과도현상 해석을 위한 EAFs 부하 모델의 개발

論 文
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An Electric Arc Furnaces Load Model for Transient Analysis

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Abstract - Electric arc furnaces (EAFs) use bulk electrical energy to create heat in metal refining industries. The electric arc process is a main cause of the degradation of the electric power quality such as voltage flicker due to the interaction of the high demand currents of the load with the supply system impedance. The stochastic models have described the aperiodic physical phenomena of EAFs. An alternative approach is to include deterministic chaos in the characterization of the arc currents. In this paper, a chaotic approach to such modeling is described and justified. At the same time, 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 model in the Electromagnetic Transients Program (EMTP). The details of the module and the results of tests performed on the module to verify the model and to illustrate its capabilities are presented in this paper.

Key Words : arc furnace, chaos, load modeling, EMTP, TACS, FORTRAN interface, flicker, power quality

I. Introduction

Electric Arc Furnaces (EAFs) are used to melt large amounts of scrap and raw material in a relatively short time. The power fluctuation of these large and highly varying loads appears to be of concern in the degradation of the electric power quality of the interconnected system. In order to adequately understand and analyze the effects on the power system from EAFs, obtaining an accurate representation of the characteristics of EAFs is crucial. There have been studies of the modeling of EAFs in which researchers have assumed that the arcing process is a stochastic phenomenon because of the aperiodic, seemingly random and unpredictable behavior of these loads [1-3]. However, many of the models deal with very specific phenomenon, and it may be difficult to adapt to models to represent other loads that behave qualitatively similar, and EAFs has been identified as a deterministic system in which the present state is determined by previous states, and where future states will be determined by the present state through a defined rule. On the other hand, random or stochastic systems are those in which the present state has no causal relationship to past nor future states. Since there exists a rule or relationship for deterministic systems such as EAFs, they can be predicted even though it is not always easy. In this work, an alternative approach to the modeling [4] to include deterministic chaos to capture the chaotic characteristics of EAFs is used. Chaotic dynamics represent the aperiodic behavior of EAFs well and seem to be closer to the nature of the phenomenon than the stochastic techniques used in the previous attempts. Mathematical supports for the use of chaos theory and various studies related to chaos are provided in [5-8]. An objective of this paper is to develop a model of an EAF using chaos theory in order to have more accurate representation of the physical phenomena in the load.

As a popular simulation tool, the Electromagnetic Transients Program (EMTP) has been used to simulate the transient dynamics for the large power system, but EMTP does not have the highly varying nonlinear load models like EAFs. A main motivation for this study is the proper assessment of economics of power conditioning and filtering of EAF loads. Traditionally these loads have been filtered with simple tuned filters, and isolated from the distribution and subtransmission supply through

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transformer leakage reactance, so there is an increasing need to have an EAF model for the EMTP in studying the devices which can effectively attenuate the nonsinusoidal load current components. In this paper, an EMTP EAF module has been developed to simulate the power system which contains EAFs and study its impacts on the whole system like the voltage flicker. It allows to verify the accuracy of the chaos-based model and to illustrate its capabilities. This paper provides the approach to develop the model interface with Transient Analysis of Control Systems (TACS). It also provides the results of the simulation using a test system for the purpose of validation of the module.

II. Nonlinear, highly varying EAF model

There are two main classes of arc furnaces: AC EAFs and DC EAFs. This paper mainly discusses AC EAFs but a similar modeling approach is possible for DC EAFs. Arc furnace operation may be classified into stages, depending on the status of the melt and the time lapse from the initial energization of the unit. During the melting period, pieces of steel create nearly a short circuit on the secondary side of the furnace transformer. This creates large fluctuations of current at low power factors and a new model is needed to represent this highly varying load period. In contrast to, the arc current is more uniform and results in less impact on the interconnected system during the refining period.

There are two perspectives in the study of chaotic dynamics in EAFs. The first one is a detection problem in which the operating level of EAFs might be determined from a time series measurement of load signals. The authors in [4,9] experimentally identified chaos in the operation of an EAF. The second perspective deals with the formulation of a model that accurately captures some of the dynamics present in an EAF and it is discussed in [10] and this paper. In this paper, a typical Lorenz differential equations [11] have been used to characterize the chaotic phenomena.

The scaled Lorenz system in (1) is used to generate a time series that matches as closely as possible the given data.

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

This is done through various operations on the states x, y, and z that involve square-wave modulation, clipping and further magnitude scaling of the chaotic signal. Figure 1 describes the main parts of the model. Because the chaotic model is highly sensitive to operating point, gradient based methods to identify model parameters do not function well. Instead, a random search is used to identify model parameters. This tuning of parameters is performed such that the differences between the sample data and the chaotic model are minimized. The differences are evaluated using a set of indices that include peak value, mean value, rms value and Total Harmonic Distortion (THD). The low frequency variation of the arc current sample data is captured through a peak detector, and this information is used to modulate the model data. This modulated signal is then injected with the dominant harmonics obtained from the data. When the tuning process is complete, the simulation phase begins. The simulation will generate output current until the simulation time has lapsed.

