Experimental survey for reducing the flicker effect and the deforming regime produced by EAFs

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Abstract: Experimental results show that EAFs represent a substantial source of electric disturbances, such as voltage fluctuations, flicker, harmonics, and unbalance between phases. Improvement of the energetic performances of an EAF imposes a careful technical and economical analysis. The possible compensation solutions include passive filter, SVC (static var compensator), STATCOM (based on high frequency switching voltage – source converter), and synchronous compensator.

Key-Words: Electric arc furnace, Flicker, Deforming regime, Power factor, Harmonic analysis, Reactive compensator

1 Introduction

Due to the fact that during operation the EAF presents a large variation of input power and the phase load is unequal, the asymmetric work regime appears. This leads to distortion of current and voltage waveforms, a large variation of the reactive energy, also leads to the appearance of high order harmonics in the current, in the voltage [1]-[3] and to the flicker effect [4]-[6]. Voltage fluctuations in electric power system may cause significant illumination changes in lighting equipment [7]. This unsteadiness of visual sensation which is induced by a light stimulus whose luminance or spectral distribution fluctuates with time, is called flicker. When flicker exceeds some certain threshold, the phenomenon becomes annoying and the annoyance very rapidly depending on the fluctuation’s amplitudes [8], [9].

In contrast to other types of loads which are usually operated by voltage steps, EAFs produce random flicker which cannot be easily calculated with standard curves and methods [10], [11].

In Romania, the oldest metallurgical plants are in Reşiţa, Oţelu Roşu, Cugir and Hunedoara, being built in 18th and 19th centuries. In the last 13 years, were shut down permanently the obsolete technological flows of Siemens-Martin (open-hearth) type, replacing the production conceived in integrated flow with the production based on electric arc furnaces.

Starting with 1989 the steel production in steel industry has decreased from 13.4 million tones to 4.35 million t in 1999, after which it started a slight re-launch in 2002 being registered a production of 5.49 million t, and in 2007 a production of 6.26 million t. In fig. 1 is represented the evolution of steel production in Romania according to the statistic of World Steel Organization.

In perspective of 2011 for the steel industry in Romania is estimated a steel production of about 4.5 million t and for 2012 is estimated a production of about 5.5 million t [12].

The current general situation of the Romanian steel plants marked by technological lags against the world competitors imposes the increase of the energetic performances of EAFs, EBT type [12].

The paper is organized as follows: Section 2: proposed mathematic model of the furnace, Section 3: quality indicators in non-sinusoidal systems, Section 4: experimental investigations and solutions for EAF improvement performances, Section 5: conclusions.

Fig. 1. Steel production evolution in Romania
2 Mathematic model of the furnace

In order to determine the optimal operation conditions of an EAF, it should be determined a mathematic model as accurate possible of it, that should be used in the automatic management system.

Normally, the optimal operation conditions refer to the current’s and voltage’s effective values, and to the power factor value in the connecting point of the supply grid.

The EAF’s simplified model is presented in fig. 2 where by ur was noted the grid’s phase voltage, Xt the total reactance of the circuit between the transformer from the electric station and the one of the furnace, Xf – reactance of the furnace transformer’s secondary, the connecting cables and the low voltage grid and by Ra was modeled the electric arc [13].

By u and i were noted the voltage and current at the terminals of the furnace phases.

The theorem of the optimal power transfer towards load at minimum costs is given by the relation:

\[ P = \frac{1}{T} \int_0^T u \cdot i \cdot dt \]  \hspace{1cm} (1)

When in the analysis of the furnace operation is considered a form of sinusoidal variation of the signals, the maximum active power at electrodes is obtained when:

\[ X = R_a \]  \hspace{1cm} (2)

\[ X = X_t + X_f \]  \hspace{1cm} (3)

The greater the arc’s length is, the more its resistance increases. The power factor is:

\[ \cos \varphi = \frac{R_a}{\sqrt{R_a^2 + X^2}} \]  \hspace{1cm} (4)

At transfer of maximum power to the electric arc (according to the relation (2)) we’ll have:

\[ \cos \varphi = \frac{\sqrt{2}}{2} = 0.707, \quad \varphi = 45^0 \]  \hspace{1cm} (5)

Using of these values involves important errors because the voltage and current of the electric arc are non-sinusoidal.

