ANALYSIS OF OPERATING MODES AND ENERGY EFFICIENT PRACTICES DURING THE OPERATION OF INDUSTRIAL INDUCTION FURNACES WITH NETWORK AND MIDDLE FREQUENCY

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Abstract: *Among the main problems of the induction furnaces are the clearly manifested worsened power factor during operation, the asymmetry, the deflection and the variance of the supply voltage in their power supply. Induction furnaces in all their operating modes are a non-linear load with significant and varying consumption of active and reactive energy. Compensation devices are set for the heaviest mode of operation - metal melting. There remains a question of the limits of the low inherent power factor for individual regimes, the size of the penalties for this on an annual basis, and the potential energy saving measures taking into account the possibilities of waste heat utilization. In this connection, the task of implementation of modern optimal management according to predefined criteria is current.*

Keywords: INDUCTION HEATING, INDUCTION FURNACES, NON-LINEAR LOAD, POWER FACTOR, ENERGY EFFICIENCY

1. Introduction

Metal casting in the industry is a highly energy-intensive process characterized by a low inherent power factor and wide range of changes in the consumption of active and reactive energy. Achieving high energy efficiency is associated with technical risks associated with disruption of the production process, the application of inappropriate technology, lack of time and qualified personnel and increased capital costs. Energy savings can be realized in two ways - direct savings through lower energy consumption and indirect savings - through less consumption of material resources. Therefore, the goal is to achieve a certain amount of quality output with less energy and fewer raw materials. In order to do this, energy and material flows in the metal casting process should be explored and understood.

2. Research tasks

The object of the research and analysis is the operation of two induction furnaces (IF), one operating at a network frequency $f = 50Hz$ and the other one with an middle operating frequency $f = 250Hz$. One of the advantages of the crucible furnaces is the short melting times due to the high specific power, with the minimum melting times of the metal depending on the frequency [1].

It is known that the energy emitted by the inductor depends on the frequency of the current, the ratio between the geometric dimensions of the crucible and the inductor, the dimensions and the electrophysical properties of the melting material. There are dependencies between the required thickness of the pipe walls of the inductor Δ_i and the size of the pieces of burst material from the operating frequency. Recommended at operating frequency $f = 50Hz,\ \Delta_i = 13-20mm,$ and the pieces dimensions have to be $200-350mm$. At operating frequency $f = 250Hz,\ \Delta_i = 2-4mm,$ and smaller pieces sizes – $150-2000mm$, [2, 3].

The dependences of the inductor's energy on the size of the crucible and the electro-physical properties of the process are of great importance for the operation of the induction furnaces in terms of their power supply and efficient operation. Changing the temperature of the metal pieces in the crucible changes both their geometrical dimensions and the contact area between the individual pieces, as well as their magnetic permeability and their specific electrical resistance. This dependence determines a continuous change in the energy emitted by the inductor and requires a flexible control system that ensures that optimum process parameters are maintained throughout its duration. The electrical parameters through which the metal melt process can be controlled are the magnitude and frequency of the supply voltage. Failure to comply with certain conditions in the construction and operation of the crucibles may result in severe accidents which will remove the furnaces for a long time and create an immediate danger to the service personnel. The principle of inductive energy transfer requires, if possible, the smallest wall thickness of the crucible, since it decreases the electrical efficiency factor along with its increase [4]. This thickness cannot be reduced below certain limits in order not to shorten the life of the crucible and to break through. Every 120-150 melts the crucible is beated out and imbed again according to strict requirements followed by sintering. Induction sintering is a process of switching on and off the furnace at a minimum power to achieve a rate of increase in temperature $100^oC/h$ to reach a temperature $t = 800^oC$. Then, increase the rate of temperature rise to $150^oC/h \div 200^oC/h$ until the temperature reaches in the crucible $t = 1000^oC$. The sintering temperature is then maintained for 1-2 hours at 50°*C* above the working temperature, after which the metal can be spilled.

