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Evaluation of energy efficiency and improvement in power quality using the E-POWER apparatus

SCIENTIFIC REPORT

SUMMARY OF THE RESEARCH COMMISSIONED BY THE COMPANY

ENERGIA EUROPA SPA

FROM THE UNIVERSITY OF FLORENCE

DEPARTMENT OF INFORMATION ENGINEERING

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12 April 2016

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Abstract

This scientific report has been drawn up on the basis of the research agreement between the Department of Information Engineering and the company Energia Europa S.p.A. and summarises the results obtained from the study, analysis, characterisation and testing of the performance levels provided by the E-POWER system, with regard to its ability to reduce harmonic content in supply networks and improve energy performance and **power quality** in systems and connected devices. Furthermore, as a result of its construction features, the E-POWER system can regulate electrical network parameters and, thanks to the presence of the certified E-Controller measurement system, measure the amount of energy saved in accordance with the requirements of the incentive schemes based on final consumption for obtaining energy performance certificates (EPCs).

The results outlined in this short report were obtained using methods illustrated in detail in the full report, and enable the evaluation of energy savings and the increase in reliability achieved with the improvement in power quality obtainable using the E-Power apparatus.

The results obtained have been verified through computer simulations and experimental laboratory measurements on various installations already implemented by industrial users in various product sectors, with power levels ranging from 500 to 1750 kW. The measurement and calculation procedures are outlined in detail in the full report. The values obtained with the measurements comply with required tolerance levels and the measuring instruments were suitably calibrated and tested.

Florence, 12 April 2016

Prof. Francesco Grasso
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1 Introduction

Power quality is an area concerned with studying, evaluating and reducing disturbances in the electricity supply caused by the increasing use of electronic and power equipment. These disturbances include widespread transient and stable events such as short and long interruptions, micro interruptions and voltage dips, impulsive current and voltage surges, current and voltage imbalances and harmonics, and flicker etc.

They affect the correct operation of system components significantly, even compromising the normal implementation of energy and production processes in the most serious cases.

In the industrial and service sectors for example, these disturbances can give rise to inefficient production activity which, in addition to being costly, is also unacceptable. International technical sources have estimated the annual turnover of companies operating in the power quality sector at billions of dollars.

In particular, power quality is directly linked to 2 aspects of extreme importance for the operation of systems and apparatus:

- energy efficiency
- reliability, availability, and serviceability

The main cause of reduced performance in a system and/or apparatus is the presence of harmonics in the mains power supply. Harmonics have a significant financial impact on systems and electrical equipment in terms of:

- Increase in energy costs
- Increased wear and tear on materials
- Lower system and component reliability
- Increased losses in productivity

In fairly recent times, harmonic phenomena have added to the already known phase shift phenomena, increasing the criticality of electrical systems and leading to a re-evaluation of methods and systems for reducing these effects.

Initially it was sufficient to oversize capacitors for power factor correction to prevent them from deteriorating rapidly, and it was only recently that the problem shifted to the need to reduce, if not eliminate, the harmonic content of systems in order to increase overall system performance, with users employing devices to reduce and compensate for disturbances (filters, UPS systems, auxiliary generators, surge arresters etc.), a necessary practice which is often paramount.

Various indicators that characterise power and energy during distorted operation are required to understand how the presence of harmonics can affect the power quality of a system.

System efficiency and power quality levels are defined by measuring the characteristic electrical quantities voltage and current, and are evaluated in relation to the parameters and statistics set out in reference standards.

Power quality is rarely planned or managed. This means that most electrical systems and connected devices waste large amounts of energy and have issues with reliability and availability, in addition to requiring significant amounts spent on maintenance.

It is now possible to plan, measure and improve power quality in systems and electrical apparatus thanks to systems that manage the quality of electrical supply network quantities. As a result, in addition to reducing energy consumption, the improvement in power quality makes it possible to obtain higher performance levels from systems and devices, as well as potentially reducing costs relating to maintenance.

This document illustrates how it is possible to measure and evaluate the effectiveness of the E-POWER device in relation to measuring and improving power quality and, as a result, energy efficiency, reliability, availability and serviceability, and the benefits resulting from regular evaluation with respect to continual monitoring are compared.

Throughout the document reference will be made to power quality with its full meaning, with specific aspects concerning energy efficiency and a reduction in disturbances being dealt with in specific areas on a case-by-case basis.

2 Types of disturbances

Devices connected to the mains which are defined as 'disturbing' are characterised by a level of disturbance introduced into the supply network which varies over time. Depending on its nature, each individual disturbance introduced can propagate towards sensitive equipment along lines (electrical supply lines and/or control/signalling connections) or by means of radiation (propagation of electromagnetic fields). This study is limited to the analysis of line disturbances only, as operating frequencies are such that any disturbances due to radiation can be considered as negligible.

Figure 2 outlines the generation and distribution of disturbances with reference to interaction between the public mains network and user systems. As line disturbances can be transferred between stages of the network with different voltage levels, they can only be contained within acceptable limits through global coordination. This

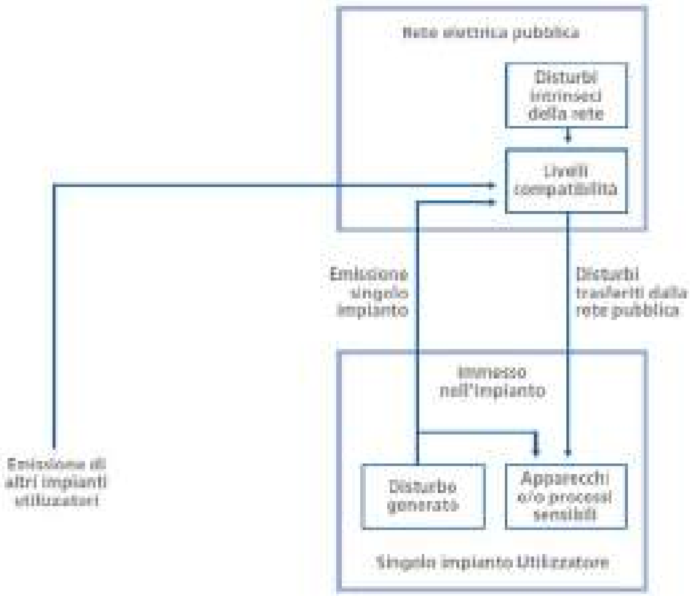

Figure 1 - Layout of the generation and distribution of line disturbances

coordination depends on the structure of the distribution system and the density of disturbing loads present and/or expected in a given network.
In other words, in-depth knowledge of the system structure and connected devices is required to enable effective corrective action to be implemented.

The types of disturbances that can generally transpire in an electrical network are outlined in Figure 2. Figure 3 shows

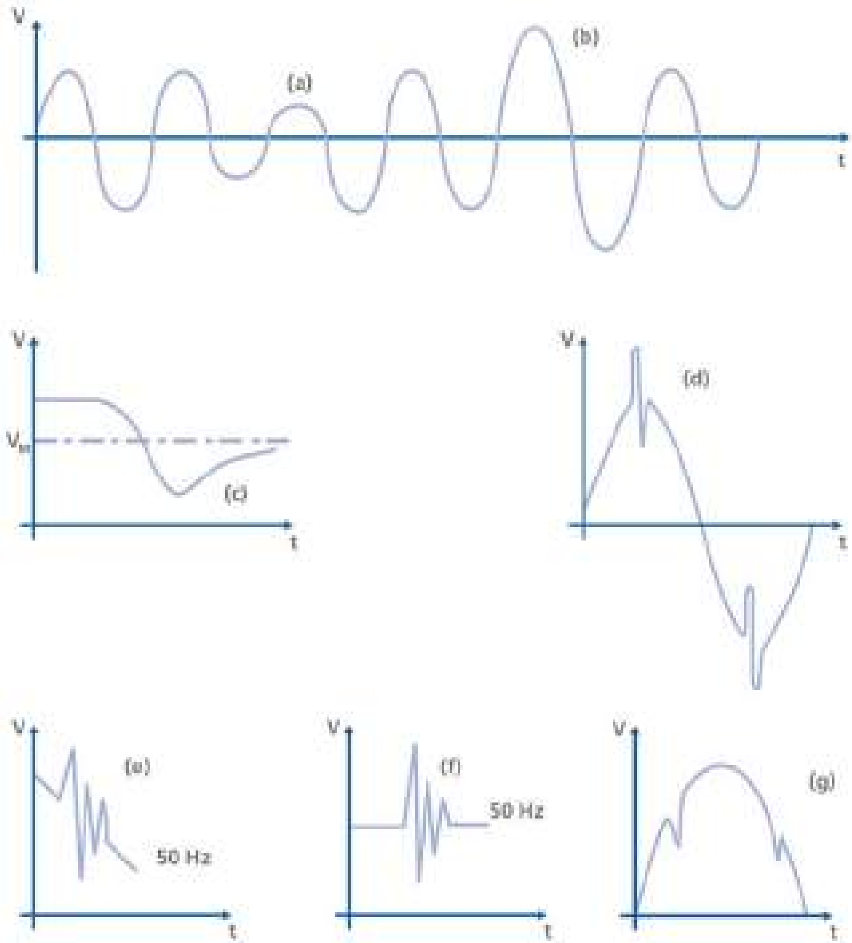

Figure 2 - Diagram of type of variation in voltage amplitude. (a) Voltage dips or flicker; (b) Non-impulsive surge voltages (c) Slow variations (d) Impulsive surge voltages of long duration (e) Impulsive surge voltages of medium duration (f) Impulsive surge voltages of short duration (g).

an example of network voltage fluctuation due to the presence of a 10 Hz disturbance.

