SENERQON GROUP SCIENTIFIC ENERGY QUALITY OPTIMIZATION

Enhancing Electrical Energy Efficiency: Theoretical Validation of Voltage and Current Quality Improvement

The Issue

Low voltage and current quality are widespread problems in electrical installations worldwide, primarily caused by:

1. Power electronics such as inverters, DC converters, and soft starters used for motor control and soft starting. These devices introduce harmonics, which pollute electrical installations.
2. Incompatibility between electrical motors and the mechanical loads they supply. Due to standardization constraints and varying load requirements, motors often have higher nominal mechanical power than necessary. This results in inefficiency and additional supply currents, diminishing voltage-current quality.
3. Inductive loads, like motors, require reactive currents to generate electromagnetic fields necessary for operation.

The consequences of low voltage-current quality include:

i) Increased electromagnetic field losses in electrical installations ii) Reduced efficiency of electrical motors and power transformers iii) Additional energy consumption iv) Increased maximum power demand v) Reduced usage capability of electrical installations vi) Premature wear of electrical equipment and higher maintenance costs

The following sections delve into the underlying causes of low voltage-current quality.

The primary cause is the presence of current and voltage harmonics. Harmonics arise from power electronics or improperly tuned capacitor banks in electrical installations. They lead to over-compensation and the generation of voltage-current harmonics, exacerbating the issue.

Harmonics contribute to decreased voltage-current quality, particularly by:

1. Amplifying the skin effect, restricting current flow to a small part of the cable's cross-section, resulting in increased thermal losses.
2. Inducing eddy currents in neighboring metallic equipment, leading to additional thermal losses.
3. Exacerbating proximity effects among supply cables, inducing higher currents and opposing voltages in neighboring cables, further increasing thermal losses.

Additionally, harmonics cause:

1. The occurrence of braking torque in motors throughout the electrical installation, reducing efficiency.

2. Dangerous increases in neutral current, compromising the grounding system's safety.
3. Overload and losses in power transformers, reducing efficiency and causing additional thermal losses in windings.
4. Unintended activation of thermal switches, halting main loads and production lines, resulting in significant economic losses.
5. Damage to PLCs and other automation control systems, disrupting production processes and causing economic losses.

Apart from harmonics, the incompatibility between electrical motors and mechanical loads exacerbates electromagnetic field thermal losses and reduces motor efficiency. This mismatch occurs due to technical reasons inherent in electrical installations worldwide. The surplus power consumed by the motor, due to the load being less than the motor's nominal power, converts to thermal losses rather than beneficial mechanical power, further increasing losses.

Lastly, reactive currents present in every electrical installation, even with central compensation systems, contribute to increased electromagnetic field thermal losses and reduced electrical motor efficiency.

The Solution

SENERQON conducts a scientific study to determine tailored solutions based on the unique requirements of each installation. To achieve optimal energy management and savings, SENERQON's scientific team follows this procedure:

a) **Measurement and Data Collection:** Initially, SENERQON gathers all relevant data regarding the installation and conducts real-time measurements using specialized equipment. This involves measuring basic electrical values, current-voltage harmonics up to the 35th order, and transitional effects. Data collection includes information on power transformers, low and medium voltage panels, electrical drawings detailing cable length and cross-section, sub-panel positions, motor nominal values, inverters, soft starters, and cable rack configurations. Real-time measurements encompass various components such as power transformers, panels, sub-panels, inverters, soft starters, and other power electronics. Portable oscillographs are utilized for measuring transient phenomena, especially in cases of significant tuning effects. This meticulous process is crucial for identifying individual installation problems.

b) **Comprehensive Scientific Study**: Based on measurement and recording data, SENERQON's scientific team prepares a thorough scientific study. They model the electrical installation using the gathered data and initiate simulations using SENERQON's theoretical models, grounded in finite element methods and artificial intelligence. These models have been extensively published in reputable international scientific journals. Initial simulations help identify individual problems, such as tuning effects, motor inefficiencies, and over-compensation. SENERQON's staff then designs active or passive harmonic reduction filters, power electronics for voltage control, and reactive power compensators based on the identified issues. Subsequent simulations iteratively improve results until criteria for voltage-current quality improvement and motor efficiency maximization are met.

c) **Design of Energy Saving Systems**: Once the scientific study is complete, SENERQON's team proceeds to design tailored energy-saving systems using international components and SENERQON's proprietary knowledge, customized for each installation's specific requirements.

d) **Implementation of Energy Saving Systems**: SENERQON's scientific staff installs the energy-saving systems seamlessly into the electrical installation without disrupting factory operations or productivity, utilizing their expertise for a smooth integration process.

