A NOVEL AC ELECTRIC ARC FURNACE MODEL AND SIMULATION FOR POWER QUALITY STUDY

[1]DUAN XU, [2]YANG YONGMING

[1]Ph.D candidate, State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing, 400030, China

[2]Prof., State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing, 400030, China

E-mail: [1]dx_196710@sina.com, [2]yangyym@cqu.edu.cn

ABSTRACT

In this paper, we study the establishment of AC electric arc furnace model via chaotic circuit. First, the static model based on energy conservation theory is established. Then, a dynamic model based on static model created previous is built to simulate AC electric arc furnace dynamic characteristics. Chua's chaotic circuit is selected to generate modulation wave. The results obtained by using the proposed model are compared with measurements. The comparison indicates a relatively good correlation between our model and the experimental data.

Key words: *AC electric arc furnace model, chaotic, Chua's circuit, power quality*

1. INTRODUCTION

The steel production of electric arc furnace (EAF) occupies more and more proportion in the total steel output of major industrial countries. The current EAF steel production has accounted for more than 30% of world steel production [1]. With the improvement of EAF equipment and smelting technology, the cost of EAF steelmaking continues to decline.

Accurate description of the EAF model has significant meaning in enhancing power quality. As a heavy load, EAF may cause various power quality problems, such as reactive power impact, three-phase voltage unbalance, and harmonic power, etc [2]-[4]. These effects may happen in every smelting process including solid materials melting period, oxidation period, and reduction period. The development of intelligent grid researches has the potential to enhance power quality [5]. EAF is a typical highly non-liner load, not only it would bring voltage fluctuation within frequency band of 0.1~30Hz, as a strong harmonic current source it would also cause voltage distortion which may increase the probability of grid voltage resonance accident.

A precise EAF model will benefit both grid harmonic analysis and power quality study as well as researches on corresponding suppression measures. Research efforts have been made to simulate EAF features so far and many mathematic and simulation models have already been established. The early EAF models are mainly based on stochastic theory due to their highly time-varying and random features. The band-pass white noise modulation of arc voltage is a common EAF model. White noise is superimposed on arc length or arc voltage, which is obtained according to either the principle of conservation of energy or the empirical formulas of arcing process, to simulate its random time-varying feature in [6]-[7].

In recent years, chaotic characteristics have been found in the EAF voltage fluctuation [8], which leads directly to another EAF modeling method. EAF load operating characteristics are described with chaotic dynamics by O'Neill-Corrillo E for the first time, in which a time-domain Lorenz system is applied. A macro output voltage model of EAF is obtained through integrating a modulation circuit which is a low-frequency chaotic signal circuit with an arc radius equation circuit.

Some scholars have pointed out that, compared to the early EAF models using white noise as modulation wave, the models based on chaos theory better describe the essential characteristics of EAF [9]. A new EAF model based on chaos theory is presented in this paper. Symmetric double-scroll chaotic attractors generated by Chua's circuit are used in the model. Simulation results of power quality problems such as harmonic and voltage fluctuation, voltage flicker have demonstrated a

high level match with results gathered in steel plants.

In this paper, the mathematical model and the simulation model of EAF, as well as the simulation test system are presented in section 2. Analysis and comparison of the simulation results and the actual statistic data are given in section 3, which proves the validity of the model proposed in this paper. The conclusion is given in the last section of the paper.

2. MODELING METHOD

2.1 AC Electric arc Furnace Mathematical Model.

According to the analysis in [7], the EAF arc energy equation which describes the relationship of arc current and arc radius is

$$k_1 r^n + k_2 r \frac{dr}{dt} = \frac{k_3}{r^{m+2}} i^2 \qquad (1)$$

where i is the arc current; r is the arc radius; k_1, k_2, k_3, m, n are variables.

When the environment temperature is relatively high, $n=0$; when the arc length is relatively long, $n=1$, while it's short, $n=2$; the value of m varies among range of 0, 1, 2 when arc radius increases; k_1, k_2, k_3 vary according to practical situations.

The relationship between arc voltage and current is described as

$$u = \frac{i}{g} \qquad (2)$$

where g is arc conductivity which is defined as

$$g = \frac{r^{m+2}}{k_3} \qquad (3)$$

With general situations considered, the actual EAF arc length is assumed to be short, thus $n=2$, $m=1$, and (1) can be rewritten as

$$k_1 r^5 + k_2 r^4 \frac{dr}{dt} = k_3 i^2 \qquad (4)$$

The arc radius can be obtained by solving (4)

$$r = \left\{ \left[\int \frac{5k_3}{k_2} e^{5k_1 t/k_2} i^2 dt \right] e^{-k_1 t/k_2} \right\}^{1/5} + C' \qquad (5)$$

where C' is initial value of the arc radius.

