EVALUATING THE QUALITY OF THE LOCAL GRID SUPPLY VOLTAGE WITH ARC FURNACES

Nguyen Thi Mai Huong*, Nguyen Huong Quynh, Nguyen Tien Hung

Abstract: *Electric arc furnaces are widely used in many steel companies. The arc furnace can be considered as an unbalanced load with nonlinear and time-varying nature. Therefore, in order to have a permission to be connected to the grid, it is required that the effect of the arc furnace has to be evaluated and the local power system quality should be maintained at a level specified by authority. However, since the arc furnaces exhibit their nonlinear and time-varying characteristics as mentioned above, it is not easy to obtain an accurate model of a real arc furnace. This paper presents a modification of arc furnace models based on the classical Cassie and Mayr equations. The obtained appropriate model can be used in reality to appraise the quality of the local supply grid with the arc furnaces. The flicker calculation as well as the simulation results show that the nonlinearity of the arc furnace produces the distortion of the secondary voltage of the supply transformer but this may not make significant effect on producing harmonics to the grid.*

Keywords: Arc furnace model; Harmonic distortion; Voltage distortion; Current distortion; Power quality problems.

1. INTRODUCTION

Arc furnaces are considered to be electrical loads with nonlinear dynamics. An arc furnace can be modeled as a circuit with nonlinear resistors. However, since the resistor of an arc furnace is very small, calculating and describing them are complicated tasks since it requires to solve nonlinear differential equations. Therefore, in order to find arc voltages and current responses in particular operations, it is required to establish the mathematical model for representing the arc furnace, compute necessary parameters, and simulate the arc furnace to obtain the characteristics of the arc furnace and electrical supply systems.

The models of arc furnaces can be developed from their voltage-current characteristics [1]. Another way to obtain arc furnace model is to consider the nonlinear, and time-varying behavior of arc furnaces [2, 3]. There are also two arc models widely used in reality that are Mayr and Cassie [4- 6]. The Mayr model is advisable for small current arc furnaces while Cassie model is reasonable for higher current ones. In stead of representing by resistance, these models are described by their conductance because the arc resistances are very small. In [7], a new time domain model for electrical arc furnaces is presented for simulating both nonlinear and time-varying nature of their loads. This study uses the Mayr and Cassie models in three-phase mode and takes into account the system inter-relation of parameters as well as arcing conditions. In this paper we propose an arc furnace model that is developed from the combination and modifications of the classical Cassie and Mayr equations. The model equations have been expressed in a form suitable for incorporation into circuit simulators employing the nodal-analysis method of equation solving. The simulation results obtained from this model can be used to evaluate the quality of the local supply grid where the arc furnaces are installed in term of the total harmonic distortion.

2. ARC FURNACE MODELS

In order to obtain a better representation for both high and low current arc furnace one can combine Mayr and Cassie models into the following description [4].

$$\begin{aligned} \frac{1}{g} &= \frac{1}{g_m} + \frac{1}{g_m} \\ \frac{dg_m}{dt} &= \frac{1}{\tau_m}\left(\frac{u^2 g^2}{P_0} - g_m\right) \\ \frac{dg_c}{dt} &= \frac{1}{\tau_c}\left(\frac{u^2 g^2}{U_c^2 g_c^2} - g_c\right) \end{aligned} \tag{1}$$

where g is the total conductance of the arc, u is the voltage across the arc, i is the current through the arc, τ_c is the Cassie time constant, U_c is the Cassie constant arc voltage, g_c is the conductance of the arc described by the Cassie equation, τ_m is the Mayr time constant, P_0 is the Mayr constant steady-state power-loss of the arc, g_m is the conductance of the arc described by the Mayr equation.

The combination of Mayr and Cassie models as expressed by equation (1) is quite rigid. Therefore, in order to make it more flexible for the combination of the Mayr and Cassie models, one defines an addition transition current I_0 and a transition function [8, 7, 1]

$$\sigma(i) = e^{\left(-\frac{i^2}{I_0}\right)} \tag{2}$$

and build the following relation

$$g = (1 - \sigma(i))g_c + \sigma(i)g_m \tag{3}$$

The transition function $\sigma(i)$ value varies in the range of $(0, 1)$. When the arc current i is larger than I_0 the Cassie model produces more effects. Conversely, when the arc current i is smaller than I_0 the Mayr model produces more effects [5].

