TẠP CHÍ KHOA HỌC
TRƯỜNG ĐẠI HỌC QUY NHƠN

Xây dựng và khảo sát sự thay đổi của các thông số lò hồ quang điện dựa trên mô hình bảo toàn năng lượng bằng phần mềm Pscad

Đoàn Đức Tùng, Lương Ngọc Toàn*

Khoa Kỹ thuật & Công nghệ, Trường Đại học Quy Nhơn, Việt Nam

Ngày nhận bài: 19/03/2020; Ngày nhận đăng: 23/06/2020

TÓM TẮT

Phân tích thực tế cho thấy dòng điện lò hồ quang có chứa nhiều sóng hài gây ảnh hưởng xấu đến chất lượng điện năng. Có nhiều báo cáo trong và ngoài nước về mô hình hóa và đánh giá ảnh hưởng của EAF đến lưới điện dựa trên các mô hình khác nhau. Tuy nhiên việc lựa chọn công suất của EAF để nghiên cứu và áp dụng các thiết bị cải thiện chất lượng điện năng phù hợp với mức công suất vẫn chưa được đề cập, các mô hình này chủ yếu được xây dựng trên phần mềm Matlab Simulink nên chủ yếu mang tính học thuật. PSCAD là một trong những phần mềm được sử dụng rộng rãi cho việc mô phỏng hệ thống điện và được các công ty lớn sử dụng như ABB, tập đoàn điện lực Hàn Quốc Kepco. Xây dựng mô hình EAF bằng phần mềm PSCAD sẽ làm tăng khả năng áp dụng kết quả mô phỏng vào thực tiễn. Mục tiêu của bài báo đi vào xây dựng mô hình lò hồ quang điện dựa trên mô hình bảo toàn năng lượng bằng phần mềm PSCAD, từ đó đánh giá sự thay đổi của các thông số trong mô hình và ảnh hưởng của phụ tải này đến lưới điện trong quá trình vận hành.

Từ khóa: *Lò hồ quang điện, chất lượng điện năng, mô hình phi tuyến, pscad.*

**Tác giả liên hệ chính.*
Email: lntoan@ftt.edu.vn

JOURNAL OF SCIENCE
QUY NHON UNIVERSITY

Construction and survey of changes in electric arc furnace parameters based on energy conservation model using Pscad software

Doan Duc Tung, Luong Ngoc Toan*

Faculty of Engineering and Technology, Quy Nhon University, Vietnam

Received: 19/03/2020; Accepted: 23/06/2020

ABSTRACT

Actual analysis showed that the arc furnace current contains many harmonics that adversely affect the power quality. There are many domestic and foreign reports on modeling and assessing the impact of EAF on the grid based on different models. However, EAF's selection of capacity for research and application of power quality improvement devices suitable to the power level has not been mentioned. These models mainly built on Matlab Simulink software are primarily academic. PSCAD is one of the widely used software for electrical system simulation and is used by large companies such as ABB, Korean power corporation Kepco. Building EAF model with PSCAD software will increase the ability to apply simulation results into practice. The objective of the paper is to build an electric arc furnace model based on the energy conservation model with PSCAD software, thereby assessing the change of parameters in the model and the effect of this load on electricity grid during operation.

Keywords: *Electric arc furnace, power quality, nonlinear model, pscad.*

1. INTRODUCTION

Electric arc furnaces (EAFs) use the heat to fuse metal produced by an electrical discharge between electrodes or between an electrode and a metallic material to melt. When the electric arc furnace is in operation, the current causing the arc current to constantly change with the molten metal, at the same time due to the operation of the melted material that changes the distance between the electrode and the material, when adjusting the electrodes, blowing oxygen into the furnace also makes the arc currents change rapidly in a wide range and not stable. Electric arc furnaces also consume the active and reactive power of the grid.

The EAF model is built on the arc characteristic of the furnace, which represents the arc current and voltage value during operation. The actual EAF model data is difficult to obtain because the equipment working environment is arc environment with very large currents. However, precise arc values are really necessary for the design process.

