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A NEW TIME DOMAIN MODEL FOR ELECTRIC ARC FURNACE

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The electric arc furnace (EAF) behaves like a non-linear load that draws the attention of many researchers. At first in this paper, the important time domain models of EAF are investigated. Then, an optimal time domain model for EAF is proposed to describe the performance of the EAF for different operating situations. In this paper, after deriving a model for EAF, its effects on the power system are studied by means of the PSCAD software. Several characteristics for different operating conditions are then investigated to analyze the proposed method. In addition, for a time-variant and non-linear load which generates voltage flicker and unbalanced voltage, the EAF are modelled. In order to study the effect of voltage flicker on the systems with EAF, random and sinusoidal voltage flickers are considered. Also, in this paper, the effects of the transformer of EAF and common inductance of the flexible cables are investigated. Finally, results of the simulation show the validity of the proposed model of EAF model in this paper.

K e y w o r d s: electric arc furnace modelling, unbalanced voltage, flicker, electric arc

1 INTRODUCTION

The EAFs are time-variant and non-linear loads and create the power quality problems such as unbalanced voltages and currents, voltage flickers as well as odd and even harmonics. These problems need to be rectified in the EAF. Therefore, an optimal model is necessary to tackle the problems. Also, the characteristic of the time response of the EAF has an important role in the power quality issues.

The dynamics characteristic of the electric furnace at any instant is dependent on the conditions of the EAF at that time and previous instants of time. Because, when the arc is generated, a sudden change in electrons, ions and temperature of gas due to a sudden change of the electric current is not possible. As a result, the sudden change of the current will not result in a sudden change of the arc characteristic and this takes place slowly. In other words, due to the effects of the current in the previous instants of time on the present time, there is a hysteresis phenomenon in the dynamic characteristic of the arc. Thus, the time response of the EAF is influenced by the length of arc, positions of electrodes and topology of the external circuit.

The main issue is the modelling of the arc in the EAF [1-14]. There are several methods used to describe the electric arc. The balanced steady state equations are employed in [1, 2]. Some of the models are based on stochastic characteristics of the EAF which are mainly suitable for voltage flicker analysis [3, 4]. The differential equations based time domain methods are presented in [5, 6]. The methods described in [7, 8, 13, 14] to analyze the performance of the EAF are based on the linerization methods and linearized approximation. Other methods such as frequency response [7], $V-I$ characteristic [7, 10] and non-linear differential equations [11, 12] are employed to analyze the behaviour of the EAF. In the following, the advantages and disadvantages of the mentioned methods are reviewed briefly.

The use of steady state equations is very useful in computational work. Nevertheless, it considers only the balanced situation of the three phase currents. In addition, an approximated step model is used to model the waveform of the voltage-current characteristic (VIC) of the EAF.

In the time domain analysis, the parameters are determined based on the harmonic source voltages and the unbalanced three phase currents. However, like the previous method, it uses an approximated step [5]. Another method to analyze the arc model in the time domain is based on the Cassi-Mayer equation [6]. In this method Cassi and Mayer equations are employed for the low and high current of the arc, respectively. In the method of linearization and approximation of the arc voltage is determined based on the current of in the $V-I$ characteristics of the arc [2, 7].

Comparison the EAF model in the time domain and frequency domain [9], shows that the modelling in the time domain is more useful in studying the arc furnace

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elements and EAF analysis. But, the frequency domain models are more helpful for harmonic analysis of the external network. The external network is the model of a linear system considered at each harmonic.

In the above explained methods, there are some restrictions such as initial conditions for the differential equations, balanced situation of the three phase currents and use of complicated mathematical equation for the modelling of the arc model.

Regarding the mentioned limitations, this paper proposes a new model for the EAF in the time domain. The main feature of the proposed model is modelling of the explained method with a good approximation without need of the initial conditions of the EAF. Also, the proposed method can be used to describe different operating situation of the EAF and power system. Finally, the proposed method presents an efficient model with a very good approximation for the VIC. In order to increase the accuracy of the load model, random and sinusoidal noises are used to establish a new model of the furnace load. Then, unbalanced conditions of the currents and voltages and the effects of the furnace load and voltage flicker are studied in the new model. Also, in this paper the effect of voltage flicker on the voltage arc furnace is analyzed directly, in the forms of both random and sinusoidal noises in the frequency range of human vision (between 4-14 Hz). In addition, regarding the effects of the transformer of the EAF,and the resistance of the flexible cables, it is necessary to find an actual model in the time domain to describe adequately the EAF performance for different operating conditions.

