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Harmonic analysis of an electric arc furnace through time-based dynamic modeling of the electric arc

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ABSTRACT: nonlinear electrical load over time. The electric arc in furnaces leads to distortions in the voltage waveform, voltage asymmetry, and fluctuations in the power supply system. To analyze the high harmonics generated by electric arc furnaces in the power supply system, it is essential to develop an accurate mathematical model of the electric arc.

KEYWORDS*:* electric arc, steel melting furnace, harmonic analysis, voltage-current characteristics, dynamic modeling, high harmonics, arc resistance, power supply system, simulation, non-sinusoidal distortion, feed forward neural network (FNN).

I. INTRODUCTION

It is advisable to study the volt-ampere characteristics of the electric arc depending on its operation cycle. Figure 1 shows the dynamic volt-ampere characteristics of the electric arc occurring at the beginning of the operation cycle in a steel melting furnace [1].

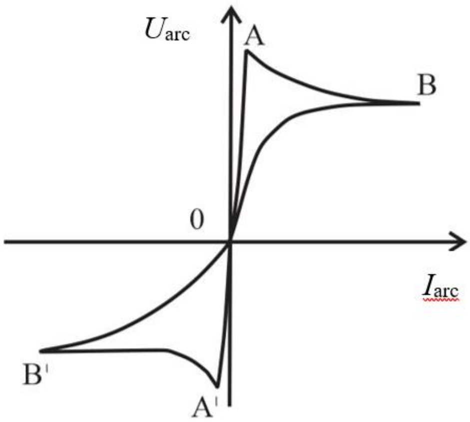

Figure 1. Dynamic volt-ampere characteristics of the electric arc in a steel melting furnace at the beginning of the operation cycle.

As seen in Figure 1, the electric arc voltage-ampere characteristic (VAH) can be divided into three characteristic phases. The first phase (0A and 0A' section) represents the current rise period of the arc, the second (AB and A'B') is the steady burning phase, and the third (BO and B'O) represents the current reduction phase. It is noteworthy that the VAH matches the stable burning mode of the arc in the furnace.

In the first phase of the established regime, the arc is formed based on the residual current left from the previous phase. During this phase, the intermediate conductivity results from residual conductivity and the increase in electrons caused by the electric field. In the AB section, the process of electron multiplication transitions into thermal ionization.

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As the current increases, the temperature and conductivity of the arc rise. In the third phase, the reduction in current in the cooling plasma occurs. The final rate of heat dissipation from the arc leads to a decrease in the plasma temperature relative to the current.

In the third phase, the conductivity at the same voltage is higher compared to the first phase. Therefore, the arc has a hysteresis form of VAH.

At low currents, when the current passes through zero, the plasma conductivity decreases significantly. In this established mode, the arc reignites when the ignition voltage of the arc is reached. While the voltage across the arc remains below the ignition voltage, the equivalent circuit is considered an open circuit.

During the melting process, the dynamic VAH of the arc may change [2]. This change is not only due to the inherent burning characteristics of the arcs but also due to the inertia of the arcs, which increases significantly during the melting process. As a result, the hysteresis VAH changes noticeably. In the initial phase of smelting and deep melting, the VAH has sharply nonlinear characteristics with growing and decaying segments. After deep melting, the VAH retains all these characteristics, but the transition between sections becomes smoother, and the hysteresis form strengthens. During the smelting process, there is an asymmetry in the VAH relative to the current axis, leading to the development of steady-state components of arc voltage and current.

In this phase, the value of the steady-state component of the voltage reaches 10-12% of the arc voltage. During the formation of the molten metal, the steady-state component decreases to 2-5%. The VAH also changes, with nonlinearity significantly reducing, hysteresis increasing, and the expansion of the loop at the transition point through the current axis becoming particularly noticeable. In the final stage of melting, the distortions in the VAH disappear, resulting in a sharp reduction in the non-sinusoidal nature of the currents and voltages[3,4].

To calculate the high harmonic voltage levels generated by the electric arc furnace in the electrical network, a mathematical model of the dynamic VAH is required. The best fit criterion for the mathematical model is the best alignment between the calculated results and the experimental data obtained from DSPs. The following basic model used in the calculations is analyzed to determine the compatibility.

