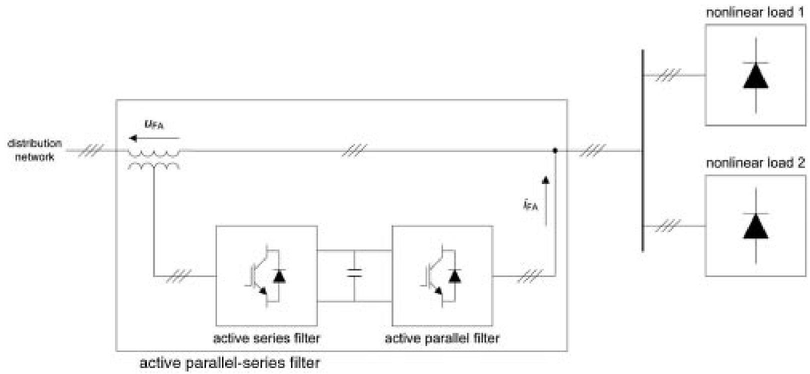
This category of filters resulted from the combination of active and passive filters in order to obtain lower costs for more efficient structures. Figure 5.14 shows three hybrid filter structures and Table 5.7 presents a comparison of these filters [27].

Table 5.6 Types of active filters

<table>
<tr><th>Type of active filter</th><th>Basic diagram</th><th>Description</th></tr>
<tr><td>Parallel</td><td></td><td>The parallel active filter is a device that accomplishes the functions of a current source. The current signal synthesized by the filter i_{FA}, is injected into the connection point with the purpose of:
• compensating the current harmonics produced by the consumer;
• compensating the reactive power consumption of the receiver;
• damping the effects produced by potential resonance phenomena that could occur due to the presence of a parallel passive filter connected to the same point;
• balancing the current system absorbed in the connection point.</td></tr>
<tr><td>Series</td><td></td><td>The series active filter fulfils the function of a voltage source (the synthesized signal produced by the filter has been marked with u_{FA}), which is connected in series to the distribution grid using a matching transformer in order to:
• reduce the distortions of voltage signals;
• balance the voltage system;
• reduce voltage dips and voltage fluctuations;
• assure only short interruptions in power supply;
• decrease the transitory high frequency phenomena that distort the voltage system;
• reduce the flicker levels;
• regulate the voltage rms.</td></tr>
</table>

(*continued overleaf*)

Table 5.6 (*Continued*)

Type of active filter	Basic diagram	Description
Parallel–series		These complex devices combine a current source with a voltage source to unite the performances of both parallel and series active filters both in name and in function.

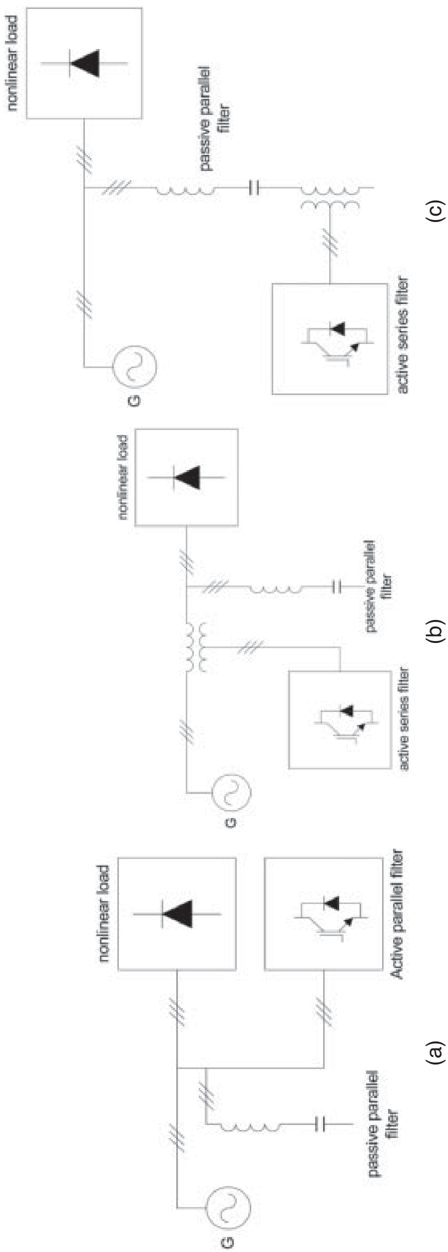


Figure 5.14 Hybrid filters: (a) parallel–parallel; (b) series–parallel; (c) parallel–series

Table 5.7 Comparative study of hybrid filter structures

Configuration of hybrid structure	parallel–parallel (parallel active filter + parallel passive filter)	series–parallel (series active filter + parallel passive filter)	parallel–series (series active filter connected in series with a parallel passive filter)
	Figure 5.14(a)	Figure 5.14(b)	Figure 5.14(c)
Type of static converter used to implement the active filter	Voltage source converter with PWM inverter and current loop control	Voltage source converter with PWM inverter without current loop control	Voltage source converter with PWM inverter with/without current loop control
Functions of active filter	• Compensating harmonic pollution • Reducing harmonic pollution	• Isolating the distortion consumer • Reducing harmonic pollution	• Reducing harmonic pollution • Compensating harmonic pollution
Advantages of the configuration	• Permits the use of every type of active parallel filter • Allows compensation for the reactive power consumption	• Permits the use of already existing passive filters • The active filter blocks the flow of harmonic currents	• Permits the use of already existing passive filters • Permits an easy and efficient protection of the active filter
Disadvantages of the configuration	Splitting the working frequencies range between the passive filter and the active one	• Difficulties in the overcharge protection of the active filter • Does not allow compensation for reactive power consumption	Does not allow compensation for reactive power consumption

Observations	The two filters parallel connected complete each other and it is recommended that the range of harmonic currents be split in such a way that the active filter does not act over the frequency of the passive filter. The presence of the active filter considerably improves the efficiency of the compensation and allows the reduction in the number and size of the passive filters used but does not prevent their overcharge with harmonics propagated through the distribution grid, neither does it prevent the appearance of resonance between the passive filters and the grid.	The series active filter presented in this hybrid structure acts as an isolating element between the distribution grid and the load, thus avoiding on one hand the pollution of the grid by the customer and, on the other hand, overcharging the downstream passive filter due to harmonic currents in the grid. The disadvantage of this structure that the matching transformer of the series active filter is run through by a significant amount of current (the entire load current), hence the high costs and weight together with the difficulty in protecting the active filter in the case of a short circuit.	In this configuration, the active filter acts only on the harmonic currents, thus improving the effectiveness of the passive filter by (i) avoiding the amplification of harmonic voltages with a frequency above the anti-resonance frequency of the passive filter; (ii) a strong reduction of harmonic currents that circulate between the customer and the grid by lowering the impedance of the circuit. Since the active filter is not run through by the entire load current, it can be re-sized accordingly, thus resulting in reduced costs and weight (especially for the matching transformer). The structure is recommended for the reduction of harmonic pollution in high power grids and higher voltages (medium-voltage networks).

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