3 Quality indicators in non-sinusoidal systems

The deforming regime sources can be classified in harmonic voltage sources and harmonic current sources.

In Romania is in force the Norm PE 143/2001 regarding the limitation of the deforming and non-symmetric regime in electric grids. This norm provides a harmonic analysis of electric signals up to the rank \( k = 40 \) of harmonics (respectively, the frequency field between 100 Hz and 2000 Hz).

The harmonic total distortion for voltages and currents is [14]:

\[ I_{THDi} = \frac{\sum_{k=1}^{40} |I_{harmk}|^2}{I_{harmli}} \cdot 100 \]  \hspace{1cm} (6)

\[ V_{THDi} = \frac{\sum_{k=1}^{40} |V_{harmk}|^2}{V_{harmli}} \cdot 100 \]  \hspace{1cm} (7)

where I is the line current, V voltage, i phase number (i = 1, 2, 3) and k the harmonic’s order.

In non-sinusoidal regime the powers have the expressions [15], [16], [17]:

\[ S = U \cdot I \]  \hspace{1cm} (8)

\[ U = \sqrt{U_0^2 + \sum_{k=1}^{\infty} U_k^2} \]  \hspace{1cm} (9)

\[ I = \sqrt{I_0^2 + \sum_{k=1}^{\infty} I_k^2} \]  \hspace{1cm} (10)

\[ P = U_0 \cdot I_0 + \sum_{k=1}^{\infty} U_k \cdot I_k \cdot \cos \varphi_k \]  \hspace{1cm} (11)

\[ Q = \sum_{k=1}^{\infty} U_k \cdot I_k \cdot \sin \varphi_k \]  \hspace{1cm} (12)

\[ D = \sqrt{S^2 - P^2 - Q^2} \]  \hspace{1cm} (13)

\[ \cos \varphi = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} \]  \hspace{1cm} (14)

where S is the apparent power, P the active power, Q the reactive power and D the deforming power.

4. Experimental investigations and solutions for EAF improvement performances

The measurements, presented further, where achieved in the electric station of the Electric Steel Shop no.2 Mittal Steel Hunedoara. Were achieved two groups of measurements: for the electric arc furnace supplied from the transformer with power of 105 MVA, 33/0.8kV and for the steel treatment installation supplied from the transformer of 50 MVA, 33/0.8kV. In both situations,
The measurements were achieved in the power transformer’s primary. There were used voltage measuring transformers with the transformation ratio \( k_U = 300 \) and current measuring transformers with the transformation ratio \( k_I = 400 \). For measuring the voltages \( L_1, L_2 \) and \( L_3 \) where used three voltage transformers, and for measuring the currents were used only two current transformers on phases \( L_1 \) and \( L_3 \) [14].

The principle diagram of the power installation is presented in fig. 3.

The measurements were achieved by means of the three-phase power quality analyzer CA 8334 (Chauvin-Arnoux, France, 2007) [18].

CA8334 gave an instantaneous image of the main characteristics of power quality for the analyzed furnace. The main parameters measured by the CA8334 analyzer 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.

In fig. 4a is presented the variation form of the power factor during a heat and in fig. 4b for a stop and restart of the furnace. Is noticed the great variation of the power factor in the melting’s beginning. During oxidation, this does not vary anymore in so great limits. Could be noticed on the graphic also the time periods when the furnace was charged with the raw material, or were collected samples to establish the steel composition. In fig. 4b could be noticed the negative values of the power factor corresponding to the period when the medium voltage cables are fed and there’s no electric arc, they behaving as capacitors, compensating the reactive power from trafo 220/33 kV.

In fig. 5 is presenting the voltage’s variation form, in fig. 6 the effective current on two phases, the current’s distortion factor in fig. 7, apparent, active and reactive power in fig. 8, 9 and 10, current’s and voltage’s superior harmonics in fig. 11, 12, 13 and in fig. 14 is presenting the current’s rank-2 harmonic.

Is noticed that, when occurring the electric arc, the line voltage on the medium voltage grid decreases against the period when the electric arc is not energized.