In this model, the VAH of the electric arc is divided into three phases [5,6]. In the first phase, the extinguished arc begins to reignite. When the arc voltage reaches zero, the arc current also passes through zero. As the arc voltage reaches the reignition voltage U_{reig} the network's equivalent resistance remains within a limited range. In the second phase, the arc stabilizes at a constant voltage. As the arc voltage transitions from the reignition voltage U_{reig} to the constant value U_n a transient process occurs. This process is explained by the exponential function of time T_1 which is mainly defined by the heating time through plasma current to the thermal ionization temperature[7].

In the third phase, the arc extinguishes. The arc voltage decreases smoothly in the exponential function through the time constant T_2. T_2 – represents the characteristic time of plasma cooling, and its value is typically between 15-20 ms.

The mathematical expression of the model can be written in the form of the following system:

$$R_{arc} = \begin{cases} R_{S1} & 0 \le I < i_{reig}, \quad \dfrac{dI}{dt} > 0 \\ \dfrac{u_n + (u_{reig} - u_n)exp\left(\frac{i_{reig}-I}{T}\right)}{I} & I \ge i_{reig}, \quad \dfrac{dI}{dt} > 0, \\ \dfrac{u_m + (u_{reig} - u_m)\,exp\left(\frac{-I}{T_2}\right)}{I + i_{reig}} & \dfrac{dI}{dt} < 0 \end{cases}$$

here $I = |i(t)|, \quad u_n = \frac{u_{reig}}{1.15}$

$$u_m = \left[\frac{I_{max}+i_{reig}}{I_{max}}\right] \cdot u_n \qquad \frac{u_n+(u_{reig}-u_n)\exp\left(\frac{i_{reig}-I}{T_1}\right)}{I} = R_{S2}.$$

This model shows that the VAH of the arc is dependent on the resistance of the arc and the current passing through it, while accounting for the inertia of the thermal processes.

To obtain the VAH of the arc based on this model, a schematic was constructed using the Matlab (Simulink) library, as shown in Figure 2. The test time for obtaining the VAH of the arc in normal mode lasts 31.92 seconds.

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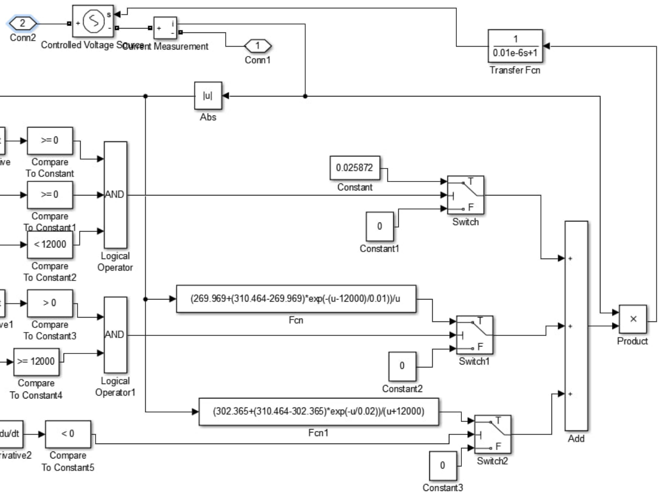

Figure 2. Schematic for Obtaining the VAH of the Arc Based on the Model in Matlab (Simulink).

In this model, the dynamic VAH of the arc is analyzed using a system of three equations, which express the three phases of the arc: the initial ignition phase, the melting phase, and the extinction phase. This allows for a comprehensive analysis of the VAH across the different stages of the arc's operation. Analyzing the VAH of the arc helps assess the impact of the arc's non-linear behavior as a load on the voltage quality in the Electrical Transmission System (ETS).

The VAH of the arc obtained from the model is shown in Figure 3, and the graph depicting the relationship between the arc's dynamic resistance and the VAH is presented in Figure 4.

As shown in the graph, the dynamic resistance of the arc changes depending on the value of the alternating current passing through the arc. At the maximum current of the arc, the dynamic resistance reaches its minimum value, and conversely, when the current of the arc approaches zero, the dynamic resistance reaches its maximum value.