2. ARC CHARACTERISTICS

The nature of the electric arc is radioactive phenomenon with a very large current density.[1]

*Corresponding author.
Email: lntoan@ftt.edu.vn

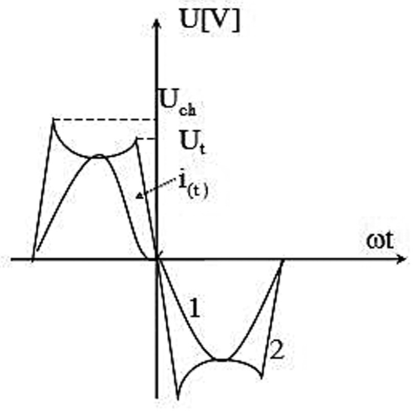

Figure 1. Wave voltage and current of the arc

In alternating electric arcs, the supply current and voltage fluctuate periodically with the grid frequency. Since the arc is a nonlinear resistance, the current and voltage of the arc are in phase. From the actual measurement results shown in Figure 2, the current has a waveform that is almost like a sine wave, and the voltage has two peaks in half a cycle corresponding to the two values of the burn voltage (Uch) and the off voltage (Ut) of the electric arc.[1,2]

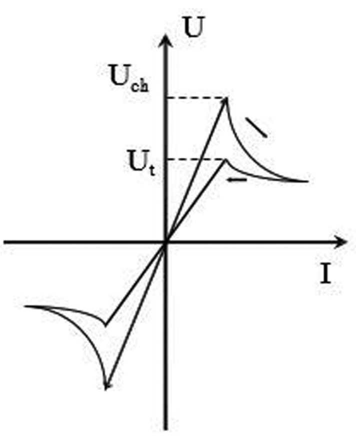

Figure 2. Volt-ampere characteristics of alternating electric tanks.

During the first cycle, the arc voltage increases rapidly to the burn value (according to the supply voltage). When the arc burns, the voltage gradually decreases. The current increases from 0 to the point of fire, the current increases sharply and when t = T/4, the current reaches its maximum value and the arc voltage is almost constant. In the following cycle, the current gradually decreases, by the time of shutdown, the arc voltage increases, then declines to zero and the current also returns to zero.

3. MATHEMATICS MODEL OF ARC FURNACE

To study the properties of the EAFs, it is necessary to build an accurate three-phase model for steady-state analysis and oscillation analysis. The arc melting is a fixed random process, so it is very difficult to make an exact model which leads to many different acrobatic models being built to simulate electric arc furnaces.[3]

The factors that influence the operation of the arc furnace are the molten or refined materials, electrode position, electrode arm control scheme, and the voltage and impedance of the supply system. Therefore, the description of the arc furnace load depends on the following values: arc voltage, arc current, and arc length (determined by the position of the electrode). In general, different methods for arc furnace modeling can be classified into "time domain" and "frequency domain" methods.

Frequency domain analysis method represents the arc voltage and arc current by its harmonic components. These models use several test parameters to reflect arc furnace performance. Since these parameters are experimental and inaccurate, these models are not widely used

Since the arc current is a different nonlinearity and time phenomenon, it is easier to describe its behavior in the time domain than in the frequency domain. The real-time method is the basis for analyzing oscillation processes in electric arc furnaces.

3.1. Hyperbolic model

In this model, the V - I characteristic of the EAF is taken as a voltage function according to the current V = V (I) as shown in Equation (1).[4,5]

$$V(i) = Vat + (C / D + i) \qquad (1)$$

where i and V are the arc current and voltage of a given phase. In addition, Vat is the magnitude of the voltage at the time of the electrode approach that increases current, which depends on the arc length. Constants C and D are two coefficients that depend on the arc power and the arc current related to the sign of the arc current derivative and they can have different values. Since (1) is similar to the hyperbolic function, it is named the hyperbolic model.

3.2. Exponential model

The V- I characteristic of the electric arc furnace in this model is determined exponentially as follows:[4,5]

$$V(i) = Vat + (1 - e^{i/I_0}) \qquad (2)$$

In the equations describing this model, constant current (I 0) is used to simulate the slope of the positive and negative current, and the exponential function is used to describe the characteristic V - I of the arc. This model can be used in the matter of EAF optimization and reliability.

