Comparative study between the melting process of an aluminum batch and a steel batch in a high frequency induction furnace

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Abstract. In this work we analyzed a laboratory induction furnace, having a small capacity, fed by a high-frequency static converter. The measurements were carried out in the case of an aluminum batch, and a steel batch, using the power quality analyzer CA8334B. We studied the influence of the type, temperature and amount of processed material, on the electrical parameters of induction furnace during the melting process. Large electromagnetic disturbances (harmonic currents, current unbalances, reactive power consumption) were recorded, especially during the preheating period of crucible and the first stage of heating, when the furnace worked at low power, for the both batches. The experiments allowed the elaboration of some measures for optimization of melting process in the analyzed induction furnace, in terms of efficiency and mitigation of electromagnetic disturbances.

1. Introduction

Induction melting is the preferred method in modern metallurgy plants since the 1980s, being used both for non-ferrous metals melting, as well as steel or cast iron melting [1].

The crucible furnaces are suitable for the production of stainless steel, carbon steel and high alloyed steels [1, 2].

Physical processes that occur during the heating and melting process are very complex and interrelated. The electromagnetic field generated by inductor coil causes the heating of furnace batch. The increase of temperature causes the change of processed material properties (both electrical and magnetic). As the batch is melted, the distribution of eddy currents and electromagnetic forces change very much [3-7].

The main advantages offered by crucible furnaces are: simplicity of construction; easy operation and maintenance; low metal losses; high yield, because the heat is generated directly in the processed material; the inductive bath agitation ensures the homogenization of the chemical composition and temperature; low dust and noise emissions [1], [2].

Although do not cause environmental pollution, induction furnaces generate electromagnetic disturbances at all frequency levels at which they operate (low, medium or high frequency) [2], [8-10].

2. Experimental measurements

We analyzed a laboratory induction furnace fed by a high-frequency static converter, with rated power of 20 kW and output frequency of 5...12 kHz. The static converter consists of a three-phase uncontrolled bridge rectifier, a LC filter and a single-phase full-bridge inverter with IGBT transistors.
For supplying the inductor is used a HF transformer. The capacitor bank for power factor correction forms a series resonant circuit with the furnace inductor. Figure 1 presents the electric scheme of analyzed induction furnace.

![Electric scheme of laboratory induction furnace](image)

Figure 1. Electric scheme of laboratory induction furnace

The measurements were carried out in the case of an aluminum batch (2.5 kg), and a steel batch (7 kg), using the power quality analyzer CA8334B [11].

The analyzer was connected on AC low voltage side (0.4 kV), before the static converter. The main parameters measured by CA 8334B analyzer were: True RMS AC phase voltages and True RMS AC currents; active, reactive and apparent power per phase; harmonics for voltages and currents up to the 50th order. The values computed by the CA8334B analyzer were: total harmonic distortion (THD) of voltages and currents; power factor (PF).

We studied the influence of the type, temperature and amount of processed material, on the electrical parameters of induction furnace during the melting process.

2.1. Crucible preheating and batches heating

The experiments were started from the cold state of crucible, being necessary a preheating stage of this, in both situations.

![Waveforms (a) and harmonic spectra (b) of supply voltages in the case of aluminum batch (5%PN, crucible preheating)](image)

Figure 2. Waveforms (a) and harmonic spectra (b) of supply voltages in the case of aluminum batch (5%PN, crucible preheating)
The supply voltages were very close to sine wave during the crucible preheating (Figure 2 and Figure 3.a), but also during the heating and melting processes of the two batches. Total harmonic distortion of supply voltages was below 4.5% and the unbalance remained below 1% during all monitoring for both batches. Therefore, these issues will not be further presented.

During the crucible preheating, harmonics of load currents exceed very much the EMC limits, for the both batches (Figure 4.a and Figure 5.a) [12], [13]. It is noted especially the levels of 5th, 7th, 11th...
and 13th harmonics; 5th harmonic level was 90% for aluminum batch and 80% for steel batch; 7th harmonic level was 78% for aluminum batch and 60% for steel batch; 11th harmonic level was 50% for aluminum batch and 25% for steel batch; 13th harmonic level was 37% for aluminum batch and 14% for steel batch.

In the preheating stage of crucible, the current harmonic levels and the current unbalances were higher in the case of aluminum batch (3.2% compared to 1.9% for steel batch).

In order to avoid the cracking of crucible (during its preheating period, in particular), the active power was increased in steps.

