

## **ELECTRICAL ENERGY SAVING WITH IMPROVEMENT OF VOLTAGE AND CURRENT QUALITY -THEORETICAL VALIDATION-**

### **I. The Problem**

**There is no doubt that low voltage and current quality is very common to all electrical installations around the world.** This is happening due to:

1) **Power electronics** (inverter, dc converter, soft starter), for motors control and soft starting, which, however, «pollute» electrical installations with harmonics.

2) **Incompatibility between electrical motors and mechanical loads that motors supply.** Namely, because of standardization aspects, starting needs of each motor, changes of load from big to very small values, motors, in their majority, have bigger nominal mechanical power than loads supplied. This fact leads to low efficiency and to additional supply currents, which reduce the voltage-current quality as they are totally useless.

3) **Inductive loads (motors)** that should be supplied with reactive currents in order to electromagnetic fields, required for their operation, be generated.

**Low voltage-current quality leads to [1], [2], [3]**

- i) increase of electromagnetic field losses in electrical installation
- ii) reduction in efficiency of electrical motors and power transformers
- iii) additional energy consumption
- iv) increase in maximum power demand
- v) reduced usage capability of electrical installation
- vi) premature wear of electrical equipment and higher maintenance cost

In the following, it is examined in detail the causes that produce low voltage-current quality.

**The first cause is current and voltage harmonics.** As it was mentioned before, harmonics are produced either by the presence of power electronics or by the presence of capacitor banks in the electrical installation that are not properly tuned amongst themselves or amongst the rest of electrical equipment. As a result, over-compensation and voltage-current harmonics are produced in the electrical installation.

**Harmonics, by decreasing the voltage-current quality, increase especially electromagnetic field losses because they lead to**

1. increase of the skin effect. In this case, current cannot pass through the whole cross-section of the cable but only through a small part of it, which cause increase in thermal losses.
2. increase of eddy currents, which are inducted to neighboring metallic equipment, with a result of extra thermal losses.
3. increase of proximity effects among supply cables. The existence of harmonics means higher current values, thus, bigger opposite voltages induced in neighboring cables which result in thermal losses increasing.

**Furthermore, harmonics cause:**

1. Breaking torque occurrence (torque that works as a brake) in motors all-around the electrical installation, which results in reduction of the efficiency.
2. Increase in the neutral current which is very dangerous because it reduces the safety of the grounding system (because of neutral grounding).
3. Overload and losses increase of power transformers that lead to low efficiency. This is happening because power transformers are built to work with magnetic flows in their ferromagnetic circuit which are produced by currents of 50Hz and not by current harmonics of 150,250,350Hz. Moreover, current harmonics produce additional thermal losses in windings of the transformer.
4. Unreasonable activation of thermal or thermo magnetic switches, that cause stopping of main loads, production lines and therefore cause

major economical “damage”. These unreasonable activations are happening because harmonic currents are added up to the real load current, thus the whole current is much bigger.

5. Damage of PLC’s and other automation control systems in electrical installations, which cause blockage of the production procedure and therefore economical “damage”.

Apart from harmonics, **incompatibility between electrical motors and mechanical loads that motors supply cause increase in electromagnetic field thermal losses and major reduction to motors efficiency.** As it was mentioned before, this incompatibility happens for some technical reasons and takes place in all electrical installations around the world. Because the mechanical load is less than the nominal power of the motor, the surplus of power and energy consumed by the motor is not converted to beneficial mechanical power but it is converted to thermal losses on windings and ferromagnetic circuit of motor. In the same time, surplus of power cause bigger load current (than that which is actually required), major voltage drops and thus increases the electromagnetic field losses.

Finally, reactive currents, which run every electrical installation (even if there is a central compensation system resulting in power factor almost equal to 1, something that benefits mainly each Electrical Energy Distributor), is the 3<sup>rd</sup> reason of electromagnetic field thermal losses increase and electrical motor efficiency decrease.