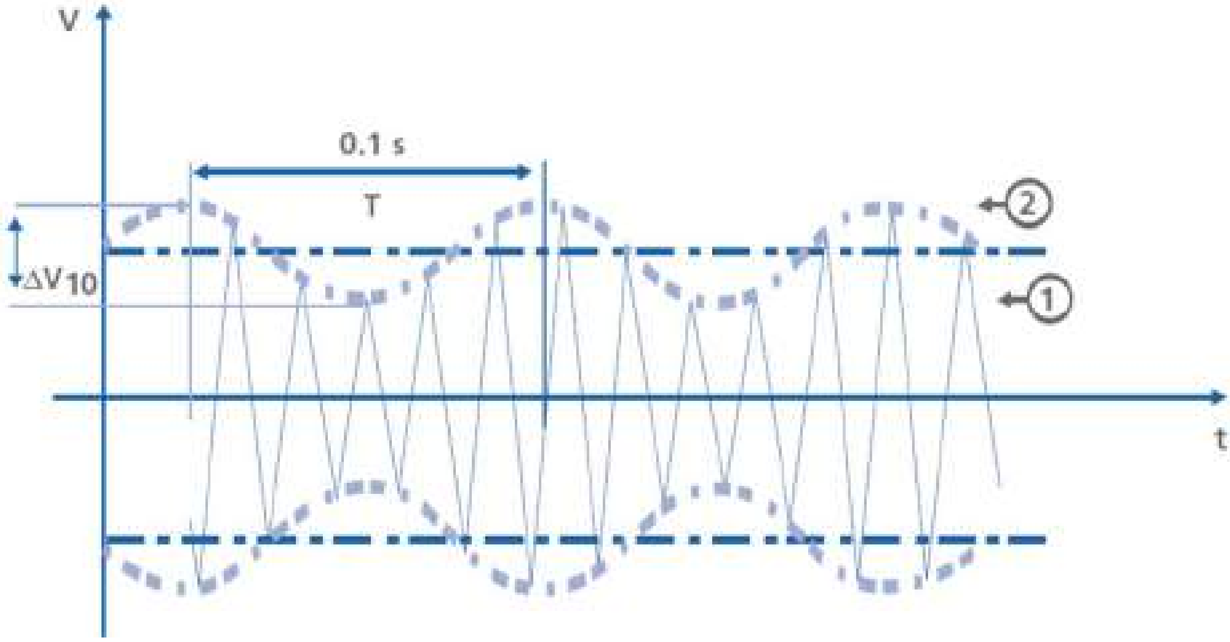

Figure 3 - Example of sinusoidal voltage fluctuation at a frequency of 10 Hz.

3 Parameters and normal limits for power quality

To evaluate the effects that the E-POWER system has on power quality accurately, a set of parameters that are recognised universally must be used, from which it is possible to obtain indications on the effectiveness of the E-POWER system in relation to a system and connected devices. Although there is a significant amount of technical standards on the subject (see the full report for details), the following standards have been considered for the purpose of this research: CEI EN 50160, CEI EN 61000, CEI EN 61642 and IEEE-519-2014.

The parameters of interest, acceptable limits of variation, criteria and statistical evaluation methods for characterising network voltage at supply points on the public mains network establish:

- Slow/rapid voltage variations (voltage dips);
- Voltage drops and flicker;
- Interruptions to the supply;
- Surge voltages;
- Variations in voltage frequency;
- Voltage imbalance;
- The severity of flicker;
- Harmonic distortion;
- The presence of voltage interharmonics.

The use of these parameters to evaluate the reduction in losses and improvement in system reliability is outlined in detail in the full report. In the interests of brevity, the summary description of E-POWER system operation, and the main evaluations and conclusions on achieving savings and reducing disturbing effects involving connected devices are outlined below.

4 The E-POWER apparatus

Figure 4 shows the E-POWER apparatus involved in this research. The principle of operation is based on a family of inductive passive filters connected in series between the

(a) (b)

Figure 4 - The E-POWER apparatus: (a) closed (b) open.

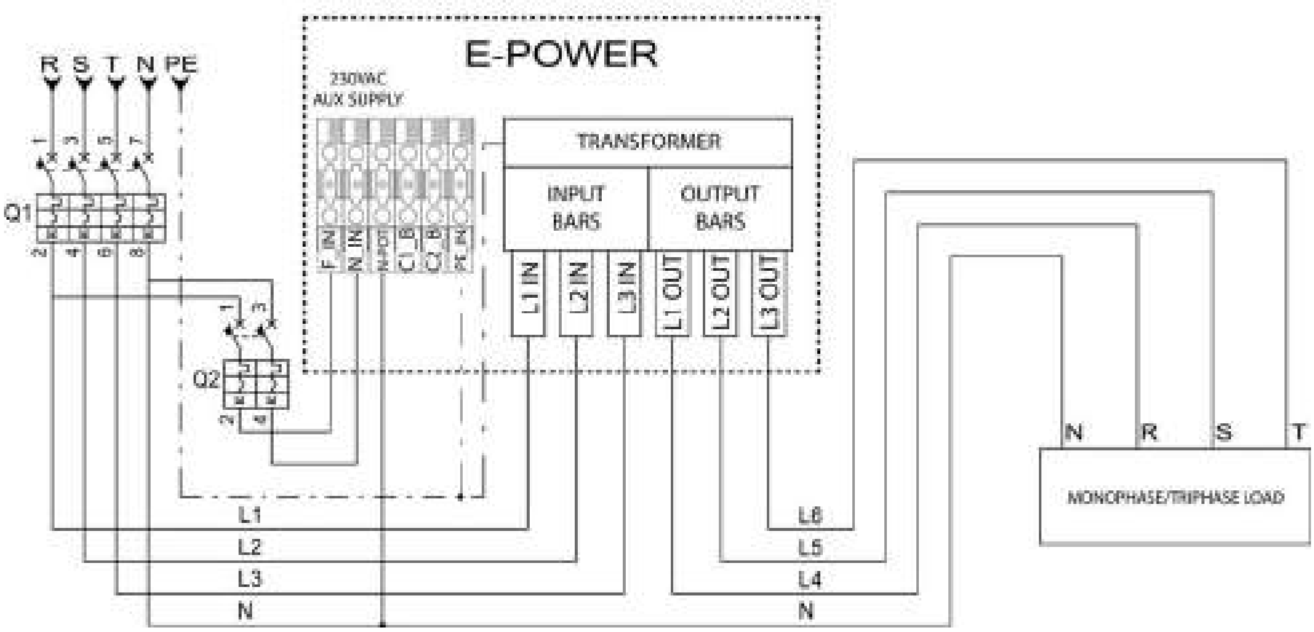

Figure 5 - Typical configuration of a system equipped with E-POWER

power source and the load, but with the peculiarity that the inductance is not constant. In practice, thanks to a mutually-coupled system of contactors and inductances, the E-POWER system inductance changes value dynamically in order to adapt to the harmonic contribution present in the supply network, maximising its effectiveness. Consequently, the E-POWER system can be considered as a hybrid active/passive system, but without the problems related to power devices for active filters. Losses introduced by installing the E-POWER system can be considered as practically nil due to the presence of reactive components and switches/contactors alone, unlike the situation with active filters with resistors and switching power devices (SCR, MOSFET). Furthermore, the circuit configuration is such that the E-POWER apparatus can be connected or disconnected from a system without compromising its operation in any way, thanks to a patented bypass system. Figure 5 shows the typical electrical layout for a system with the E-POWER apparatus installed. When the E-POWER apparatus is connected in series to the system it is defined as operating in saving mode, and when disconnected it is defined as operating in bypass mode. These definitions will be referred to throughout the report when evaluating the effects on systems.

Finally, thanks to the presence of a remote control system named E-CONTROLLER, it is possible to also implement monitoring, supervision, analysis and measurement activities remotely. The measurement system implemented in E-POWER using E-CONTROLLER is based on international performance measurement and verification protocol (IPMVP) and can be endorsed by the UTF (Italian Customs & Excise), therefore the E-POWER system can be used to obtain energy performance certificates (EPCs) under the final evaluation scheme.

For obvious reasons concerning the confidentiality of intellectual property, further details on the E-POWER system operating modes cannot be outlined in this report. However, a quick perusal is sufficient for understanding that the information above describes the principle of operation in a sufficiently comprehensive manner. The measurements taken in the laboratory and on real systems have confirmed the technical characteristics indicated.