The conductance of the arc is also provided by

$$g_k = g_{min} + \left(1 - e^{\left(-\frac{i_k^2}{I_0^2}\right)}\right)\frac{v_k \times i_k}{U_c^2} + e^{\left(-\frac{i_k^2}{I_0^2}\right)}\frac{i_k^2}{P_0} - \tau_k \frac{dg_k}{dt} \tag{4}$$

where $k = 1, 2, 3$ is the index of phases. g_{min} is a constant depending on the distance between electrodes, the shapes of electrodes, air and temperature, $i_k = g_k \times v_k$.

Normally, τ_k is a function of the arc current. Hence

$$\tau_k = \tau_{0k} + \tau_{1k} e^{(-\alpha_k |i_k|)} \tag{5}$$

where τ_{0k}, τ_{1k}, and α_k are coefficients.

Equation (4) can be rewritten as follows

$$g_k = g_{min} + \left(1 - e^{\left(-\frac{i_k^2}{I_0^2}\right)}\right)\frac{i_k^2}{g_k \times E_k^2} + e^{\left(-\frac{i_k^2}{I_0^2}\right)}\frac{i_k^2}{P_0} - \tau_k \frac{dg_k}{dt} \tag{6}$$

The voltages across the arc in a different phase is modeled by a stochastic signal with zero expectation and frequency spectrum in the frequency range varying from 1 - 14Hz. In this case, the value of the arc voltage is given by

$$E_k = E_{0k}(1 + m_1 W_k(t)), \tag{7}$$

where $W_k, k = 1, 2, 3$ is a white noise with a finite length and zero expectation unity variance, $m_k, k = 1, 2, 3$ is the modulation indexes. The variation of m_k leads to the variation of the magnitude oscillation of the arc voltages.

Rewrite equation (6) in the form of

$$\frac{dg_k}{dt} = \frac{1}{\tau_k}\left(g_{min} + \left(1 - e^{\left(-\frac{i_k^2}{I_0^2}\right)}\right)\frac{i_k^2}{g_k \times E_k^2} + e^{\left(-\frac{i_k^2}{I_0^2}\right)}\frac{i_k^2}{P_0} - g_k\right) \quad (8)$$

or

$$\frac{dg_k}{dt} = \frac{1}{\tau_k}\left(g_{min} + a_k + b_k - g_k\right) \quad (9)$$

In which

$$a_k = \left(1 - e^{\left(-\frac{i_k^2}{I_0^2}\right)}\right)\frac{i_k^2}{g_k \times E_k^2} \quad (10)$$

$$b_k = e^{\left(-\frac{i_k^2}{I_0^2}\right)}\frac{i_k^2}{P_0} \quad (11)$$

Solving equation (8) and making a nonlinear resistor can be implemented by a structure as shown in fig. 1. The Simulink model for taking the characteristic of the arc furnace and the distributed grid is shown in fig. 2 where the model of the arc furnace is built based on above mathematical models.