## II. The solution

**SEMAN’s scientific study determines case-specific solutions, based on the individual needs of each installation.** In order to achieve the optimal energy management and energy saving objective, SEMAN’s scientific staff acts according to the following procedure:

### **a) Measurements and recordings in the electrical installation**

First of all, SEMAN collects all necessary data concerning the installation and then performs real time measurements in the electrical installation. This task is undertaken by SEMAN's scientific staff according to company's know-how. SEMAN uses specific measurement equipment for measuring basic electrical values, current-voltage harmonics up to 35<sup>th</sup> plus transitional effects.

**The collection of** all necessary data involves power transformers, low and medium voltage General Panels, drawings of electrical installation with the length and the cross-section of all cables, position of supply sub-panels, nominal values of motors, Inverter, Soft Starter, number of cables in each rack and contiguity with metal constructions.

**Real time measurements** in an electrical installation involve power transformers, low and medium voltage General Panels, various supply sub-panels, Inverter, SS, other power electronics and motors if this is necessary according to SEMAN's know-how. Measurements are instant or are taking place over a long period of time and data are loaded to computers which are connected to the specific measurement equipment. In some cases when serious tuning effects are taking place, SEMAN uses specific portable oscillographs for the measurement of the various transient phenomena. These oscillographs can be used even in medium voltage.

The above procedure is extremely essential in order to find the individual problems of each installation.

### **b) Elaboration of a thorough scientific study**

According to measurement and recording data which give an integrated view of theoretical approach and real operation of the electrical installation, SEMAN's scientific staff prepares a **thorough scientific study**.

First of all, SEMAN's scientific staff, by the use of all measurement data, realizes the modeling of the electrical installation and then starts the simulation procedure according to SEMAN's theoretical simulation models.

**These theoretical models are designed by SEMAN's scientists and** are based on finite element method and on artificial intelligence models.

**SEMAN's scientists have published an abundance of essays around**

**these models to the most reputable international scientific magazines.**

Details about the theoretical model for the calculation of electromagnetic field losses which is based on finite element method can be found in the following lines.

With the aid of the initial simulations it is very easy to be found all individual problems of each installation such as tuning effects which produce harmonics, low efficiency of electrical motors, over-compensation which leads to capacitive  $\cos\phi$  and increases harmonics etc. Then, according to company's know-how, SEMAN's staff design active or passive harmonic reduction filters, power electronics for voltage control according to the load, reactive power compensators on motors windings or combination of all the above. After that new simulations are taking place.

**Each new simulation improves the results of the previous one through an iterative algorithm. This procedure finishes when the criterion for the improvement of current-voltage quality and for the maximizing of electrical motors efficiency is achieved.**

The above procedure is essential in order to determine the optimum case-specific solution, as in an electrical installation all parts and devices interact with each other. Namely, in an electrical installation an energy saving project may give solution to a specific problem but may cause other problems such as tuning effects and increase of harmonics and so on. For this reason it is considered each electrical installation as unique and thus every electrical installation requires special treatment.

*This procedure of the iterative simulation algorithm according to SEMAN's know-how leads finally to the optimum solution. In such a case, all energy saving systems are in absolute co-operation with each other. As a result, voltage-current quality is improved, motors efficiency is maximized and last but not least maximum savings are ensured.*

### c) Design of energy saving systems

When the thorough scientific study is completed and an optimum solution for the specific electrical installation is found, then SEMAN's scientific staff moves to the next step which is the final design of energy saving systems.

This design involves the configuration of unique systems according to SEMAN's know-how by using stuff from recognized international houses, depending on the particularity of each electrical installation.

### d) Application of energy saving systems

Afterwards, SEMAN's scientific staff installs all energy saving systems to the electrical installation, **without bothering and impeding the operation and the productive process of the factory**. This is achieved by using the corresponding suitable know-how that SEMAN has developed for that specific reason.

**Finally SEMAN delivers to each customer a complete saving solution.**

In the following chapter it is presented the analysis of the electromagnetic field losses calculation model which is used for the theoretical simulations of the scientific study.

