Analysis the electrical parameters of a high-frequency coreless induction furnace

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Abstract. The paper analyzes the most important electrical parameters of a coreless induction furnace, having a capacity of 7 kg molten iron (i.e. 2.5 kg aluminum). The furnace is supplied by a high-frequency (HF) static converter ITS2 12K20, with the output frequency 5...12 kHz, 600...1200 Vac rated HF voltage, and 20 kW rated HF power. Monitoring of electrical parameters was done for an aluminum charge, using a power quality analyser CA8334. The measurement results showed that induction furnace operation causes unbalance and harmonics in three-phase currents absorbed from the distribution network. Harmonics in the line currents are caused mainly by static converter, and to a lesser extent by furnace load and interaction of eddy currents induced in the charge and the magnetic field of the inductor. To reduce the negative impact of the current harmonics on the distribution network is necessary the design and achievement of electrical filters for odd-order harmonics (5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th).

1. Introduction

The Induction melting is currently the fastest electric technology in metal production [1], [2]. Medium and high-frequency coreless induction furnaces are suitable for melting, re-melting and alloying, due to the advantages related to low installation cost, low operating cost, maximum alloy flexibility (can be emptied very quickly), good heating efficiency, precise temperature control. Induction melting involves automatic stirring, resulting increases of homogeneity and quality of metal alloy. These furnaces are used for elaboration of low-carbon high alloyed steel, alloy cast iron, hard iron, bronze, nickel and precious metals [1-8].

New installations of medium and high-frequency induction melting are characterized by performant power supplies, improved furnace refractory linings, heat recovery, and overall system control [1], [2], [3].

Electronic power supplies control current and frequency for efficient induction melting, providing high-power density in the furnace charge [1].

Static converters have the following advantages: very good yield; variable and auto-adjust frequency during the melting process (eliminate the need to modify the capacitors bank for power factor correction); are compact and easy to install; low wear; maintenance is minimal due to the absence of moving parts.
Two main types of static converters are used in medium and high-frequency induction melting installations: voltage-fed power supply (with series-resonant furnace circuit) and current-fed power supply (with parallel-resonant furnace circuit) [2].

Voltage-fed power supply takes advantage of switching technology that is capable of handling high currents. Current-fed power supply takes advantage of rugged and economical switching-device technology, but has less control over the furnace current than voltage-fed power supply [2], [3], [6].

Beside of these advantages, both current and voltage-fed supplies generate harmonics and interharmonics [3], [4], [5].

Moreover, current-fed power supply generates voltage notching, that can cause tripping of other power supplies and DC drives [2].

Induction furnaces, as nonlinear loads, can produce significant distortions that affect the correct functioning of other neighboring loads, resulting interferences on the control systems, heating of rotating machines and capacitors banks, increasing electrical losses [1], [7], [9].

Further are analyzed the most important electrical parameters of a high-frequency coreless induction furnace, having a capacity of 7 kg molten iron (i.e. 2.5 kg aluminum), and power quality problems caused in distribution network.

2. Technical characteristics for electrical installation of analyzed induction furnace

The installation of furnace (figure 1) is supplied from the three phase low voltage (0.4 kV) through a general distribution board equipped with an automat circuit-breaker with thermal protection (Ir=50 A), electromagnetic protection (Iem=5It), differential protection (Id=300 mA) and overvoltage at 50 Hz protection (U>=260-280 V). The on/off switching of the installation is made with three static contactors (Solid state relay-SSR).

The furnace is supplied by a high-frequency (HF) static converter ITS2 12K20, with following electric characteristics: mains supply voltage 3x400 V, 50 Hz; maximum mains current 3x40 A; power factor 0.95; output frequency 5...12 kHz; rated HF voltage 600...1200 Vac; rated HF power 20 kW, control voltage 24 Vdc [10].

![Electric scheme of the high-frequency coreless induction furnace](image)

**Figure 1.** Electric scheme of the high-frequency coreless induction furnace.

Also, the electric scheme from Figure 1 includes a diode bridge rectifier DD B6U 85N with following electric characteristics [11]: repetitive peak reverse voltage 1600V; non-repetitive peak reverse voltage 1700V; RMS forward current (per chip) 60A; output current 85...104 A; surge forward current 550A; P=1500 A²s; forward voltage max. 1.44 V; reverse current 5 mA.
In DC link is placed a large DC choke \( L_f = 1.5 \, \text{mH} \) and two parallel-connected DC capacitors \( C_f = 2 \times 100 \, \mu\text{F}, 900 \, \text{V} \) for energy storage and filtering. The DC choke serves as a current-limiting reactor against faults on the inverter side [2].

