Study regarding the power quality improvement in functioning of nonlinear loads

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Abstract. This paper presents a study regarding the variation of the electrical parameters acquired during the functioning of a nonlinear load – an electrothermal installation with electromagnetic induction. Two different situations are presented: the installation works without harmonic compensation devices and when a three phase passive filters are connected at the point of common coupling.

1. Introduction
Electrothermal equipment usually represents important electric energy consumers. Many electrothermal equipment generate significant distortion regime into the power system that affects the power quality for other consumers connected to the same power network.

In developing studies about the variation of the current and voltages in some specified power distribution areas, must be analysed if the power quality indicators are maintaining between standard limits.

Usually, the aspects about the harmonic pollution of the power network are considered from the beginning of designing the electrical installations. By adopting these measures established within reason in technical and economic terms, at the point of common coupling with nonlinear load must be connected filtering devices to bring the system in normal limits.

2. Description of electrical power analysis system
The electrothermal installation with electromagnetic induction that is studied in this paper is composed by an electronic converter CTC100K15 and a hardening inductor. The electrical characteristics are the followings: supplying voltage 3x400V, frequency of the supplying voltage 50Hz, rated current 27A, control voltage 24Vdc, consumed power at high frequency 15kW, voltage at medium frequency 500Vac.

In order to study the distorting regime effect induced into the power network (0.4kV) by the functioning of the electrothermal installation, 10 measuring sets were accomplished by increasing with 10% the consumed power of the installation. In this scope an acquisition application designed in LabVIEW together with a data acquisition board were used. Communication with data acquisition board was accomplished taking into consideration the maximum sampling rate of 250kS/s. Using 10 analogical channels, the maximum sampling rate for a single channel is 25kS/s.
Instantaneous values of the three phase currents and voltages at the point of common coupling were acquired in order to study the variation of active, reactive, distorted and apparent powers and the total harmonic distortion for the phase currents and voltages. In Table 1 the values of these electrical parameters accomplished during the functioning of the electrothermal installation without compensation devices are synthesized.

Studying the variation of the electrical parameters presented in Table 1, the increasing of the effective values of the phase current with the increasing of the consumed power of the installation can be observed. As well, the effective values of the phase voltages are balanced. The total harmonic distortion of the phase voltages stands between the standard limits, but the total harmonic distortion of the phase currents riches very high values, 140%. Due to the current harmonic distortion, the distorted power has high values, as well.

In order to compensate the harmonic distortion, the electrothermal installation must be equipped with harmonic compensation devices for bringing the parameters into standard limits and a power quality improvement system was designed. This system contains an adapting interface. The main function of the interface is to ensure the compatibility between voltage levels of the acquired signals and also the data acquisition board requirements.

![Figure 1. Block scheme of electrothermal installation.](image)

| Installation power [kW] | Phase voltage [V] | Phase current [A] | Active power [W] | Reactive power [VAR] | Distorted power [VAd] | Apparent power [VA] | THD voltages [%] | THD currents [%] |
|-------------------------|-------------------|-------------------|------------------|----------------------|----------------------|-------------------|----------------|----------------|
| 1.5                     | 226.5             | 3.5               | 1300             | 180                  | 1750                 | 2187              | 2.95           | 140            |
| 3                       | 227               | 6                 | 2700             | 300                  | 3100                 | 4122              | 2.8            | 120            |
| 4.5                     | 226.5             | 10                | 4700             | 500                  | 4800                 | 6737              | 2.65           | 105            |
| 6                       | 226.6             | 10.5              | 4800             | 500                  | 4900                 | 6878              | 2.7            | 105            |
| 7.5                     | 226.5             | 11                | 5500             | 750                  | 5300                 | 7675              | 2.65           | 100            |
| 9                       | 226.5             | 13                | 6200             | 800                  | 6000                 | 8665              | 2.5            | 98             |
| 10.5                    | 226.3             | 15.5              | 7500             | 1000                 | 7000                 | 10308             | 2.4            | 95             |
| 12                      | 227               | 19                | 9500             | 1500                 | 8500                 | 12835             | 2.35           | 92             |
| 13.5                    | 227               | 24                | 11500            | 1700                 | 10000                | 15334             | 2.1            | 90             |
| 15                      | 226.5             | 27                | 14000            | 2000                 | 12000                | 18547             | 2              | 85             |
Another condition that must be accomplished is the galvanic isolation between power supply system and data acquisition board. The improvement system also uses NI-6221 data acquisition board for acquiring samples from phase voltages and phase currents.

In order to decrease the total harmonic distortion of the phase currents, the system contains a three phase passive filtering system accorded on 5th, 7th, 11th and 13th harmonic currents.

In Figure 2 the passive filter connection to the point of common coupling is presented.

![Figure 2. Passive filter system connection.](image)

**Description of the passive filtering system**

The passive filtering system are composed by serial circuits with inductivities and capacities which are connected in parallel with the nonlinear load and also with the power distribution. These circuits accomplish a reduced impedance at one or more frequency values. The achievement of these filters is to shortcircuitle the harmonic current as close to the distorting source is possible. In this way the harmonic penetration into the local network can be avoided and also the voltage and current distortion.