3. Measurements and results obtained

Data of the induction furnaces with network frequency research

The object of the analysis is the operation of the TDM 3150-20 induction furnace with operating frequency $f = 50Hz,$ rated power $S_N = 2500kVA,$ 9-degree adjustment of the capacitor battery, capacity of the furnace - 10 *t*. At the beginning of the melting, when the molten metal is in a smaller quantity and the burden is still solid, all the stages of the capacitor bank are included. As the melting speed increases, some of the capacitors are turned off. The main disadvantage of these furnaces is the low melting speed and the need for symmetry to increase the efficiency of the furnace. Therefore, these furnaces are always allowed to work with a 'marsh', that is, leaving molten metal from the previous melt. The most economical mode of operation occurs when 25% - 35% of the molten metal is left. Then the duration of the melting is reduced to 1.5 - 2 *h*, with an energy consumption of 550 - 800 *kWh /t* [5, 8]. According to the aforesaid dependence, when left over from the previous melt 'marsh' 10, 25 and 40%, the power of the furnace required for the next melting process is reduced by (0.25; 0.48; 0.65) S_N. The electrical supply of such furnaces is carried out with the so-called Steinmetz scheme. Due to the low natural power factor, compensation is a must and should not be interrupted during the melting process. Since the consumption of active and reactive energy during the melting process is highly variable, therefore the symmetrical power needs to be altered by a similar load schedule.

Measurements of active, reactive and full power, consumed by the furnace in basic and finishing mode have been carried out. The duration of the process is 6 h. 25 measurements have been carried out, Fig. 1. For the purposes of the research, data from electric meters with specialized software EMH-Combi Master 2000, [6] are available for graphical representation of the current state of the network (current and peak current and voltage values, active, reactive and full power, power factor, frequency; load schedules).

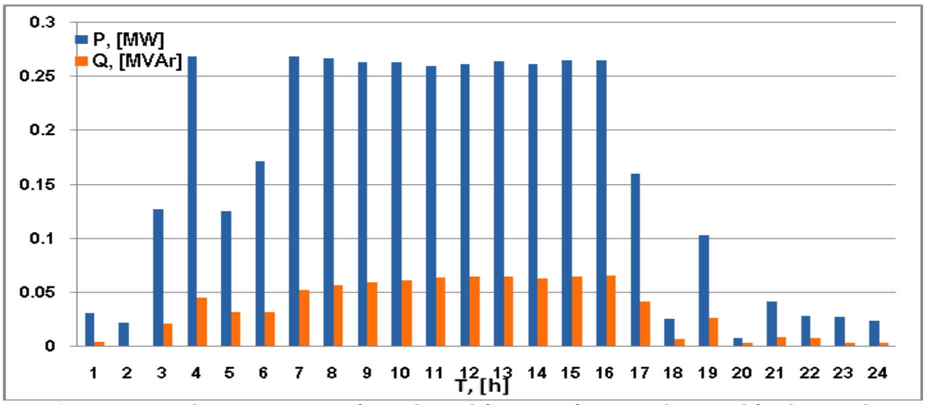

Fig. 1. *Active and reactive powers of an industrial-frequency furnace in basic and finishing mode.*

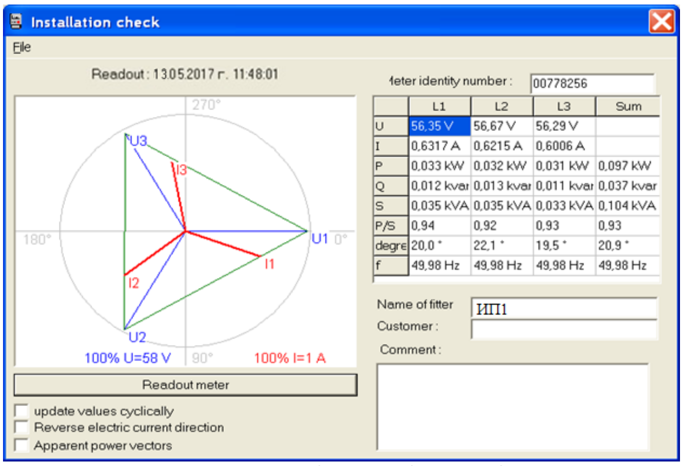

Fig. 2. *Voltages and currents of the main-frequency furnace in basic mode.*

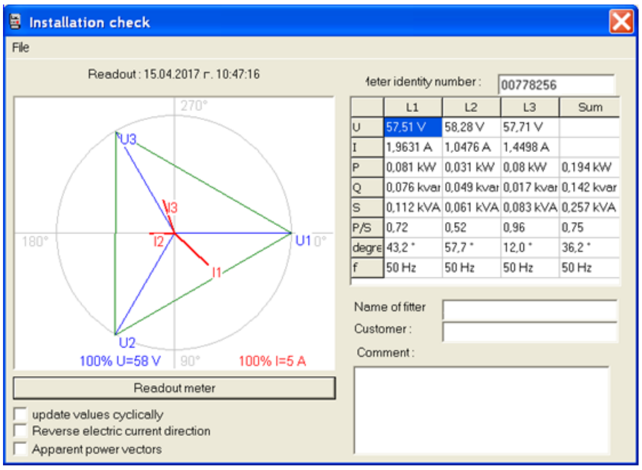

Fig.3. *An unbalanced induction furnace with a network frequency.*

Data of induction furnaces with middle frequency research

This kind of furnaces are mostly used for smaller parts and cold bent steel materials. Compared to induction furnaces with a mains frequency, these furnaces have a higher melting speed at the start of the solid burden process, therefore cosφ is easier to adjust.