2 LOAD MODELLING OF EAF

In this section, the equations of EAF for three main models are studied based on VIC of the arc. Then, the proposed model is presented to describe the performance of the EAF.

1 – Hyperbolic Model

In this model the VIC of the electric EAF is considered in the form $V = V(I)$ as

$$V(I) = \left[V_T + \frac{C_{i,d}}{D_{i,d} + |I|}\right] \text{signum}(I) \tag{1}$$

where I and V are the arc current and voltage of a given phase, respectively. In addition, V_T is the magnitude of the voltage threshold to which the voltage approaches as the current increases. This voltage is dependent on the arc length. Constants $C_{i,d}$ and $D_{i,d}$ are corresponding to the arc power and arc current respectively, and regarding the sign of the derivative of the arc current, they can take different values. Since (1) is similar to the hyperbolic function, it is named a hyperbolic model. There are different paths to increase or reduce the current. The first describes the increasing current $I(t)$, and the second the decreasing current (d). Thus, constants $C_{i,d}$ and $D_{i,d}$ are distinguished. The constants for the first path are C_i and D_i and constants of the second path are C_d and D_d.

2 – Complete Exponential Model

The VIC of the arc in this model, is approximated by an exponential function as follows

$$V(I) = V_T(1 - e^{-|I|/I_0})\text{signum}(I) \tag{2}$$

In the equation describing this model, a current constant (I_0) is employed to model the steepness of positive and negative currents, and an exponential function is used to describe the VIC of the arc. This model can be employed in optimization issue and reliability of the EAF.

3 – Exponential-hyperbolic Model
(Proposed Model)

In the proposed model, the positive current branch of an antisymmetric VIC of the electric arc is described as

$$V(I) = \begin{cases} V_T + \frac{C}{D+I} & \frac{dI}{dt} \geqslant 0,\ I > 0 \\ V_T(1 - e^{-I/I_0}) & \frac{dI}{dt} < 0,\ I > 0 \end{cases} \tag{3}$$

In (3), I_0 is a current steepness constant. As shown in (3), regarding the hysteresis property of the arc, there are two cases for the positive current. In order to increase and decrease the current of the EAF, the hyperbolic equation and exponential-hyperbolic form of the equation are utilized, respectively. The proposed method describes the EAF behaviour in time domain using differential equation [6, 9]. In addition, it is able to analyze the behaviour of the EAF in the frequency domain without solving complicated differential equations. In addition, the proposed method can describe different operating conditions of the EAF such as initial melting (scrap stage), mild melting (platting stage) and refinement of the EAF. The results are in agreement with actual situations of the EAF in the steel industries.

3 ANALYSIS OF DIFFERENT OPERATING CONDITIONS USING PROPOSED EXPONENTIAL–HYPERBOLIC MODEL FOR ELECTRIC ARC

In this section, different operating conditions for the EAG are investigated. In order to study the effect of unbalanced situation on the proposed exponential-hyperbolic model of load of the EAF, different values for the voltage V_T in (3) for different phases are chosen. In addition, different values of V_T are considered for positive and negative parts of each phase current to study the effect of even harmonics which are generated in the early stage of charging the furnace.

3.1 Power System with Actual Model of EAF

The electric diagram of a source supplying an electric EAF is illustrated in Fig. 1. In this figure, Bus 1 is the point of common coupling (PCC) which is the supplying bus of the transformer of the EAF. In order to change the active input power of the arc furnace, a furnace transformer, T_F, (MV/LV) is used. This transformer is equipped with a tap changer located at the secondary winding to change the voltage of the furnace. The EAF is also connected to the point of common coupling, PCC, through the substation. In this figure, X_C and R_C are the reactance and resistance of the connecting line and between the furnace electrodes. Also, $X_{L,sc}$ is the short circuit reactance at bus PCC. As can be seen in this figure, the resistance and inductance of the cables are also considered in the modelling. This leads to the point that the proposed method has very good agreement with the real situation of the EAF of the steel industry. Therefore, the actual model of electric arc is used in the power system that can be described as

$$F(I) = V(I) + R_c I + L_c \frac{dI}{dt} \tag{4}$$

where $F(I)$ stands for VIC of the arc in the actual situation of the power system and $V(I)$ is related to (1). Also, L_c and R_c shown in Fig. 1.