In conclusion, the E-POWER system is a purely inductive series passive filter with dynamic inductance operated by zero-resistance contactors. The patented switching system makes it one of a kind. Comparisons made with similar systems have demonstrated how the E-POWER system encompasses the sum of functions partially implemented by other equipment - reduction in harmonic content, bypass possibility, voltage regulation and reduction in quick disturbances.

5 Harmonic phenomena in electrical networks

Technological development in the industrial and domestic fields has led to the distribution of electronic equipment which, as a result of its principle of operation, draws a non-sinusoidal current (non-linear loads). Consequently, even the voltage becomes non-sinusoidal, therefore linear loads are also powered by a distorted voltage.

The theory of harmonic analysis (or Fourier series) is used to describe the effects of distorted currents and voltages, whereby each periodic waveform can be analysed as an appropriate set of sinusoidal quantities. Figure 6 shows a distorted current (in red) and its main harmonic components.

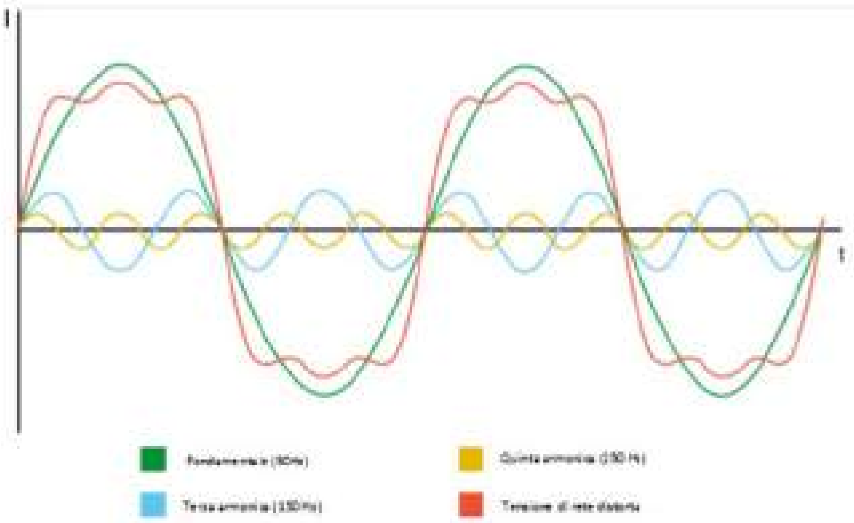

Figure 6 - Distorted current (in red) and its main harmonic components.

6 Effects of harmonics on electrical systems

As mentioned previously, the effects of harmonic disturbances in power supply networks can be grouped into two areas:

- reduction in system reliability, service ability and availability;
- reduction in energy efficiency.

Both aspects can be quantified and measured, therefore it is possible to evaluate the effectiveness of the E-POWER system in improving power quality.

When assessing reduced reliability, it should be remembered that some devices can be disturbing and sensitive simultaneously, and the nature of emissions and sensitivity in relation to disturbances is intrinsically statistical, therefore the objective evaluation of reliability must be carried out through statistical methods. In this case it is possible to use the concept of **susceptibility** for devices i.e. the risk assessment of malfunction or damage as a function of level of disturbance and consequences (damage) that can transpire.

To measure reduced efficiency it is sufficient to evaluate additional losses introduced by harmonics affecting various components in the system. The total losses will be given by summing the losses for the individual devices.

7 Evaluation of susceptibility

All user devices are, to varying degrees, sensitive to irregularities or disturbances in the power supply. These devices are in turn incorporated into specific industrial processes to a lesser or greater extent, whose level of sensitivity will depend on the role/level of integration of the sensitive device within the process itself, and the actual consequences the network disturbance will have on that process (specifics of the process in question).

By way of example, table I summarises the apparatus which is most sensitive to various phenomena, with references to types of voltage variations indicated in Figure 2.

With reference to voltage dips and short interruptions, figure 7 and figure 7 show examples of experimental susceptibility curves that identify, at the level defined by the percentage value of residual supply voltage V% (or percentage amplitude ΔV% of the voltage dip) and the duration Δt of the voltage dip, pairs of values for V% (ΔV%) and Δt at which device operation can/cannot be guaranteed.

Table I - Susceptible apparatus		
Digital electronic process control equipment or computing devices in general. Variable speed drives (power electronics).	Voltage dips: $\Delta V > 30\ \%\ V_N$ $\Delta t < 60 - 100$ ms	Process/machinery anomalies and/or shutdown. Intervention of safety devices for power electronics.
In addition to above failure of electro-mechanical devices (auxiliary relays, remote control switches etc.)	Voltage dips: ΔV > 30 % VN $\Delta t < 60 - 100$ ms	Almost total shutdown of all users.

Motors and electric machines. Contactor coils. Incandescent lamps.	Non-impulsive surge voltages (long duration)	Reduced insulation lifetime
Lighting systems. Digital electronic process control equipment or computing devices in general. Variable speed drives (power electronics). Motors and electric machines. Contactor coils. Incandescent lamps.	Slow voltage variations: $\Delta V = \pm 10\ \%\ V_N$	In the case of reduction, slowing or shutdown of electric motors. Process/machinery anomalies and/or shutdown. Intervention of safety devices for power electronics. Reduced insulation lifetime
Electronic power and control components. Motors, cables and electric machinery in general.	Impulsive surge voltages	Insulation perforations. Damage to electronic circuits.
Low power signal and data transmission lines. Electronic control equipment.	Switching transients (bridges, converters, chopper techniques)	Malfunctioning of data processing and control systems.
Capacitors. Safety relays. Low power connections. Motors and rotating machinery. Transformers. Electric cables.	Harmonics	Capacitor damage and overheating. Untimely intervention of data safety relays. Malfunctioning transmission and control systems. Increases in losses in motors, transformers, cables and resulting overheating.
Electric motors and rotating machinery in general.	Dissymmetries and imbalances.	Overheating.

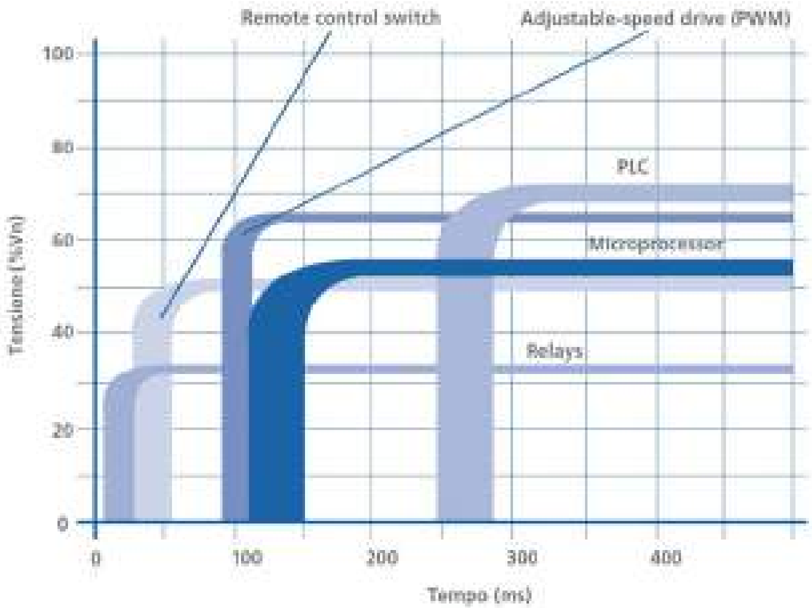

Figure 7 - Susceptibility curves for PLCs, relays, microprocessors and variable speed drives.