![Fig. 3. Principle electric diagram of Electric Station OE2 220/33 kV](image3)

![Fig. 4. a) Power factor variation during a heat.
  b) Power factor at stopping and restarting the furnace](image4)

![Fig. 5. Effective values’ variation of the line voltages during a heat](image5)
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Fig. 6. Variation of the current’s effective values on phases R, T, during a heat

Great current fluctuations take place at the beginning of the heat, and, in moment of oxidation, these variations are reducing.

High peaks of the current’s distortion factor on the two phases (reaching values up to 275% from fundamental) take place generally at the heat’s beginning and electric arc’s energizing.

Can be noticed the great skips of the apparent power at the beginning of the heat and in periods when the furnace is supplied with scrap. The variations reduce towards the final heat when the arc is operating stable.

From the active power’s factor is noticed that this has the same characteristics as the apparent power.

The reactive power’s average value consumed during a heat is of 50MVAR. Is imposed the necessity to use batteries of capacitors (or using a SVC ) to compensate it.

Fig. 7. Variation of the current’s distortion factor on phases R, T, during a heat.

Fig. 8. Variation of total apparent power during a heat

Fig. 9. Variation of total active power during a heat

The rank-3 current harmonic’s jumps reach in certain moments of the heat the fundamental’s value. In the beginning of melting they are the greatest (the average value being of 10% from fundamental) reducing towards final.

The rank-5 current harmonic reaches also the fundamental’s value, but its average value is smaller than the one of rank-3 during the complete heat.

Fig. 10. Total reactive power variation during a heat

Fig. 11. Variation of the rank-3 harmonic’s proportion from the current on phases R, T, during a heat.

Fig. 12. Variation of the rank-5 harmonic’s proportion from the current on phases R and T, during a heat.
From fig. 14 are noticed the great values of this harmonic. These values are due to the fact that the furnace transformer work in certain moments at the rated apparent power and the core reaches to saturation, thus introducing even harmonics into the grid.

In fig. 15 is presented a proposal of automatic system for compensation, filtration and balancing. There were made the following notations:

- T1, T2 – power transformers (one active and one for spare);
- T3 – EAF’s transformer;
- T4 – LMF’s transformer;
- TC – current transformers;
- TT – voltage transformers;
- EAF – electric arc furnace for melting;
- LMF - electric arc furnace for treatment and alloying;
- E – electrodes;
- AB – adaption block;
- PLC – programmable logic controller for compensation, filtration and balancing;
- FBSH – filtration block for superior harmonics;
- RECB – reactive energy compensation block with reactances of fixed capacity;
- ARECB – additional reactive energy compensation block and load balancing.

The PLC receives the current and voltage information from the current and voltage transformers, for each phase, by means of the adaption block. Based on the implemented management program, is controlled the harmonics filtration, respectively the compensation of the reactive energy and load balancing on phases. The harmonics’ filtration block contains coils and capacitors tuned on the frequency corresponding to the harmonics 3, 5, 7, 11, 13 which in practice was found that they have a higher proportion. Their connection or disconnection is made by static contactors controlled by the PLC. The reactive energy’s compensation block with fixed capacity reactance’s (RECB) is connected in circuit during the entire heat and, is calculated in such way that at the average value of the reactive energy on a heat to be achieved a neutral power factor. When the furnace is in stand-by, this block is disconnected. The additional compensation block of the reactive energy (ARECB) introduces and takes out dynamically, at the command given by the PLC, by static contactors, batteries of capacitors for compensating the reactive energy that exceeds the average on a heat in such way that the power factor to not decrease under the neutral value. Also within this block there is the load balancing installation with coils and capacitors, which in real time introduces or takes out reactance’s from the circuit in such way that the distortion factor of the currents respectively voltages to be under the permitted limits and the values of the phase differences between currents and between voltages to correspond to a symmetric system. In this block have plane important transitory phenomena. The state-of-the-art installations are using frequency converters that create a capacitive or inductive regime depending on the process requirement, instead of the ARECB block [5].

The proposed solution is in progress to be implemented.
5. Conclusions

Electric arc furnaces are placed among the main steel production equipments. Using the compensation of reactive energy, harmonic filtering and load balancing determines the increase of the power factor more than neutral value (0.94), reduction of the harmonic emission in the electric grid, reduction flicker and deforming effect on the grid. Another advantage of the solution presented here is the possibility of realizing of optimal process control with the possibility of obtaining maximum of the active power in the electric arc during all the phases of the melting process.

References: