Development of Enhanced Electric Arc Furnace Models for Transient Analysis

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ABSTRACT

Electric arc furnaces (EAFs) are a main cause of voltage flicker due to the interaction of the high demand currents of the loads with the supply system impedance. In order to adequately understand and analyze the effects on the power system from these loads, obtaining an accurate representation of the characteristics of the loads is crucial. In this paper, a mixed chaotic EAF model to represent the low frequency and high frequency variations of the arc current respectively and a chain-shaped chaotic EAF model to characterize the current variation have been proposed. The concept of chaotic parameters, such as chaotic resistance, inductance or admittance has been also proposed for the characterization of arc furnace operation and the highly nonlinear physical processes. In addition, a DLL--*Dynamic Link Library* module, which is a FORTRAN interface with TACS--*Transient Analysis of Control Systems*, is developed to implement the chaotic load models in the EMTP--*Electromagnetic Transients Program*. The simulation results are presented in comparison with the actual data to illustrate the validity of the models.

Keywords: Chaos, Load modeling, Arc furnace, EMTP, TACS, FORTRAN interface, Flicker, Power quality indices

I. INTRODUCTION

A large amount of steel accounting for 40% of total tonnage in the United States was made in electric arc furnaces (EAFs) [1]. Besides, the power fluctuation of EAFs appears to be of concern in the degradation of the electric power quality of the interconnected system. Because of its severe impact on the power quality problems due to its nonlinear and highly varying characteristics, the dynamic characteristics of EAFs have been a subject of study to provide high quality power to all customers. Even though the EAF has been studied for many years, it is still difficult to obtain a complete representation of such load and its impact on the power system. Some researchers used the stochastic models to represent the operation of the EAF because of the aperiodic, seemingly random behavior of these loads [2-4]. An alternative approach to include the deterministic chaos in the modeling of the EAF [5] was proposed, for chaos has been detected in the arc current. This chaotic model proves to be a better representation of the EAF operation when assessing the impact of the EAF on power systems.

The main purpose of this paper is to develop enhanced chaotic EAF models which have a better representation of the EAF operation when assessing the impact of the EAF on power systems. New chaotic models, such as mixed chaotic model and chain-shaped chaotic model, have been proposed in this paper to serve as the improvements of the model based on the chaos theory. The mixed chaotic model combines both the Lorenz system and the logistic system to represent the low frequency and high frequency components in EAF current, and the chain-shaped chaotic model uses the patterns detected in the EAF current to characterize its variation. In addition, EMTP EAF modules of the proposed models have been developed to simulate the power systems which contains EAFs and it allows to verify the accuracy of the chaos-based models and to illustrate their capabilities.

II. EAF EQUIVALENT SYSTEM

The main discussion in this paper relates to AC electric arc furnaces, although a similar modeling approach is possible for dc furnaces. Electric arc furnace operation may be classified into several stages, depending on the melting status and the time lapse from the initial energization of the unit. During the melting period, sets of steel nearly create a short circuit on the secondary side of the furnace transformer, and it creates large fluctuations of current at low power factors. These current fluctuations cause variations in reactive power, which cause a momentary voltage drop or flicker, both at the supply bus and at nearby buses in the interconnected system. The arc currents are more uniform during the refining period, and result in less impact on the power quality of the system.

A typical and detailed arc furnace structure is shown in Figure 1. It includes a system equivalent at substation bus S, substation transformer T_s, cable run to furnace D_1, power factor correction equipment C, arc furnace transformer T_a, flexible cables D_2, bus conductors B, graphite electrodes G and the melting vessel M.

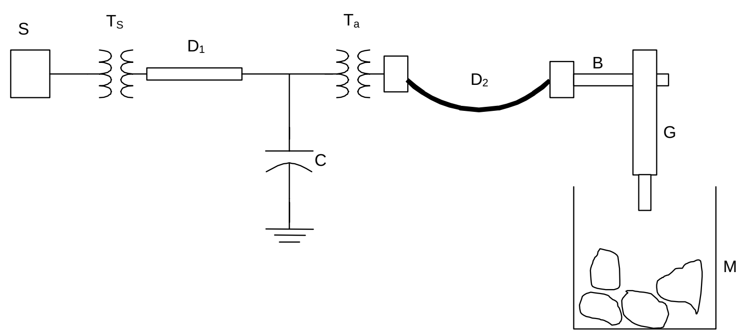

Figure 1 Structure of a Typical Arc Furnace

In order to analyze the arc process and the interaction between the arc furnace and power system, a mathematical simplification of the given system is performed. The simplification in Figure 2 is reasonable because the mechanical process is much slower than the electrical dynamics.