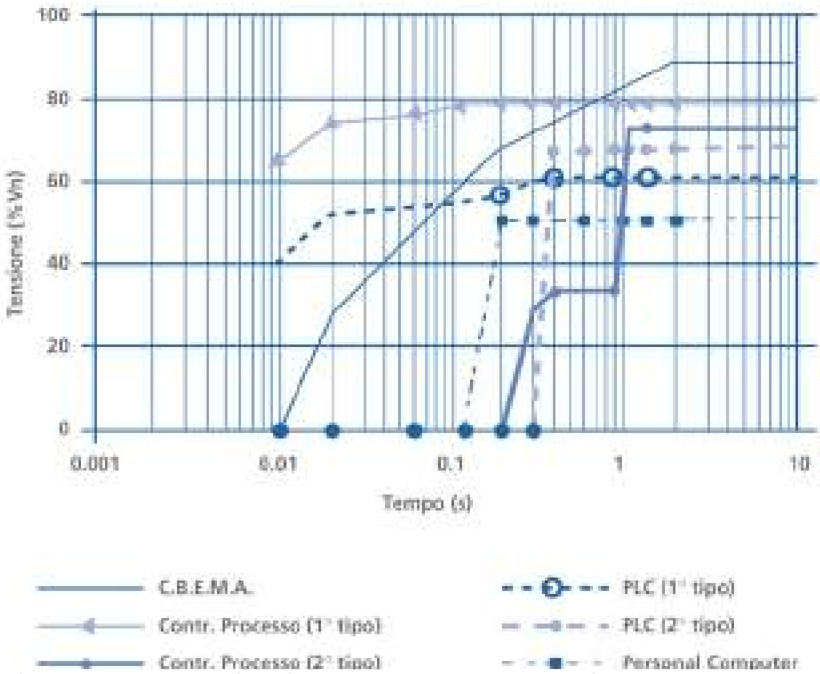

Figure 8 - Susceptibility curves for PCs and control equipment (PLCs and process controllers)

As mentioned above, the evaluation of the effects of disturbances on apparatus is based on statistical analysis. A recent study by the international association Leonardo Energy (http://www.leonardo-energy.org/) provided data on over 60 surveys carried out in 8 countries over 16 different sectors. In the conclusions for the study on power quality it appeared that the most sensitive sectors, representing 20% of European turnover and approximately 30% of the industrial sector, confirmed that the cost of low power quality amounted to approximately 4% of their turnover. In particular, 24% of this amount is due to the effects of voltage dips, whereas 19% is due to short interruptions. The cost of each voltage dip is between €2,120 and €4,682, and short interruptions are, on average, 3 times more costly for industry and over 9 times more costly for the service sector. **All users reported, on average, 13 voltage dips and 6 short interruptions per year.**

The main results relating to the cost of low power quality in electrical systems are outlined below.

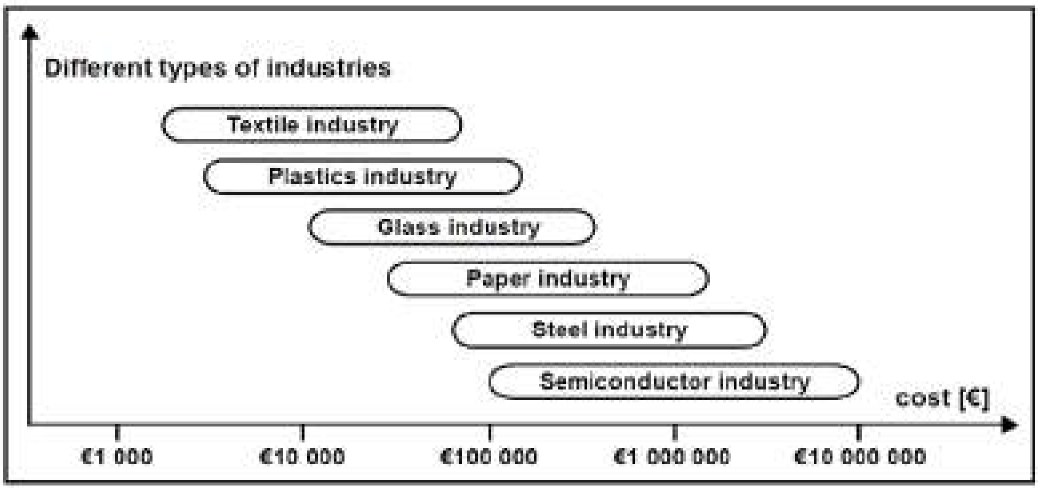

Figure 9 - Costs relating to voltage dips in the various industries.

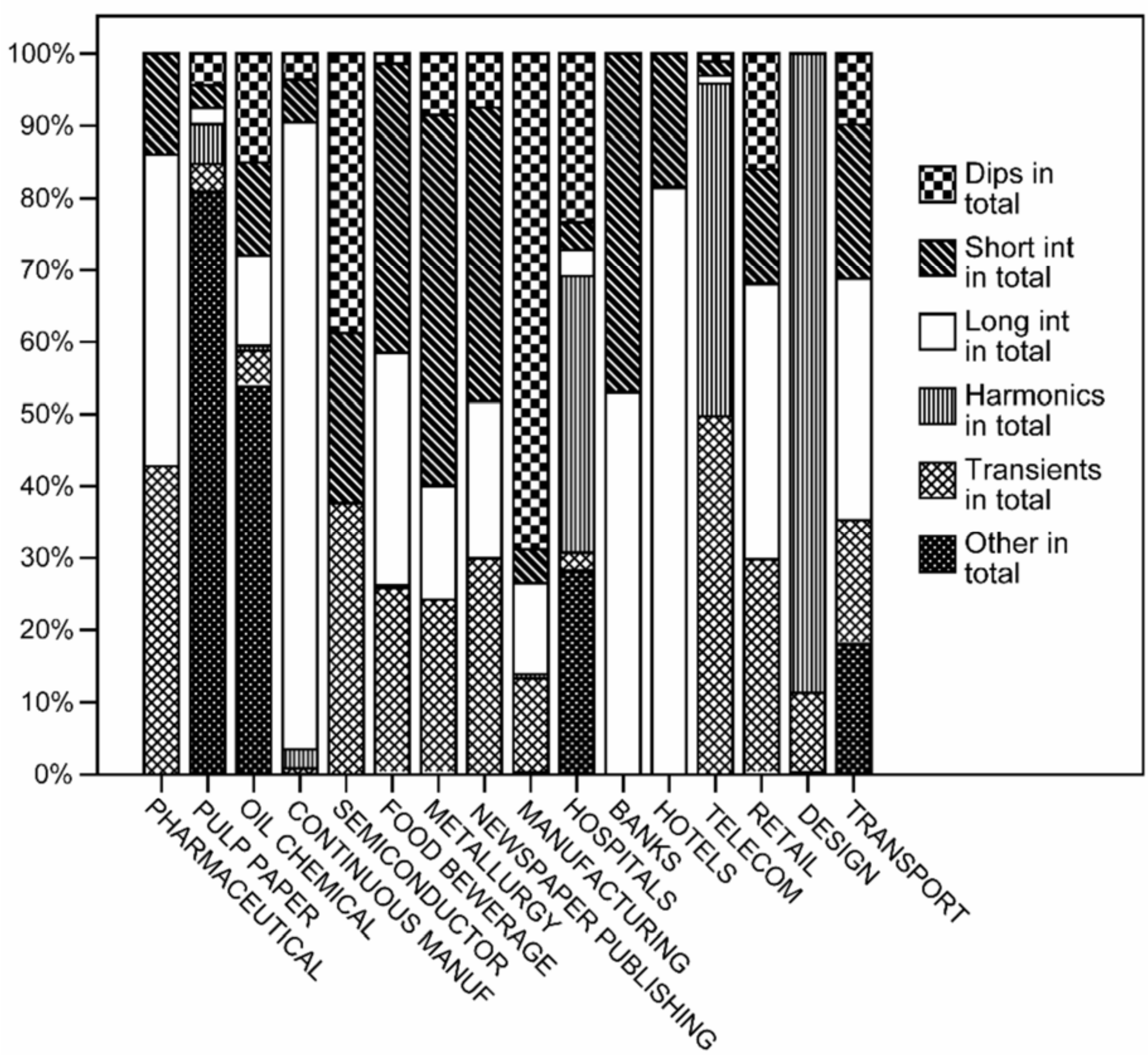

Figure 10 - Breakdown of total costs on the basis of disturbance type.

