Power Quality Measurement for Line Frequency Coreless Induction Furnaces in MV Network

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Abstract: - This paper presents a study about power quality problems generated by line frequency coreless induction furnaces. We analyzed a furnace with 12.5 t capacity of cast-iron. The measurements have been made in the primary of the furnace transformer, on the MV line, using the CA8334 three-phase power quality analyser. Experimental results emphasized the presence of harmonics and interharmonics in the phase voltages and harmonics in the currents absorbed from the MV network. Further to harmonic analysis of the measured signals, we have been proposed some optimization methods for operation of analyzed furnace, in such way to comply with the European norms of Electromagnetic Compatibility (EMC).

Key-Words: - Power quality measurement, Harmonics, Interharmonics, Induction furnace

1 Introduction
Today, power quality studies are becoming a growing concern.

The most important parameters which affect power quality are harmonics, voltage instability and reactive power burden [1-3]. They cause low system efficiency, poor power factor, cause disturbance to other consumers and interference in the nearly communication networks [1-3].

The increased problems in power networks impose to identify the sources of power quality deterioration.

Induction heating equipments do not introduce dust and noise emissions in operation, but cause power quality problems in the electric power system [4-6].

Induction-melt furnaces supplies by medium-frequency converters generate fixed and variable frequency harmonics [1,2,5]. Also, large furnaces operating at a few hundred hertz can generate interharmonics. Interharmonics can overload power system capacitors, introduce noise into transformers, cause lights to flicker, instigate UPS alarms, and trip adjustable-speed drives [1,5].

High-frequency systems, which operate at greater than 3 kHz are relatively small and limited to special applications. Power quality problems produced by the operation of these equipments are small.

The induction furnaces supplied at line frequency (50 Hz) are of high capacity and represent great power consumers. The operation of these furnaces also produces important disturbances in the power network. Being single-phase loads, these furnaces introduce unbalances that lead to the increasing of power and active energy losses in the network [4,6].

Because the specialty literature does not offer detailed information regarding the harmonic distortion in the case of line frequency coreless induction furnaces, we proposed ourselves to analyze the power quality problems introduced by the operation of these furnaces.

On the other side, it must kept in view also the fact that in Romania are still operating line frequency coreless induction furnaces, and the cumulated effect of the electromagnetic pollution generated by these could be important.

2 Electrical Installation of the Analyzed Induction-Melt Furnace
It was analyzed a coreless induction furnace with 12.5 t capacity of cast-iron; the furnace is supplied from the three-phase medium-voltage network (6 kV) through a transformer in Δ/Y connection, with step-variable voltage. Load balancing of the three-phase network is currently achieved by a Steinmetz circuit, and the power factor correction is achieved by means of some step-switching capacitor banks (fig.1).

In electric diagram from fig.1: Q1 is an indoor three-poles disconnector, type STIm–10–1250 (10 kV, 1250 A), Q2 is an automatic circuit-breaker OROMAX (6 kV, 2500 A), T is the furnace
transformer (2625 kVA; 6/1.2 kV), $K_1$ is a contactor (1600 A), (1) is the symmetrization installation of three-phase network, (2) is the power factor compensation installation, $TC_1$, $TC_2$ (300/5 A) are current transformers, $TT_1$, $TT_2$ (6000/100 V) are voltage transformers, and $M$ is the flexible connection of the induction furnace CI.

![Fig.1. Experimental electric diagram](image)

Within the study the following physical aspects were taken into account [4]:
- induction heating of ferromagnetic materials involve complex and strongly coupled phenomena (generating of eddy currents, heat transfer, phase transitions and mechanical stress of the processed material);
- the resistivity of cast-iron increases with temperature;
- the relative magnetic permeability of the cast-iron changes very fast against temperature near to the Curie point (above the Curie temperature the cast-iron becomes paramagnetic).

As consequence, we analyzed the influence of the following factors upon the power quality of the induction furnace: the charge, the supply voltage, the symmetrization installation and the power factor correction installation.

### 3 Measured Signal Waveforms in Electrical Installation of the Furnace

The measurements have been made in the primary of the furnace transformer T (fig.1), using the CA8334 three-phase power quality analyser [7].

CA8334 gave an instantaneous image of the main characteristics of power quality for the analyzed induction furnace.