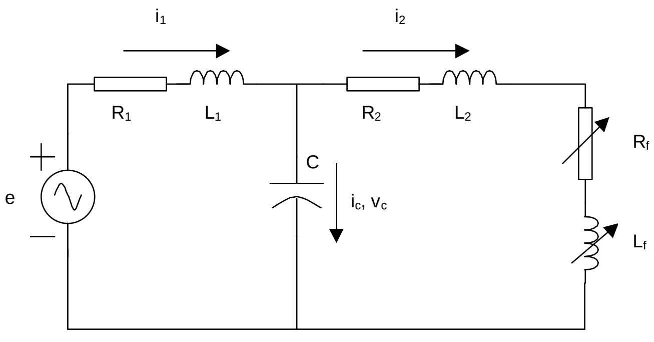

Figure 2 Circuit Representation of the Arc Furnace

In Figure 2, R_1 and L_1 represent the resistance and the reactance of power system at substation level, the substation transformer winding and the cable run to the furnace transformer, and R_2 and L_2 represents the resistance and the reactance of the flexible cables, the bus conductors and the graphite electrodes. The dynamic variation of arc resistance and inductance is represented by R_f and L_f , and both nonlinear variables are time varying and bounded. All the circuit parameters except the R_f and L_f can be obtained from the given conditions.

III. MODELING OF ARC FURNACES USING CHAOS THEORY

The modeling of AC electric arc furnaces has traditionally been done with either fixed circuit elements or fixed elements plus a stochastic component. However, recent tests using actual furnace load data suggest that there may be a chaotic component to the model. The term chaos in this context implies a mathematical property in which the dynamic model is highly sensitive to starting point of the system state vector. If the evolution of an initial state is denoted as X(t), and the evolution from a very nearby initial state is X'(t), then X-X' is found to diverge even if the initial states become close together. Chaotic properties are observed in some physical systems that are nonlinear and high order. There are some tests for chaos, and AC arc furnace data appear to qualify as having a chaotic component. Note that chaos is a deterministic phenomenon -- there is no stochastic element. It is possible that actual EAF load currents have a usual linear and nonlinear component, a chaotic component, and a stochastic component. In this study, focus on the chaotic component is made and found to give reasonable results.

A. Lorenz Model

In references [5,6], evidence of chaotic behavior is shown in the current from an AC EAF. The calculation of the largest Lyapunov exponent of the EAF provides a mathematical support for the modeling of arc furnaces using chaos theory. In the chaotic model in [5], load current data from an EAF is used as inputs to a feed-forward model which is composed of tuning and simulation stages. A time scaled version of the Lorenz system[7] is used to represent the highly varying behavior of the currents in an EAF. The scaled version of the Lorenz system is shown in equation (1). A time scale factor of 30 is needed to model the highly varying load at 60 Hz. The state variables are x, y and z, whereas σ, r and b are constants whose values were initialized as 10, 8/3, and 28 respectively,

$$\begin{aligned} \dot{x} &= 30\sigma(y - x) \\ \dot{y} &= 30x(r - z) - 30y \\ \dot{z} &= 30xy - 30bz \end{aligned} \tag{1}$$

In the Lorenz model, the arc resistance is expressed as below

$$R_f = C_1 x \tag{2}$$

In (2), C_1 is a constant and *x* is one of the state variables. According to [8], the value of arc reactance is proportional to the arc resistance with coefficient α. i.e.

$$L_f = \frac{\alpha R_f}{2\pi f_1} \tag{3}$$

where, f_1 is the network frequency.

Using this Lorenz model together with a typical 50 MVA EAF system [9], the simulation has been performed. The simulated arc current and arc admittance are shown in Figure 3.