3.3. Energy conservation model

Because of the importance of the EAF, many characterization models are offered throughout the operation of the equipment. Each model will give a characteristic under different conditions. However, the simulation results of the reference[6] are particularly useful with results that are close to the actual model and can be easily built in other software. Therefore, this model can be applied in research conditions and this result can be used for analysis and evaluation.

We build the dynamic model of the arc according to the differential equations based on the conservation of energy principle.

Equation of the power balance of the arc:

$$p_1 + p_2 = p_3 \qquad (3)$$

Where:

p_1: Capacity to transfer heat from arc furnace to the outside environment.

p_2 : The power inside the arc when the arc energy changes, corresponding to the change in the arc radius.

p_3: Total power when the arc is formed and converted to heat.

Based on formula (3) we see that the cooling effect of the arc furnace depends only on the radius r of the arc. Therefore:

$$p_1 = k_1 r^n \qquad (4)$$

This effect is, in fact, related to the temperature of the arc, so this dependency is considered negligible for the simplification of the model. Hence the radius of the arc is treated as a state variable. If the arc surroundings are hot, cooling the arc can be considered independent of the furnace radius. In this case n = 0. If the ambient is not hot and the furnace arc is considered to be long then cooling is primarily its side surface and n = 1. If the arc radius is short then n = 2. [7]

The power component is proportional to the derivative of the energy within the arc radius.

$$p_2 = k_2 r \frac{dr}{dt} \qquad (5)$$

From there we have the final formula for the total capacity:

$$p_3 = vi = \frac{k_3 / r^m}{r^2} i^2 \qquad (6)$$

In this equation the resistivity of the arc is assumed to be inversely proportional to where m has a value between 0 and 2. This reflects the fact that the arc inside the furnace can get hotter if the tank radius optical larger.

Replacing these equations with equation 3, we get the differential equation of electric arc furnaces like (7):

$$k_1 r^n + k_2 r \frac{dr}{dt} = \frac{k_3}{r^{m+2}} i^2 \qquad (7)$$

Arc Radius:

$$r = \int \left(\frac{k_3}{k_2} \frac{i^2}{r^{m+3}} - \frac{k_1}{k_2} r^{n-1} \right) dt \qquad (8)$$

We have arc voltage:[6]

$$v = \frac{k_3}{r^{m+2}} i = \mathrm{R.i} \qquad (9)$$

Where: k_1, k_2, k_3, m, n are the constants of the model, r is the radius of the arc in centimeters.

Conceptually, the arc furnace model will simulate the random nature of the arc length. The relationship between the voltage value and the electric arc length is given by (10).[8]

$$e_{arc} = a + bl_{arc} \quad (10)$$

Where :

e_{arc} : is the instantaneous voltage of the arc

a: is a constant with a value of 40V

b: is the amplification factor from 3.9 to 11.8V

l_{arc} : is arc length

4. MODEL OF ELECTRIC ARC FURNACE SYSTEM

The schematic diagram of the power supply to the EAF is illustrated in Figure 3. In this figure, node 3 (PCC) is the low-voltage busbar that powers the arc furnace and other equipment in the system. To change the active input power of the EAF, we use transformer T_F, (MV / LV). This transformer is equipped with a converter located on the secondary winding so that it is possible to change the voltage of the furnace. In this figure, X_n is the supply reactance and Z_{dz} is the impedance of the cable connected to the transformer TF. The model parameters are shown in Table 1.

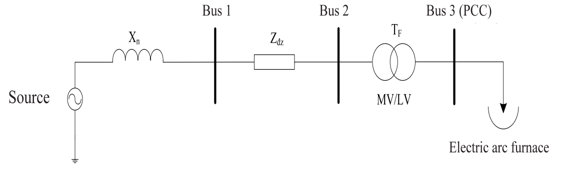

Figure 3. The schematic of the EAF connected to the electrical system

Table 1. Parameter schematic EAF connected to electrical system

Device	Parameter
Source	U = 22 kV; f = 50 Hz; S_{cb} = 100 MVA, X_n = 3 Ω
Line	R = 0,783 Ω/m; X_L = 3,9226 Ω/m; X_C = 4,08 MΩ.m, L = 10 km
Transformer T_F	S_{dm} = 25 MVA; U_1 = 22 kV; U_2 = 0,4 kV; Y/Δ; X = 0,0636pu; X_{st} = 0,2pu; I_o = 0,4%
Electric arc furnace	k_1 = 2.600, k_2 = 0,5, k_3 = 30 [9]

Based on equations (4) to (10) and parameters in Table 1, building the model in Pscad software, we have the results as shown in Figure 4.