Let current be

$$i = I_m \sin(2\pi f t) \qquad (6)$$

Substituting (6) into (5) yields an analytic expression of arc radius within one period

$$r(t) = \left\{ \begin{array}{l} \dfrac{k_3 I_m^2}{2k_1} - \dfrac{k_3 I_m^2}{2\left[k_1^2 + \left(4\pi f k_2/5\right)^2 \right]} \\[3mm] \bullet \left[k_1 \cos 4\pi f t + \dfrac{4\pi f k_2}{5} \sin 4\pi f t \right] + C' e^{-5k_1 t/k_2} \end{array} \right\}^{1/5} \qquad (7)$$

In this paper, the initial value of the arc radius C' is set to 0.5, I_m is the current amplitude, k_1, k_2, k_3 are constant values of 3000, 1, 1.25 respectively.

Since EAF is known as aperiodic, highly time-varying and long-term unpredictable, in order to simulate voltage fluctuation and flicker of EAF, arc parameters used to establish model are determined by chaos modulation signals, thus an equivalent models revealing the stochastic time-varying feature of EAF is obtained. The arc radius is

$$r = r(t) + w_{noise}(t) \qquad (8)$$

2.2 Modeling Principles of EAF.

It's been proved in paper [8] that arc voltage fluctuations have chaotic characteristics, and models based on chaos theory better describe essential characteristics of EAF [9]. In this article, Chua's circuit is used to generate low-frequency chaotic signal to modulate EAF voltage signal and therefore to achieve the purpose of simulating dynamic characteristics of EAF load.

Chua's circuit is one of the simplest non-liner chaotic circuits that generate complex dynamical behaviors based on deterministic equations. The chaotic behavior of Chua's circuit has been strictly proved by the Shil'nikov theorem. The entire process from DC equilibrium to double-scroll chaotic attractor through Hopf bifurcation and period-doubling bifurcation can be observed by changing circuit parameter values. Chaotic signals of different frequencies can be obtained if storage component values of Chua's circuit are changed to the same scale. Thus we can use Chua's circuit to generate chaotic signals of 0.1 ~ 30Hz for the EAF load simulation and to modulate EAF arc voltage signal so as to simulate EAF operation state. This also proves that chaotic phenomenon generated by chaotic Chua's circuit used for simulation of actual chaotic systems is practical.

2.3 Simulation Model of Chua's Circuit.

Schematic diagram of the Chua's circuit is shown in Fig. 1 [10]. The figure includes a linear inductor L, a variable linear resistor R, two linear capacitors C1, C2, and a nonlinear resistor NR, i_L and i_{nr} are the current that goes through L and NR, U_{c1} and U_{c2} are voltage of C1 and C2 respectively, U-I characteristic of the non-linear resistor is shown in Fig. 2.
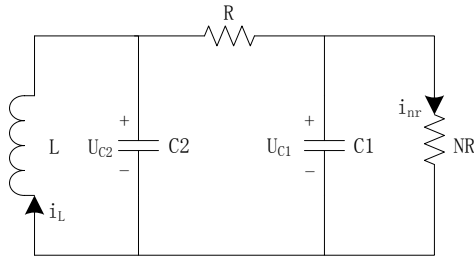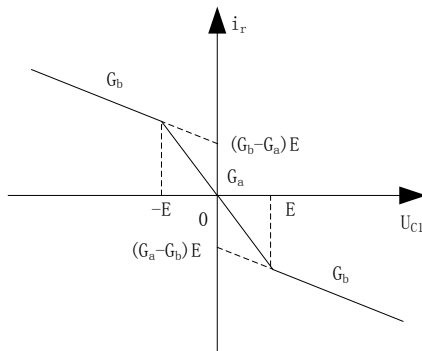