The object of the analysis is the operation of the same type of induction furnace TDM with operating frequency $f = 250Hz$, rated power $S_N = 2 \times 2505kVA$, with thyristor rectifier and inverter, capacity of the furnace – 7.5 *t*. The furnace is controlled by changing the unlocking angle of the inverter thyristors. The researches have been carried out for the following furnace operating conditions: sintering mode - 16 *h* 30 *min*, 70 measurements recorded, Figures 4 and 5; basic melting and finishing mode with "marsh" 40% with duration 3 *h* 15 *min*, 15 measurements recorded, Figures 6 and 7; basic melting and finishing mode with "marsh" 10% with duration 3 *h*, 13 measurements recorded, Figures 8 and 9.

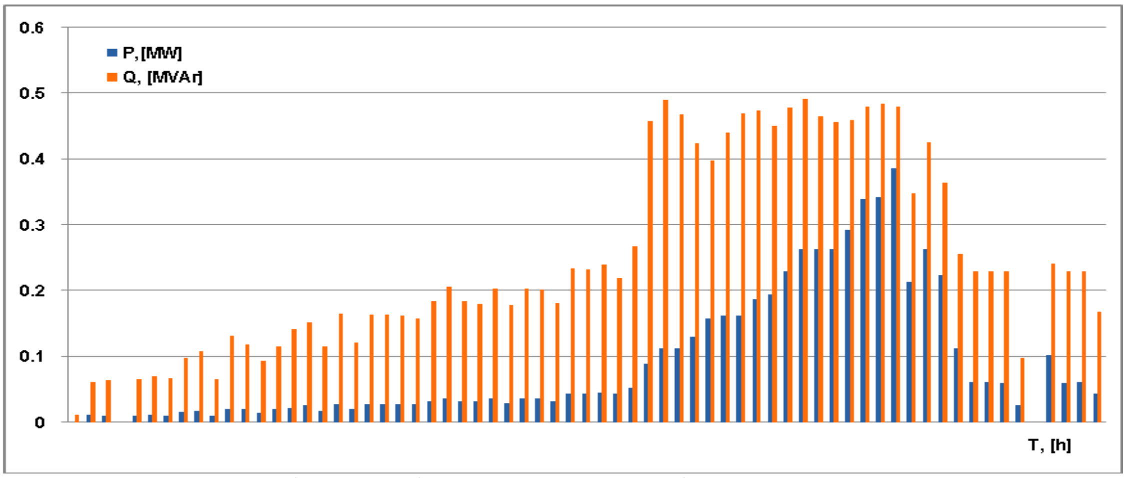

Fig. 4. *Active and reactive powers of an induction furnace operating with middle frequency* $f = 250Hz$ *observed in sintering mode.*

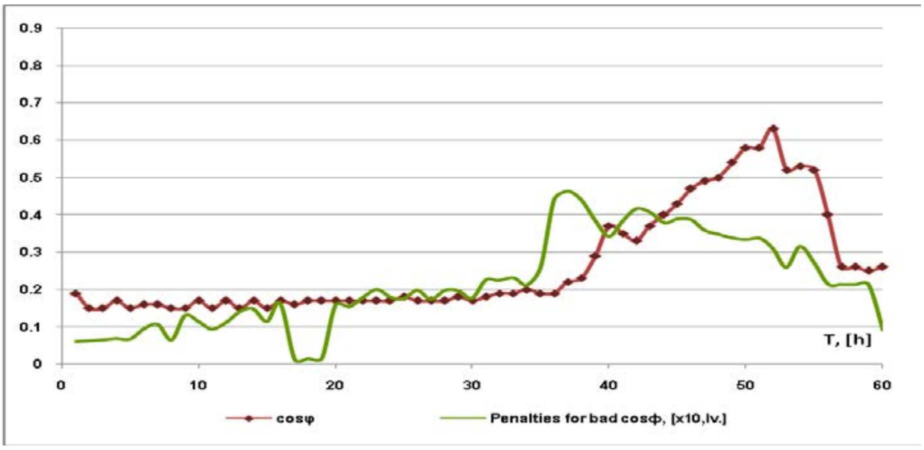

Fig. 5. *Modification of power factor in sintering mode and penalties for bad cosφ.*