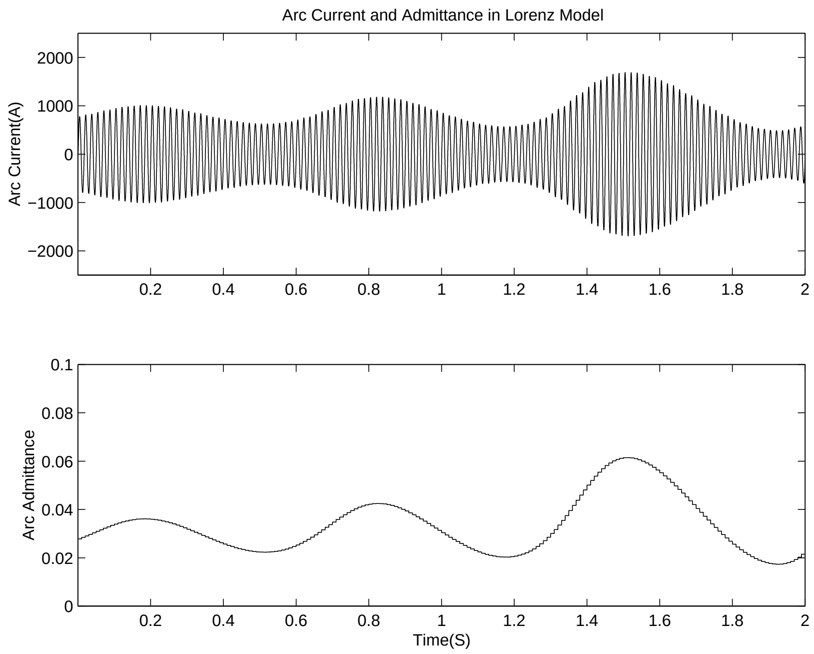

Figure 3 AC Electric Arc Current and Admittance in Lorenz Model

B. Logistic Model

The logistic equation is a classical iterative equation with the appropriate value of parameter k. The formula is rewritten in equation (4).

$$x_{n+1} = k \cdot x_n (1 - x_n) \ \ , \ \ x_0 \in [0 \ , \ 1] \tag{4}$$

Because x_n is a discrete time series with an unknown time step, we could designate different time steps or different chaotic frequencies to characterize the variation of arc admittance Y. Hence, Y consists of the summation of the time series from the logistic equation with different chaotic frequencies.

$$Y_f = a_1 X_{1f} + a_2 X_{2f} + a_3 X_{3f} + \ldots \tag{5}$$

where, X_{1f} , X_{2f}, X_{3f}, … represent the time series with different chaotic frequencies like 30Hz, 60Hz, 120Hz and so on.

Therefore, the arc admittance corresponding to different harmonic components can be represented by this model. Figure 4 shows the simulated arc current, arc admittance and arc voltage using this model.

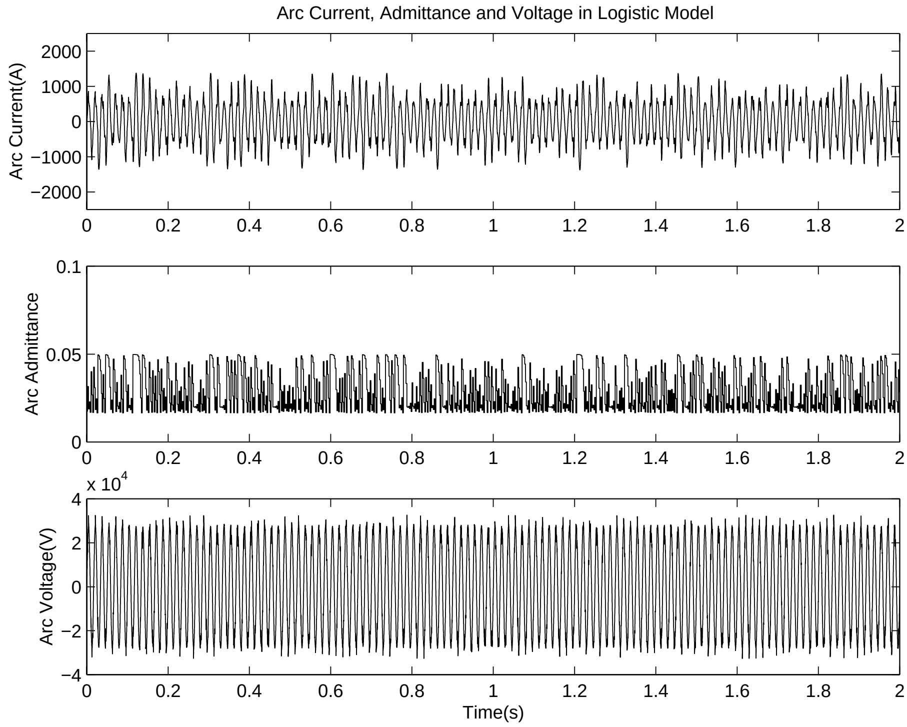

Figure 4 Simulated Arc Furnace Current, Arc Admittance and Arc Voltage using Logistic Model

This model covers the characteristics of the high frequency behavior of an EAF like the harmonics. The voltage drop on the transformer winding impedance is caused by the nonlinear variation of the arc resistance and inductance. Largely the voltage drop due to the winding inductance is caused by the erratic arc current variation.

