論 文
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전력 품질 해석을 위한 개선된 전기아크로 모델 개발

Development of a Mixed Chaotic Electric Arc Furnace Model

張 吉 洙* · Weiguo Wang** · 李 炳 峻*** · 權 世 爀§
(Gilsoo Jang · Weiguo Wang · Byongjun Lee · Sae-Hyuk Kwon)

Abstract - Electric arc furnaces (EAFs) has a process to cause the degradation of the electric power quality such as voltage flicker. 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 has been proposed. The Lorenz system may contribute to the low frequency components of arc current and the logistic equation may contribute to the high frequency components, and the proposed mixed model will be a combination of both Lorenz and logistic model. 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. The power quality indices are calculated from the simulated waveforms and compared with the actual power quality indices statistics in order to illustrate the model's capabilities.

Key Words : Chaos, Electric Arc Furnace, Lorenz System, Logistic System, Power Quality

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 small variable 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. For the use of this model, selection of the sample input data is a big problem due to the erratic variation of actual EAF current.

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. Also, a detail data analysis is presented to get insights for the realistic EAF modeling.

2. Approach

2.1 Data Preparation and Analysis

The data discussed in this paper are from a typical 50 MVA arc furnace (Figure 1) in Roanoke Electric Steel Company. The test system data contains the 34.5 kV bus voltage, the 138 kV bus voltage, and the arc furnace transformer secondary current and three-phase arc furnace current. The data are provided for 128 seconds operation of the mill with a sampling frequency equal to 10 kHz. A general view of these waveforms is given in Figures 2, 3 and 4, and they illustrate the irraticism and irregularity of the arc current graphically.

* 正 會 員 : 高麗大 電氣·電子·電波工學部 助教授·工博
** 非 會 員 : ESCA-Alstom, WA, USA
*** 正 會 員 : 高麗大 電氣·電子·電波工學部 副教授·工博
§ 正 會 員 : 高麗大 電氣·電子·電波工學部 教授·工博
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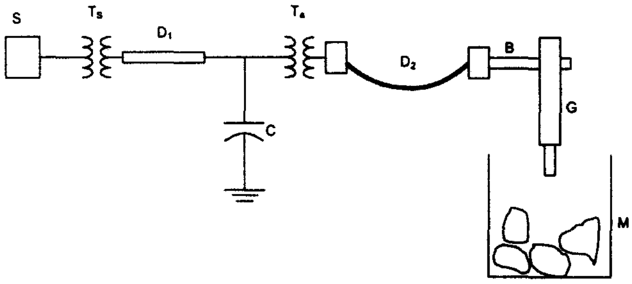

Figure 1: Structure of a Typical Arc Furnace

Figure 2 shows the arc furnace current in phase A for the first 10 seconds. The characteristic for this period of time is that there are some regions in which the arc furnace current reaches zero for a certain time, where the arc extinguishes. It is extremely difficult to identify the current will fall down to zero and estimate how long the status will last. This period corresponds to the beginning of the melting phase, and the arc is not stable.

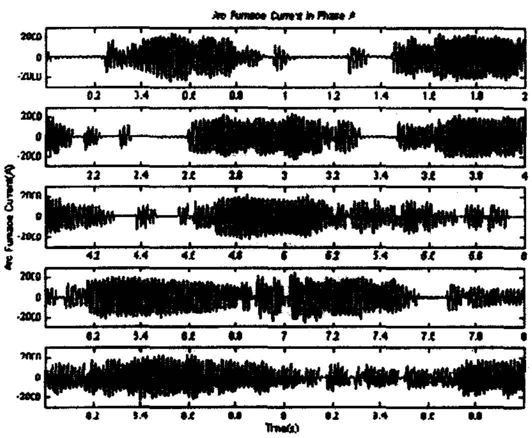

Figure 2: Arc Furnace Current (the First 10 seconds)

Figure 3 illustrates the arc furnace Phase A current between 40 and 50 seconds. In this period, the arc furnace current becomes relatively stable in terms of the magnitude compared to that in the first 10 seconds. But still the arc current is erratic and irregular. Figure 4 shows the Phase A arc current between 90 and 100 seconds. During this period, the arc current becomes relatively more unstable than that between 40 and 50 seconds. The reason for such a change is still not clear due to the various factors relating to the arc furnace operation like the temperature, types of materials and so on.

As seen from Figures 2, 3 and 4, the arc furnace current is erratic because one may not be able to easily predict the waveform in the next few seconds or minutes. In addition to this, the waveforms also vary with different melting phases.

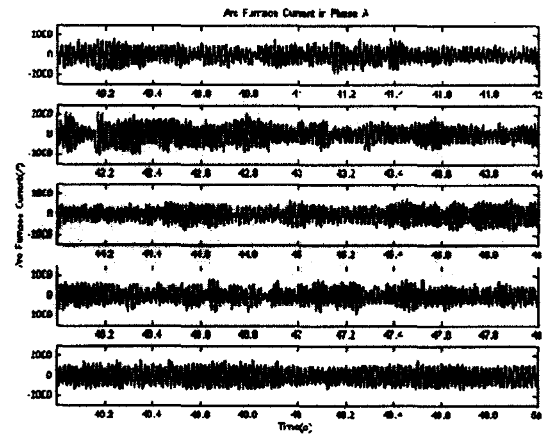

Figure 3: Arc Furnace Current (40 to 50 seconds)

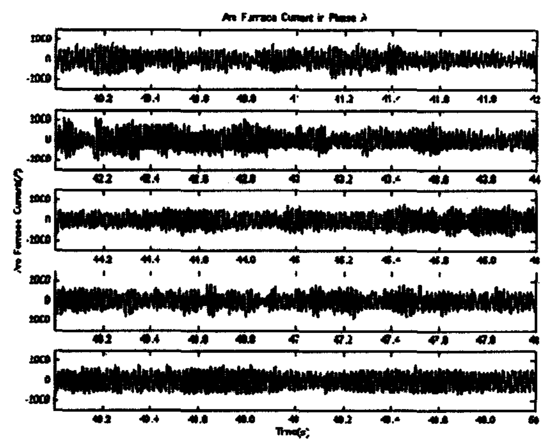

Figure 4: Arc Furnace Current (90 to 100 seconds)

In order to analyze the harmonic content and its variation in the arc current, the Fourier analysis and FFT have been used to get the spectrum of each three-phase arc current data set lasting for 10 seconds. Therefore, the total number of data sets for phase A current is 12. This arc current spectrum indicates that there are some side peaks close to the 60Hz, generally between 55-65 Hz. Most of them are between 58 and 62Hz, but some of them are beyond this range. This could be identified as arc current flicker which finally leads to the voltage flicker. Although the whole spectrum should be considered in the aperiodic signals, what is of concern in power systems is the integer order harmonics like 3^{rd} and 5^{th} harmonic and other odd multiple harmonics. For low frequency harmonics, it seems that there is no obvious law to govern the variation. In some senses, it is either random or chaotic (See Figure 5). High frequency harmonics (higher than 60Hz) vary with different modes. The maximum one in magnitude in this range is 300 Hz (5^{th} harmonic), then comes with 180 Hz (3^{rd} harmonic), 120 Hz (2^{nd} harmonic). These three frequencies are dominant in the harmonics. The entire harmonic spectrum up to 25th is given in Table 1.

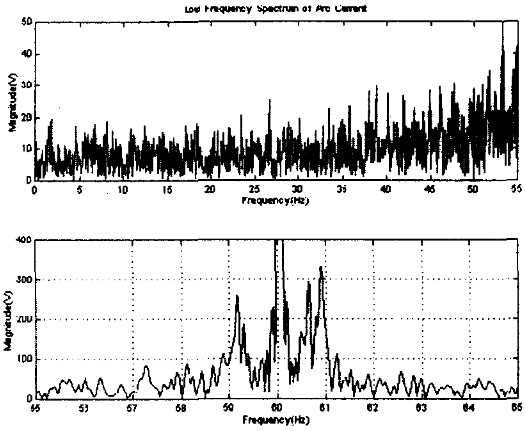

Figure 5: Low Frequency Harmonics in Arc Current (the first 10 seconds data set)

Table 1: Harmonic Statistics in the Arc Current of Phase A (12 data sets)

Harmonic Order	Minimum	Maximum	Average
1	0.934475	1.059270	1.000000
2	0.011726	0.023647	0.016561
3	0.016646	0.036081	0.025559
4	0.002911	0.015595	0.007296
5	0.010080	0.048555	0.028012
6	0.001497	0.007673	0.003584
7	0.002356	0.012675	0.005989
8	0.000821	0.004784	0.002064
9	0.000937	0.003427	0.002112
10	0.000706	0.001744	0.001102
11	0.000872	0.002885	0.001867
12	0.000434	0.000735	0.000557
13	0.000366	0.001110	0.000661
14	0.000271	0.000603	0.000410
15	0.000272	0.000561	0.000407
16	0.000212	0.000399	0.000305
17	0.000163	0.000524	0.000306
18	0.000192	0.000384	0.000250
19	0.000194	0.000330	0.000249
20	0.000135	0.000280	0.000190
21	0.000126	0.000317	0.000198
22	0.000121	0.000211	0.000160
23	0.000115	0.000221	0.000157
24	0.000105	0.000167	0.000139
25	0.000092	0.000192	0.000134

Although the arc furnace usually has a close loop control system to control the average arc resistance by regulating the length of the graphite electrodes, the calculation results show that the average arc admittance for each second vary in a range of about 0.2 to 0.55 (1/). Such variation is irregular, say random or chaotic. Also one could see that the control system has errors due to the highly varying characteristic of arc furnace and its small time constant compared with the slow mechanical response. Under steady state, the arc admittance for each cycle has been computed to illustrate the arc admittance change in the long term, say 100 seconds. If there are some laws governing such change, they may explain how the arc impedance or admittance varies with respect to the time. This directly leads to the mixed chaotic model and in which the variation of admittance has been considered. The new chaotic models are based on the whole data set with 128 seconds.

2.2 General Assumption

In power systems, what utilities are concerned is the impact of the arc furnace 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

2.3 Lorenz Model

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

$$\dot{x} = \sigma(y - x)$$
$$\dot{y} = rx - y - xz$$
$$\dot{z} = xy - bz \quad (1)$$

It is important to define the nonlinear arc admittance in Figure 6 for the modeling of the arc furnace. In the Lorenz model, the arc resistance is expressed as below

$$R_f = C_1 x \quad (2)$$

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

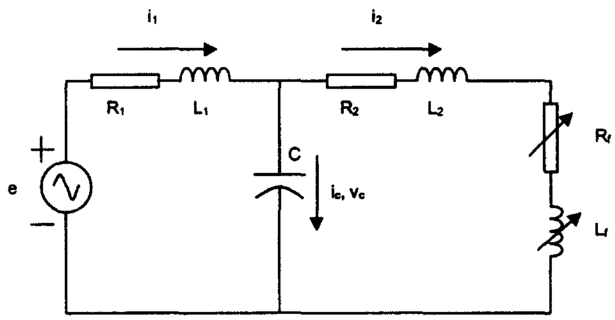

Figure 6: Circuit Representation of the Arc Furnace

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

$$L_f = \frac{\alpha R_f}{2\pi f_1} \quad (3)$$

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 7.

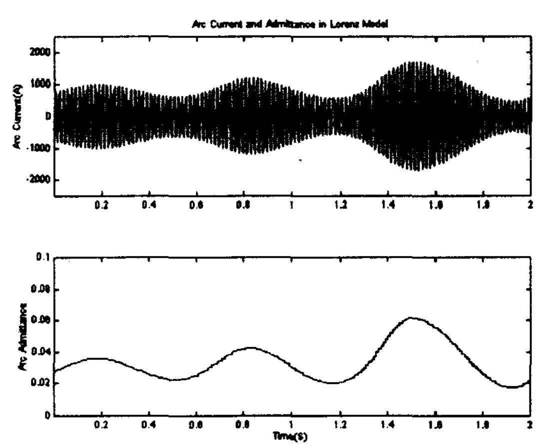

Figure 7: Arc current and admittance in Lorenz Model

2.4 Logistic Model

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

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

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.

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

Here, X_{1f} , X_{2f}, X_{3f} and etc. represent the time series with different chaotic frequencies like 30 Hz, 60 Hz, 120 Hz and etc. Hence the logistic model is used to generate the arc admittance corresponding to different harmonic components. Figure 8 shows the simulated arc current, arc admittance and arc voltage from the Logistic model.

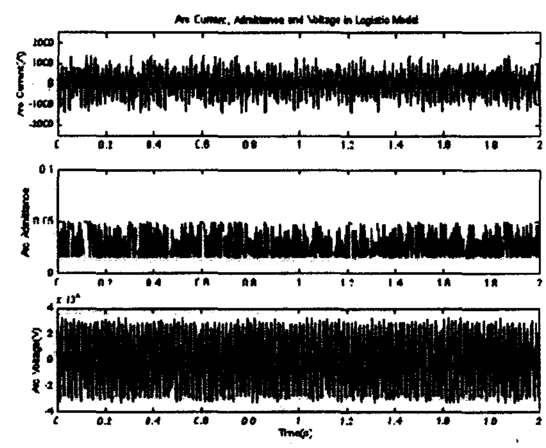

Figure 8: Arc Current from the Logistic Model

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 explains the nonlinearity of the arc furnace could contribute to the voltage flicker, especially to 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.

2.5 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.

$$Y_f = Y_0 + C_1 Y_{lorenz} + C_2 Y_{logistic}$$
$$Y_0 = 0.005, C_1 = 0.003, C_2 = 0.02 \qquad (6)$$

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.

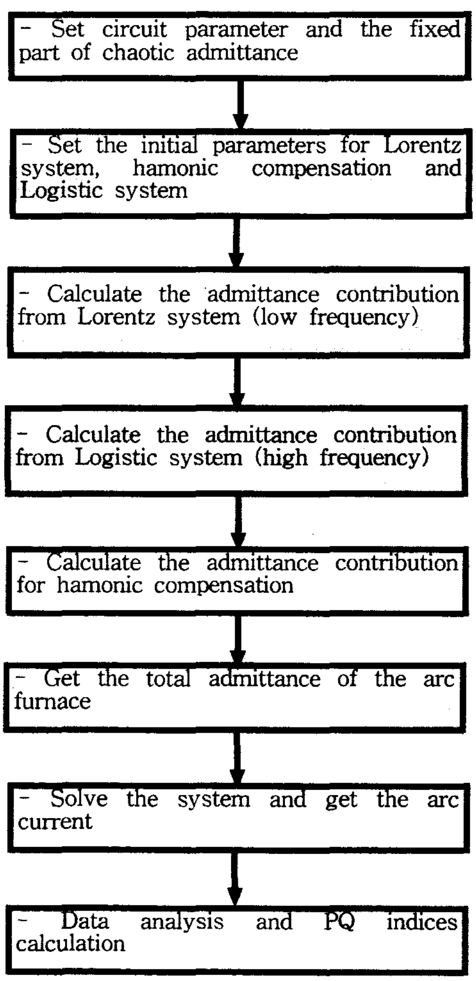

Figure 9: Flowchart of the Mixed Chaotic Model

The flowchart for the mixed chaotic model is illustrated in Figure 9 and the simulated arc current and voltage are shown in Figure 10.