## III. The electromagnetic field losses calculation model

### a. Ohmic Resistance

Assume a conductor with cross-section  $S$  which is constructed from a material with electrical resistivity  $\rho$ . If the conductor has length  $l$ , then its ohmic resistance in DC voltage is:

$$R_{dc} = \rho \frac{l}{S} \quad (\text{Formula 1})$$

If however the conductor is supplied by AC voltage then its resistance is increased due to skin effect. Current cannot pass through the whole cross-section of the cable but only through a small part of the cross-section. Current flows mostly in the external surface of the conductor and causes increase in ohmic resistance. Especially, when current harmonics are big enough, skin effect becomes more intense.

For a conductor with circular cross-section it is proved [4] that the resistance in AC voltage is as follows:

$$R_{ac} = l \frac{k\rho}{2\pi\alpha} \frac{M_o(ka)}{M_1(ka)} \sin \left[ \theta_1(k\alpha) - \theta_o(ka) - \frac{\pi}{4} \right] \quad (\text{Formula 2})$$

Where:

- $k^2 = 2\pi f \mu \sigma$ ,  $f$  = frequency,  $\mu$  = conductor's magnetic permeability,  $\sigma$  = conductor's electrical conductivity
- $\rho$  = conductor's electrical resistivity
- $\alpha$  = conductor's radius
- $M_o, \theta_o$  = absolute value and phase of first type Bessel function, zero class  $J_o$  so that:  $J_o(x)^{0,5} = M_o(x) e^{j\theta_o(x)}$
- $M_1, \theta_1$  exactly like previously, but for first class Bessel function, thus  $J_1(x)^{0,5} = M_1(x) e^{j\theta_1(x)}$

## b. Mutual induction

Assume two conductors named 1 and 2 respectively, which are presented in Figure 1. If conductor 1 is supplied by current  $I_1$ , then, because of  $I_1$ , a magnetic flow  $\Psi_1$  will be induced. Part of this flow, named  $\Psi_{21}$ , will also flow through conductor 2. The constant ratio in Formula 3  $M_{21}$  is called mutual induction

$$M_{21} = \frac{\Psi_{21}}{I_1} \quad (\text{Formula 3})$$

On account of compound magnetic flow  $\Psi_{21}$ , in conductor 2 is produced an induced voltage which is given by the next formula:

$$U_{21} = M_{21} \frac{dI_1}{dt} \quad (\text{Formula 4})$$

In the same way it is also defined mutual induction  $M_{12}$ . When two conductors are inside a homogeneous, linear and isotropic environment, it can be proved [5] that  $M_{12}=M_{21}=M$ . It is obvious that the inductance of each conductor is a special case of mutual induction, that is to say:

$$L_{11} = \frac{\Psi_{11}}{I_1} \quad \text{και} \quad L_{22} = \frac{\Psi_{22}}{I_2} \quad (\text{Formula 5})$$

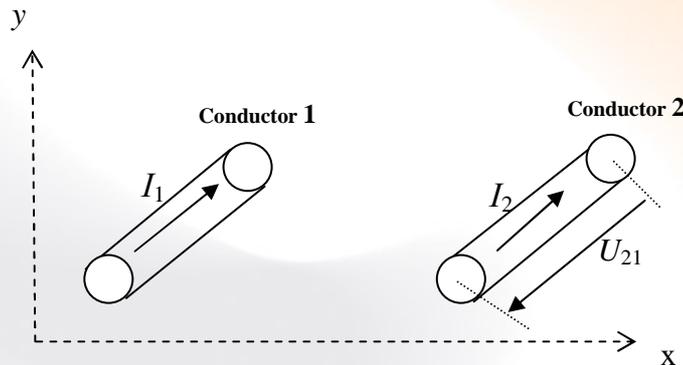


Figure 1: Cables electromagnetic interference

### c. Inductance of a system with n conductors

Assume n conductors, with radius  $\alpha_i$  ( $i=1,\dots,n$ ) and relative magnetic permeability  $\mu_{ri}$ , which are supplied by current  $I_i$ . The induced voltage along conductor i, on account of compound magnetic flows of the other conductors, is at the time field as follows:

$$U_i(t) = M_{i1} \frac{dI_1}{dt} + M_{i2} \frac{dI_2}{dt} + \dots + L_{ii} \frac{dI_i}{dt} + \dots + L_{in} \frac{dI_n}{dt} \quad (\text{Formula 6})$$