In the case of aluminum batch, during the crucible preheating (9:08-9:39), the furnace operated at a very low power level (5%P_N). In the heating stage of aluminum batch (9:40-10:10), the power level was increased to 25%P_N.

In the case of steel batch, the power steps have been set as follows: 8:00 - 10%P_N; 8:30 - 15%P_N; 8:45 - 20%P_N; 9:00 - 25%P_N; 9:13 - 30%P_N; 9:23 - 35%P_N; 9:34 - 40%P_N; 9:45 - 50%P_N. Furnace charging began at 9:25. Starting at 9:50, the furnace operated with the maximum power (100%P_N).

The RMS values of load currents track the step growth of the active power, being higher in the case of steel batch (Figure 6).

In order to avoid the cracking of crucible (during its preheating period, in particular), the active power was increased in steps.
Experiments showed that harmonic distortion of load currents was extremely high during the crucible preheating, and decreased slightly as the batches were heated. THD of load currents varied between 137%, during the crucible preheating, and 105%, during the heating of aluminum batch (Figure 7.a). In the case of steel, THD of load currents (Figure 7.b) were lower than in the case of aluminum (106%...87%).

![Figure 8. Crest factor CF[-] of load currents during the crucible preheating and batches heating: a – aluminum batch; b – steel batch](image)

Due to the high harmonic content of load currents, their crest factor far exceeded the value of 1.41, characteristic for sinusoidal regime, in the case of both batches (Figure 8).

In the case of aluminum batch (Figure 8.a), crest factor of load currents ranged from 3.26 (crucible preheating) to 2.7 (heating of aluminum). Crest factor of load currents had lower values in the case of steel batch (Figure 8.b, from 2.66 to 2.18).

![Figure 9. Unbalance [%] of load currents during the crucible preheating and batches heating: a – aluminum batch; b – steel batch](image)

It is found that in the first stage of crucible preheating (Figure 9.a), the unbalance of load currents was very pronounced (4...8)%), but decreased as the power of furnace increased and the aluminum batch was heated (2.6...0.7)%.

In the case of steel (Figure 9.b), the unbalance of load currents was smaller, and decreased (2.3...0.7)% as the batch was heated and the power of furnace increased.
Figure 10. Active power P[W] (a) and reactive power Q[VAR] (b) during the crucible preheating and aluminum batch heating

Figure 11. Apparent power S[VA] during the crucible preheating and aluminum batch heating

Figure 12. Active power P[W] (a) and reactive power Q[VAR] (b) during the crucible preheating and steel batch heating

Figure 13. Apparent power S[VA] during the crucible preheating and steel batch heating
During the heating of aluminum batch (9:38-10:09) the active power consumption increased 3 times, compared to crucible preheating. The reactive power consumption per phase was higher than the active power (Figure 10).

In the case of steel batch, the active power consumption was double compared to the case of aluminum batch, and the reactive power was lower than active power (Figure 12).

The values of PF per phase varied between 0.6 and 0.7 during the crucible preheating and the heating stage of aluminum batch (Figure 14.a).

In the case of steel batch PF had higher values, between 0.7 and 0.767 (Figure 14.b), but still much lower than neutral value (0.9).

### 2.2. Melting stage of batches

In the melting stage, the levels of current harmonics were lower than in the heating stage, but 5th and 7th harmonics were still much higher than the EMC limits (Figure 15.a and Figure 16.a).

Harmonic spectra of currents were almost identical for both batches (Figure 15.a and Figure 16.a): 5th harmonic level was 70% for aluminum batch and 71% for steel batch; 7th harmonic level was 50% for aluminum batch and 47% for steel batch; 11th harmonic level was 11% for aluminum batch and 10.5% for steel batch; 13th harmonic level was 4% for aluminum batch and 4.4% for steel batch.

Currents unbalance was lower than in the previous stages (Figure 15.b and Figure 16.b). Above the Curie temperature the steel batch becomes paramagnetic.
In the melting stage of aluminum, the RMS values of load currents varied within the limits of 23…31 A (Figure 17.a). The RMS values of load currents were higher in the case of steel batch (between 31.6 A and 34.1 A, Figure 17.b). In this period the entire rated power of furnace installation was used for melting the batches.
It is found that harmonic pollution of load currents was high even during the melting period, for both batches (Figure 18).