Fig.1 Chua's circuit schematic

Fig.2 Volt-ampere characteristics of nonlinear resistors

G_a and G_b are the slope of lines in the U-I characteristic of the non-linear resistor, E is the inflection voltage. Dynamic state equations of the Chua's circuit can be deduced according to the Kirchhoff's voltage and current law

$$\begin{cases} C_1 \dfrac{du_{C1}}{dt} = \dfrac{1}{R}(u_{C2} - u_{C1}) - g(u_{C1}) \\ C_2 \dfrac{du_{C2}}{dt} = \dfrac{1}{R}(u_{C1} - u_{C2}) + i_L \\ L \dfrac{di_L}{dt} = -u_{C2} \end{cases} \quad (9)$$

where $g(u_{c1})$ is a piecewise linear function

$$g(u_{C1}) = G_b u_{C1} + \frac{1}{2}(G_a - G_b) \times (|u_{C1} + E| - |u_{C1} - E|) \quad (10)$$

For the purpose of convenience, (9) are normalized to

$$x = u_{C1}, y = u_{C2}, z = i_L R, t = C_2 R\tau,$$

$$a = \frac{C_2}{C_1}, b = \frac{C_2 R^2}{L}$$

Then (9) become

$$\begin{cases} \dfrac{dx}{d\tau} = a(-x + y - g(x)) \\ \dfrac{dy}{d\tau} = x - y + z \\ \dfrac{dz}{d\tau} = -by \end{cases} \quad (11)$$

In (11):

$$g(x) = b_1 x + \frac{1}{2}(a_1 - b_1) \times (|x + l| - |x - l|) \quad (12)$$

The dynamic equations of the Chua's circuit are symmetrical about original point. There are three balance points Q1, Q2, Q3 in the circuit when R satisfies certain conditions. R can be changed by adjusting the locations of the system balance points and the system eigenvalues at the balance points. When the circuit balance points are saddle focus equilibrium points which meet certain conditions, the system may generate chaos [11]-[12]. A Matlab simulation of the Chua's circuit is shown in Fig. 3.
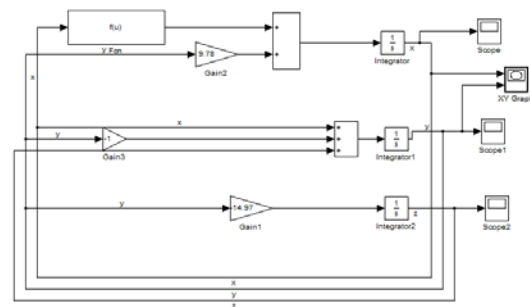

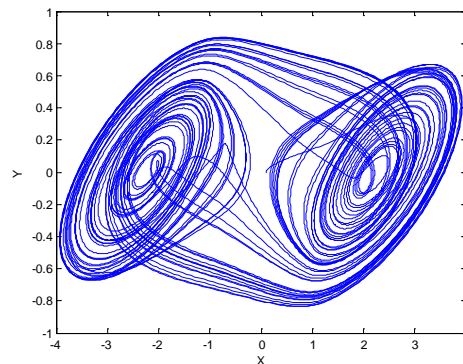*Fig.3 Simulation of the Chua's circuit in Matlab*

Fig.4 Symmetrical double scroll chaotic attractor

Parameters of the Chua's circuit model (11) are a=9.78, b=14.97, and symmetrical double vortex suction Chaos primer is shown in Fig. 4. The output and the spectral distribution U_{c1} are shown in Fig. 5 and Fig. 6 respectively. It can be seen in Fig. 6 that frequencies of the chaotic signal mainly range from 0.1~0.5Hz.
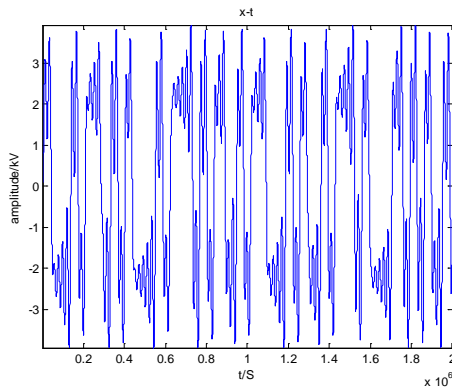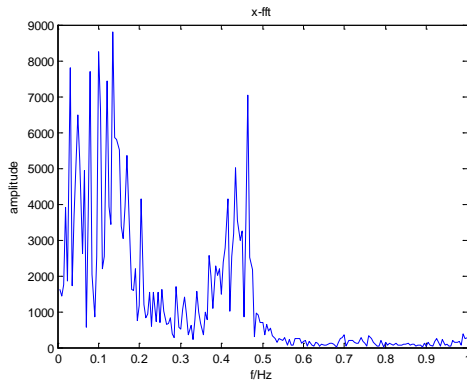