C. Mixed Chaotic Models

A mixed chaotic model is proposed to represent the dynamic characteristics of EAFs in wide frequency ranges. As in equation (6), the Lorenz contributes to the low frequency components of arc current and the logistic system to the high frequency components.

$$\begin{aligned} Y_f &= Y_0 + C_1 Y_{lorenz} + C_2 Y_{\mathrm{log}istic} \\ Y_0 &= 0.005, C_1 = 0.003, C_2 = 0.02 \end{aligned} \tag{6}$$

In (6), Y_0 is fixed admittance, and Y_f represents the total admittance of the arc furnace. C_1 and C_2 are constants, depending on the historical data and scaling of both systems. Y_{lorenz} represents the contribution of admittance from the Lorenz system. $Y_{logistic}$ represents the contribution of admittance from the logistic equation. These parameters can be optimized and tuned to further characterize the operation of the arc furnace. Figure 4 shows the procedure to develop the proposed model. The simulated arc current and voltage in the test system [9] are shown in

Figure 5

~~Figure 5~~. The power quality indices are calculated from the simulated waveforms and compared with those from the actual waveforms in Table 1. Clearly we can see they are matched very well through the comparison with the actual power quality indices.

Table 1 Power Quality Indices in the Mixed Chaotic Model

Power Quality Indices	Simulated Data	Min	Max	Average
THD	0.037378	0.029583	0.061930	0.044522
K-Factor	1.021513	1.008624	1.073438	1.034753
Crest Factor	2.888085	2.496126	3.146561	2.824822
Zero-Peak Flicker Factor	1.176755	0.907654	1.534109	1.291042
RMS Flicker Factor	0.047134	0.039731	0.112681	0.077426