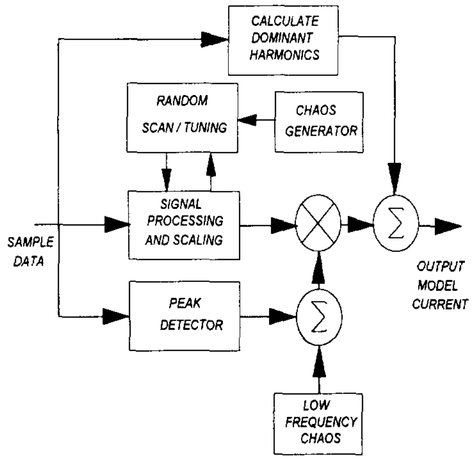

Figure 1: Pictorial of the chaotic model of an EAF

III. The EMTP / model interface

The chaos-based load model for an EAF, which is derived in the Section II, is developed in FORTRAN. Since the developed model involves two different processes for the tuning and the simulation, it can not be regarded as a typical nonlinear element in the EMTP. In order to implement the model for the study on system performance and design into the EMTP, the FORTRAN subroutines for the model need to be interfaced with TACS in EMTP. Interface between TACS and the FORTRAN subroutines allows to use all the flexibility of FORTRAN language and it makes easy to represent complex features of the chaos-based model. 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 like an independent current source. Detailed information about using EMTP source can be found in [12]. The mechanism of interaction among the EAF model, TACS and the EMTP network is shown in Figure 2.

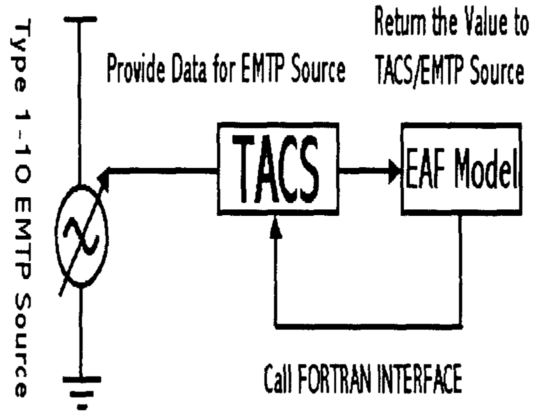

Figure 2: Mechanism of the interaction in the interface of the EMTP and the EAF model

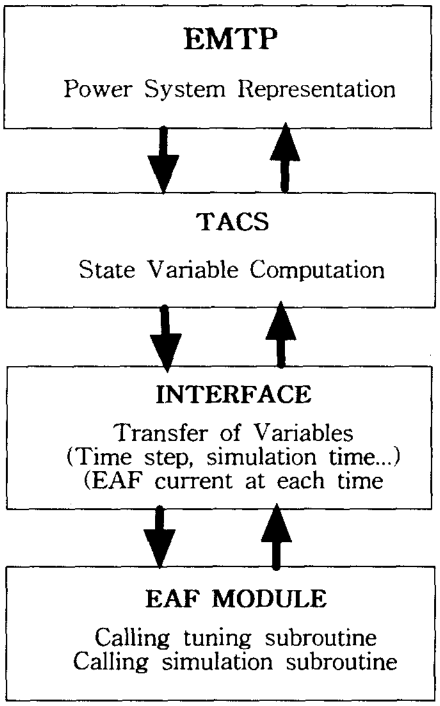

Figure 3: Execution order of the EAF module

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 the EMTP. Finally, EMTP simulates the electrical network with the EAF data. The procedure to use the EAF module is illustrated in Figure 3. Because the linear interpolation is used in simulating the EAF, the user is recommended to consider the simulation time step less than that of sampling cycle of the historical data. The EMTP used for this study is the DCG/EPRI EMTP Version 3.0 (EMTP96) and the developed model need to be a Dynamic Link Library (DLL) module in order to be incorporated to the Windows based EMTP.

IV. Case Study

The developed module is applied to a test system and a typical circuit diagram of the system supplying an EAF is shown in Figure 4. The unit is a 50 MVA furnace, connected to a 34.5 kV bus. The furnace transformer is rated at 100 MVA, with a high voltage side of 138 kV. The module is tested using phase current data from this system. The sampling frequency of the data is 10 kHz, and the tuning phase is performed using 2 seconds of data. The EAF module simulates the EAF currents for 3 seconds.