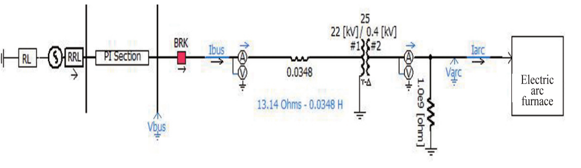

Figure 4. Circuit diagram of electric arc furnace in Pscad software

5. SIMULATION RESULTS

5.1. No voltage fluctuation

The arc furnace model in the paper is generally built as a symmetric three-phase model. For viewing convenience, the selected EAF voltage, current and V-I characteristic values are displayed per phase. From the Formulas (7), (8), (9), after running the simulation, we have arc properties as shown in Figure 5.

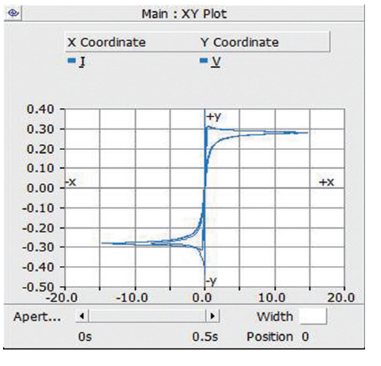

Figure 5. Features V - I electric arc furnace

Figure 6 shows the results of current, voltage and arc resistance corresponding to the model.

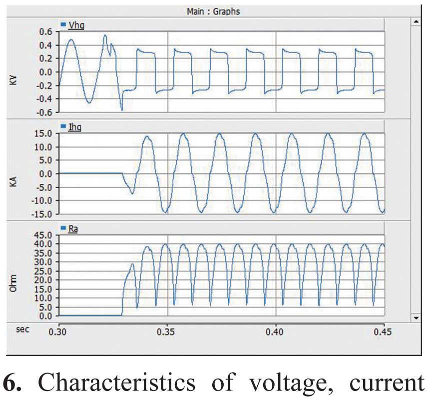

Figure 6. Characteristics of voltage, current and electric arc furnace resistance

The arc voltage has a waveform similar to the square pulse and the current is shaped like a sine wave, but it includes the harmonic components. As shown in Figure 7, the harmonic composition consists of the 1st fundamental harmonic and components Level 3, 5, 7. It has been shown that the model has reflected in detail the properties of electric arc furnaces and it can be used for simulation in the three-phase case.

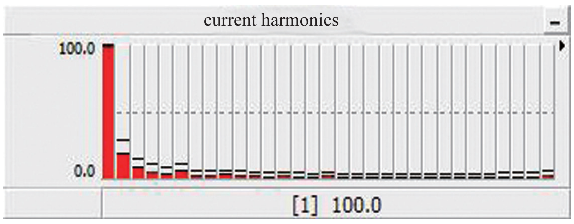

Figure 7. Current harmonic order

With the value of current and arc power, we have the results of active and reactive power as shown in Figure 8. Based on the simulation results, we can see that the arc furnace both consumes active and reactive power. From equation 8, we see that the arc radius depends on the coefficients k_1, k_2, k_3. And when these coefficients change, the active and reactive power will change as shown in Figure 9.

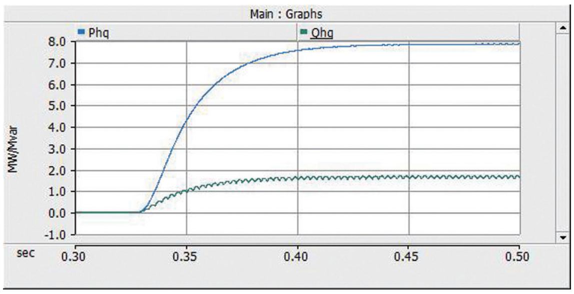

Figure 8. Active and reactive power of electric arc furnaces

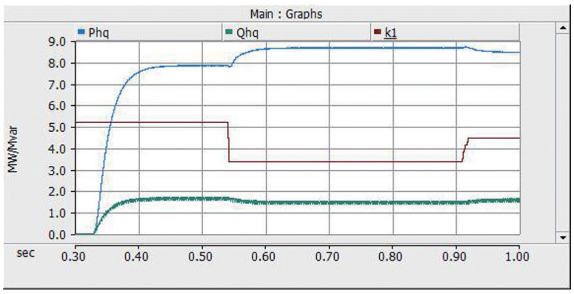

Figure 9. Change the active and reactive power of the electric arc furnace according to the k_1 value