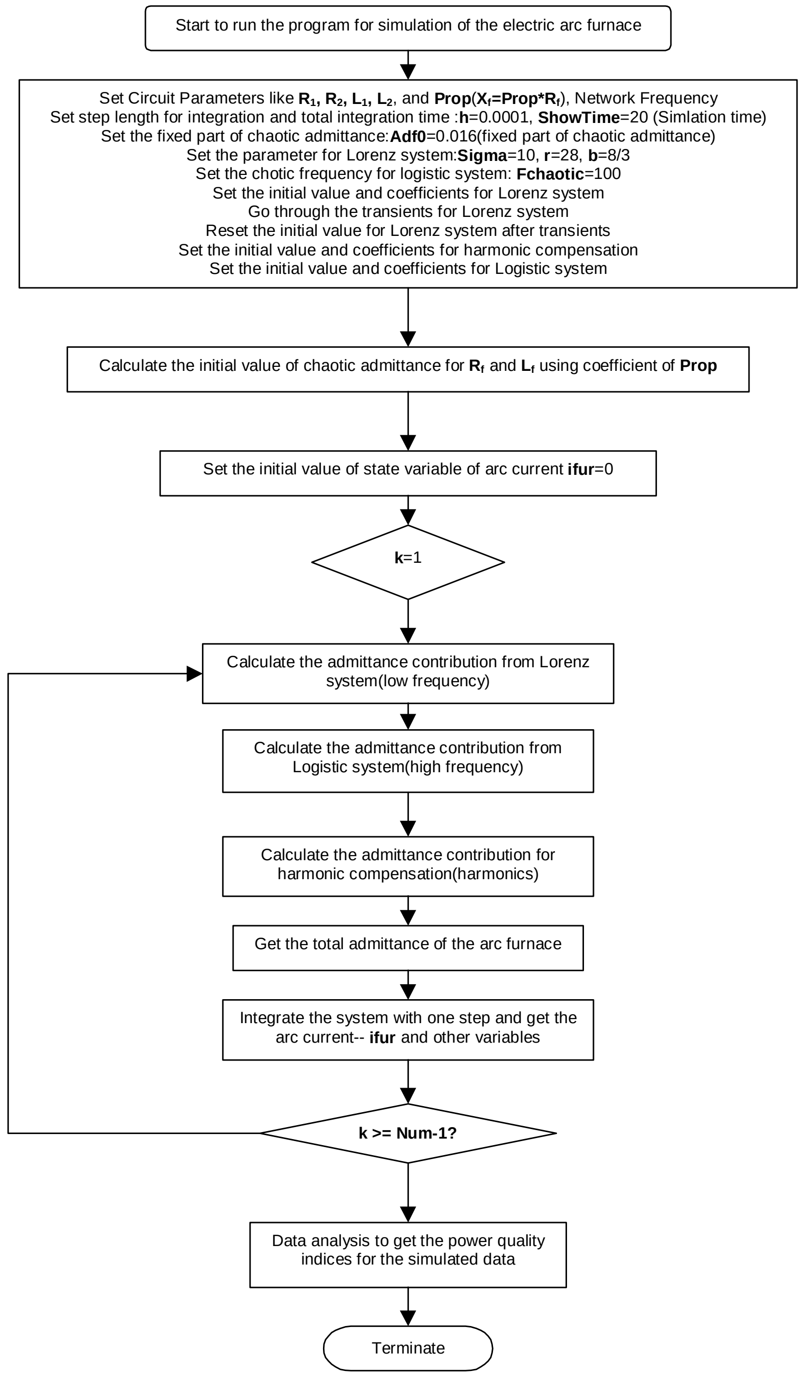

Figure 4 Flow Chart of the Mixed Chaotic Model

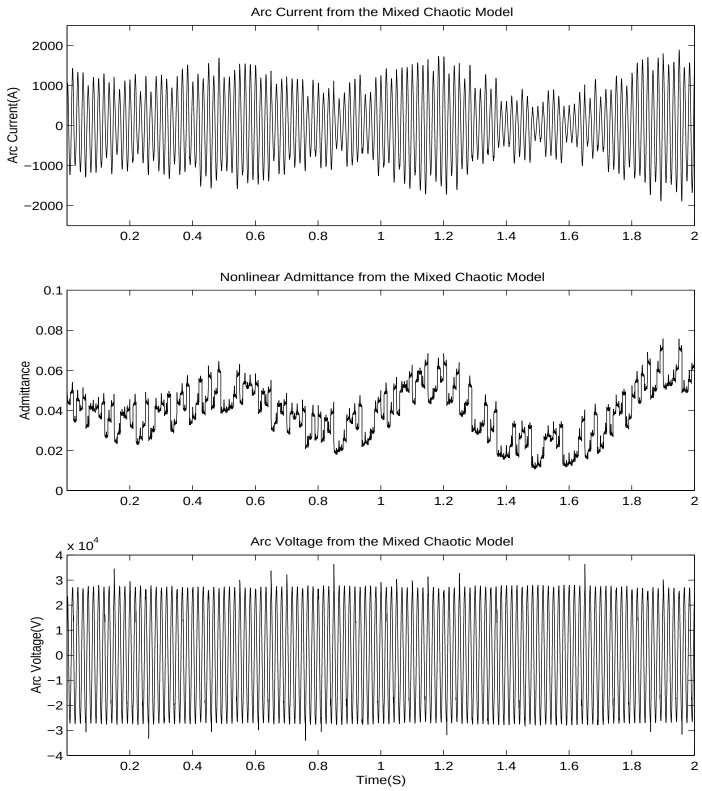

Figure 5 Simulated Arc Current, Admittance and Bus Voltage According to the Mixed Chaotic Model

D. Chain-Shaped Chaotic Model

A pattern, chain-shaped envelope pattern, is detected from a typical EAF, and it can be identified in Figure 6 and 7 in which some sample waveforms together with their tuned waveforms are shown. It is just like someone's drawing which is composed of a lot of sinusoidal arcs (not the physical arc) with different length, magnitude, angle and frequencies. With the following assumptions, the chain-shaped chaotic model to represent this pattern can be developed.

- The length of the arc varies chaotically
- The magnitude of the arc varies randomly
- The angle of the arc keeps constant
- The frequency of the sinusoidal arc varies chaotically with logistic equation