The main parameters measured by the CA8334 analyser were: TRMS AC phase voltages and TRMS AC line currents; peak voltage and current; active, reactive and apparent power per phase; harmonics for voltages and currents up to the 50th order.

This analyser provide numerous calculated values and processing functions in compliance with EMC standards in use (EN 50160, IEC 61000-4-15, IEC 61000-4-30, IEC 61000-4-7, IEC 61000-3-6). The current $I_2$ (fig.1) was impossible to be measured because the CA8334 three-phase power quality analyser was connected to the watt-hour meter input. The watt-hour meter had three voltages ($U_{12}, U_{23}, U_{31}$) and two currents ($I_1$ and $I_3$).

#### 3.1 The Cold state of the Charge

This is the first heating stage of the cast-iron charge. The waveforms of phase voltages and currents absorbed from the network after 15 minutes from the beginning of the heating process are shown in fig.2 and fig.4.

Harmonic spectra of the voltages and currents in the cold state of the charge are shown in fig.3 and fig.5.

![Fig.2. Phase voltages in the cold state of the charge](image)

![Fig.3. Harmonic spectra of the voltages in the cold state of the charge](image)
In the first heating stage, the electromagnetic disturbances of the phase voltages are very small. The 5\textsuperscript{th} harmonic is within compatibility limits [8]. Also, it can be observe the presence of interharmonics in voltages waveforms. Voltage interharmonics exceed the compatibility limits [8].

![Fig.4. Line currents in the cold state of the charge](image)

Waveform distortion of the currents in cold state is large.

![Fig.5. Harmonic spectra of the currents in the cold state of the charge](image)

At the beginning of the cast-iron heating process the 2\textsuperscript{nd}, 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, 9\textsuperscript{th}, 11\textsuperscript{th}, 13\textsuperscript{th} and 15\textsuperscript{th} harmonics are present in the line currents. The 5\textsuperscript{th} harmonic exceeds the compatibility limits [8].

### 3.2 The Intermediate State of the Charge

In the intermediate state, part of the charge is heated above the Curie temperature and becomes paramagnetic, and the rest of the charge still has ferromagnetic properties. The furnace charge is partially melted. The waveforms of phase voltages and currents absorbed from the network after 5 hours and 40 minutes from the beginning of the heating process are shown in fig.6 and fig.8. Harmonic spectra of the voltages and currents in the intermediate state of the charge are shown in fig.7 and fig.9.

In the intermediate state of the charge, phase voltages present interharmonics. Distortion of waveform is small.

![Fig.6. Phase voltages in the intermediate state](image)

In the intermediate state the 5\textsuperscript{th} harmonic do not exceeds the compatibility limits, but the voltage interharmonics exceed the compatibility limits [8].

![Fig.7. Harmonic spectra of the voltages in the intermediate state](image)

![Fig.8. Line currents in the intermediate state](image)

In the intermediate state, harmonic spectra of the currents present the 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, 9\textsuperscript{th}, 11\textsuperscript{th}, 13\textsuperscript{th}, 15\textsuperscript{th}, 17\textsuperscript{th}, 25\textsuperscript{th} harmonics and even harmonics (2\textsuperscript{nd}, 4\textsuperscript{th}, 6\textsuperscript{th}, 8\textsuperscript{th}). The 5\textsuperscript{th} and 25\textsuperscript{th} harmonics exceed the compatibility limits [8].

![Fig.9. Harmonic spectra of the currents in the intermediate state](image)
3.3 The End of the Melting Process

The furnace charge is totally melted, being paramagnetic.

The waveforms of phase voltages and currents at the end of melting (after 8 hours from the beginning of the heating process) are shown in fig.10 and fig.12.

Harmonic spectra of the voltages and currents at the end of melting are shown in fig.11 and fig.13.

[Diagram of phase voltages at the end of the melting process]

Fig.10. Phase voltages at the end of the melting process

[Diagram of harmonic spectra of phase voltages]

Fig.11. Harmonic spectra of the phase voltages at the end of the melting process

At the end of the melting, interharmonics are present in the phase voltages waveforms. Voltage interharmonics exceed the compatibility limits [8]. The 5th harmonic is within compatibility limits [8].