Fig.5 U_{c1} output waveform

Fig.6 U_{c1} spectral distribution

2.4 EAF Simulation Model.

As mentioned in the modeling principle, Chua's chaos circuit is adopted to generate low-frequency signals which serve as modulation waves for the static EAF voltage so as to simulate dynamic characteristics of EAF. The EAF simulation model established in Simulink is shown in Fig. 7. In Fig. 7, in order to realize static EAF simulation, the value of the gain module is set to zero. U-I curve of EAF is shown in Fig. 8.
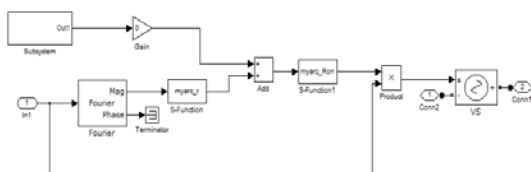

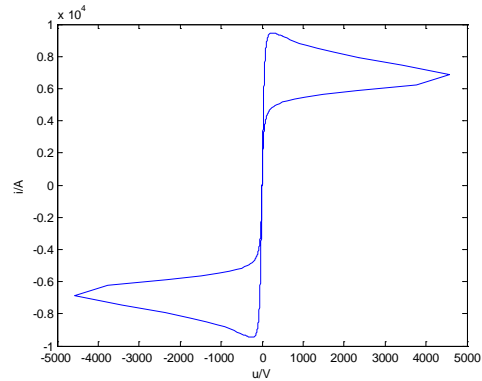*Fig.7 Electrical arc furnace simulation system*

Fig.8 Electric arc furnace U-I curve

2.5 Simulation Test System.

In order to verify the model, a test system is established in the Simulink as shown in Fig. 9 whose system parameters are set according to the practical data coming from a steel plant: AC voltage source amplitude is 50.6kV with a frequency of 50Hz, series resistance of the first side is 0.346Ω, the reactance is 3.077Ω; EAF transformer is rated at 60MVA, rated voltage of the first side is 46kV, winding resistance and inductance per-unit value are 0.002 and 0.55 respectively, the secondary side voltage is 770V, electrical winding and inductance per-unit value are 0.002 and 0.55 respectively.
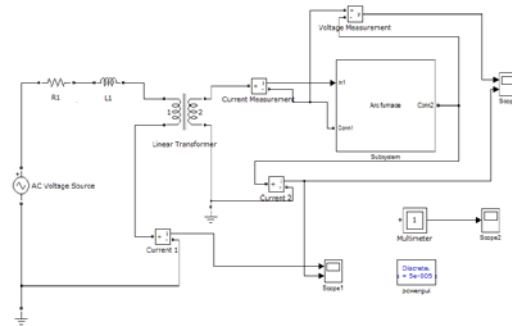

Fig.9 Electric arc furnace test system

3.   SIMULATION RESULTS ANALYSIS

3.1 Static Simulation Analysis.

Static simulation is executed with the EAF test system given in the previous section and the gain module in Fig. 7 is set to zero, whose experimental results include EAF voltage waveform and harmonic analysis as shown in Fig. 10. Through Fourier analysis of the arc voltage within one period, distributions of all the harmonics are obtained and are shown in Fig. 11, which consists mainly of the odd harmonics and matches the results in [13]. While applying this model, asymmetric U-I curves can be used, so that both the

odd and the even harmonics will be included, which is more authentic to practical situations.

proposed model can be applied in the EAF harmonic analysis field of power quality research.
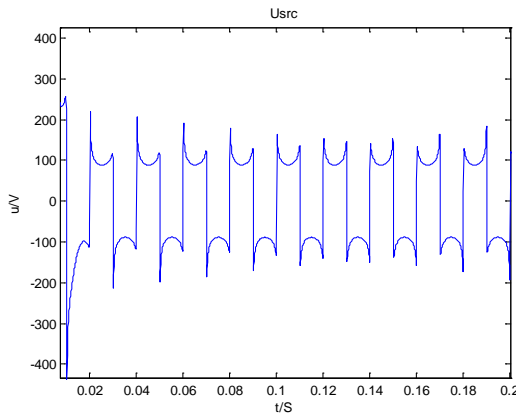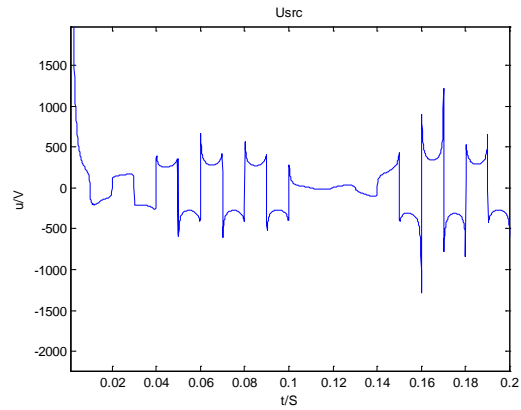