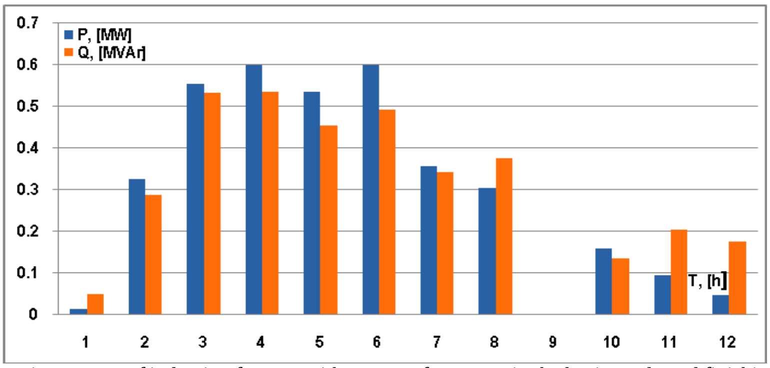

Fig. 6. *Active and reactive powers of induction furnace with average frequency in the basic mode and finishing with 'marsh' 40%.*

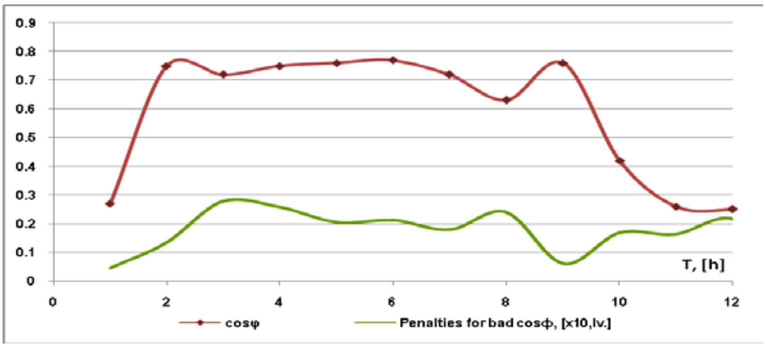

Fig. 7. *Modification of power factor in basic mode and finishing with 'marsh' 40% and penalties for bad cosφ.*

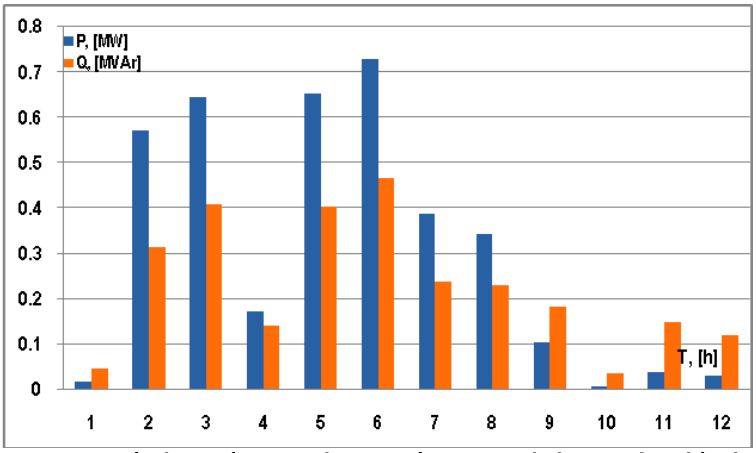

Fig. 8. *Active and reactive powers of induction furnace with average frequency in the basic mode and finishing with 'marsh' 10%.*

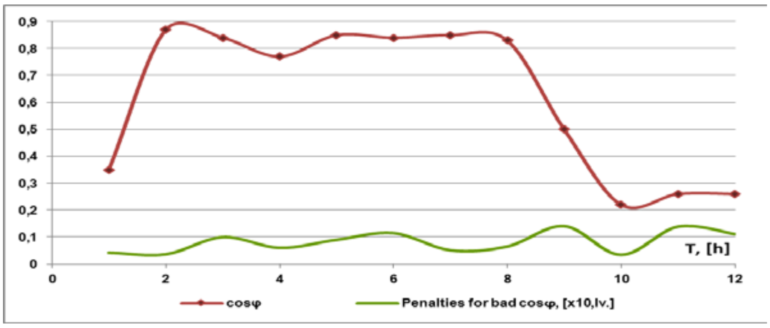

Fig. 9. Modification of power factor in basic mode and finishing with 'marsh' 10% and penalties for bad cosφ.