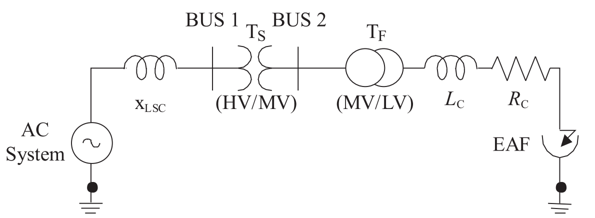

Fig. 1. Circuit diagram of an electric arc furnace connected to the rest of power system

3.2 Reactive Power Analysis in a Power System with EAF

As mentioned previously, the EAF's are non-linear and time-variant loads. In the EAF's, the rate of variations of the reactive power is high. Thus, it is necessary to measure the value of the reactive power accurately. In this paper, the reactive power at each buses of Fig.1 is computed by an averaging method in the half period as [10]

$$\begin{aligned} Q &= \frac{2}{T} \int_{t-T/2}^{t} V(\tau - \frac{T}{4})\, I(\tau)\, d\tau \\ &= \frac{2}{T}\left[\int_{\circ}^{t} V(\tau - \frac{T}{4})\, I(\tau)\, d\tau - \int_{\circ}^{t-T/2} V(\tau - \frac{T}{4})\, I(\tau)\, d\tau\right] \end{aligned} \tag{5}$$

If the value of $V(t - \frac{T}{4}) \cdot I(t)$ is replaced by $F(t)$ in (5), then we have:

$$Q = \frac{2}{T} \int_{\circ}^{t} \left(F(\tau) - F(\tau - \frac{T}{2})\right) d\tau \tag{6}$$

This equation is used later to find the values of the reactive power of the EAF.

4 EFFECT OF VOLTAGE FLICKER IN PROPOSED MODEL

To study the effect of voltage flicker on the systems with electric EAF, the time-variant form of $V - t$ is considered. In this section, the effects of two types of flicker on the dynamic characteristic of the EAF are studied. In the first type, the voltage will be considered in the form of a sinusoidal voltage flicker. In the second type, this voltage will be a random voltage flicker in the frequency range of the human vision (between 4-14 Hz). In the following, the two types of voltage flicker are considered.

4.1 V_T with Sinusoidal Waveform

In this case the voltage V_{at} is considered to be a sinusoidal with the same frequency as the frequency of flickering (in the range of 4-14 Hz).

$$\begin{aligned} V_{T1} &= V_{T01}(1 + k_1 . \sin \omega_f t) \\ V_{T2} &= V_{T02}(1 + k_2 . \sin \omega_f t) \\ V_{T3} &= V_{T03}(1 + k_3 . \sin \omega_f t) \end{aligned} \tag{7}$$

Where $V_{T(j=1,2,3)}$ are three phase voltages of the furnace load, $V_{T0(j=1,2,3)}$ are constant values of the voltages if no flickering would occur, ω_f is the flicker angular frequency and $k_{(j=1,2,3)}$ are the flickers "amplitudes" for different phases.

4.2 V_T with Random Variations

In this part, the voltage V_T is chosen such that it varies randomly. In this regard, the voltage V_T is modulated with a random signal in the different phases. This signal has the mean of zero with the frequency spectrum in the range of 4-14 Hz. Thus, in this case the voltage V_T for different phases can be written as

$$\begin{aligned} V_{T1} &= V_{T01} + k_1 N_1(t) \\ V_{T2} &= V_{T02} + k_2 N_2(t) \\ V_{T3} &= V_{T03} + k_3 N_3(t) \end{aligned} \tag{8}$$

where $N_{(j=1,2,3)}(t)$ is a band limited white noise with zero mean and a variance of 1. Also, the modulation index and variance of the random signal are labelled by $k_{(j=1,2,3)}(t)$ and $k_j N_j(t)$, respectively. It should be noted that the flicker intensity can be changed with k_j.

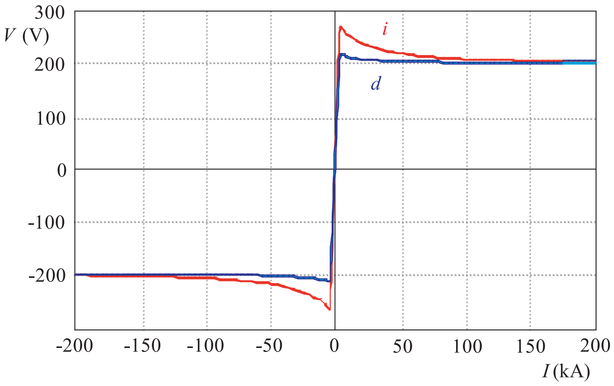

Fig. 2. The VIC of the arc the in hyperbolic model, increasing (i) and decreasing (d) currents paths