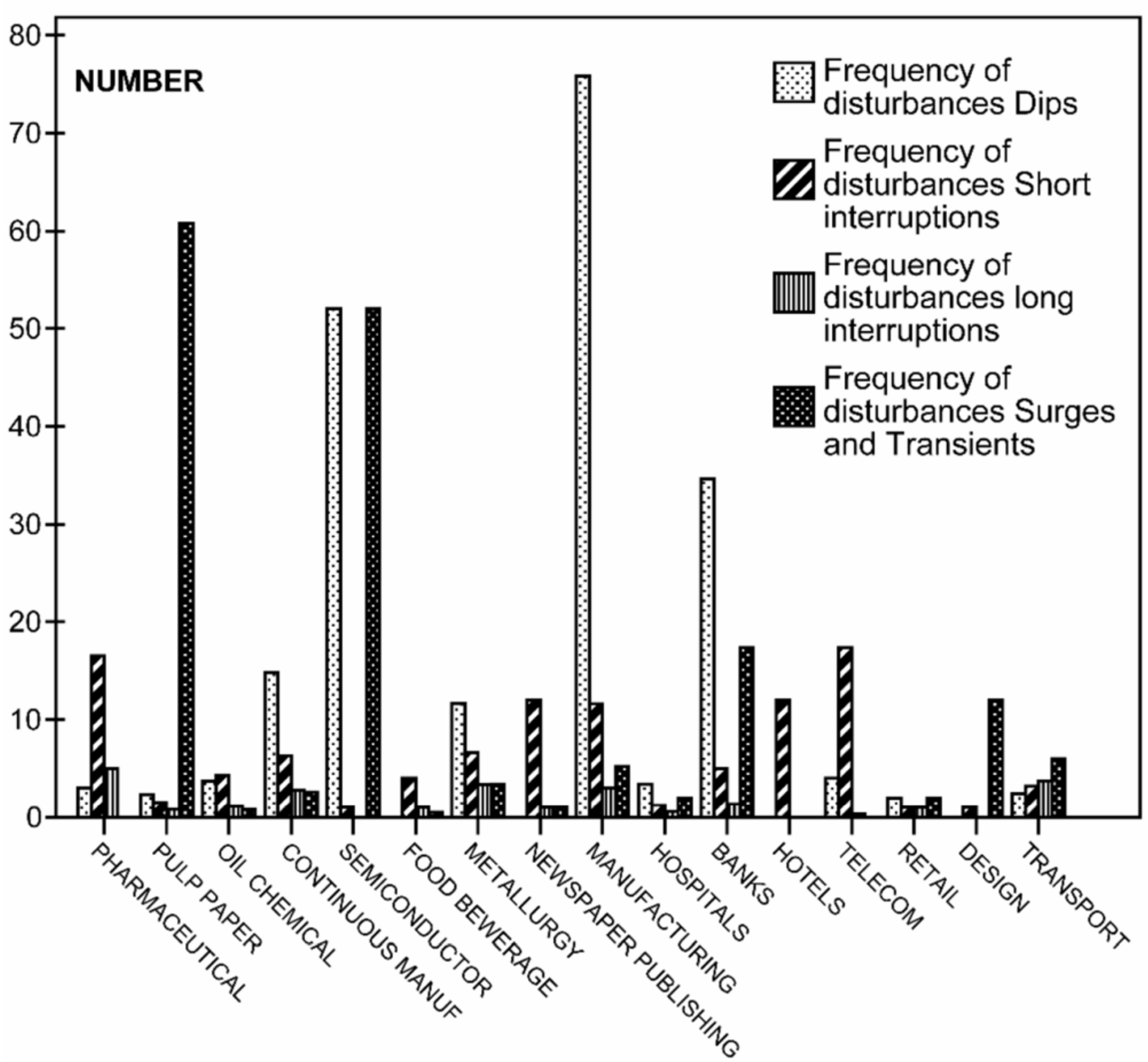

Figure 10 - Breakdown of total costs on the basis of disturbance type.

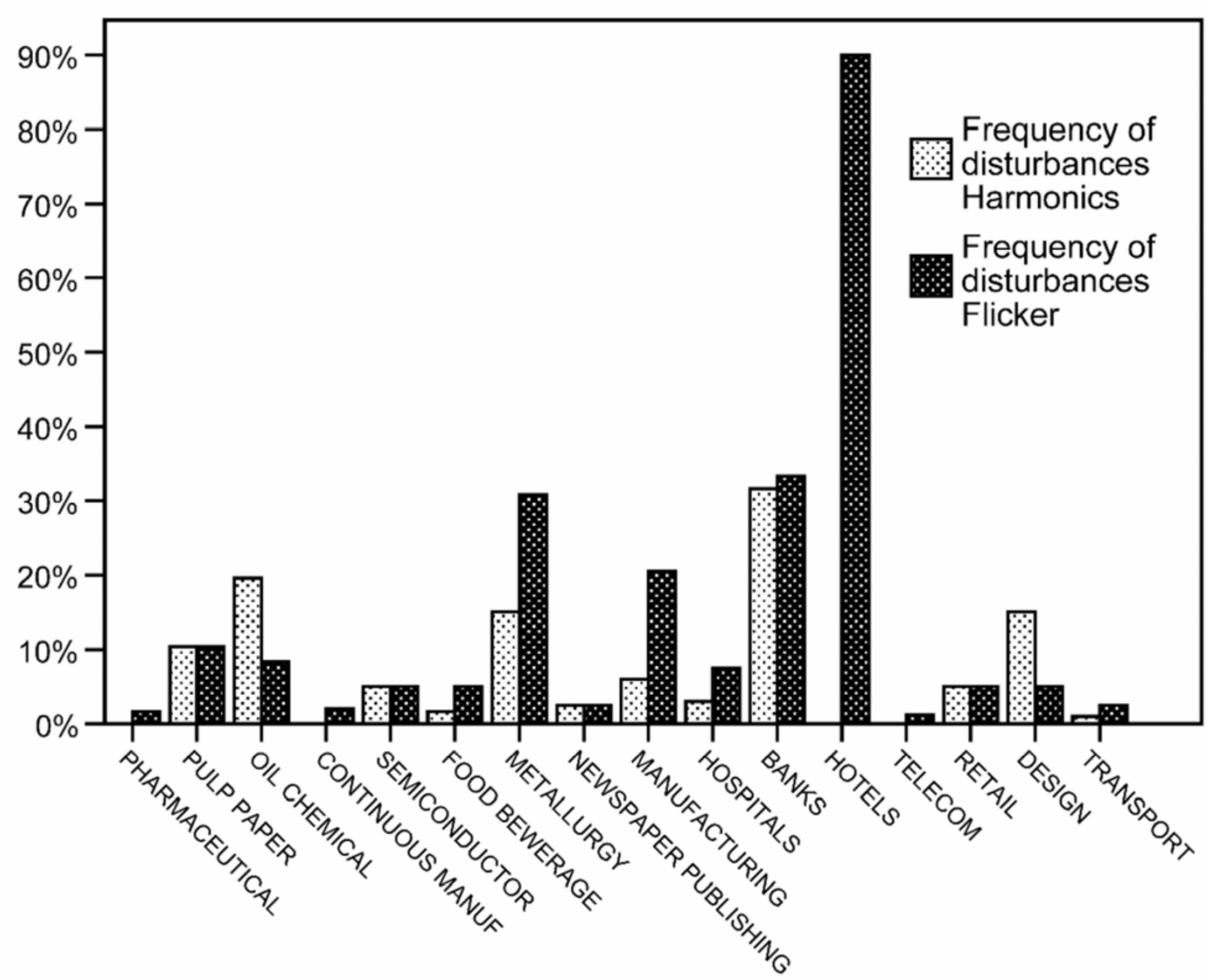

Figure 12 - Percentage of annual disturbances caused by harmonics and flicker, listed by sector.

Table II - Cost by event and sector group.

Sector	*Voltage dips*	*Short interruptions*	*Surges and transients*
Industry	141,635 €	205,300 €	186,260 €
Service	22,064 €	47,762 €	122,602 €
Media	119,357 €	163,153 €	175,871 €

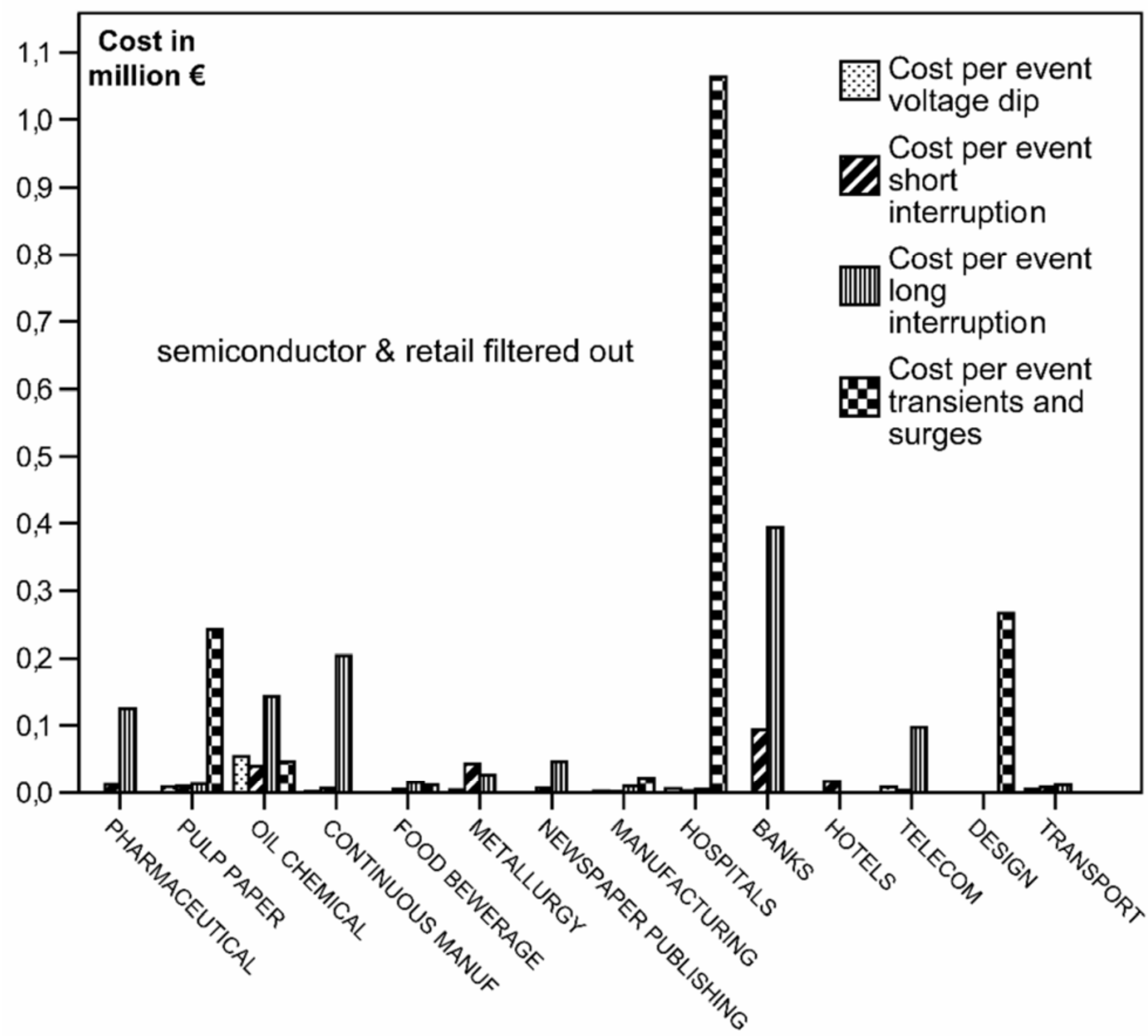

Figure 14 - Cost by event and sector in millions of euros.