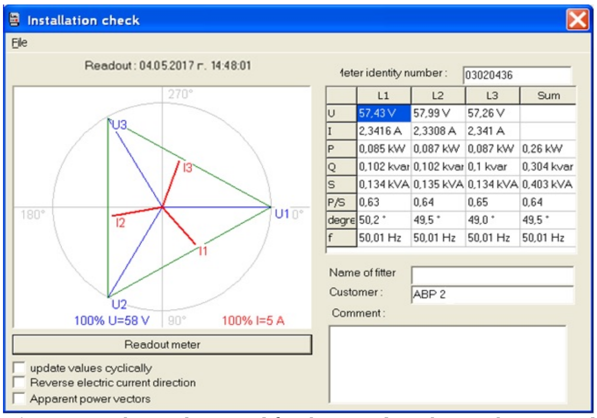

***Fig. 10.** Graphics in basic and finishing mode with 'marsh' 10% and increased consumption of the furnace.*

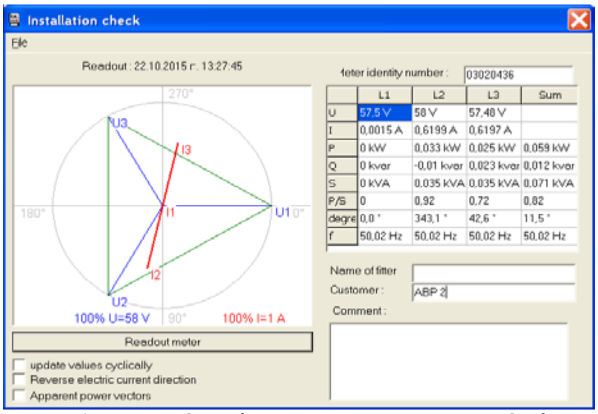

***Fig. 11.** Graphics of emerging asymmetry as a result of an emergency situation (burnt thyristor).*

4. Conclusions

The load asymmetry in the operating modes of the induction crucible furnace with a thyristor converter is minimal. Fragrant deflections occur in emergency situations, Fig. 11. This is not the case with the power factor. Data analysis shows that drying (sintering) mode is the most severe mode of influence on the power supply and power system due to the deterioration of the power factor. In the case at hand it varies $\cos\varphi = 0.15 \div 0.19$. During the setting of the sintering temperature and then cos increases, but not enough, because the power supply becomes smooth and reaches only 40% of the installed one. From the load schedules, it is observed that during the induction melting process there is a strong uneven consumption of active electrical energy. The same applies to the size of the supply voltage, where the induction crucibles furnaces with network frequency are clearly expressed, Fig. 3. According to [7] the process can be divided into three distinct stages: 1st stage - melting of the metal pieces placed in the crucible, followed by zero electricity consumption, refining and sampling of the metal to be tested in a laboratory; Stage II - overheating of the metal up to 1520°*C*, correction of the metal, if needed, followed by zero consumption; Stage III - preheating and spilling the metal from the crucible. Thus, it is clear that the greatest amount of electricity consumption is in the basic mode of operation about 70-75%, which includes this first stage. The supply voltage during this mode changes to small limits (varies in the range 1300-1500*V*). In this mode of induction crucibles furnaces operation with a mains frequency is the most advantageous time for performing compensation and carry out symmetry of the load.

Data analysis for basic and finishing modes with 'marsh'

Under Basic Mode (First Stage): duration 1.4 hours (about 84 minutes); active power - an average of 2624 *kW*; power factor - average $\cos\varphi = 0.67$.

The second and third stages are in the finishing mode.

On finishing mode: overheating time - second stage (1420°*C* to 1520°*C*), about 21 minutes; active power 500 *kW*; power factor - average $\cos\varphi = 0.41$.

In the third stage: d uration 1.5 hours (about 90 minutes) in this case and active power 380 *kW*.

The energy required for melting and overheating is 3141 *kWh*, hence about 698 *kWh /t* of molten metal - a relatively high value of the specific power. This is not the case when using more power at the remaining 'marsh' 10%. Total energy consumed for melting and overheating is increased to 3520 *kWh*, hence about 521 *kWh /t* of molten metal. Consequently, the specific furnace power drops by 25.4%. In the 'marsh' 40% is used almost 55% of the power through the basic mode is maintained average $\cos\varphi = 0.72$. With a 'marsh' of 10% this process is maintained with a higher power output of about 70%. During the first stage of the process, $\cos\varphi$ increases to an average value for the basic mode $\cos\varphi = 0.88$.

If there is a very good symmetry achieved of the furnace with a network frequency (which leads to a high $\cos\varphi \geq 0.9$) there are no financial penalties.

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