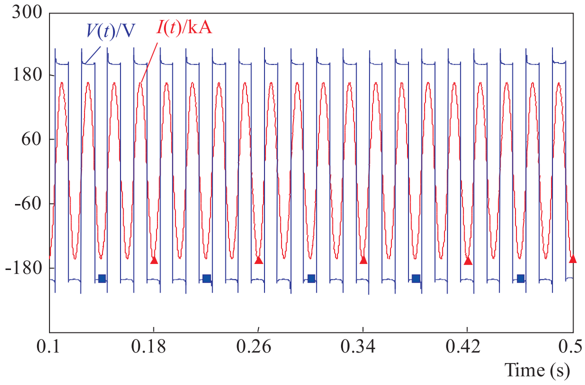

Fig. 3. Waveforms of the arc voltage and current in the hyperbolic model

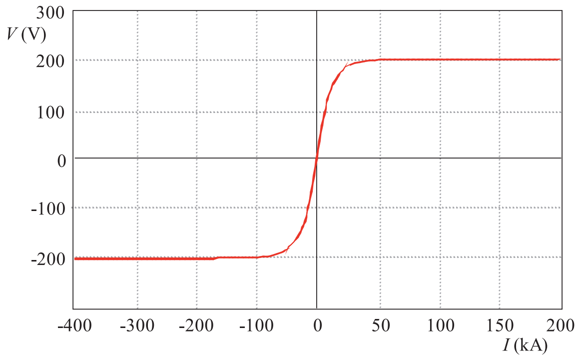

Fig. 4. The VIC of the arc the in the exponential model increasing and decreasing currents paths are identical

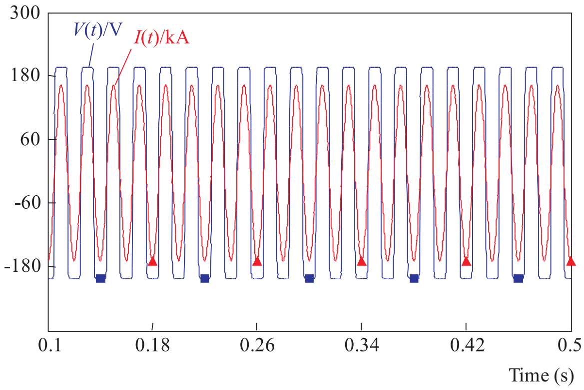

Fig. 5. Waveforms of the arc voltage and current in the exponential model

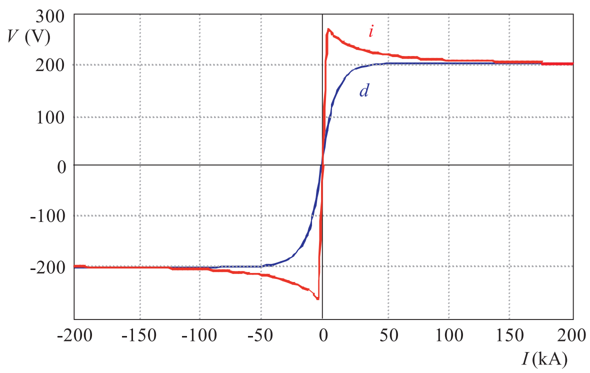

Fig. 6. The VIC of the arc in the proposed exponential-hyperbolic model, increasing (i) and decreasing (d) currents paths

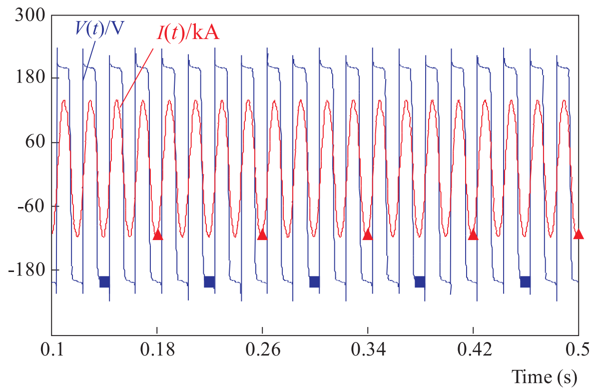

Fig. 7. Waveforms of the arc voltage and current in the proposed exponential-hyperbolic model

5 MODELLING AND SIMULATION OF EAF

5.1 Comparison of Different Models of Furnace Load

In order to compare the proposed exponential-hyperbol-ic model with other models, firstly the results of simulations hyperbolic load model are presented. In Model 1, the parameters of arc characteristics are considered to be: $V_T = 200$ V, $C_i = 190000$ W, $C_d = 39000$ W and $D_i = D_d = 5000$ A. The values in (9) are chosen with regard to a specific EAF [11]. For particular values of these parameters, the VIC of the EAF is shown in Fig. 2, and the waveforms of the current and voltage of the arc are shown in Fig. 3.

5.2 Analysis of Simulation Results for Proposed Exponential-hyperbolic Method

In this part, the proposed exponential-hyperbolic method is simulated based on the combination of (9) and

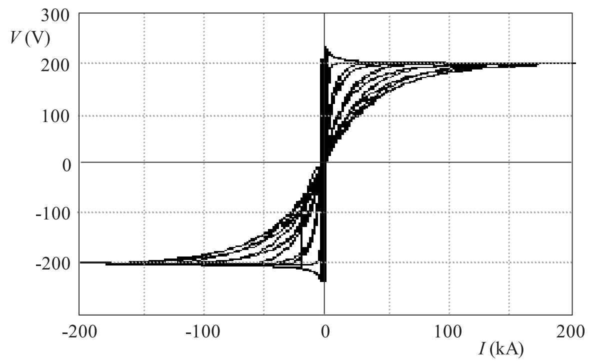

Fig. 8. The VIC of the arc in the refining stage (or melting down process) stage in the proposed exponential-hyperbolic model

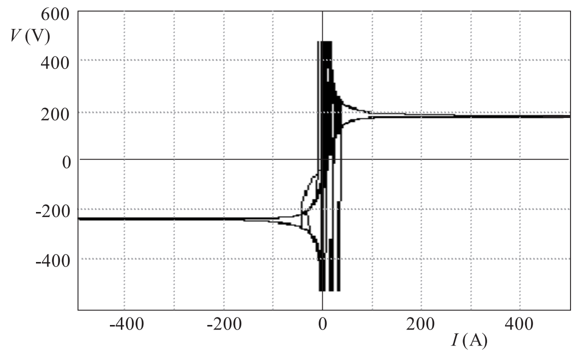

Fig. 9. The VIC of the arc in the scrap stage (or melting process) in the proposed exponential-hyperbolic model

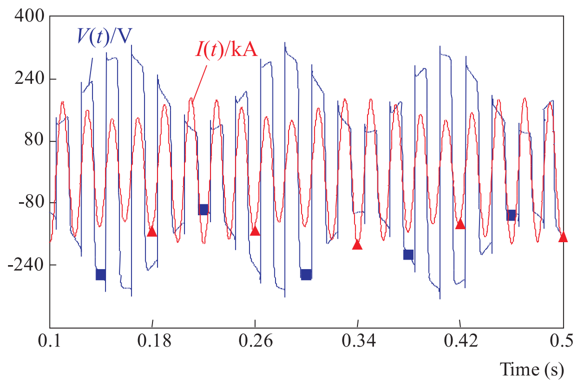

Fig. 10. Waveform of the arc voltage and current in the situation of the sinusoidal flicker

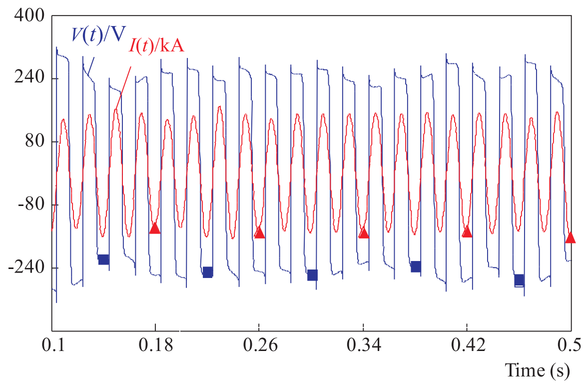

Fig. 11. Waveform of the arc voltage and current in the situation of random flicker

(10). The derived VIC of the arc is shown in Fig. 6. At the points of this characteristic where the length of the arc is not changed with time, it is assumed that this characteristic constant (at the refining process). In this situation, the EAF does not generate any flicker at PCC and it produces only odd harmonics in voltage and current; because the VIC has a symmetric characteristics. This situation explains the actual performance of the EAF at the plating period. In this period, the level of melting material is nearly constant and the melting is distributed uniformly in the furnace. Figure 7 shows the waveform of voltage and current for the proposed exponential-hyperbolic model of the EAF. The results indicate that if the furnace load does not produce any flicker, then the arc voltage, current, and voltage and current of the primary side of PCC oscillate similarly. When the EAF is in the melting process (or scarp stage), the VIC of the arc is in the form of Fig. 8. Finally, for the refining stage (melting down stage) of the arc material, the VIC of the furnace is given in Fig. 9. It should be noted that the parameters in this section are obtained using curve fitting.