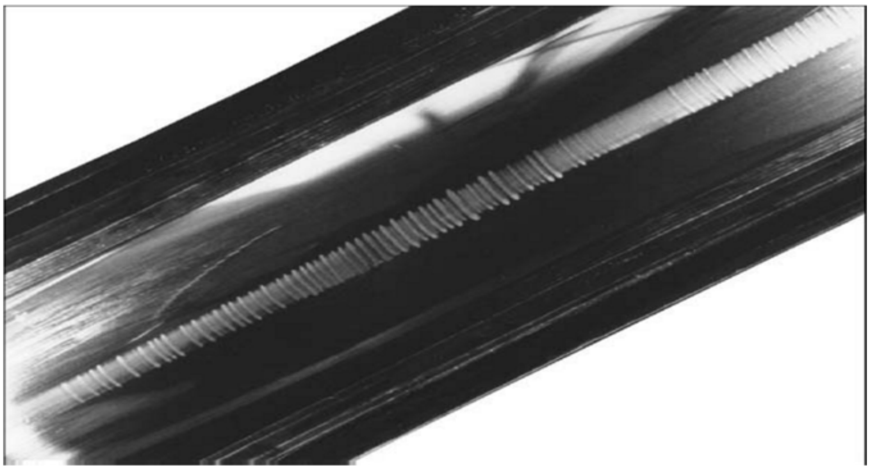

Figure 13 - Effects of disturbances on work cycles for a numerical-control machine.

8 Evaluation of energy efficiency

8.1 Power and energy in electrical networks with harmonic distortion

In the case of distorted operation, conventional theory on the analysis of power and energy under sinusoidal operation is no longer applicable. By way of example, figure 15 shows the progress of voltage and current in three different operating conditions. The definition of active power, or rather the average value of instantaneous power at equal amplitude (figure 15 (a) and (b), gives a zero result in case (b). Figure 15 (c) shows the effect of the presence of harmonics on instantaneous and average power. To this effect, other methods must be used to evaluate power and energy in distorted operation.

Electrical power is, by definition, equal to the product of voltage and current at the ends of a pair of terminals:

$$p(t) = v(t) \cdot i(t) \text{ [W]} \tag{1}$$

i.e. for a three-phase system:

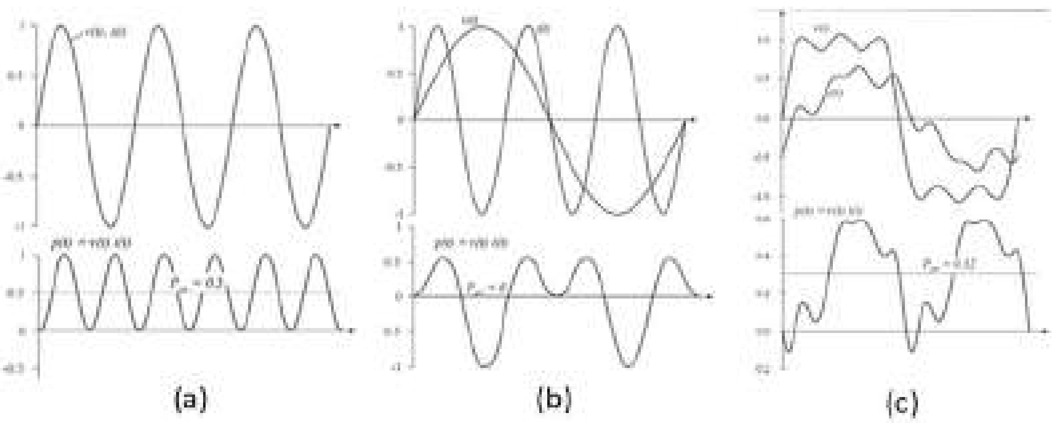

Figure 15 - Instantaneous and average power.

$$p(t) = v_1(t) \cdot i_1(t) + v_2(t) \cdot i_2(t) + v_3(t) \cdot i_3(t) \text{ [W]} \tag{2}$$

The work the system can carry out i.e. the energy, is obtained from these definitions:

$$E(T) = \int_{t_0}^{T} p(t)\,dt = \int_{t_0}^{T} v(t) \cdot i(t)\,dt \text{ [J]} \tag{3}$$

Dividing (3) by 3600 gives the energy in Wh. If the quantities considered are periodic and we have the period *T*, the average power can be defined as:

$$P = \frac{1}{T}\int_{t_0}^{T} v(t) \cdot i(t)\,dt = \frac{1}{T}\int_{t_0}^{T} p(t)\,dt \text{ [W]} \tag{4}$$

With perfectly sinusoidal operation, (4) gives the known expression for active power:

$$P_a = \frac{1}{T}\int_0^T p(t)\,dt = \frac{1}{T}\int_0^T v(t)\cdot i(t)\,dt = V_{rms} I_{rms} \cos\phi \text{ [W]} \quad (5)$$

Furthermore, it is possible to derive the expression for reactive power and total power:

$$Q = V_{rms} I_{rms} \sin(\phi) \quad (6)$$

In particular, the apparent power per phase is generally defined as:

$$S = V_{eff} I_{eff} \text{ [VA]} \quad (7)$$

The generalisation of apparent power and active power produces the definition of the power factor as the **ratio between active power and the corresponding apparent power:**

$$\lambda_a = PF_a = \frac{P_a}{S_a} \quad (8)$$

It is evident how, in the pure sinusoidal case, the power factor is simply equivalent to the phase shift between voltage and current:

$$\lambda_a = PF_a = \frac{V_{eff} I_{eff} \cos\phi}{V_{eff} I_{eff}} = \cos\phi \quad (9)$$

It should be emphasised that pure sinusoidal operation enables the introduction of simplifications in the treatment of power and energy, therefore it is easy to obtain the potential saving in energy, in other words it is sufficient to evaluate the effects of a simple phase shift between the sine wave for the voltage and the sine wave for the current to obtain an order of magnitude for losses in power, and hence energy. For example, if we consider losses on the line, it is possible to demonstrate that the saving in energy resulting from the phase shift from ϕ_1 to ϕ_2 is equivalent to:

$$E_{risparmiata} = p_1 \left[1 - \left(\frac{\cos\phi_1}{\cos\phi_2} \right)^2 \right] \cdot h \text{ [Wh]} \quad (10)$$

where p_1 are the losses before the phase shift, $\cos\phi_1$ is the power factor before the phase shift, $\cos\phi_2$ is the power factor after the phase shift and *h* represents hours of operation for the line considered. It can be observed from the formula, for example, that by changing the power factor from 0.7 to 0.9 losses can be reduced by 39.5%. This evaluation can be made by considering the average monthly power factor, and by measuring the actual system power factor moment by moment. In this second case the saving in energy is probably greater, as if we change from 0.5 to 0.95 for example, the saving amounts to 72.3% for the time this situation remains.

This simple treatment is applicable in networks with distorted operation, however the concept of the power factor and its improvement must be extended.

8.2 Power and energy in periodic distorted operation

There have been numerous theories over the years that have tried to identify characteristic parameters for power in distorted operation along similar lines for power in sinusoidal operation. Some of the most important work includes that of Budenau, Fryze, Kuster and More, Sharon, Depenbrok, Czarnecky and Emanuel. The main aspect emerging from these studies is that in the presence of distorted operation a level of power typically considered as active, in other words able to produce work, is converted into a form that cannot always be actively used, thereby increasing the amount of losses in the system.

When evaluating the effects of harmonics on power and energy in the system, Fourier analysis must be used and the voltage and current waveforms no longer considered as purely sinusoidal, but as containing an arbitrary number of harmonics. In this case it can be demonstrated that the effective values of voltage and current in distorted operation are equal to:

$$\begin{aligned} V_{rms}^2 &= V_{DC}^2 + V_{s,1}^2 + \sum_{n=2}^{\infty} V_{s,n}^2 = V_{DC}^2 + V_{s,1}^2 + V_H^2 \\ I_{rms}^2 &= I_{DC}^2 + I_{s,1}^2 + \sum_{n=2}^{\infty} I_{s,n}^2 = I_{DC}^2 + I_{s,1}^2 + I_H^2 \end{aligned} \tag{11}$$

where V_H^2 and I_H^2 correspond to the harmonic components of the voltage and current respectively.