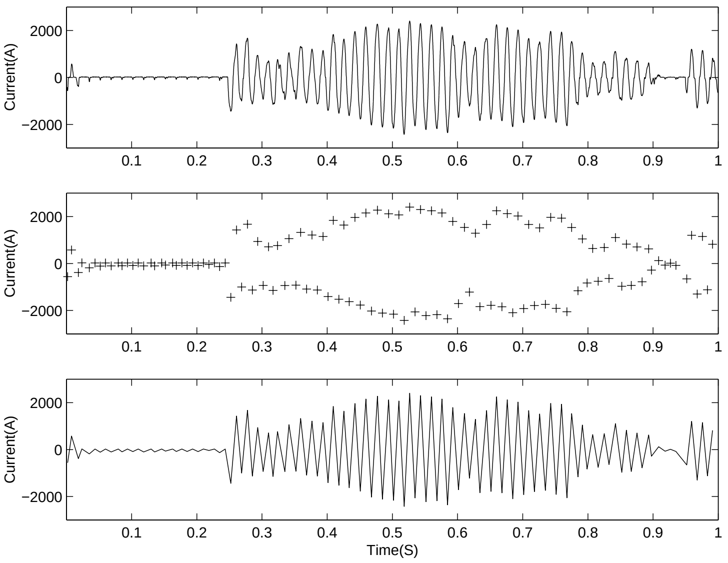

Figure 6 Tuned Arc Current Waveforms-Sample A (first 1 second)

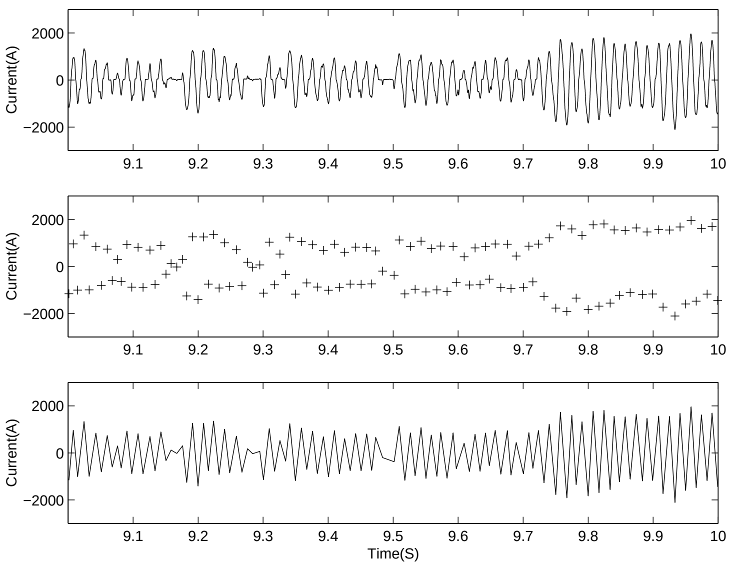

Figure 7 Tuned Arc Current Waveforms—Sample B (between 9 and 10 seconds)

The arc admittance from this model can be expressed as follows.

$$
\begin{aligned}
&Y_f = Y_0 + Y_{\sin arc} + a_1 Y_{1f} + a_2 Y_{2f} + a_3 Y_{3f} + \ldots \\
&Y_0 = 0.004, a_1 = 0.001, a_2 = 0.001, a_3 = 0.0003, \\
&\qquad a_4 = 0.001, a_5 = 0.0003, a_5 = 0.001
\end{aligned} \tag{7}
$$

In (7), Y_{1f}, Y_{2f}, etc. are chaotic time series generated from the logistic equation with different time steps and initial values, and $a_{1,}$ a_2, etc. are scaling constants. Y_0 is a constant which can characterize the minimum variation of arc admittance. Y_{sinarc} is given by

$$
\begin{aligned}
&Y_{\sin arc} = Y_M \sin(\omega t + \theta_0) \\
&Y_{M0} = 0.5, \theta_0 = 0
\end{aligned} \tag{8}
$$

Here Y_M is the magnitude of the sinusoidal arc, θ_0 is the initial angle of the sinusoidal arc served as the low frequency envelope, and ω is the frequency governed by the logistic equation. The outcome of this simulation model is promising in characterizing the general behavior of the arc furnace. The procedure for developing this model is illustrated in Figure 8. The simulation results using this model are shown in Figure 9 and Table 3. The power quality indices derived from the simulated arc current matched well with those from the actual data. As seen from Table 1 and Table 2, the chain-shaped chaotic model has better results than the mixed chaotic model in terms of power quality indices. Hence, the chain-shaped chaotic model is suitable to characterize the general behavior of the electric arc furnace operation.