THD of load currents decreased in the melting stage of aluminum batch (105% ... 84%), compared to previous stages (Figure 18.a). THD of load currents in the melting stage of steel batch was about 83%, lower than in the case of aluminum (Figure 18.b).

![Figure 19. Crest factor CF[-] of load currents during the melting stage of batches: a – aluminum batch; b – steel batch](image)

In the melting stage of aluminum batch, the crest factor of load currents (Figure 19.a) was lower than in the previous stages and approximately constant (average value of 2.2).

Crest factor of load currents had lower values in the melting stage of steel batch (average value of 2.14, Figure 19.b).

Even in this stage, the crest factor of load currents exceeded the value characteristic for sinusoidal regime, for both batches, due to harmonic pollution.

![Figure 20. Unbalance [%] of load currents during the melting stage of batches: a – aluminum batch; b – steel batch](image)

The unbalance of load currents decreased during the melting stage of both batches (Figure 20).

In the case of aluminum batch, the unbalance of load currents varied between 3.2 and 0 (Figure 20.a).

In the case of steel batch, the unbalance of load currents was smaller, between 2 and 0 (with the exception of one moment, 11:30, when the maximum value of 9 was reached, Figure 20.b).
Figure 21. Active power $P[W]$ (a) and reactive power $Q[VAR]$ (b) during the melting stage of aluminum batch.

Figure 22. Apparent power $S[VA]$ during the melting stage of aluminum batch.

Figure 23. Active power $P[W]$ (a) and reactive power $Q[VAR]$ (b) during the melting stage of steel batch.

Figure 24. Apparent power $S[VA]$ during the melting stage of steel batch.
In the melting stage of aluminum batch, the active power consumption per phase was double compared to the previous stage. The reactive power consumption was very high, comparable to the active power (Figure 21).

For steel batch, the active power absorbed per phase was maximum (approximately 5900 W). In the last 10 minutes of recording, the active power decreased to 3300 W per phase. The reactive power per phase was lower than the active one (4850 VAR), but still very high (Figure 23).

The values of PF per phase varied between 0.7 and 0.765 during the melting stage of aluminum batch, being slightly larger than in the previous stages (Figure 25.a).

Also, in the case of steel batch PF increased slightly (0.778) compared to previous stages, but remains below the neutral value, due to the high reactive power consumption and harmonic distortion of load currents (Figure 25.b).

3. Conclusions

For both batches, largest electromagnetic disturbances (harmonic currents, current unbalances, reactive power consumption) are recorded during the preheating period of crucible and the first stage of heating, when the furnace worked at low power.

The worst case was the preheating of crucible for the aluminum batch, when the furnace operated at 5%\%_{\text{N}}.

The electromagnetic disturbances decreased slightly as the batches were heated and the power of furnace increased.

The experiments showed that large amount of harmonic currents were generated due to the six-pulsed rectifier, from the static converter (the order of harmonics, k, were an integer multiple of pulse \pm 1, k=\pm 6i\pm 1, i=1, 2, 3,...; e.g. 5^{\text{th}}, 7^{\text{th}}, 11^{\text{th}}, 13^{\text{th}}, 17^{\text{th}}, 19^{\text{th}}, 23^{\text{rd}}, 25^{\text{th}}). Due to unbalances and eddy currents, other harmonics were present (2^{\text{nd}}, 3^{\text{rd}}, 4^{\text{th}}, 9^{\text{th}}, 15^{\text{th}}), but with much lower levels.

In the case of steel melting, the power factor was slightly higher (but much lower than neutral value) and the unbalance of currents was smaller comparative to aluminum melting.

The operation of induction furnace at low power factor, causes the increase of melting cost.

The electrical efficiency of steel melting process was better than in the case of aluminum, which is non-magnetic and has lower electrical resistivity. The electrical efficiency is mainly due to the better magnetic coupling between the inductor and the steel batch.

It was found that the melting time of aluminum batch represents 40\% from the melting time of steel batch, due to the much lower melting temperature.
In terms of energy consumption and efficiency, it is advantageous to be melt several batches per day (5-6), with the most compact batch (small chunks of metal).

In order to increase the efficiency of induction furnace, the power-off periods must be minimized and the furnace must be maintained full in order to draw maximum power.

Operating at maximum power increases the yield of induction furnace and reduces the harmonic pollution of load currents.

For mitigate of harmonic distortion must installed harmonic filters (passive, active or hybrid) for decrease of 5th, 7th, 11th, 13th and 17th current harmonics, that exceed the compatibility limits.

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