In presented situation, the algorithm for designing the passive filters are based on the nominal values of the 5th, 7th, 11th and 13th harmonic currents:

- nominal current for 5th harmonic: $I_n^5 = 20A$
- nominal current for 7th harmonic: $I_n^7 = 15A$
- nominal current for 11th harmonic: $I_n^{11} = 5A$
- nominal current for 13th harmonic: $I_n^{13} = 5A$

Present algorithm is following four methods.

The first method permits the dimensioning based on the conditions concerning the voltage and thermal requirement of the capacitors. The first condition imposes that the value of filter voltage (due to the fundamental component and also to the $k$ harmonic rank) to be lower that the admitted voltage of the chosen capacitor:

$$ U_{C50} + U_{ck} \leq U_{adm} $$  \hspace{1cm} (1)

The second condition imposes that the filter power to be lower that the admitting power:

$$ \omega \cdot C \cdot U_{C50}^2 \cdot t \delta + \frac{k \cdot I^k_n}{k \cdot \omega \cdot C} \cdot t \delta \leq \omega \cdot C \cdot U_{adm}^2 \cdot t \delta $$  \hspace{1cm} (2)

Filter inductivity based on $k$ harmonic rank can be calculated as the following:

$$ L = \frac{1}{k^2 \cdot \omega^2 \cdot C} $$  \hspace{1cm} (3)
In presented relation, $U_{c50}$ represents the voltage loss due to the fundamental component, $U_{ck}$ - the voltage loss due to k harmonic rank, $U_{adm}$ - admitted voltage of the chosen capacitor, $tg\delta$ - loss angle tangent.

The second dimension method consists in determining of the capacitor number in parallel connection with respect to the conditions:

\begin{align*}
\text{a)} & \quad U_{c50} + U_{ck} \leq U_0 \\
\text{b)} & \quad \sqrt{\left(I_{c50}^2 + \left(I_n^k\right)^2\right)} \leq 1.3 \cdot I_{adm}
\end{align*}

$U_0$ - admitted voltage on one connection side.

The third method is based on the admitted voltage and current conditions. In presented situation must be accomplished the condition presented in (3) and also:

\begin{align*}
I_{c50}^2 + (I_n^k)^2 \leq (1.5I_0)^2
\end{align*}

The forth method is based on the admitted voltage and power conditions. In presented situation the condition presented in (3) must be accomplished and also:

\begin{align*}
\omega C \cdot U_{c50}^2 \cdot tg\delta + k\omega C \cdot U_{ck}^2 \cdot tg\delta \leq \omega C \cdot U_0^2 \cdot tg\delta
\end{align*}

Taking into consideration the conditions presented in (1)-(6), the values of inductivities and capacities of the passive filtering system are the followings:

- passive filter accorded on 5th harmonic current: $L_5 = 16.21mH, C_5 = 25\mu F$
- passive filter accorded on 7th harmonic current: $L_7 = 2.5mH, C_7 = 80\mu F$
- passive filter accorded on 11th harmonic current: $L_{11} = 2.1mH, C_{11} = 40\mu F$
- passive filter accorded on 13th harmonic current: $L_{13} = 1.5mH, C_{13} = 40\mu F$

After connecting the passive filtering system, another 10 measurement set were accomplished, by increasing with 10% the consumed power of the installation. These measurements permit to study the electrical parameters during the functioning of the electrothermal installation using passive filters for harmonic compensation [2], [3], [4]. The active filtering system is described in the following paragraph.

Using passive compensation, the acquisition system acquires samples from phase voltage and phase current at the point of common coupling and saves them into .txt documents. The computing system designed in LabVIEW is able to calculate the electrical parameters and to display their variation on the front panel of the application.

Presented application also contains an active filtering system. The input data of the active filter application represent the .txt files that contain the samples acquired from phase voltages and phase currents. The purpose of this application is to improve the electrical parameters, the phase currents are expected to be more sinusoidal, so the THD for phase currents will be decreased.

The algorithm of the present subroutine computes the electrical parameters using the acquired samples during the functioning of the electrothermal installation equipped with the passive filtering system. The voltage and current samples are assumed from the loading vector in the first sequence [7], [8], [9]. Using appropriate functions from LabVIEW library, the algorithm separates the current from the voltage samples, computing the effective values of the phase currents and voltages on each period of the power system.

The effective values of the voltage on each phase are computed with the following relation:

\begin{align*}
U_{eff}(\tilde{t}) = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} U(\tilde{t}, n)^2}
\end{align*}
The effective values of the current on each phase are computed with the following relation:

\[ I_{ef}(i) = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} I(i,n)^2} \]  
\[(8)\]

where \( N \) is the number of samples/period, \( N = 500 \), \( i \) is the phase, \( i = 1...3 \).

So, \( U(i, n) \) represents the amplitude of the voltage sample on \( i \) phase, on \( n \) position in the vector having the length equal with \( N \).