The arc furnace voltage has a square pulse shape, but the voltage on the primary side of transformer TF has a near-sine waveform as shown in Figure 10 and it contains the 3rd, 5th, and 7th harmonic components as shown in Figure 11.

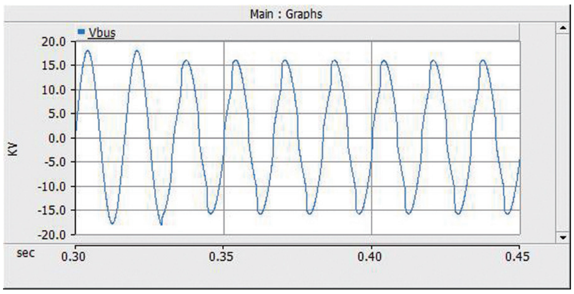

Figure 10. The voltage characteristic on the primary side of transformer T_F

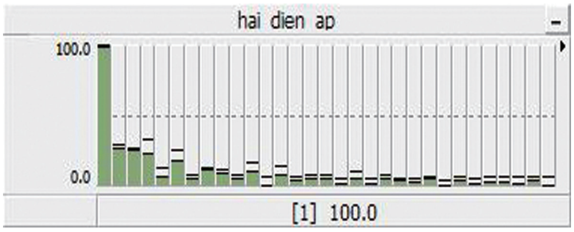

Figure 11. Voltage harmonic order

5.2. Parameter change in electric arc furnace model

We know that arc furnaces' capacity in fact depends on their size. However, to serve the research and simulation process, from Equation (7) we see that the arc furnace capacity is related to the coefficients k_1, k_2, k_3. With k_1, k_2 is constant related to the heat transfer capacity from the arc furnace to the outside environment and the power of the change in arc energy in the furnace. When these values change, the furnace parameters such as voltage, current, and capacity will be affected.

We will examine two change cases k_1 and k_2 starting the simulation with the values $k_1 = 1000$, $k_2 = 0.5$, $k_3 = 30$ and then making incremental adjustment k_1 with the values: 2.000, 3.000, 4.000, 5.000. For easy assessment, ki's impression rate is 1/500 and Vhq_A's impression rate is increased by 10 times. We have the result as shown in Figure 12.

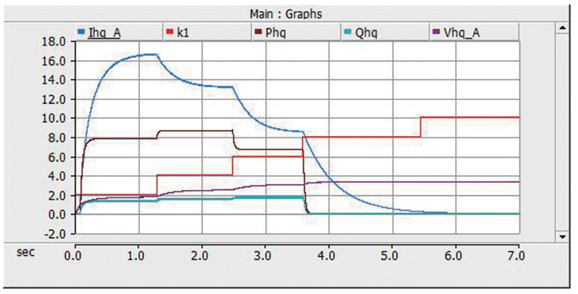

Figure 12. The influence of k_1 on EAF parameters

Based on the graph in Figure 12 we see that when k_1 increases from 1.000 to 3.000 current and active power will decrease. Meanwhile the arc voltage and reactive power will increase. However, when k_1 increases to a value greater than 3.000, the arc voltage will not increase but it remain at a constant value and the active power, reactive power and current will decrease to a very small value.

Similar to k_2, we also start the simulation with k_1 = 2.600, k_2 = 0.5, k_3 = 30 then let k_2 increase with different levels and we have the results as shown in Figure 13.