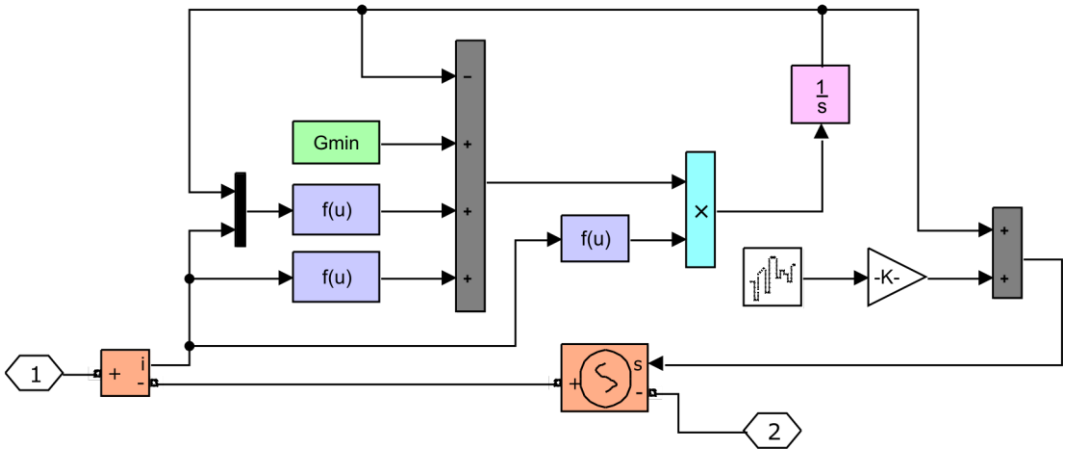


Fig. 1. *Modified Mayr-Cassie model.*

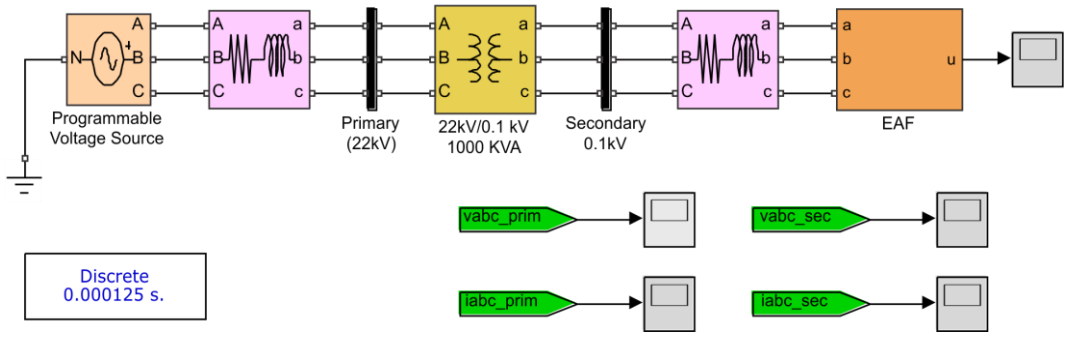


Fig. 2. *Simulink model of the Arc furnace.*

3. VOLTAGE FLICKERING AND SIMULATION RESULTS

The simulation is carried out with the following parameters

- The source impedance $Z_s = R_s + jX_s = 0.0081 + j0.0807$.

- The transformer apparent power S_t = *1000 kV A*.
- Transformer primary voltage: 22 kV.
- Transformer secondary voltage: 70 V.
- Transformer primary resistance: 4.850 Ω.
- Transformer secondary resistance: 0.0002 Ω.
- Transformer primary inductance: 0.16177 H
- Transformer secondary inductance: 2.1056×10^{-6} H.
- Cable resistance of of electrodes: 8.1667 × 10^{-5} Ω.
- Cable inductance of of electrodes: X_c = 0.0807 Ω.
- The short-circuit voltage $U_n = 6.1\%$.
- Power coefficient $\cos\varphi$ = 0.85 ($\sin\varphi$= 0.53).
- $g_{min} = 120$.
- $\tau = 0.0005$.
- $p = 5.5$.
- $P_0 = 500$.
- $C_i = 7.5$.

3.1. Short-term voltage flickering

The calculation of the short-term voltage flickering is performed with the following assumptions:

- For sake of simplicity, the voltage flickering level is calculated for the maximum value of electrical load (maximum voltage dip) corresponding to the maximum power of the transformer.

- The frequency of the arc voltage is $n = 40$ times per minute. This means that electrodes go down 40 times and produce arc with maximum currents in every minute.

- All parameters are calculated following IEC 868 standard [9] with more detail described in IEC 6100-4-15 standard [10].

Let Z_t be the impedance of the transformer converted into the primary side we can write

$$Z_t = \hat{R}_t + j\hat{X}_t, \tag{12}$$

where

$$\hat{R}_t = R_{t1} + R_{t2} \times \frac{u_1}{u_2} = 4.850 + 0.0002 \times \frac{22 \times 10^3}{70} = 4.9129(\Omega)$$

and

$$\hat{X}_t = X_{t1} + X_{t2} \times \frac{u_1}{u_2} = 50.8215 + 6.6149 \times 10^{-4} \times \frac{22 \times 10^3}{70} = 51.0294(\Omega)$$