Upon completion, SENERQON delivers a comprehensive energy-saving solution to each customer.

The next chapter presents an analysis of the electromagnetic field losses calculation model used in the theoretical simulations of the scientific study.

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 ρ. If the conductor has length l , then its ohmic resistance in DC voltage is:

$$R_{dc} = \rho \frac{l}{S} \qquad \textit{(Formula 1)}$$

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 resistancein AC voltage is as follows:

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

Where:

- $k^2 = 2\pi f \mu \sigma$, f = frequency, μ = conductor's magnetic permeability, σ = conductor's electrical conductivity
- ρ = conductor's electrical resistivity
- α = conductor's radius
- M_o, θ_o = absolute value and phase of first type Bessel function, zero class I_o so that : $I_o(xj^{0,5}) = M_o(x)\, e^{j\theta o\,(x)}$
- M_1, θ_1 exactly like previously, but for first class Bessel function, thus $I_1(xj^{0,5}) = M_1(x) e^{j\theta 1(x)}$

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 Ψ_1 will be induced. Part of this flow, named Ψ_{21}, will also flow through conductor 2. The constant ratio in Formula 3 M_{21} is called mutual induction

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

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

$$U_{21} = M_{21}\frac{dI_1}{dt}$$ *(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:

$$L_{11} = \frac{\Psi_{11}}{I_1} \quad \kappa\alpha\iota \quad L_{22} = \frac{\Psi_{22}}{I_2}$$ *(Formula 5)*

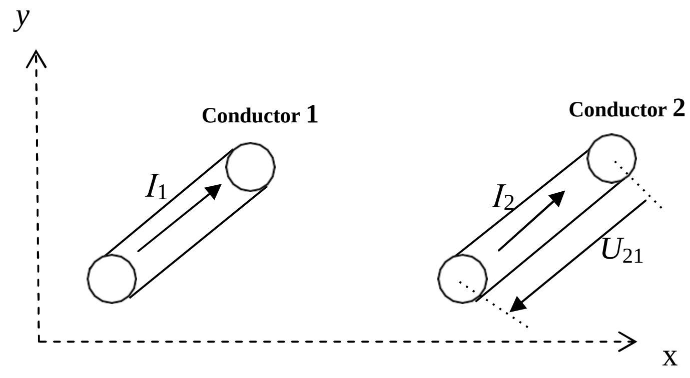

Figure 1: Cables electromagnetic interference

c. Inductance of a system with n conductors

Assume n conductors, with radius α_i (i=1,..,n) and relative magnetic permeability μ_{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:

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

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

$$\overline{U_i} = M_{i1}\cdot j\,\omega\,\bar{I}_1 + M_{i2}\cdot j\,\omega\,\bar{I}_2 + \ldots + L_{ii}\cdot j\,\omega\,\bar{I}_i + \ldots + L_{in}\cdot j\,\omega\,\bar{I}_n \qquad \text{(Formula 7)}$$

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

$$\Delta\overline{U_i} = \bar{I}_i \cdot R_{aci} + \overline{U_i} \qquad \text{(Formula 8)}$$

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 $\overline{U_i}$ 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:

$$P_{thermal} = R_e\left[\Delta\overline{U_i}\cdot\bar{I}_i\right][Watt] \qquad \text{(Formula 9)}$$

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

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

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 considered.

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.

$$\Delta\overline{U}_i' = \overline{I}_i \cdot R_{aci} + \overline{U}_i + L_{im} \cdot \overline{I}_\delta \qquad \textit{(Formula 11)}$$

and

$$P_{thermal} = \Delta\overline{U}_i' \cdot \overline{I}_i \, [Watt] \qquad \textit{(Formula 12)}$$

Where L_{im} is the mutual induction between a metal equipment (for example cable rack) and conductor i, and $\overline{I}_\delta$ 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,…, 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 Ψ_{ij} that flows in conductor i because of the field of j conductor [6-8] is given by the next formula:

$$\Psi_{ij} = \iint_S B \cdot dS = \iint_S \nabla \times A \cdot dS$$

(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 $\nabla \times A$ is the vector of the magnetic potential, which is calculated [6-12] with FEM and artificial intelligence models. If compound magnetic flows Ψii can be calculated, then it is easy to calculate mutual inductions Mii και Lim which finally gives the value of electromagnetic field losses by using Formula 12.

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