5.3. Analysis of Voltage Flicker

5.3.1 Sinusoidal Flicker

Regarding (7), the simulation of sinusoidal voltage flicker is performed in this section and the used values are: $V_{T01} = V_{T02} = V_{T03} = 200$ V, $k_1 = k_2 = k_3 = 0.5$ and $\omega_f = 50$ rad/s.

Results of simulation are obtained using the above values. The arc voltage and current as well as arc conductance are plotted in Fig. 10.

The results of the simulation show that if the furnace load generates sinusoidal flicker, the arc voltage and current, are varied sinusoidally with the flicker frequency.

5.3.2 Random Flicker

In this part, the simulation of the voltage flicker using the random voltage is performed based on (8). The values used in (8) are chosen as: $V_{T01} = V_{T02} = V_{T03} = 200$ V, $k_1 = k_2 = k_3 = 1$.

Also, $N_1(t)$, $N_2(t)$ and $N_3(t)$ in this equation are three white noise voltages with zero mean and variance of 1 in the limited band (between 4-14Hz).

The waveforms of the voltage and current of the arc are shown in Fig. 11. Similar to the previous part, when the random flicker is applied, the load specifications of EAF are varied randomly. Thus, voltage, current and the three phase current of the primary side of the PCC bus are changed randomly. In the other words, in this case, furnace load flicker leads to a little variation in the voltage of the bus supplying the EAF.

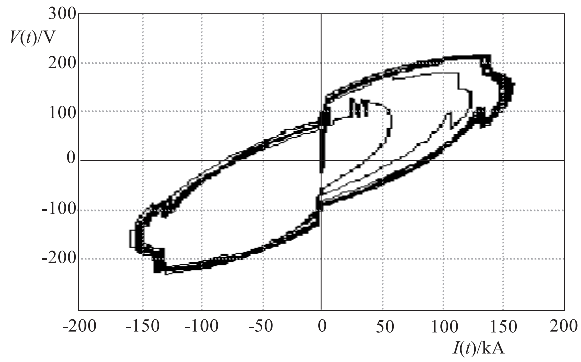

Fig. 12. The VIC of the arc in the actual situation

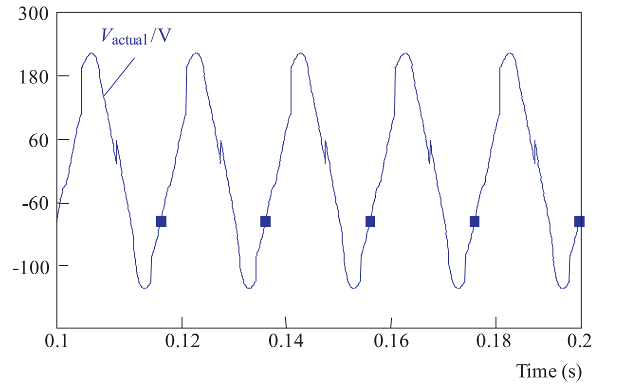

Fig. 13. Waveform of the voltage of the EAF in the actual situation

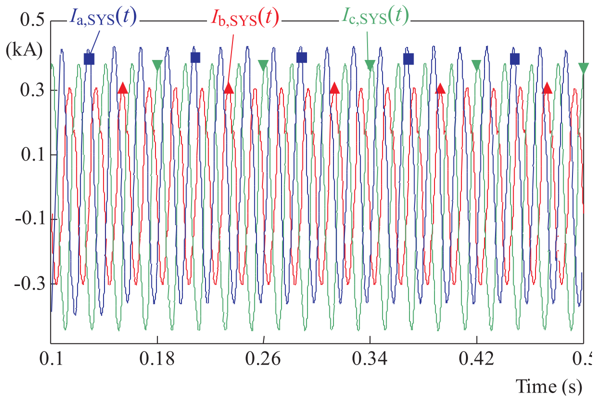

Fig. 14. Waveform of the three phase current at the primary side of PCC bus in the unbalanced situation with the different three phase voltages in the proposed exponential-hyperbolic model