Similarly, let Z_c be the impedance of the electrode's cables converted into the primary side we have

$$Z_c = \hat{R}_c + j\hat{X}_c, \tag{13}$$

in which

$$\hat{R}_c = R_c \times \frac{u_1}{u_2} = 8.1667 \times 10^{-5} \times \frac{22 \times 10^3}{70} = 0.0257(\Omega)$$

and

$$\hat{X}_c = X_c \times \frac{u_1}{u_2} = 0.0807 \times \frac{22 \times 10^3}{70} = 25.3524(\Omega)$$

Therefore, if Z_{tt} is the impedance from the source to the electrodes we have

$$\begin{aligned} Z_{tt} &= Z_s + Z_t + Z_c \\ &= 0.0081 + j0.0807 + 4.9385 + j51.0294 + 0.0257 + j25.3524 \\ &= 4.9466 + j76.4625 = R_{tt} + jX_{tt} \end{aligned}$$

The level variation of the relative voltage can be calculated as follows [11]

$$d = \frac{R_{tt} \times \Delta P + X_{tt} \times \Delta Q}{u_1^2} \times 100\%$$

where ΔP and ΔQ are the active and reactive power changes of the load at the investigated time. With an assumption that the changing level of the voltage is calculated adapting to the maximum load we have

$$\begin{aligned} d &= \frac{R_{tt} \times S_t \times Cos\varphi + X_{tt} \times S_t \times Sin\varphi}{u_1^2} \times 100\% \\ &= \frac{4.9466 \times 1000 \times 0.85 + 76.4625 \times 1000 \times 0.53}{22 \times 10^6} \times 100\% = 9.2417\% \end{aligned}$$

The flicker time t_f is calculated as follows \[12, 11]

$$t_f = 2.3 \times d^{3.2} = 2.3 \times 9.2417^{3.2} = 2.8322 \times 10^3 (s)$$

The flicker level of short-term voltage P_{st} in the secondary side of the transformer is computed by taking the summation of all flicker times in the interval of $T_p = 10$ minutes. With a hypothesis that the flicker frequency of the voltage is 40 times per minute we have

$$P_{st}^* = \left(\frac{\sum tf}{T_p}\right)^{\frac{1}{3.2}} = \left(\frac{10 \times 40 \times 2.8322 \times 10^3}{10 \times 60}\right)^{\frac{1}{3.2}} = 10.5624$$

The flicker level of short-term voltage converted to the primary side of the transformer is

$$P_{st} = P_{st}^* \times U_n\% = 10.5624 \times 0.061 = 0.6443(\%)$$

Because we assume that the flicker level of the voltage corresponding to the maximum load in the whole interval. Therefore

$$P_{st95\%} = P_{st} = 0.6443(\%)$$

Thus, the short-term voltage flickering $P_{st95\%} = 0.6443$ at the busbar 22 kV is smaller than the allowed level 1% following from IEC 868 standard.

3.2. Long-term voltage flickering

Similarly to the short-term voltage flickering case, we also assume that the flicker level of the voltage corresponding to the maximum load in the whole interval. Therefore, the long-term voltage flickering is

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{i=1}^{12} P_{st}^3} = P_{st} = 0.6443(\%)$$

and

$$P_{lt95\%} = P_{lt} = 0.6443(\%)$$

Thus, the long-term voltage flickering $P_{st95\%} = 0.6443$ at the busbar 22 kV is smaller than the allowed level 0.8% following from IEC 868 standard.

3.3. Simulation results

The current and voltage responses of the arc furnace as well as the grid are shown in fig. 3. It can be seen that, due to the nonlinearity characteristic of the arc furnace, the currents and

voltages of the arc are distorted. The primary currents are also distorted. However, since the magnitude of the secondary voltages is quite small in comparison to the primary voltages (70 V and 22 kV), the distortion of the secondary voltages produces a small effect into the primary voltages.