Static converter includes an inverter with IGBT transistors FF300R12KS4, having following electric characteristics [12]: collector-emitter voltage 1200 V; continuous DC collector current 370 A; repetitive peak collector current \( (t_p = 1 \, \text{ms}) \) 600 A; total power dissipation 1.95 kW; gate-emitter peak voltage \( \pm 20 \, \text{V} \); collector-emitter saturation voltage 3.75 V.

For supplying the inductor is used a HF transformer (T) with primary voltage 1200 V, apparent power 480 kVA and frequency domain 5…12 kHz. In Figure 1, R, L represent the equivalent parameters of inductor-charge system.

### 3. Electrical parameters from induction furnace installation

Monitoring of electrical parameters from induction furnace installation was done for an aluminum charge, using a power quality analyser CA8334 [13]. Measurements were made on AC low voltage side, between breaker and static converter.

The following table presents informations about the heating stages of aluminum charge, power set on each stage, power absorbed by inductor, frequency, supply voltage of inductor and current absorbed on medium-frequency side.

| Table 1. Heating stage of aluminum charge |
|------------------------------------------|
| Time period   | %P<sub>N</sub> | P<sub>inductor</sub> [kW] | f [kHz] | U<sub>MF</sub> [V] | I<sub>MF</sub> [A] | Heating stage                             |
|---------------|----------------|--------------------------|--------|----------------|----------------|-------------------------------------------|
| 9:08-9:39     | 5%             | 4,5                      | 5      | 555            | 130            | Crucible preheating                       |
| 9:40-10:10    | 25%            | 14,5                     | 6,3    | 1040           | 324            | Heating of aluminum charge                |
| 10:11-10:23   | 100%           | 26,2                     | 6,7    | 1300           | 435            | Melting of aluminum charge                |
| 10:24         | 100%           | 27                       | 7,1    | 1273           | 454            | End of melting (furnace emptied)          |

Preheating of the crucible start at 8:30 with an active power set of 5%P<sub>N</sub>. At 9:40 was set a new level of active power (25%P<sub>N</sub>) and at 10:11 the active power was set to maximum (100% P<sub>N</sub>). At 10:24 the aluminum charge was ready for casting.

CA8334 gave an instantaneous image of the main characteristics of power quality for the analyzed furnace. The main parameters measured by the CA8334 analyser were: True RMS (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 [13].

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 61000-3-4). The values computed by the CA8334 are [13]: total harmonic distortion of voltages and currents, distortion factor of voltages and currents, K factor for current, voltage and current unbalance, power factor and displacement factor, extreme and average values for voltage and current, peak (crest) factors for current and voltage.

#### 3.1. Crucible preheating and heating stage of aluminum charge

The following figures show the time variation of TRMS AC line currents, total harmonic distortion (THD), crest factor (CF) and unbalance of line currents, active, reactive, and apparent powers, power factor (PF) and displacement factor (DPF) recorded in crucible preheating and heating stage of aluminum charge (time period 9:08-10:10). By green is presented phase 1 (L<sub>1</sub>), by yellow phase 2 (L<sub>2</sub>) and by magenta phase 3 (L<sub>3</sub>).

THD of line currents (Figure 2.b) was 138% at the crucible preheating stage, and decreased to 104% in the heating stage of aluminum charge.

During the entire period of aluminum charge heating, crest factor of currents (Acf) exceeds 1.41, characteristic value of sinusoidal waveforms (Figure 3.a). This indicates very high harmonic pollution
of the line currents. In the crucible preheating stage (9:08-9:39), crest factor of currents had an average value of 2.9 (maximum 3.2). In the time interval 9:40-10:10 average value ridge drops to 2.38 (maximum 2.7), due to the reduction of current harmonics.

Figure 2. TRMS [A] (a) and THD [%] (b) of line currents during the crucible preheating and heating stage of aluminum charge.

Figure 3. Crest factor CF [-] (a) and unbalance [%] (b) of line currents during the crucible preheating and heating stage of aluminum charge.