The simplified equivalent circuit diagram of the test system (Figure 4) for the EMTP simulation is shown in Figure 5. R is the resistance of the transformer, L is the leakage inductance, and C is the shunt capacitor. An EAF is represented as an independent current source. Voltage source E is the infinite bus, in this case, the 138 kV bus. In order to observe the EAF current in EMTP, a closed switch is added between buses NX and NY.

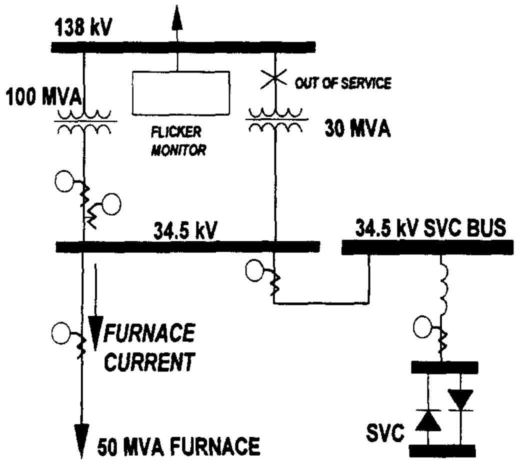

Figure 4: Test system

Figures 6 and 7 show both the historical data used and the data generated using the chaos-based model for the EAF at 34.5 kV bus. These figures validate the model since it shows that the actual and simulated data are qualitatively similar. For the detailed comparison of

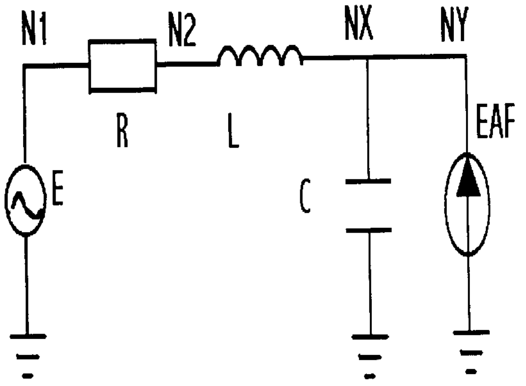

Figure 5: Simplified one-line diagram of the test system

both waveforms, the following results have been obtained in the tuning phase. The tuning phase is a procedure which seeks the best parameters for the chaotic system with different matching criteria. In this paper, criteria such as mean value in time domain and frequency domain, frequency components, peak value, and RMS value have been used, and these criteria are well matched after tuning phase. The result including the errors between the simulated data and the actual data is illustrated in Table 1.

Table 1: Comparison between the actual and model arc current

Criteria	Actual(A)	Model(A)	Error(A)
DC Comp.	4.11	5.96	1.84
60 Hz	1094.68	1094.68	0.002
120 Hz	12.80	12.80	7.6e-5
180 Hz	3.31	3.30	6.9e-5
Peak Value	1876.8	1792.7	-84.09
RMS Value	826.91	808.06	-18.85

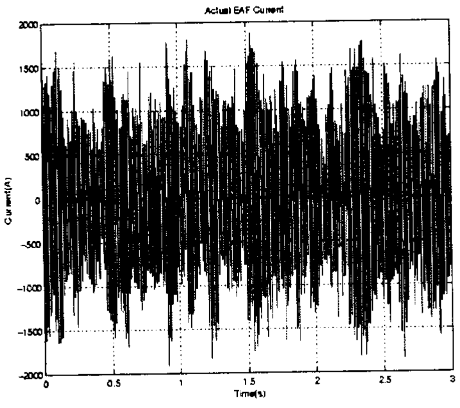

Figure 6: Actual EAF current

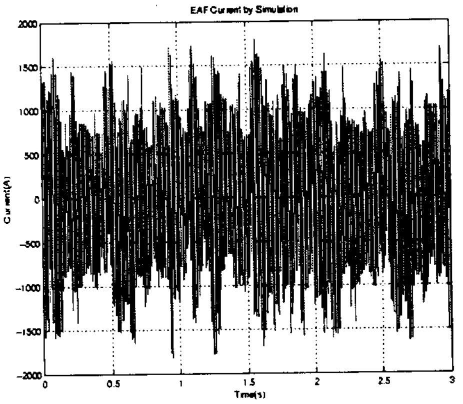

Figure 7: EAF current by the EMTP simulation

The model performs well in terms of predicting the general behavior of the load current, although the prediction of exact current levels is not the purpose of the model. It is desired that selected dynamic characteristics of the data such as electrical parameters and control aspects be preserved such that the impact of the load can be studied using the model. Table 2 shows a comparison between the indices from the historical data and those obtained from a simulation longer than the historical data time interval. These indices describe conditions such as flicker, system losses, and interference, and are given by the following equations.

$$THD = \frac{\sqrt{\sum_{i=2}^{\infty} I_i^2}}{I_1} \quad (2)$$

$$K-factor = \frac{\sum_{i=1}^{\infty} (i \cdot I_i)^2}{\sum_{i=1}^{\infty} (I_i)^2} \quad (3)$$

where I_i refers to the ith harmonic of i(t).

$$Zero-peak\ flicker\ factor = \frac{[I_{peak} - I_{1.0-pk}]}{I_{1.0-pk}} \quad (4)$$

where $I_{1.0\ pk}$ is the zero to peak value of the 60Hz current component.