4 The Values Computed by the CA8334 Analyser [7]

The values computed by the CA8334 analyser are:

1. Total harmonic distortion of voltages and currents:

\[
V_{THD i} = \sqrt{\frac{\sum_{n=2}^{50} (V_{harm i n})^2}{V_{harm i 1}}} \cdot 100
\]

(1)

\[
I_{THD i} = \sqrt{\frac{\sum_{n=2}^{50} (I_{harm i n})^2}{I_{harm i 1}}} \cdot 100
\]

(2)

V represents the phase voltage, I represents the line current, \( i \) represents the phase (\( i = 1, 2, 3 \)) and \( n \) represents the order of harmonics.

2. Power factor:

\[
PF_i = \frac{P_i}{S_i}
\]

(3)

\( P_i \) [W] and \( S_i \) [VA] represent active power and apparent power per phase (\( i = 1, 2, 3 \)).

Fig.14-16 show the recorded parameters (total harmonic distortion of phase voltages and currents - \( V_{THD i}, I_{THD i} \) - and power factor PF per phase 1) in the first stage of the heating. Total recording period was 11:20-12:18.
Fig. 15. Recorded values of $I_{\text{THD}}$ in the cold state
In the recording period of cold state, THD of line currents exceed the compatibility limits.

Fig. 16. Recorded values of $PF$ per phase 1 in the cold state
$PF$ per phase 1 is less than unity, and in the time period 12:00 - 12:18, $PF$ is less than neutral value (0.92).

Fig. 17-19 show the recorded parameters in the intermediate state of the heating. The furnace charge was partially melted in the recording period, 13:20-14:18.

Fig. 17. Recorded values of $V_{\text{THD}}$ in the intermediate state
In the intermediate state, THD of phase voltages do not exceed the compatibility limits, but are bigger comparatively with cold state.

Fig. 18. Recorded values of $I_{\text{THD}}$ in the intermediate state
THD of line currents are remarkably high in intermediate state and exceed the compatibility limits.

Fig. 19. Recorded values of $PF$ per phase 1 in the intermediate state
$PF$ per phase 1 is less than unity, and in the time period 13:20-13:35, $PF$ is less than neutral value (0.92).

Fig. 20-22 show the recorded parameters in the last stage of the heating. The furnace charge was totally melted (and paramagnetic) in the recording period, 18:02-18:12.

Fig. 20. Recorded values of $V_{\text{THD}}$ in the last stage of the melting process
THD of phase voltages are within compatibility limits, being smaller comparatively with cold state or intermediate state.

Fig. 21. Recorded values of $I_{\text{THD}}$ in the last stage of the melting process
THD of line currents are smaller in the last stage of melting comparatively with cold state or intermediate state, but exceed the compatibility limits.

In the last stage of the melting process $PF$ per phase 1 is less than unity. In the time period 18:06-18:12, $PF$ is less than neutral value (0.92).
5 Conclusions

The measurements results show that the operation of the analyzed furnace determines interharmonics and harmonics in the phase voltages and harmonics in the currents absorbed from the network.

THD of phase voltages are within compatibility limits, but voltage interharmonics exceed the compatibility limits in all the analyzed situations.

THD of line currents exceed the compatibility limits in all the heating stages. Because $I_{THD}$ exceed 30%, which indicates a significant harmonic distortion, the probable malfunction of system components would be very high.

THD of line currents are bigger in intermediate state comparatively with cold state, or comparatively with the end of melting.

This situation can be explained by the complex and strongly coupled phenomena (eddy currents, heat transfer, phase transitions) that occur in the intermediate state.

Harmonics can be generated by the interaction of magnetic field (caused by the inductor) and the circulating currents in the furnace charge.

In the case of currents, 5th and 25th harmonics exceed the compatibility limits.

To reduce the heating effects of harmonic currents created by the operation of analyzed furnace it must replaced the furnace transformer by a transformer with K-factor of an equal or higher value than 4.

The capacitors for power factor correction and the ones from Steinmetz circuit amplify in fact the harmonic problems.

PF is less than unity in all the analyzed situations. But, Steinmetz circuit is efficient only for unity PF, under sinusoidal conditions [4].

For optimizing the operation of analyzed induction furnace, it’s imposing the simultaneous adoption of three technical measures: harmonics filtering, reactive power compensation and load balancing.

That is why harmonic filters must be introduced in the primary of furnace transformer to solve the power quality problems.

In order to eliminate the unbalance, we suggest to add another symmetrization system in the connection point of the furnace to the power supply network.

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