By the use of Laplace Transform Formula 6 becomes in frequency field:

$$\bar{U}_i = M_{i1} \cdot j \omega \bar{I}_1 + M_{i2} \cdot j \omega \bar{I}_2 + \dots + L_{ii} \cdot j \omega \bar{I}_i + \dots + L_{in} \cdot j \omega \bar{I}_n \quad (\text{Formula 7})$$

The total voltage drop at conductor i, by taking into account its ohmic resistance, is given by the next formula:

$$\Delta \bar{U}_i = \bar{I}_i \cdot R_{aci} + \bar{U}_i \quad (\text{Formula 8})$$

Where  $\bar{I}_i$  is the current that flows through conductor i,  $R_{aci}$  is the ohmic resistance in AC voltage of conductor i which is given by Formula 2, and  $\bar{U}_i$  is given by Formula 7.

#### d. Electromagnetic field losses

Total losses at conductor i, due to current  $\bar{I}_i$  and due to electromagnetic interference of neighboring conductors, are:

$$P_{thermal} = R_e [\Delta \bar{U}_i \cdot \bar{I}_i] [\text{Watt}] \quad (\text{Formula 9})$$

Formula 9 in case that there are no other conductors and there is no skin effect, becomes the familiar formula:

$$P_{thermal} = \bar{I}_i \cdot R_{dci} \cdot \bar{I}_i = I_i^2 R_{dci} [\text{Watt}] \quad (\text{Formula 10})$$

The above formula is in effect only in case of DC voltage and only if the conductor is armored against electromagnetic effects.

There is no doubt that for all industries, where cables are very close to each other and voltage-current harmonics exist, Formula 9 should be used for accurate calculation of total losses. Familiar Formula 10 will calculate only a small percentage of total losses. By using Formula 9, contiguity effects among supply cables and skin effect which is caused by current harmonics are also taken into account.

At this point it should be mentioned that Formula 9 can be expanded in order to take into account electromagnetic interferences due to eddy currents, which are supplied to neighboring metallic equipment such as cable racks or metal panels.

$$\Delta \bar{U}'_i = \bar{I}_i \cdot R_{aci} + \bar{U}_i + L_{im} \cdot \bar{I}_\delta \quad (\text{Formula 11})$$

and

$$P_{thermal} = \Delta \bar{U}'_i \cdot \bar{I}_i \quad [\text{Watt}] \quad (\text{Formula 12})$$

Where  $L_{im}$  is the mutual induction between a metal equipment (for example cable rack) and conductor  $i$ , and  $\bar{I}_\delta$  is the total eddy current which induced to cable rack on account of electromagnetic field of all cables.

Taking everything upon consideration and for the above reasons and examples in order to calculate the total losses in a conductor  $i$  it should be first calculated the mutual inductions  $M_{ij}$  ( $j=1, \dots, n$ ),  $L_{im}$  and  $R_{aci}$ . Calculation of  $R_{aci}$  is very simple by using Formula 2. Calculation of  $M_{ij}$  and  $L_{im}$  it is very complicated because it is based on the Finite Element Method (FEM), [6]. With the aid of finite element method and artificial intelligence models it is feasible to calculate compound magnetic flows in the case of  $n$  conductors [7-12].

Compound magnetic flow  $\Psi_{ij}$  that flows in conductor i because of the field of j conductor [6-8] is given by the next formula:

$$\Psi_{ij} = \iint_S \vec{B} \cdot d\vec{S} = \iint_S \nabla \times \vec{A} \cdot d\vec{S} \quad (\text{Formula 13})$$

Where B is the magnetic induction in conductor i because of the j conductor, S is the cross-section of the conductor i and  $\nabla \times \vec{A}$  is the vector of the magnetic potential, which is calculated [6-12] with FEM and artificial intelligence models. If compound magnetic flows  $\Psi_{ij}$  can be calculated then it is easy to calculate mutual inductions  $M_{ij}$  και  $L_{im}$  which finally gives the value of electromagnetic field losses by using Formula 12.

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