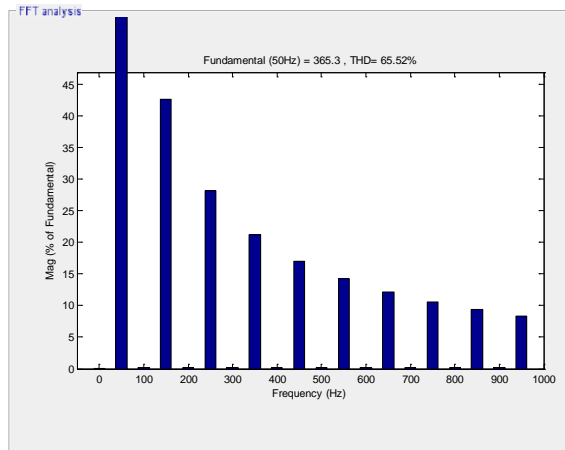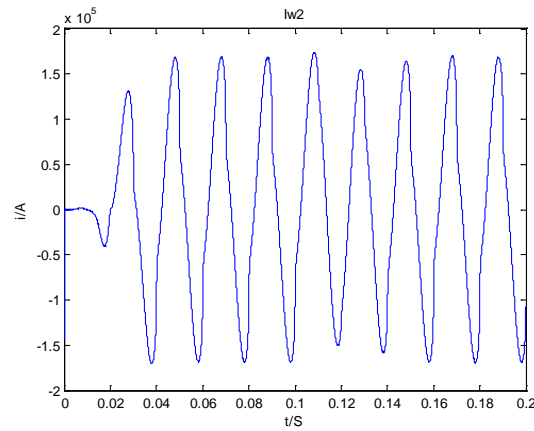*Fig.10 Static electric arc furnace voltage waveform*

(a)

Fig.11 Electric arc furnace voltage harmonic analysis

(b)

Fig.12. (a) Dynamic electric arc furnace voltage waveform,

(b) Dynamic electric arc furnace current waveform

3.2 Dynamic Simulation Analysis.

In order to realize stochastic character simulation or dynamic simulation of EAF, the gain module in Fig. 7 is set to non-zero by accessing chaotic signals to the EAF static model as modulation waves. As mentioned earlier, one of the characteristics of the Chua's circuit is that chaotic signals of different frequencies can be generated by changing values of energy storage component with the same percentage, which makes it possible to implement simulation of EAF caused voltage fluctuation ranging from 0.1~30Hz. The chaotic signals generated in this paper mainly distribute within 0.1-0.5Hz. Dynamic simulation results including the EAF voltage and the current waveforms are shown in Fig. 12. Arc current harmonic content analysis results and actual statistic results are both shown in table 1 [14]-[15]. Through comparison, data simulated from the model matches well with the actual measured values. It is proved that the

Table 1. Arc current harmonic content of dynamic electric arc furnace model

Harmonic Number	Harmonic Content (%)	Actual Statistic Results (%)
1	100	
2	8.68	5~12
3	18.54	6~20
4	4.01	3~7
5	9.56	4~9
6	2.71	1~2

| 7 | 3.32 | 2~4 |

4. CONCLUSION

To summarize, a new application of the Chua's chaotic circuit is put forward to establish the EAF model. Fourier analysis results of the arc voltage generated in the static model show that the harmonic distribution is entirely consistent with the actual situation. Thus accuracy of the static model is proved.

A random chaotic signal generated by the Chua's chaotic circuit is used as modulation wave to complete the simulation. Current and voltage wave forms and harmonic analysis results simulated from the same dynamic model of EAF are well matched with the experimental results. It proves that the proposed model can accurately describe the power quality problems of the current harmonics caused by EAF, laying foundation for the subsequent studies.

ACKNOWLEDGMENT

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