The total values of the voltages and currents can be computed as the followings:

\[ U_{ef} = \sqrt{\frac{U_{ef}^2(1)+U_{ef}^2(2)+U_{ef}^2(3)}{3}} \]  
\[(9)\]

\[ I_{ef} = \sqrt{\frac{I_{ef}^2(1)+I_{ef}^2(2)+I_{ef}^2(3)}{3}} \]  
\[(10)\]

The filtering analyser 1 contains other subroutines that calculate the active and reactive powers, and the harmonic currents and voltages as well, using appropriate functions from LabVIEW library.

The active power of \( i \) phase is computed with the relation:

\[ P(i) = \sum_{k=1}^{50} U_{efk}(i) \cdot I_{efk}(i) \cdot \cos \Phi(i) \]  
\[(11)\]

The reactive power of \( i \) phase is computed with the relation:

\[ Q(i) = \sum_{k=1}^{50} U_{efk}(i) \cdot I_{efk}(i) \cdot \sin \Phi(i) \]  
\[(12)\]

In relations (11) and (12), \( k \) represents the harmonic rank.

The harmonic voltage on \( i \) phase is computed as in the relation:

\[ U_{har}(i) = \sqrt{\sum_{n=2}^{N} \frac{(U_{har}(i,n))^2}{U_{har}(i,i)}} \]  
\[(13)\]

The harmonic current on \( i \) phase is computed as in the relation:

\[ I_{har}(i) = \sqrt{\sum_{n=2}^{N} \frac{(I_{har}(i,n))^2}{I_{har}(i,i)}} \]  
\[(14)\]

where \( N \) is the number of samples / period and \( i \) is the phase.

The total values of the active and reactive powers are computed as in the following relations:

\[ P = \sum_{i=1}^{3} P_i, \quad Q = \sum_{i=1}^{3} Q_i \]  
\[(15)\]

The total apparent power is computed as:

\[ S = 3 \cdot U_{ef} \cdot I_{ef} \]  
\[(16)\]

The distorted power is computed as in the relation:

\[ D = \sqrt{S^2 - P^2 - Q^2} \]  
\[(17)\]

The total values of the harmonic voltages and currents are computed as in the followings:
\[ U_{thd} = \sqrt{\frac{U_{thd1}^2 + U_{thd2}^2 + U_{thd3}^2}{3}} \]

\[ I_{thd} = \sqrt{\frac{I_{thd1}^2 + I_{thd2}^2 + I_{thd3}^2}{3}} \]  

(18)

Presented computing application is depicted in Figure 3.

Table 2 presents the variation of the electrical parameters during the functioning of the nonlinear load when the passive filtering system is connected to the point of common coupling.

**Figure 3.** Computing application LabVIEW code.
Table 2. Variation of electrical parameters (when the passive filtering system is connected).

| Installation power [kW] | Phase voltage [V] | Phase current [A] | Active power [W] | Reactive power [VAR] | Distorted power [VAd] | Apparent power [VA] | THD voltages [%] | THD currents [%] |
|------------------------|-------------------|-------------------|------------------|---------------------|----------------------|---------------------|------------------|------------------|
| 1.5                    | 227.6             | 17                | 1300             | -11000              | 3000                 | 11476               | 3.15             | 28.6             |
| 3                      | 228               | 17.4              | 2700             | -11000              | 3000                 | 11717               | 3                | 33               |
| 4.5                    | 228               | 18                | 4000             | -10800              | 4800                 | 12477               | 2.9              | 39               |
| 6                      | 228               | 18.1              | 4000             | -10800              | 4800                 | 12477               | 2.9              | 37               |
| 7.5                    | 228               | 18.7              | 5000             | -10800              | 5000                 | 12909               | 2.85             | 42.5             |
| 9                      | 228.4             | 19.3              | 5800             | -10700              | 5000                 | 13158               | 2.85             | 45               |
| 10.5                   | 228.8             | 19.5              | 6000             | -10700              | 6000                 | 13656               | 2.8              | 45               |
| 12                     | 228.2             | 22.2              | 8800             | -10000              | 7000                 | 15048               | 2.65             | 55               |
| 13.5                   | 228               | 25                | 11000            | -10000              | 8000                 | 16882               | 2.5              | 60               |
| 15                     | 227.5             | 28                | 13000            | -9500               | 10000                | 18954               | 2.3              | 65               |

3. Conclusions
This paper represents a comparative study regarding the variation of electrical parameters during the functioning of an electrothermal installation with electromagnetic induction. The phase voltage, active, reactive, distorted and apparent powers were studied when the nonlinear load works without harmonic compensation devices.

A very important conclusion represents the voltage balancing. The phase voltages are approximately constant during the increasing with 10% of the consumed power of the installation and they are situated between 226-227V in Table 1 and between 227-228V in Table 2 when the passive filtering system is connected. The RMS values of phase currents are increased from 27A to 28A when the filtering system is connected. The absolute values of reactive powers are decreased as well.

Another important conclusion is that the total harmonic distortion of the phase currents is decreased from 140% to 65% when the filtering system is connected.

Following the results, the distortion of the current variation falls below the standard limits and the current harmonics must be compensated using appropriate devices [1], [5], [6].

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