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전력 품질 해석을 위한 개선된 전기아크로 모델 개발

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Development of a Chaotic Electric Arc Furnace Model

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요약 : 대규모의 전력을 사용하며 전력 수요가 일정하지 않고 변동하는 제철소의 전기아크로 (electric arc furnace) 부하는 전압 플럭커 (voltage flicker) 등 전력품질을 저하시키는 현상의 주 원인이 되고 있다. 따라서, 전력품질의 향상을 위한 전력계통의 계획과 운용에 있어서 이러한 부하들의 비선형적인 전압-전류 특성을 해석하고 모델링하는 것이 우선 되어야 한다. 특히 전기아크로 부하의 비선형적이고 랜덤 신호에 가까운 특성은 stochastic 접근법에 의해 주로 모델링되어 왔으나, 전기아크로 부하에 의한 전력계통에서의 영향을 평가를 위해서는 deterministic 접근법에 의한 모델링이 필요하며 전기아크로 부하가 가지는 chaos 특성을 Lorenz 시스템으로 표현한 부하모델이 개발되었다[1]. 개발된 모델에 의해 하나의 chaos 시스템으로 예측된 전기아크로 부하 패턴은 전 동작 범위에서 부하 특성을 정확하게 반영하는데 문제가 있다. 따라서, 전기아크로 부하 패턴을 표현할 수 있는 복수의 chaos 시스템을 이용하여 보다 나은 예측 특성을 가진 부하 모델의 개발이 필요하다. 본 논문에서는 기존의 Lorenz 시스템과 전기아크로 부하의 고주파 영역 특성을 보다 적절하게 반영할 수 있는 Logistic 시스템을 혼합한 형태의 chaos 모델을 개발하고, 전력계통에서의 전력품질 저하현상을 정량화하는 지수를 통해 모델의 유용성과 정확성을 검증하고자 한다.

1. Introduction

In [1], a chaotic model of an electric arc furnace has been discussed in details. In this chaotic model, a sample input data was used, typically 2 seconds of actual arc current, and the chaotic components generated from the Lorenz system were added into the sample input waveform. Since the chaotic components from the Lorenz system are very small in magnitude compared to the actual arc current, the model output, which is usually 2 seconds in duration, is very much similar to the sample input data of arc current. It does make sense when the arc current repeats itself or is quasi-periodic in a certain period of time. However, the predicted waveform is actually similar to that during the first 2 seconds except those variable small chaotic components, which can be thought of no major influence on the model validity when doing the error analysis. Instead, the actual EAF current (totally 128 seconds) provided by Roanoke Electric Steel Company varies erratically for every 2 seconds, and they are totally different both in time domain and frequency domain. If utilities would like to use this model, selection of the sample input data is a big problem due to the erratic variation of actual EAF current. Another problem is that the predicted wave forms also can not characterize the irregular variation of arc current for the same reason that the predicted waveform is very similar to the sample input data.

In this paper, a new chaotic approach which is based on the Lorenz system and the Logistic system is proposed to represent the characteristic of EAFs over the wide operating range. The results of tests performed on the proposed model to verify the model and to illustrate its capabilities are presented in this paper.

2. Approach

2.1 General Assumption

In power systems, what utilities are concerned is the impact of the arc furnace (Figure 1) on the power network. The historic data might be used to make a reasonable prediction which can characterize the arc furnace in the sense of voltage flicker, harmonics and power quality indices, etc. For this reason, the following guidelines are presented to build up the criteria to judge the validity of the arc furnace models.

○ The purpose of the prediction is not the exact match with actual data in the time domain and in the frequency domain due to the erratic variation of arc current. The prediction is focused on the general behavior of the operation of arc furnaces.

○ Matching all the power quality indices is hard to achieve in the modeling of arc furnaces. In this approach, some appropriate indices are concerned, and they will be compared with those of the actual data.

○ The general performance of the model is evaluated in the sense of probability of power quality indices. If one predicts based on the entire attractor, it can be reasonable as well.

The following assumptions are made for the new models proposed according to chaos theory.

○ The arc impedance or admittance contains chaotic components

○ The steady state analysis is used in calculating the arc admittance

○ No consideration has been given to the arc length control system

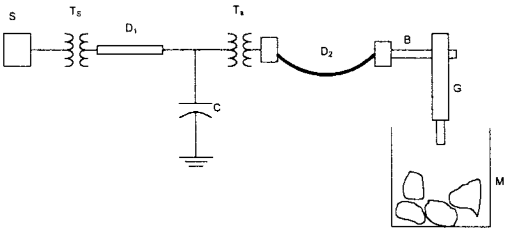

Figure 1. Structure of a Typical Arc Furnace

2.2 Lorenz Model

Lorenz model is based on the following differential equations, which are generally used to predict the weather.

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

It is important to define the nonlinear arc admittance in Figure 2 for the modeling of the arc furnace. In the Lorenz model, the arc resistance is expressed as below

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

where, C1 is a constant. x is one of the state variables in the Lorenz equation.

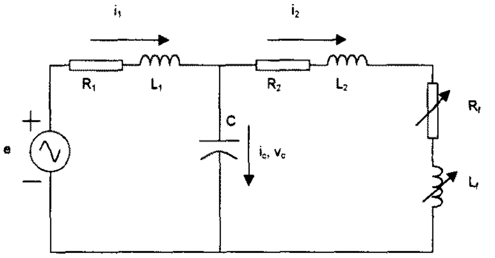

Figure 2. Circuit Representation of the Arc Furnace

Similarly, y and z can also serve for the arc resistance. Also,

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

where, f_1 is the network frequency.

Using this Lorenz model together with the test system, the simulation has been performed. The simulated arc current and arc admittance are shown in Figure 3.

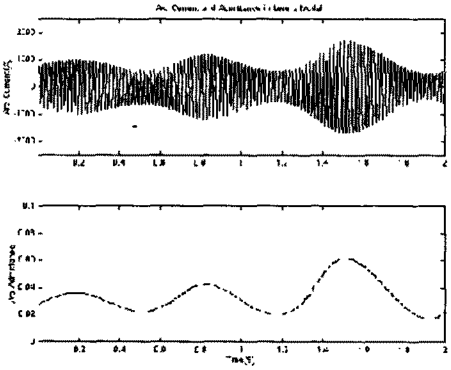

Figure 3. Arc current and admittance in Lorenz Model

2.3 Logistic Model

The logistic equation is a classical iterative equation showing chaos with the appropriate value of parameter k. The formula is rewritten as

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

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. That is, Y consists of the summation of the time series from the logistic equation with different chaotic frequencies.

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

Here, X_{1f} , X_{2f}, X_{3f} and etc. represent the time series with different chaotic frequencies like 30Hz, 60Hz, 120Hz and etc. Hence the logistic model is used to generate the arc admittance corresponding to different harmonic components. Figure 4 shows the simulated arc current, arc admittance and arc voltage from the Logistic model.

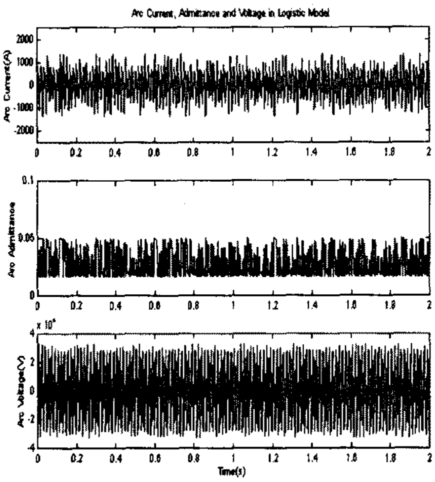

Figure 4. Arc Current from the Logistic Model

It covers the characteristic of the high frequency behavior of arc furnace like the harmonics even though it doesn't look similar to the actual data. Also from the arc voltage waveform, flicker can be clearly seen. That is, the nonlinearity of the arc furnace could contribute to the voltage flicker, especially the high frequency variation of the arc admittance. The voltage drop on the transformer winding impedance is caused by the nonlinear variation of the arc resistance and inductance.

2.4 Mixed Chaotic Models

From the analysis of the arc furnace current data, the Lorenz system may contribute to the low frequency components of arc current and the logistic equation may contribute to the high frequency components. Hence, combination of both Lorenz and logistic model can make the mode work well in both frequency ranges.

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

In the equation Y_0 is a fixed admittance. 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, specifically the state variable of x. $Y_{logistic}$ 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. The flowchart for the mixed chaotic model is illustrated in Figure 5 and the simulated arc current and voltage are shown in Figure 6.

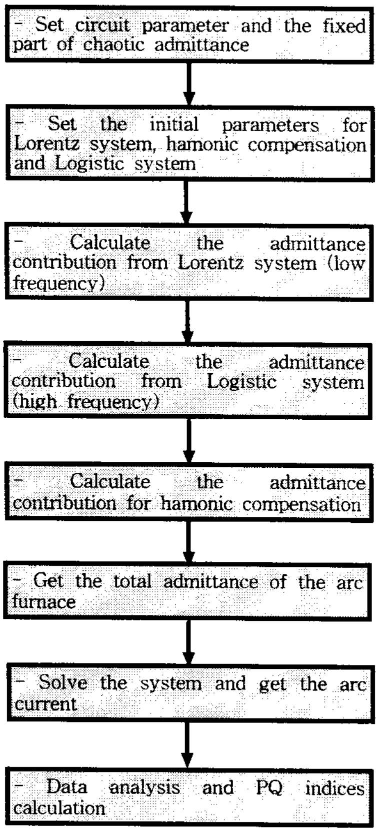

Figure 5. Flowchart of the Mixed Chaotic Model

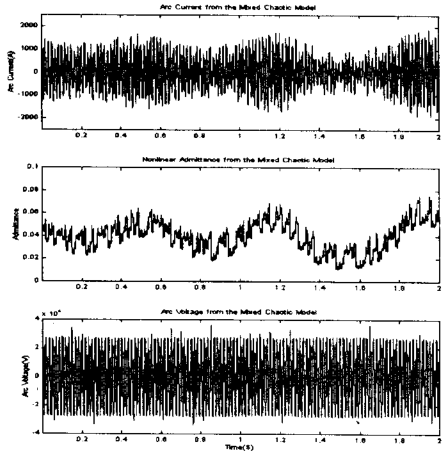

Figure 6. Simulated Arc Current, Admittance and Bus Voltage According to the Mixed Chaotic Model

Tables 1 shows the typical power quality indices from the field data (128 seconds) provided by Roanoke Electric Steel Company, and those are used to verify the model being proposed.

Table 1. Power Quality Indices from Field Data

Data Set	THD	K-factor	Crest Factor	Zero-Peak Flicker Fact.	RMS Flicker Factor
1	0.029583	1.010412	2.637332	1.396535	0.079750
2	0.042928	1.031720	2.678326	1.097614	0.066158
3	0.058492	1.073438	2.966981	1.283629	0.077995
4	0.050262	1.056763	2.496126	0.907654	0.057545
5	0.061930	1.065931	2.915973	1.253258	0.039731
6	0.048620	1.034722	2.756204	1.231582	0.053493
7	0.043178	1.033384	2.937318	1.364243	0.099624
8	0.044693	1.035842	2.870986	1.339096	0.061034
9	0.052005	1.036449	3.146561	1.534109	0.090555
10	0.037466	1.018354	2.889183	1.371570	0.096395
11	0.033624	1.011396	2.784426	1.310803	0.094154
12	0.031489	1.008624	2.818451	1.402415	0.112681

In Table 2, those indices are calculated from the simulated waveforms and compared with the actual power quality indices statistics. The length of the predicted data set is for 10 seconds. Clearly we can see they are matched very well through the comparison with the actual power quality indices.

Table 2. 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

3. Conclusions

In this paper, an enhanced chaotic model is proposed to predict the general behavior of the arc furnace operation, and to overcome the limitations of the conventional chaotic model in which the arc furnace operation based on some criteria is represented. The performance of the proposed model which is a mixed model of the Lorenz and Logistic system to represent the impact of the arc furnace model to the power quality in wide frequency range. The simulation results have been given and compared with the actual data to illustrate the validity of the mixed chaotic model and analysis has been made to show the proposed EAF model can be used for the proper assessment of power quality impact.

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