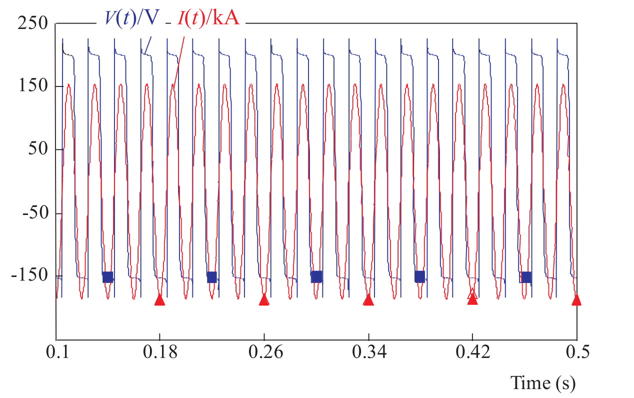

Fig. 15. Waveforms of the arc voltage and current in the case of even harmonics generation with different voltages V_T of in the proposed model of variations of the sinusoidal flicker

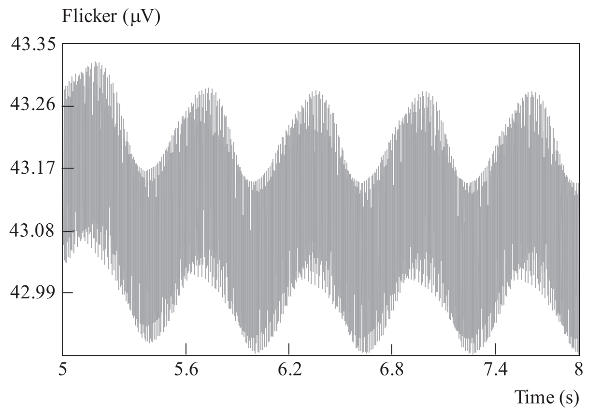

Fig. 16. The generated voltage flicker in the sinusoidal flicker situation at bus PCC

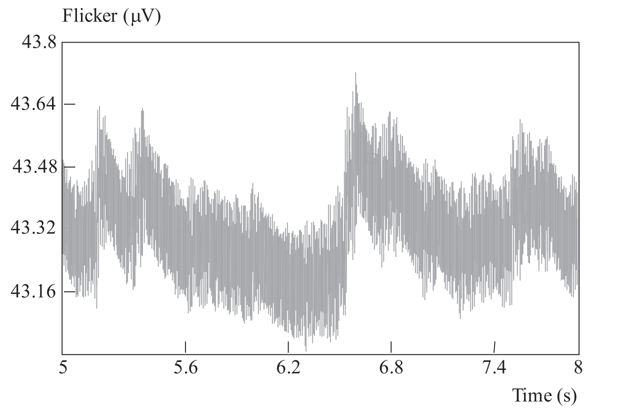

Fig. 17. The generated voltage flicker in the sinusoidal flicker situation at bus PCC

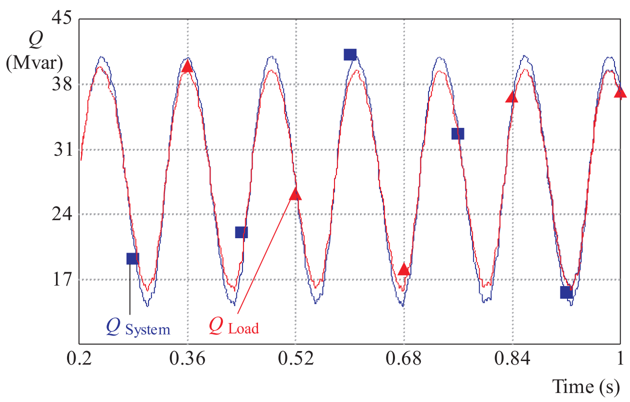

Fig. 18. The variation of the reactive power of the EAF and power system the sinusoidal flicker situation

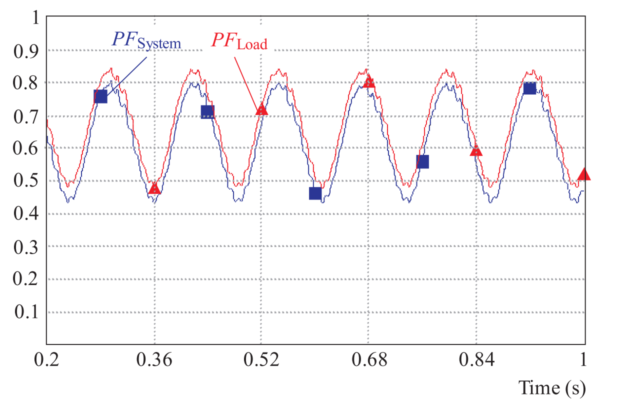

Fig. 19. The variation of the power factor of the EAF and power system the sinusoidal flicker situation