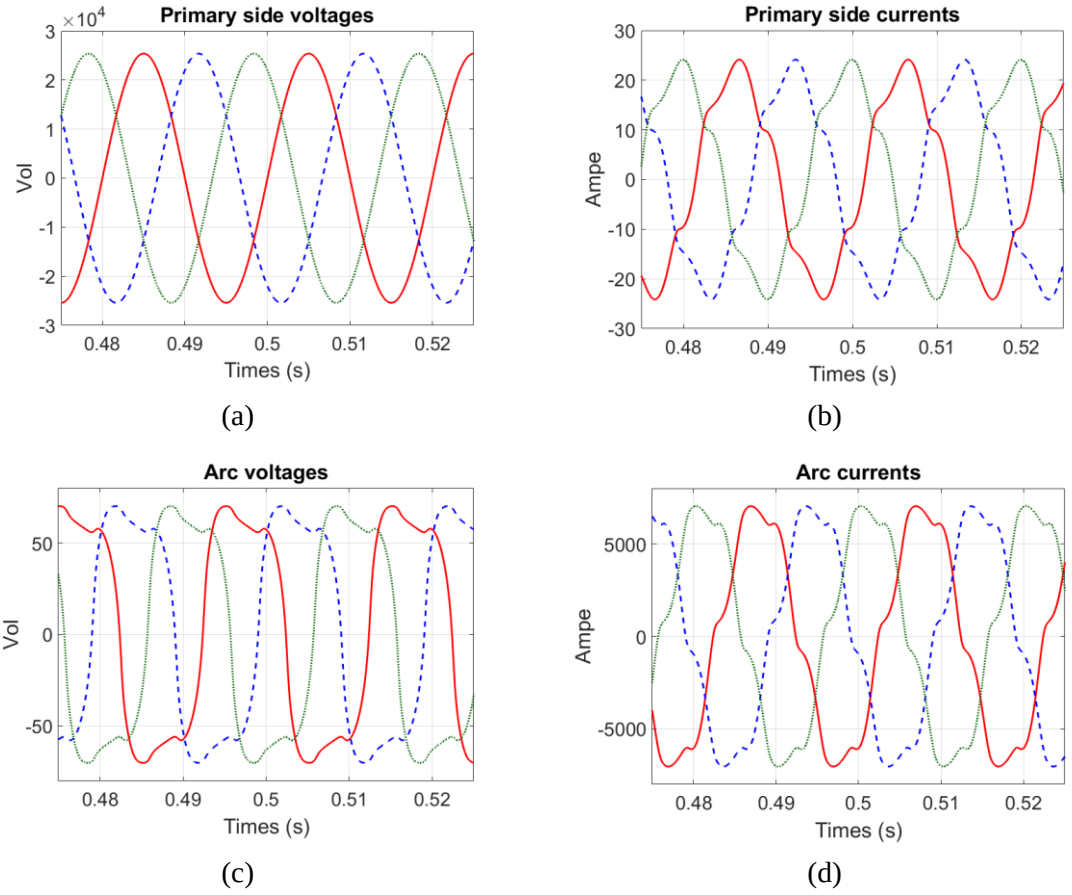


Fig. 3. *Current and voltage responses of the arc as well as the grid supply voltage.*

In order to observe the distortion of the currents and voltages at the primary and secondary sides we perform a Fourier analysis for these quantities. Fig. 4 shows the spectrum of the arc voltages including the fundamental element (50 Hz), the third element (150 Hz), and the fifth element (250 Hz). The amplitude of the fundamental element is 76.54 while the amplitudes of the other elements are quite small. The amplitude of the third element is about 27% and the amplitude of the fifth element is about 7.75% in comparison to the fundamental element. Therefore, the total harmonic distortion in the secondary side of the transformer is

$$THD_{arc} = \sqrt{\frac{(0.27 * 76.54)^2 + (0.775 * 76.54)^2}{76.54^2}} \times 100\% = 28.09\% \quad (14)$$

In addition, the Fourier analysis of the primary voltage shows that the spectrum almost contains the fundamental element with the amplitude of 2.54×10^4 and the fifth element with the amplitude of about 0.00385% comparing to the fundamental element (fig. 4). Therefore, the total harmonic distortion in the primary side of the transformer is

$$THD_{prim} = \sqrt{\frac{(0.00000385 * 25400)^2}{25400^2}} \times 100\% = 0.0039\% \quad (15)$$

This simulation results show that the distortion of the secondary voltage coming from the nonlinearity of the arc furnace makes insignificant effect on producing harmonics to the grid.