Furthermore, standard IEC 61000-2-2 defines total harmonic distortion (THD) for the voltage and current:

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_{s,n}^2}}{V_{s,1}} = \sqrt{\left(\frac{V_{rms}}{V_{s,1}}\right)^2 - 1}; \qquad THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_{s,n}^2}}{I_{s,1}} = \sqrt{\left(\frac{I_{rms}}{I_{s,1}}\right)^2 - 1}. \tag{12}$$

THD represents the amount of harmonic content with respect to the fundamental component of the quantity considered. To this effect, it is possible for the THD of a quantity to exceed the unit value when the fundamental component has an amplitude lower than one of the higher harmonics. THD is a parameter that can be measured with current instrumentation.

Similarly, it is possible to demonstrate that the average power in distorted operation is equal to:

$$P = V_{DC} I_{DC} + V_{s,1} I_{s,1} \cos(\phi_1 - \theta_1) + \sum_{n=2}^{\infty} V_{s,n} I_{s,n} \cos(\phi_n - \theta_n) = P_{DC} + P_1 + P_H \quad (13)$$

where P_{DC} is the power associated with the continuous component, P_1 is the power associated with the fundamental component of the voltage and current and P_H is the part of active power associated with the harmonic content, which can be defined as **distorted power**. It can generally be demonstrated that distorted power cannot carry out any work, and usually dissipates into the system in the form of heat. To evaluate behaviour in terms of system energy it is necessary to obtain the general expression for apparent power:

$$S^2 = (V \cdot I)^2 = (V_{s,1} I_{s,1})^2 + (V_{s,1} I_H)^2 + (V_H I_{s,1})^2 + (V_H I_H)^2 = S_1^2 + S_N^2 \quad (14)$$

and the power factor:

$$\lambda = PF = \frac{P}{S} = \frac{(P_1 + P_H)}{S_1 + S_N} = \frac{\cos(\phi_1 - \theta_1)}{\sqrt{1 + THD_I^2}} = \frac{DPF}{\sqrt{1 + THD_I^2}} \quad (15)$$

where the subscript *H* identifies the quantities associated with the harmonics and S_N is the apparent harmonic power. At this point it is possible to simplify (15) by assuming that the fundamental component of the voltage and current are in phase ($\cos(\phi_1 - \theta_1) = 1$). By doing so it is possible to outline the progress of the power factor as a function of THD, as shown in figure 16. Therefore, assuming distorted current only, a reduction in THD from 60% to 40% involves an increase in the power factor from 86% to 93%.

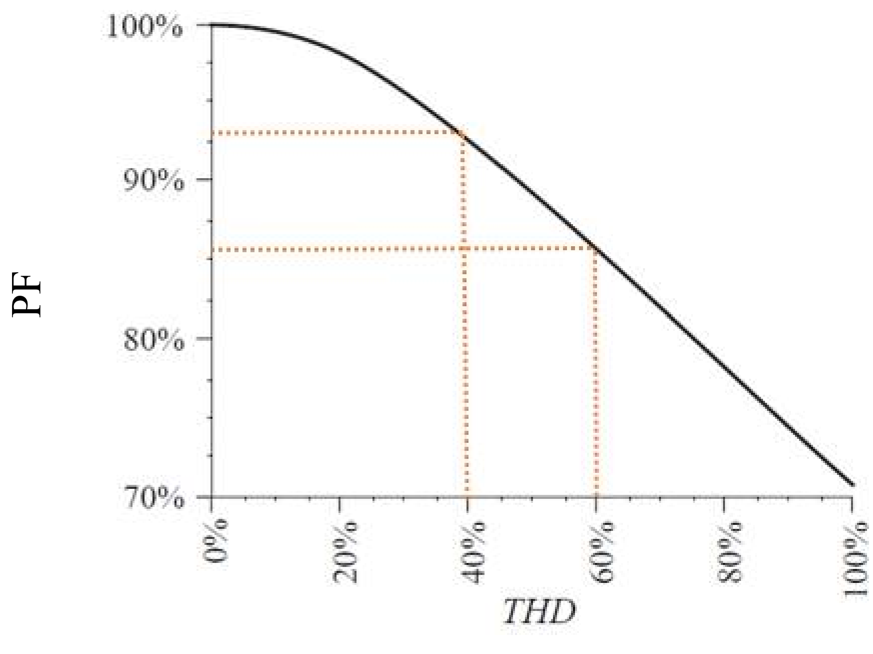

Figure 16 - Progress of PF as a function of THD.

In light of the information in the full report, it can be demonstrated that in a distorted system the saving in energy ΔE that can be obtained by changing from PF_1 to PF_2, greater than previously, is equivalent to:

$$\Delta E = p_1 \left[1 - \left(\frac{PF_1}{PF_2} \right)^2 \right] \cdot T \text{ [kWh]} \tag{16}$$

where p_1 represents the losses in the system before corrective action in kWh, PF_1 is the power factor in the absence of the E-POWER system (**bypass**) and PF_2 is the power factor in the presence of the E-POWER system (**saving**). **In the case outlined above, time periods being equal, there is a reduction in losses equivalent to 14.4%.**

It should be stressed that this calculation as made by assuming that only the current is distorted, and therefore the fundamental component of the current is in phase with the fundamental component of the voltage. There is no doubt that in the case of distorted voltage and/or fundamental current component out of phase with respect to the fundamental voltage component, the final values will definitely be higher.

To this effect it is useful to apply the evaluation of losses produced by the presence of harmonics to various important items of apparatus. The detailed evaluation of losses in a given system requires that system to be fully understood in its entirety, in addition to its modes of operation and the processes implemented. However, the theoretical background outlined in this report is general and can be applied to any system to estimate energy savings, following due consideration of the case in question. In the full relation, the experimental results obtained in the laboratory on a test system are shown, and an example of the method for evaluating energy saved, which was carried out on an industrial plant installed on production premises in Zanè (VI) with a 800 A E-POWER system is presented.

9 Evaluation of system losses

Losses in systems can transpire due to the following effects:

- equipment and electrical machinery overheating
- losses in copper and iron in motors
- changes in torque produced by motors
- mechanical oscillations (fifth and sixth harmonics)
- excessive stress on insulation
- increase in line losses
- faults due to incorrect sizing of the neutral conductor
- excessive voltage between neutral and earth due to voltage drops caused by the neutral current
- untimely intervention by switches and/or fuses

9.1 Transformer losses

Harmonic currents that travel along transformer windings cause additional losses in the windings due to the Joule effect and losses in the iron due to eddy currents. Harmonic voltages on the other hand are responsible for additional losses in the iron due to magnetic hysteresis.

Generally speaking, it can be assumed that losses in the windings are proportional to the square of the THD for current, whereas losses in the iron are proportional to the THD for voltage.

Values of THD deemed acceptable with a limited distortion rate can cause additional losses to the order of 10 to 15% in distribution transformers.

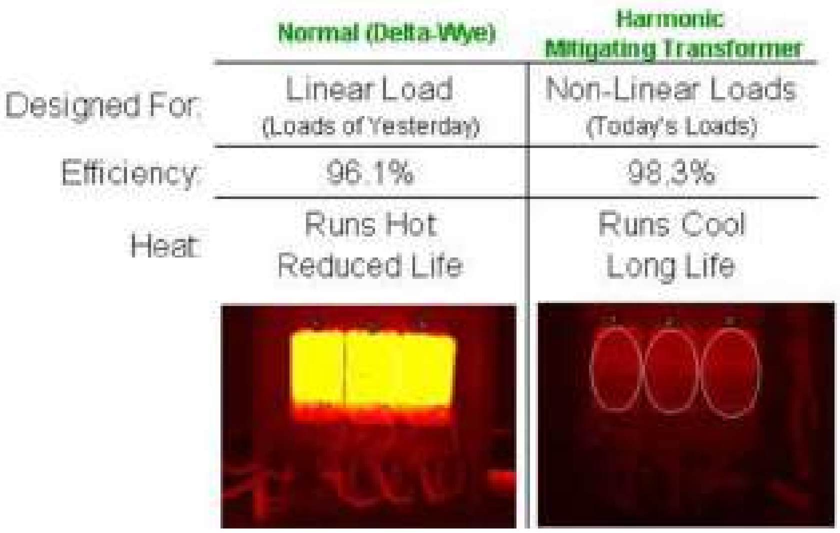

Figure 17 – Thermal effects of harmonics in a power transformer.