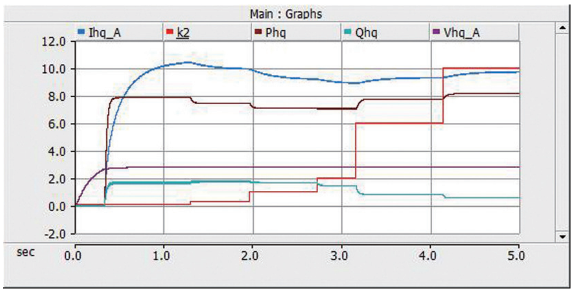

Figure 13. The influence of k_2 on EAF parameters

When k2 increases from 0.5 to 2, current and power will decrease, but when k_2 is greater than 6, active current and power tend to increase again and reactive power continues to decrease. During the k_2 increase, the arc voltage does not change.

5.3. Voltage fluctuations

One of the most common negative effects an arc furnace causes is voltage flicker or flicker. Flicker is caused by rapid change in the load side, namely the operating characteristics of the arc furnace. During the arc furnace operation, the electrodes are short-circuited and generate an extremely large peak current, which then flows into the distribution system and causes extremely rapid fluctuations and voltage instability.

Follow Equation (10) changing the arc length will cause voltage fluctuation. The change of parameter r will affect the parameters during the simulation. The amplitude of r will be adjusted to a sinusoidal signal combined with the noise we can tune. After r changes, the arc voltage value will be recalculated and fed into the system.

* *The oscillating component is cyclic*

The variation of the parameters in the model will depend on the sinusoidal signal as shown in Equation (11).

$$r_s = r.\left[1 + m_s.\sin(\omega t)\right] \tag{11}$$

Where :

m_s : Range of oscillation.

ω : Vibration frequency.

* *Random oscillation*

The model reflects the random change of the arc length close to the Gaussian change due to the fact that metal materials contained in the arc furnace are considered to be randomized even if melting is considered metal caused by the electrode.

Hence a random signal characterizing this arrangement will be used to adjust the amplitude of the arc radius obtained from Equation (12) based on (11)

$$r_g = r_s.\left[1 + m_g.g_n\right] \tag{12}$$

This randomized signal has a Gausser distribution of g_n and an amplitude of m_g. After running the simulation, we get the results of voltage fluctuations according to the cyclical component (Figure 14), and the case of the periodic oscillation with random oscillation (Figure 15).

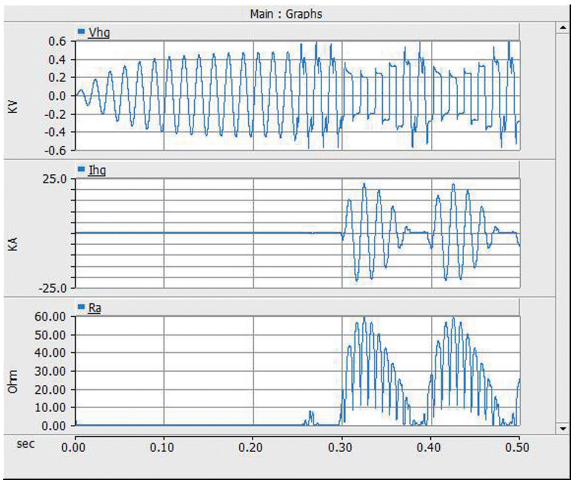

Figure 14. Characteristics of voltage, current and electric arc furnace resistance when the arc radius oscillates are in a sinusoidal cycle

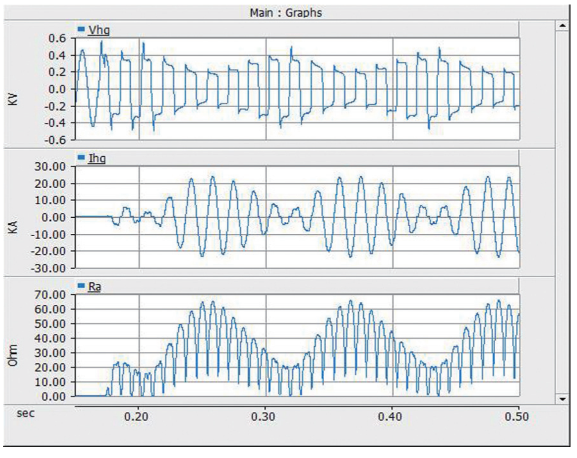

Figure 15. Electric arc furnace voltage, current and resistance characteristics when the arc radius oscillates are in a sinusoidal cycle combined with random oscillation

This change in arc radius also causes voltage and current at the connection point to fluctuate as well. As shown in Figures 16 and 17.