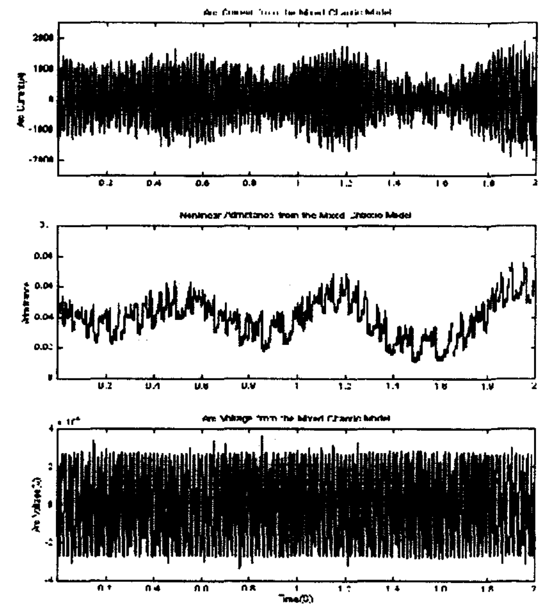

Figure 10: Simulated Arc Current, Admittance and Bus Voltage According to the Mixed Chaotic Model

Tables 2 shows the typical power quality indices which are derived from the field data (128 seconds) provided by Roanoke Electric Steel Company, and those are used to verify the model being proposed.

Table 2: Power Quality Indices from Field Data

Data Set	THD	K-factor	Crest Factor	Zero-Peak Flicker	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 3, 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 10 seconds which is significantly extended compared to the previous model [1]. Clearly we can see they are matched well through the comparison with the actual power quality indices. It shows the mixed model's capabilities for the use in power quality assessment.

Table 3: 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 whole range of the arc furnace operation is not considered. 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 is presented in terms of some criteria. 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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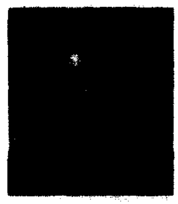
저 자 소 개



장 길 수 (張 吉 洙)

1967년 10월 26일 생. 1991년 고려대 공대 전기공학과 졸업. 1994년 동 대학원 전기공학과 졸업(석사). 1997년 Iowa주립대 전기 및 컴퓨터공학과 졸업(공박). 2000년 3월-현재 고려대 공대 전기전자전파공학부 조교수

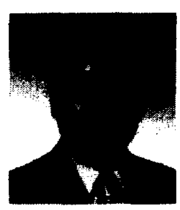
Tel : 02-3290-3246

E-mail : gjang@elec.korea.ac.kr

Weiguo Wang

1993년 중국 Tsinghua University 졸업. 1999년 Iowa주립대 전기 및 컴퓨터공학과 졸업(석사). 현재 Seattle에 있는 ALSTOM ESCA에 재직 중임.

E-mail : Weiguo.WANG@esca.com

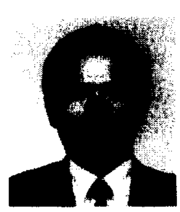


이 병 준 (李 炳 峻)

1961년 7월 16일 생. 1987년 고려대 공대 전기공학과 졸업. 1991년 미국 Iowa State Univ. 전기공학과 졸업(석사), 1994년 동 대학원 졸업(공박). 1994년~1995년 Iowa State Univ. Post Doc. 1995년 ~1996년 일본 미쯔비시 전기 근무. 현재 고려대 전기·전자·전파공학부 부교수.

Tel : 02-3290-3242, Fax : 02-921-1325/0544

E-mail : leeb@elec.korea.ac.kr



권 세 혁 (權 世 爀)

1949년 5월 14일 생. 1974년 서울대 공대 공업교육과(전기전공) 졸업. 1976년 서울대 교육대학원 공업교육과 졸업(석사). 1980년 미국 Iowa State Univ. 졸업(석사), 1984년 미국 Iowa State Univ. 졸업(공박). 현재 고려대 전기·전자·전파공학부 교수.

Tel : 02-3290-3220, Fax : 02-921-1325/0544

E-mail : SHKWON@elec.korea.ac.kr