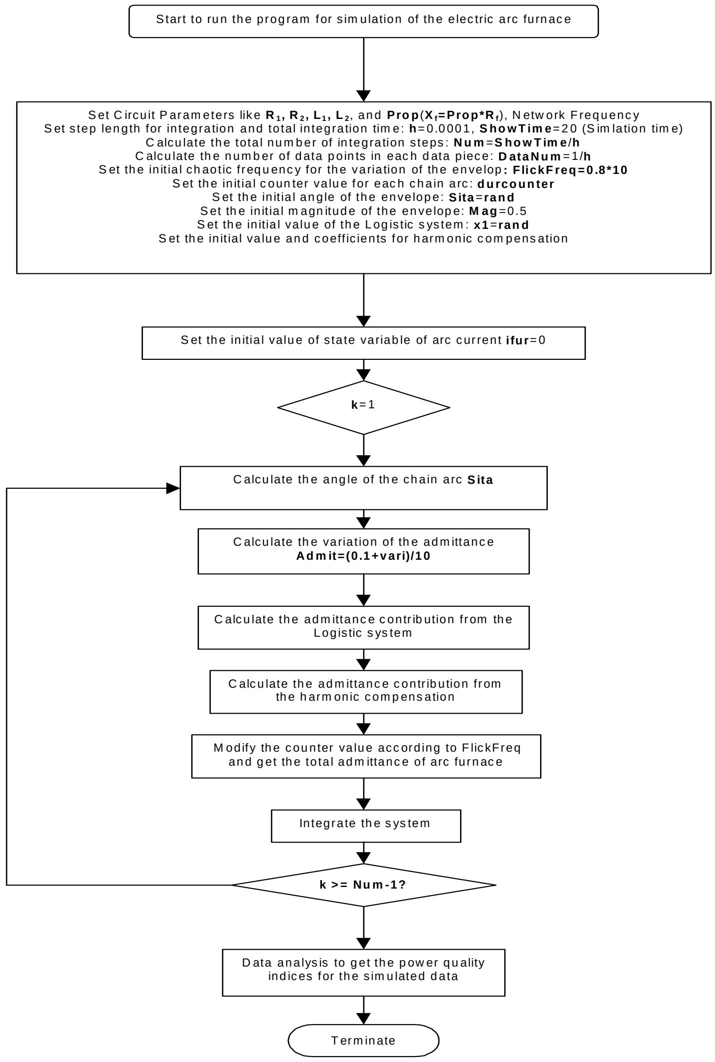

Figure 8 Flowchart for the Chain-shaped Chaotic Model

Table 2 Power Quality Indices from the Chain-shaped Chaotic Model

Power Quality Indices	Simulated Data	Min	Max	Average
THD	0.035140	0.029583	0.061930	0.044522
K-Factor	1.016711	1.008624	1.073438	1.034753
Crest Factor	2.786330	2.496126	3.146561	2.824822
Zero-Peak Flicker Factor	1.118353	0.907654	1.534109	1.291042
RMS Flicker Factor	0.067070	0.039731	0.112681	0.077426