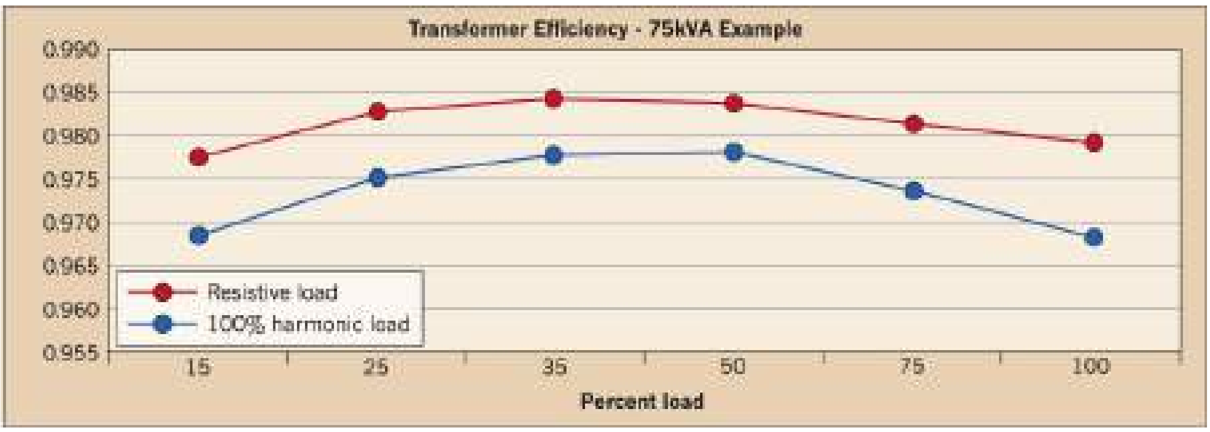

Figure 18 - Change in performance of a transformer on varying harmonic content and load.

9.2 Losses in asynchronous machines

Harmonic voltages applied to asynchronous machines cause the circulation of currents with frequencies higher than 50 Hz in the rotor windings with resulting additional losses proportional to U_{h2}/h:

- an almost rectangular supply voltage causes an **increase of 20% in rotor losses**
- a supply voltage with harmonic distortion rate to the order of h u_h:
  - u_5: 8 % of U_1, U_1 with harmonic to the order of 1 (or fundamental voltage)
  - u_7: 5 % of U_1
  - u_{11}: 3 % of U_1
  - u_{13}: 1 % of U_1

(in other words THD for voltage equivalent to 10%) implies an increase of 6% in rotor losses.

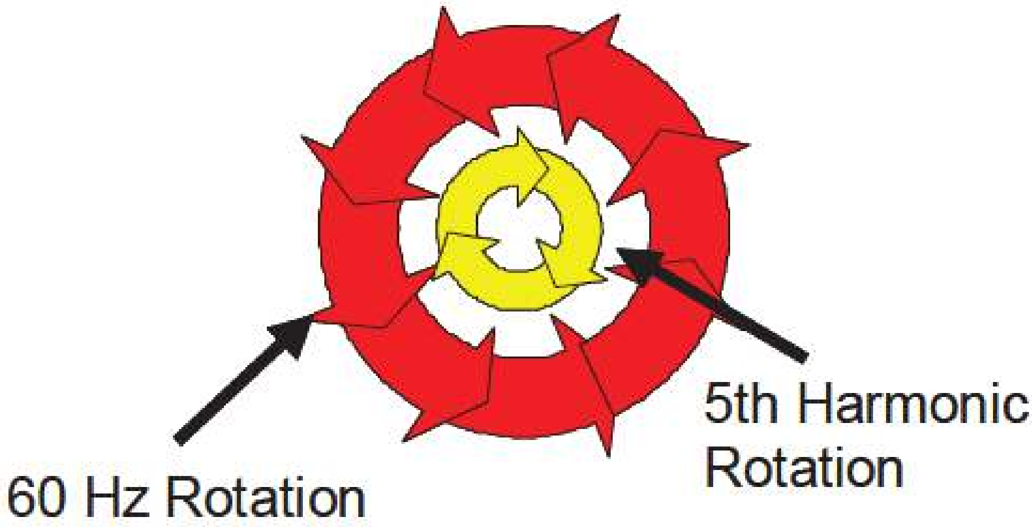

Figure 19 - Breaking effect of the harmonic V in the rotation of a motor

9.3 Losses in conductors

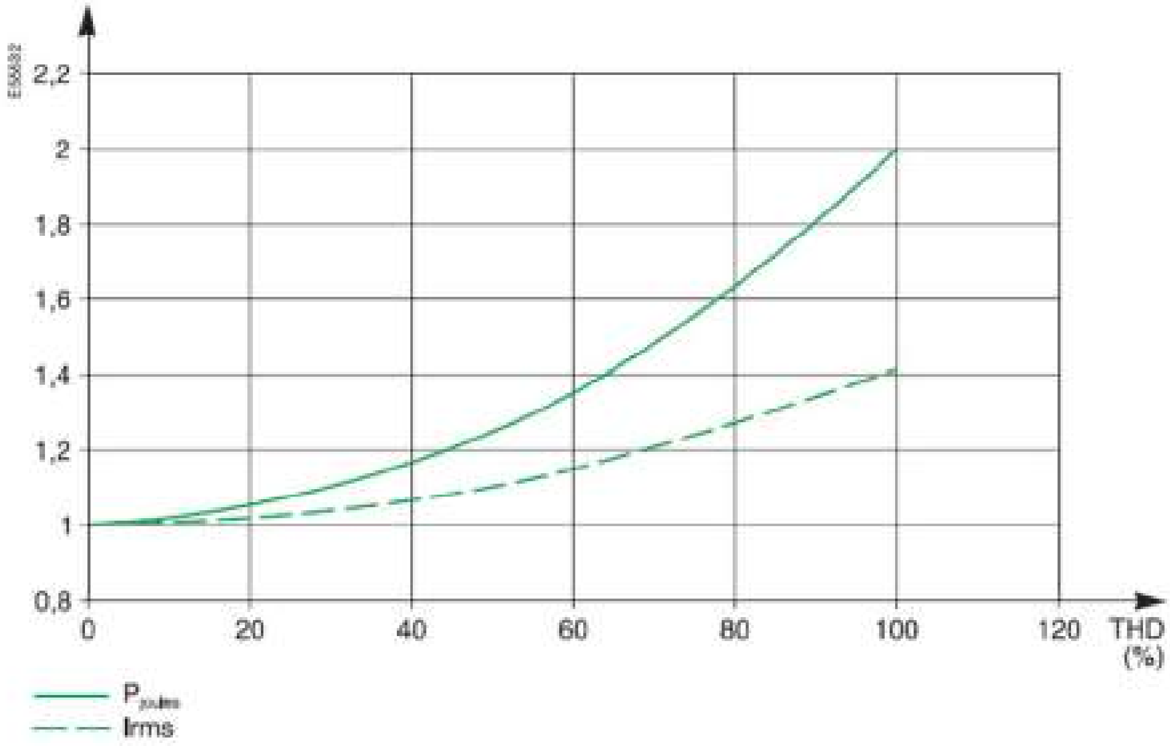

Figure 20 - Increase in the effective value of the current and losses due to the Joule effect in the conductors as a function of THD.

9.4 Losses in capacitors

Harmonic voltages applied to capacitors cause the circulation of currents proportional to the harmonic level, causing additional losses.

For example, a supply voltage with a THD rate equivalent to 10% can cause a 40% increase in losses in capacitors.

10 Conclusions

For all these reasons, it is possible to state that:

- The E-POWER system is a purely reactive and dynamic passive filter. The operating mode is exclusive and the patented bypass system makes it incomparable to similar products in terms of performance.
- The E-POWER system is capable of the adaptive filtering of harmonics i.e. dynamically modifying the filter impedance value to adapt it to real time load conditions, correcting the power factor (PF) in distorted operation.
- **Under these terms the E-POWER system can be considered as one of a kind.**
- In particular, the reduction in the THD factor, and the improvement in the power factor as a result, enables energy in the system to be saved, which can be quantified in accordance with the following expression:

$$\Delta E = p_1 \left[1 - \left(\frac{PF_1}{PF_2} \right)^2 \right] \cdot T \ \text{[kWh]}$$

  When compared with the results of statistical analysis in various international studies, the measurements taken in real time and the laboratory of saved energy achieved by installing the E-POWER system have confirmed that in the presence of average harmonic pollution (from 40% to 60%), it is possible to make an **energy saving to the order of 5% with respect to energy consumption prior to its installation**, thanks to the improvement in power quality.
- Furthermore, the E-POWER system can reduce, and for some types eliminate, disturbance that affects sensitive system components, reducing susceptibility and increasing entire system reliability, thanks to less deterioration in apparatus and fewer maintenance operations. The evaluation of effectiveness in this case is based on statistical methods, however the laboratory analysis carried out on real systems confirmed the results in the relevant literature.
- Finally, given its characteristics, the E-POWER system can also regulate electrical network parameters, further reducing the amount of reactive power and the issues related to variations in supply voltage.

Florence, 12/04/2016

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