Table 1. Harmonic magnitudes for different models of furnace load in the plate stage (in Volts)

Harmonic → ↓ Model	H_1	H_3	H_5	H_7	H_9	H_{11}	H_{13}
Hyperblic	256.38	87.39	54.25	40.58	33.48	29.46	26.28
Exponential	253.78	82.37	47.02	31.53	32.21	17.76	14.36
Proposed model	255.42	58.14	50.84	32.21	28.39	23.85	21.88

Table 2. Harmonic magnitude comparison between different operating conditions with proposed model (in Volt)

Harmonic → ↓ Model	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}	H_{13}
Balanced	255.42	-	58.14	-	50.84	-	32.21	-	28.39	-	23.85	-	21.88
Unbalanced	223.29	13.723	73.63	13.65	42.90	13.38	29.43	13.35	21.93	13.09	17.38	13.11	14.18
Flicker:													
Sinusoidal	149.23	14.1	53.62	6.40	28.08	0.82	24.64	4.82	15.82	3.03	16.59	2.92	13.623
Random	243.89	12.99	82.02	6.55	48.89	8.71	34.82	6.70	27.35	8.42	22.94	6.87	19.751

5.4 Results of Actual Model Analysis

Regarding Fig. 1, and considering the values of (4), the VIC of the EAF is shown in Fig. 12. The voltage waveform of the EFA is also shown in Fig. 13, which has a good agreement with the actual case: $X_{lsc} = 9.4245\,\Omega$, $X_c = 2.356\,\mathrm{m}\Omega$, $R_c = 0.4\,\mathrm{m}\Omega$, $f_{sys} = 50$ Hz.

5.5 Analysis of Simulation Results for Unbalanced Three Phase Furnace Load

One of the operating conditions of the EAF is performance of the EAF in the unbalance load condition which in most cases happens in the initial working condition (scrap melting) of the EAF. In order to study the unbalanced situation in the proposed exponential-hyperbolic model, the voltage V_{at} in different phases are chosen as: $V_{Ta} = 200$ V, $V_{Tb} = 350$ V and $V_{Tc} = 450$ V.

The waveforms of the three phase currents at the primary side are determined using the values given in (10). These currents are shown in Fig. 14. Also in order to show the even harmonics and asymmetry of the arc, the voltage V_T for positive and negative current respectively was considered as: $V_{T1} = 200$ V, $V_{T2} = 175$ V. With these values, the waveform of the arc voltage and current are shown in Fig. 15.

Results of Electric Power Analysis: The sinusoidal voltage flicker and the proposed method in reactive power measurement are employed to determine the reactive power and power factor of the EAF. The, the variation of the reactive power and power factor of the EAF are shown in Fig. 18 and 19.

5.6. Harmonic Analysis for Different Models

In this part, the harmonic analysis for the different models of the EAF is performed. In addition, the effects of furnace load on voltage harmonics are investigated based on the proposed exponential-hyperbolic model. In this regard, Table (1) shows the generated voltage harmonics in the situation of plating stage for the different models: hyperbolic, exponential and proposed exponential-hyperbolic model. Since the odd symmetry is present in the models, there are no even harmonics in the arc voltage.

Also, the voltage harmonics of the EAF for different operating situation are shown in Table (2). As can be seen in this table, because of lack of odd symmetry in the electric arc, the even harmonics are present in the arc voltage. As a result, these even harmonics are injected to the power system. Moreover, when there is a voltage flicker, the harmonics of the electric arc voltage can be seen in this table. It should be noted that the magnitude amount of harmonics depends on the intensity and type of the flicker.

6 CONCLUSIONS

In this paper, at first, the existing hyperbolic and exponential models for EAF are studied. Then, a new model named exponential-hyperbolic model is proposed. The new model has no limitation of the previous models. The new model also, does not require any initial conditions or special requirement for modelling. The model is also able to describe the most of the specifications of the EAF.

In this paper, a three phase structure of the electric EAF is also proposed which includes the power quality aspects such as: voltage and current unbalanced situation, voltage flicker. Also, to analyze the effect of voltage flicker on the voltage arc furnace, the voltage flicker is considered in two forms of the random and sinusoidal noises in the frequency range of the human vision (between 4-14 Hz).

The results of the simulation and comparing with existing models show the advantages of the proposed method in modelling of the EAF.

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