Figure 4. Active power P [W] (a) and reactive power Q [VAR] (b) during the crucible preheating and heating stage of aluminum charge.
Figure 5. Apparent power $S$ [VA] during the crucible preheating and heating stage of aluminum charge.

Figure 6. Power factor $PF$ [-] (a) and displacement power factor $DPF$ [-] (b) recorded in crucible preheating and heating stage of aluminum charge.

Figure 3.b shows that current unbalance is pronounced (4-8%) in the first heating stage, but decreases as the charge is melted (in the second stage of heating) to (0.7-2.6%). At the end of heating, current unbalance is within the limits of EMC standards (1.7%).

During the time period (9:40-10:10) has greatly increased active power consumption (Figure 4.a), because full active power of static converter was used to heat the aluminum charge (100% $P_N$). Figure 4.b shows that consumption of reactive power per phase was greater than the active power.

Real power factor $PF$ (per phase) is very low in the first heating stage (9:08-9:39), about 0.6, because of the reactive power consumption and harmonic pollution of currents (Figure 6.a). After 9:39 $PF$ increases slightly, but remains much lower (0.7) than neutral value (0.92).

Displacement power factor (DPF) is slightly smaller than 1 (0.999, Figure 6.b). The difference between $PF$ and DPF indicates a large deviation from sinusoidal waveform of currents.

3.2. Melting stage of aluminum charge

THD of line currents in the melting stage of aluminum charge is slightly lower than in the previous stage (84-105%, Figure 7.b). Crest factor of the line currents in this stage is very high (2.2), indicating a very high harmonic pollution.

During the period (10:13-10:27) unbalance of line currents varies between 0-2%, and in the last five minutes of recording has a maximum value of 3.2% (Figure 8.b).

The reactive power per phase is less than active power, but still very high, indicating an insufficient power factor compensation in the installation.
In the melting stage, PF increase from the heating stage and reaches the value of 0.76, but still less than neutral value (Figure 11.a); DPF (Figure 11.b) is very good (0.994), higher than neutral value.
Figure 10. Apparent power S [VA] during the melting stage of aluminum charge.

Figure 11. Power factor PF [-] (a) and displacement power factor DPF [-] (b) recorded in the melting stage of aluminum charge.

Figures 12-19 show the time variation of 5th, 7th, 11th, 13th, 17th, 19th, 23th, 25th harmonics from the line currents during the melting process of aluminum charge. Levels of these harmonics exceed very much the compatibility limits [14].

Figure 12. Time variation of 5th harmonic from line currents during the melting process.

In the first stages of aluminum charge heating: 5th harmonic level exceeds 80% (maximum 88%), 7th harmonic level exceeds 60% (maximum 77%), 11th harmonic level exceeds 25% (maximum 53%), 13th harmonic level exceeds 13% (maximum 38%), 17th harmonic level exceeds 6% (maximum 18%), 19th harmonic level exceeds 6% (maximum 10%), 23th harmonic level exceeds 2% (maximum 7%).
and 25th harmonic level exceeds 1.8% (maximum 7%). In the last stage of melting: 5th harmonic level was 70%, 7th harmonic level was 50%, 11th harmonic level was 12%, 13th harmonic level was 4%, 17th harmonic level was 4%, 19th harmonic level was 1.8%, 23th harmonic was 2%, and 25th harmonic level was 1.7%.

**Figure 13.** Time variation of 7th harmonic from line currents during the melting process.

**Figure 14.** Time variation of 11th harmonic from line currents during the melting process.

**Figure 15.** Time variation of 13th harmonic from line currents during the melting process.
Figure 16. Time variation of 17th harmonic from line currents during the melting process.

Figure 17. Time variation of 19th harmonic from line currents during the melting process.

Figure 18. Time variation of 23th harmonic from line currents during the melting process.

Figure 19. Time variation of 25th harmonic from line currents during the melting process.
4. Conclusions

Induction heating equipment does not introduce dust and noise emissions in operation, but cause power quality problems in the electric power system.

The measurement results showed that induction furnace operation causes unbalance and harmonics in three-phase currents absorbed from the distribution network. Harmonics in the line currents are caused mainly by static converter, and to a lesser extent by furnace load and interaction of eddy currents induced in the charge and the magnetic field of the inductor. To reduce the negative impact of the current harmonics on the distribution network is necessary the design and achievement of electrical filters for odd-order harmonics (5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th).

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