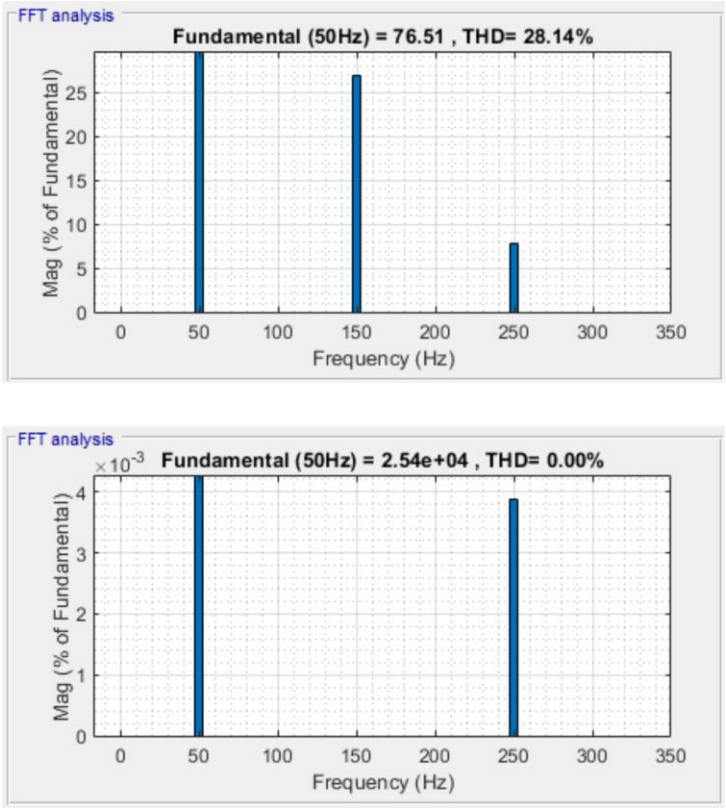


Fig. 4. *Fourier analysis of the arc and primary voltages.*

4. CONCLUSIONS

This paper proposes an appropriate model of arc furnaces based on the classical Cassie and Mayr ones for investigating the their influence of on the local grid system. The simulation results show that the use of the arc furnace can cause very poor power quality on the secondary side of the supply transformer. However, effect of the secondary voltage distortion to the primary side of the transformer may not remarkable since the amplitude of the secondary voltage is quite small in comparison to the primary voltage. The research results mentioned in this article have been approved by a steel manufacturing company when preparing to put their arc furnace into operation. However, after that, the results were not verified at the factory since it was not required by the company board. This is a limitation that needs to be studied further and adjusted the algorithm according to real operations of arc furnaces in future works.

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TÓM TẮT

ĐÁNH GIÁ CHẤT LƯỢNG ĐIỆN ÁP LƯỚI CỤC BỘ VỚI CÁC LÒ HỒ QUANG

Lò hồ quang điện được sử dụng rộng rãi trong các nhà máy sản xuất thép. Lò hồ quang có thể được coi là tải không cân bằng với thuộc tính phi tuyến và biến đổi theo thời gian. Vì vậy, để được phép kết nối với lưới thì ảnh hưởng của lò phải được đánh giá và phải đảm bảo chất lượng của hệ thống cung cấp điện cục bộ được duy trì ở mức cho phép bởi người có thẩm quyền. Tuy nhiên, do đặc tính phi tuyến và biến đổi theo thời gian như đã đề cập ở trên, không dễ để có được một mô hình lò hồ quang thực tế chính xác. Bài báo này trình bày một biến thể của mô hình lò hồ quang dựa trên các mô hình kinh điển Cassie và Mayr. Mô hình đạt được có thể được sử dụng trong thực tế để đánh giá chất lượng của hệ thống lưới cục bộ của nhà máy có sử dụng các lò hồ quang. Việc tính toán các điện áp nhấp nháy cũng như các kết quả mô phỏng chỉ ra rằng, tính phi tuyến của các lò hồ quang có thể gây ra méo dạng điện áp phía thứ cấp của máy biến áp nguồn nhưng điều này có thể không ảnh hưởng quá lớn đến việc gây ra các sóng hài phía lưới.

Từ khóa: Mô hình lò hồ quang; Méo sóng hài, méo điện áp; Méo dòng điện; Chất lượng hệ thống điện.

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Author affiliations:
Thainguyen University of Technology.
* Corresponding author: maihuongsdh@tnut.edu.vn.