The indices match within reasonable accuracy, showing that degradation after the tuning phase is small. Furthermore, the largest Lyapunov exponents [4,13] from both sets are also comparable, which gives evidence that the chaotic properties of the load are also preserved.

An important point is that the chaotic properties of the model match those of the historical load data. These chaotic properties are critical in the evaluation of power quality enhancement measures.

Table 2: Indices for the actual and model data

Index	Actual	Model
Total Harmonic Distortion (%)	14.11	11.05
K-factor	1.060	1.061
Zero-peak flicker factor	0.714	0.646
Largest Lyapunov exponent (1/s)	16.89	15.26

The spectra of both the simulated current and the actual current are shown in Figure 8 and Figure 9 respectively in order to show the frequency domain characteristics.

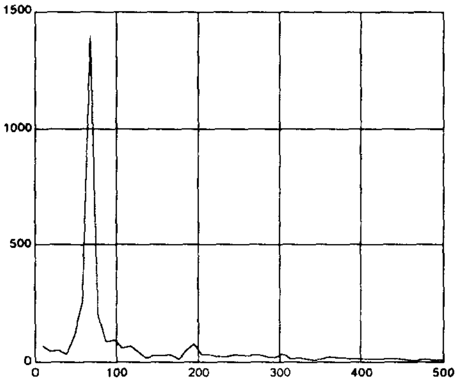

Figure 8: Spectrum of actual EAF current

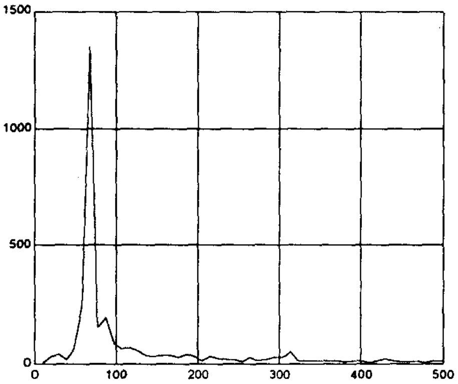

Figure 9: Spectrum of simulated EAF current

In addition to the EAF current, a bus voltage has been obtained to make an analysis of the impacts on the system caused by the EAF. A bus voltage directly connected to the EAF is shown in Figure 10. Figure 10 shows the voltage waveform from the EMTP simulation for 3 seconds and it is closely matched with the actual voltage waveform in Figure 11. An abnormal response between 1 and 1.5 seconds in the simulated one is observed and we are looking for the answers regarding this matter.

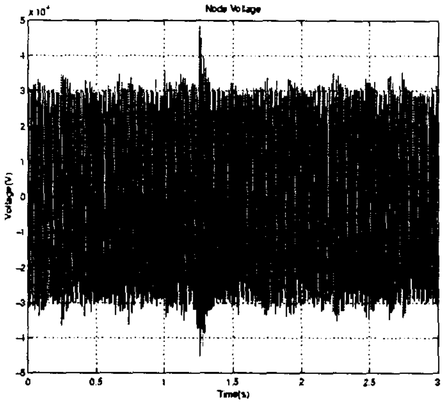

Figure 10: Voltage waveform obtained by the EMTP simulation

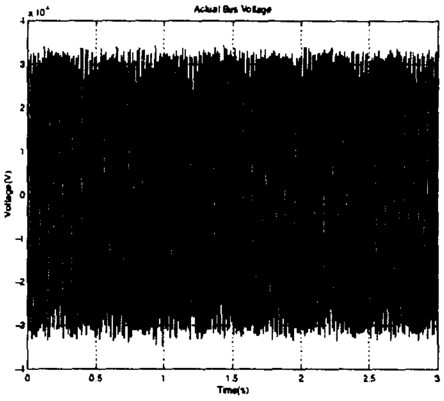

Figure 11: Voltage waveform obtained from the field

V. Conclusions

In this paper, an alternative chaos based approach for modeling of an AC EAF has been demonstrated and justified. 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 have been given and compared with the actual data to illustrate the validity of this model and analysis has been made to show the EMTP module with the EAF model can be used for the proper assessment of power quality impact, the performance of control devices on power distribution systems.

The work should be extended to investigate other highly varying loads which have chaos components and it would be desirable to compare the accuracy of the performance of the chaotic model with that of a stochastic model. Also, the effort to find other chaos systems enough to provide closer point-to-point prediction for the load currents should be continued.

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