For calculating the higher harmonic levels of current and voltage, the switching circuits of the DSP-30 electric arc furnace transformer and the short circuit parameters were used. The parameters of the furnace transformer with a power rating of 21 MVA were taken from existing data.

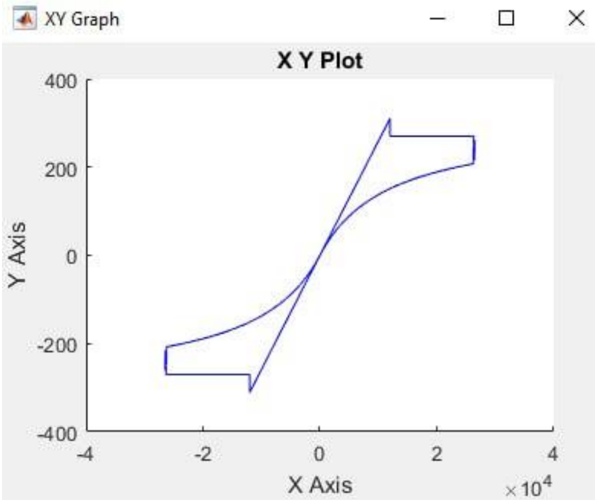

Figure 3. VAH of the arc based on the model

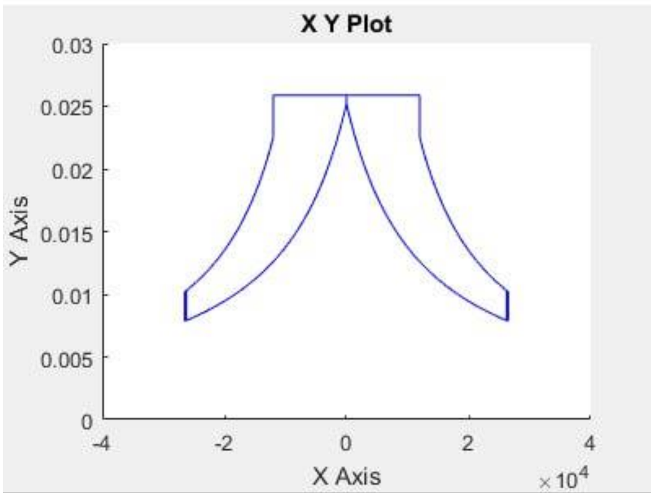

Figure 4. Graph of the arc's dynamic resistance vs. arc current

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The model for calculating the higher harmonics of current and voltage in the furnace arc is shown in Figure 5, and the parameters of the electrical power supply system and other components are provided in Table 1.

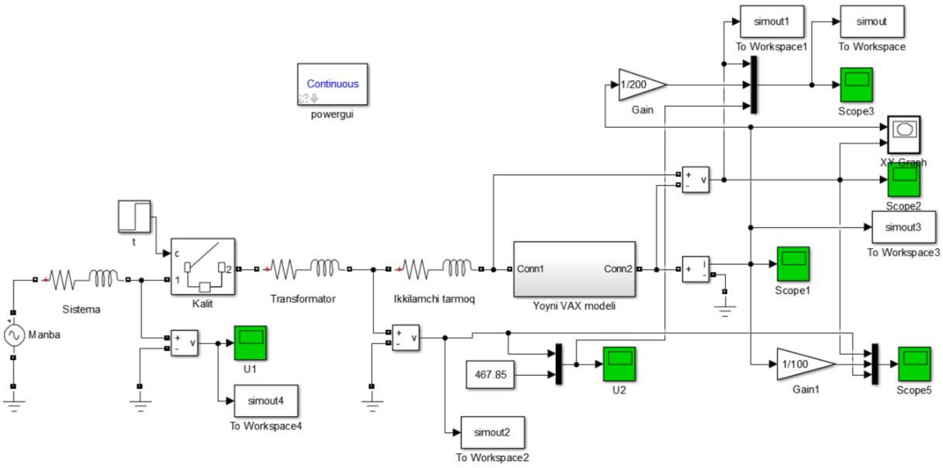

Figure 5. Matlab (Simulink) Model of the Arc Load.