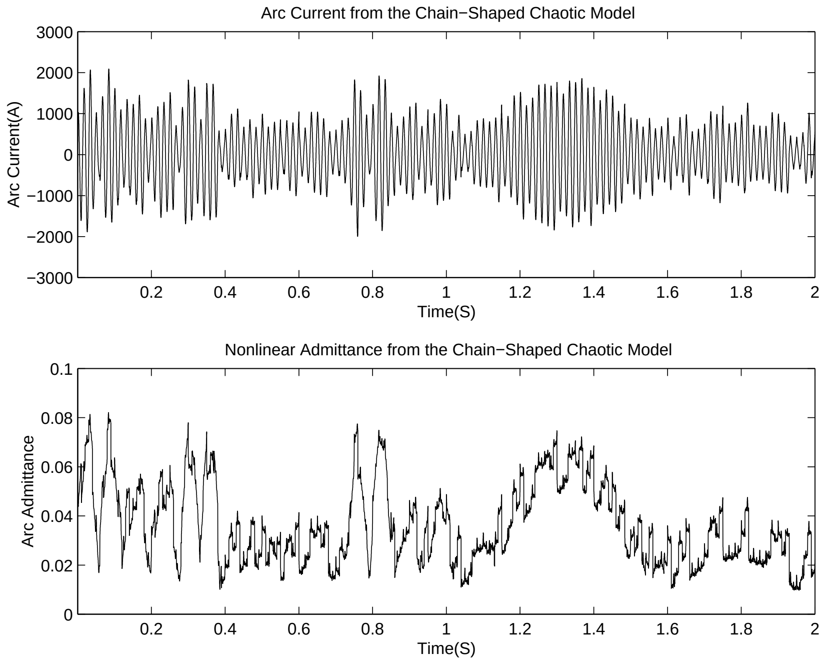

Figure 9 Simulated Arc Current from the Chain-Shaped Chaotic Model

E. Development of an EAF EMTP Model

The Electromagnetic Transients Program (EMTP) is a computer program for simulating electromagnetic, electromechanical, and control system transients on multiphase electric power systems. The basis of the software is the companion circuit method. EMTP is used to solve the ordinary differential and/or algebraic equations associated with an "arbitrary" interconnection of different electric power system and control system components [10]. The chaos-based load models for EAFs are developed in FORTRAN. Since the developed model involves two different processes for the tuning and simulation, it can not be regarded as the typical nonlinear element in the EMTP. In order to implement the model for the study on system performance and design into the EMTP, a FORTRAN interface is used with TACS in the EMTP. In the interface, the EAF model is treated as a user-defined EMTP source in order to pass its current to TACS and the electrical network treats this user-defined source as an independent current source. For detailed information about using the EMTP source, please refer to EMTP rulebook [11]. The mechanism of interaction among the EAF model, TACS and EMTP network is shown in Figure 10. Once the user-supplied input variables have been transferred to the EAF model, the model performs the tuning and simulation in its own subroutines and the output of the model is sent to TACS through the interface at each time step. Then, TACS passes the data to electrical network defined in EMTP. Finally, the EMTP simulates the electrical network using the data from TACS. Nonlinear analysis and chaos theory are used to model the arc currents in an EAF. At the same time, a DLL module, which is a FORTRAN interface with TACS is developed to implement the chaotic load model in the EMTP. The simulation results to illustrate the validity of this model were produced using the EAF EMTP module. The EAF EMTP module will be used for the proper assessment of the power quality impact, and the performance of control devices on power distribution systems.

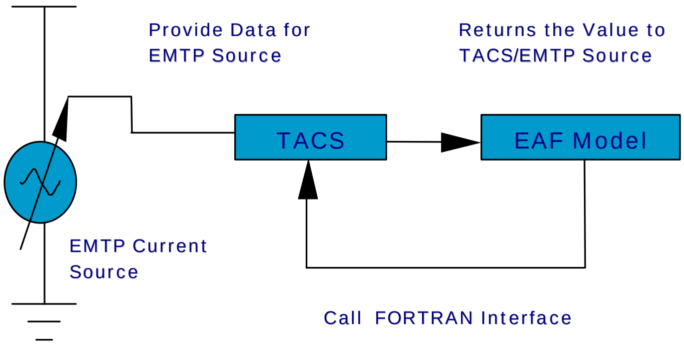

Figure 10 Use of TACS-EMTP Source

IV. CONCLUSIONS AND FUTURE WORK

In this paper, different chaotic models are proposed to predict the general behavior of the arc furnace operation. In the mixed EAF chaotic model proposed in this paper, the logistic system is added to make better representation of high frequency components in the electric arc current to the EAF chaotic model based on the Lorenz system. This model is useful when assessing the harmonic property of EAFs. An argument, and evidence is presented for the detection of chaos in electric arc furnace loads. Chain-shaped chaotic model mathematically interpret the low frequency variation of the arc current, and the simulation results showed the model is suitable to represent the general behavior of the EAFs. A FORTRAN interface with EMTP/TACS has been developed to implement the chaotic load models, by which EMTP simulation results have been presented to compare with the actual data to illustrate the validity of the models. Simulation results show that the mixed chaotic model and chain-shaped chaotic model appropriately characterize the behavior of the arc furnace operation in the sense of power quality indices and other criteria presented, and the EMTP module together with the chaotic EAF models can be used for the proper assessment of the power quality impact on power distribution systems with and without compensation devices.

Although electric arc furnace loads are typically isolated from the distribution system and subtransmission supply through transformer reactance and filtered with simple tuned filters, the nonsinusoidal current can not be effectively attenuated by the fixed and passive devices. Having obtained the model for the furnace, it may be utilized to assess the impact of an existing load in the system, and to find ways of reducing such impact. The model can also be used for planning purposes, e.g. to study the impact of a proposed installation in a power system. Although the focus of this paper is on AC electric arc furnaces, the results apply to certain nonlinear loads that behave similarly, such as plasma torches and arc weldersIn light of the patterns detected in the EAF current, neural networks could be used to train the system which governs the variation of arc admittance and thereof to predict the arc current based on the history input data. Such a system should have the function of identifying the different melting phases (different variation style of arc current) and come up with reasonable neural network parameters.

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