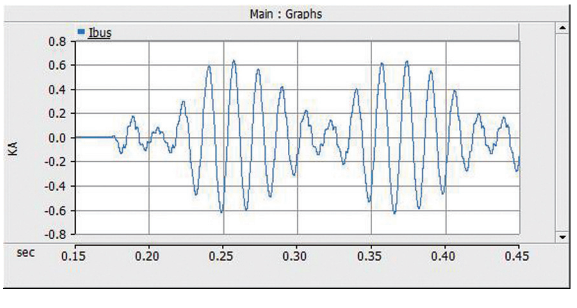

Figure 16. Current characteristics of the primary side transformer when fluctuating voltage

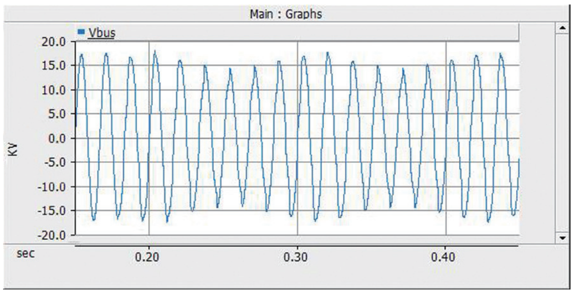

Figure 17. Current characteristics of the primary side transformer when fluctuating voltage

From the simulation results of current and voltage at the connection point as shown in Table 2, we see that the power quality is greatly affected, the voltage THD value difference is about 1,248. THD value of current has a large change about 8.6325. This will affect other devices that connect to this PCC point and cause them to fail quickly.

Table 2. Harmonics results in normal operating state and voltage fluctuation

THD	Normal operating status	Voltage fluctuation	THD value changes with voltage fluctuation
Voltage	51.6088	52.856	1,248
Electric	23.63	32.2652	8,6325

6. CONCLUSION

From the simulation results, it was shown that the operation states of the photovoltaic furnace are based on power balance and voltage fluctuation when the arc radius changes.

In the normal operating state, the electric arc furnace both consumes active and reactive power, and harmonic components when the furnace is operating are also brought to the grid. These values will be large when the arc radius changes, causing voltage fluctuations.

To improve the power quality of electric arc furnaces we can use passive, active filters at low voltage levels such as 22, 0.4 kV and use SVC at higher voltage levels.

REFERENCES

1. P. V. Choi, B. T. Huu, N. T. Ton. *Electrical Instruments*, Scientific and technical publishing, 2006.
2. P. E. King, T. L. Ochs, A. D. Hartman. Chaotic Responses in Electric Arc Furnace, *Journal of Appied. Physics*, **1994**, *76* (4), 2059-2065.
3. R. Horton, T. Haskew and R. F. Burch. A time domain AC electric arcfurnace model for flicker planning studies, *IEEE Trans. power delivery*, **2009**, *24*, 1450-1457.
4. Golkar, M. A., M. Tavakoli Bina, and S. Meschi. A novel method of electrical arc furnace modeling for flicker study, *In International conference on renewable energies and power quality*, 2007, 1-8.
5. D. C. Bhonsle and R. B. Kelkar. Simulation of electric arc furnace characteristics for voltage flicker study using matlab, *2011 International conference on recent advancements in electrical, electronics and control engineering*, IEEE, **2011**, 174-181.
6. Hariyanto, Nanang, and M. Nurdin. Characteristic study of three-phase AC electric arc furnace model, *The 2nd IEEE conference on power engineering and renewable energy (ICPERE) 2014,* IEEE, 2014.
7. E. Acha, A. Semlyen, and N. Rajakovic. A harmonic domain computational package for nonlinear problems and its application to electric arcs, *IEEE transactions on power delivery* 5.3, **1990**, 1390-1397.
8. Paschkis, Victor, and J. Persson. *Industrial electric furnaces and appliances*, Interscience Publishers, 1960.
9. Kashani, M. Ghapandar, S. Babaei, and S. Bhattacharya. SVC and STATCOM application in Electric Arc Furnace efficiency improvement, *2013 4th IEEE International symposium on power electronics for distributed generation systems (PEDG),* IEEE, 2013.