Table 1. Parameters of the system and model

Element	Parameters
System	U_{HOM}=573 f=50Hz, R_c=0.0528 mOm, X_c=0.468 mOm, R_m=0.05 mOm, X_m=0.35 mOm, $R_{\kappa m}$=0,25 mOm м, $X_{\kappa m}$=0,15 mOm
Model	U_{reig}=310.5 B, $I_{\text{мах}}$=30 кА, T_1=0,01 c, T_2=0,02 c

As a result of incorporating the specified parameters into the model, the current and voltage waveforms of the electric arc, as well as the voltage waveforms at the low-voltage bus of the furnace transformer, were obtained. The resulting graphs are shown in Figure 6.

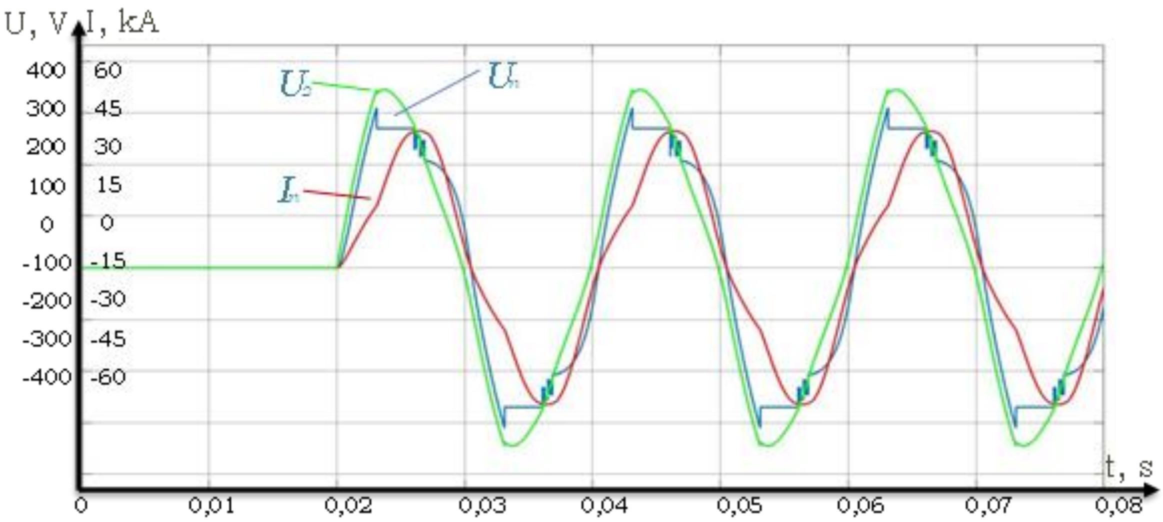

Figure 6. Current and Voltage Waveforms of the Electric Arc and Voltage Waveforms at the Low-Voltage Bus of the Transformer

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As seen in Figure 6, the shape of the current and voltage waveforms of the electric arc is distorted, significantly deviating from a sine wave. The main reason for this distortion is the nonlinear nature of the arc resistance. The time-dependent variation of the electric arc resistance is shown in Figure 7.

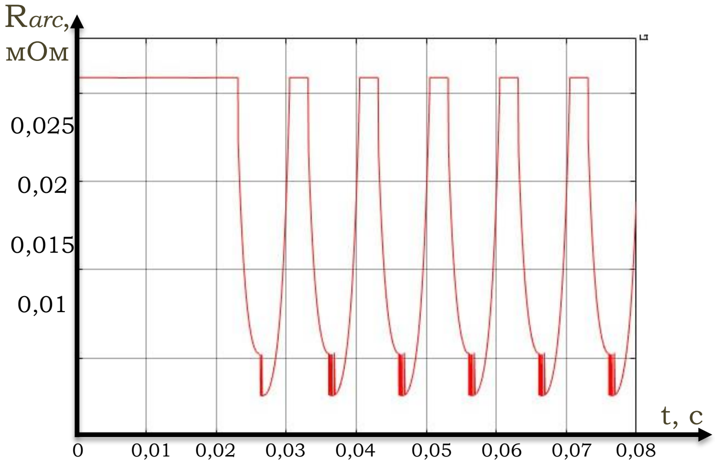

Figure 7. Time-dependent variation of the electric arc resistance.

The harmonic analysis of the electric arc voltage is shown in Figure 8.

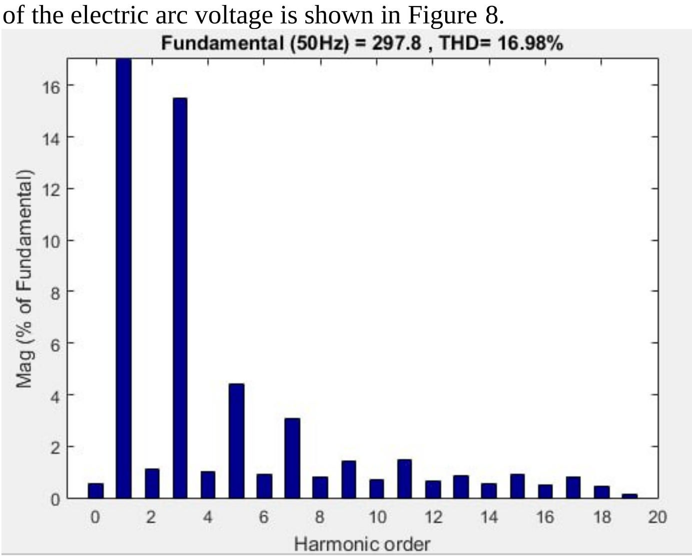

Figure 8. Harmonic Analysis of the Electric Arc Voltage.

Figure 9 shows the harmonic analysis of the electric arc voltage, indicating that the non-sinusoidal coefficient of the voltage is 16.98%. Notably, the third ν_3, fifth ν_5 and seventh ν_7 harmonics have significant contributions.

In the electric arc of the furnace, not only the voltage but also the shape of the current waveform is distorted because of the interdependency between the current and voltage parameters. The harmonic analysis of the electric arc current is shown in Figure 9.

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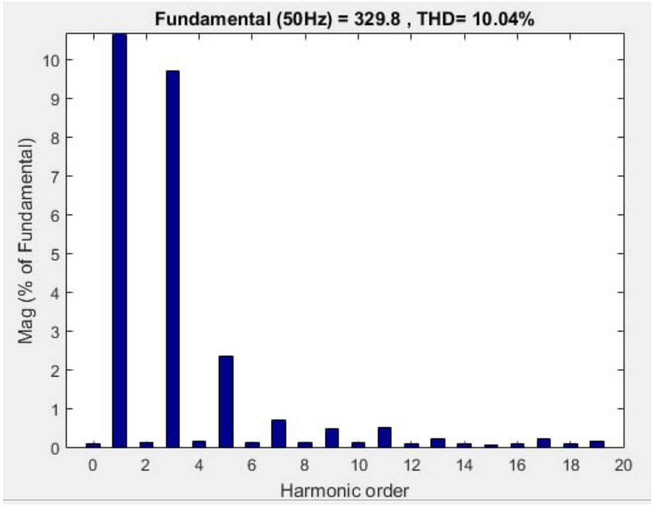

Figure 9. Harmonic Analysis of the Electric Arc Current

The degree of distortion of the current in the electric arc of the steel melting furnace in the model is 10,04%.

The values for the higher harmonics of the electric arc current are as follows: the third harmonic is 14,71 %, the fifth harmonic is 6,49%, the seventh harmonic is 3,64%, the ninth harmonic is 2,25 % and the eleventh harmonic is 1,58 %.

For the electric arc voltage, the third harmonic contributes 29,13%, the fifth harmonic 14,73%, the seventh harmonic contributes 7,76%, the ninth harmonic contributes 3,86% and the eleventh harmonic contributes 1,64%

II.CONCLUSION

In conclusion, the electric arc furnace melting process is complex, and experimentally analyzing the higher harmonics of the voltage and current generated is challenging. Therefore, the first step is to develop a dynamic model of the electric arc resistance, which is a characteristic element. The closer the volt-ampere characteristic obtained from the dynamic model is to the theoretical volt-ampere characteristic, the higher the adequacy of the dynamic model. By utilizing the dynamic model, it becomes possible to determine the higher harmonic values of the current and voltage generated during the electric arc melting process.

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