자여자 풍력 유도발전기의 캐패시터에 따른 고조파 전류의 증폭

論 文
57P-2-22

Amplification of Current Harmonics Due to Self-Excitation Capacitors for Wind Induction Generators

吳 鏞* · 崔 龍 成† · 黃 宗 善** · 李 炅 燮***
(Yong Oh · Yong-Sung Choi · Jong-Sun Hwang · Kyung-Sup Lee)

Abstract - The value of this paper is to use reduced size apparatuses to perform field measurement in order to identify and validate that the harmonic-current effects are due to the presence of self-excitation capacitance connected at stator's terminals of the studied SEIG. This paper has presented the measured electrical quantities of a three-phase Δ-connected wind induction generator (WIG) under sudden connection and disconnection of resistive loads. An intelligent power-system recorder/monitor has been employed to measure three-phase voltages and currents of the studied system at the terminals of the studied WIG and the load. The measured electrical quantities have been analyzed. Total harmonic distortion (THD) of current using cumulative probability density function has been employed to determine the penetration of harmonic distortion at load side. The results show that the harmonic currents generated by the studied WIG can be severely amplified by the connected self-excited capacitance at the stator's terminals.

Key Words : Self Excitation, Wind Induction Generator, Excitation Capacitor, Total Harmonic Distortion (THD)

1. Introduction

An induction machine driven by an external prime mover such as wind turbines or hydro turbines can sustain self-excitation when an appropriate value of a capacitor bank is appropriately connected across the stator terminals of the studied induction machine [1]. These induction machines with excitation capacitors are called self-excited induction generators (SEIG). The primary advantages of a SEIG over a conventional synchronous generator are brushless construction with squirrel-cage rotor, reduced size, without DC power supply for excitation, reduced maintenance cost, and better transient characteristics. In recent years, SEIGs have received increased attention and they have been extensively utilized as suitable isolated power sources. The same induction machines can be connected in small hydroelectric and wind energy applications to act as a grid-connected induction generator (GCIG) when its rotation speed is higher than the synchronous speed of the revolving field in the air gap.

According to available references on power quality of induction generators or wind generators, current harmonics and transient currents during grid connection of two 225 [kW] wind induction generator with pitch control were examined [2]. The prediction of synchronous and asynchronous harmonics generated by induction generators using time domain measurement was proposed [3]. Transient and harmonics of a GCIG driven by a wave-energy turbine were investigated [4]. Harmonic components in overvoltage waveform and post-fault conditions of both induction generator and synchronous generator were studied [5]. Ferro resonance of dispersed system generation (DSG) using induction generator connected to a small distribution system under islanding operation was presented [6]. Power, efficiency and current unbalance of a WIG connected to an unbalanced grid using symmetric components were examined [7]. Other power-quality analyses on wind generators can be referred to [8-12].

This paper introduces transient results of a wind self-excited induction generator connected to an isolated resistive load using a wound-rotor induction machine with short-circuited rotor-winding terminals. Although simple induction generators with squirrel cage rotors are going out of use in wind energy systems, especially the large ones, the primary reason being such systems have to operate at nearly constant speeds, with great increases

† 교신저자, 正會員 : 東新大學校 電氣工學科 敎授 · 工博
E-mail : yschoi67@dsu.ac.kr
* 正 會 員 : 東新大學校 電氣電子工學科 博士課程
** 正 會 員 : 全南道立大學 컴퓨터應用電氣科 敎授 · 工博
*** 正 會 員 : 東新大學校 電氣工學科 敎授 · 工博
接受日字 : 2008年 4月 21日
最終完了 : 2008年 5月 14日

in stresses in almost all mechanical and structural components. This paper can only use a wound-rotor induction machine with short-circuited rotor-winding terminals to act as a cage-rotor induction machine for studying the performance of a wind generator. The value of this paper is to use reduced size apparatuses to perform field measurement in order to identify and validate that the harmonic-current effects are due to the presence of self-excitation capacitance connected at stator's terminals of the studied SEIG.

2. System Configuration

Fig. 1 shows the three-phase schematic diagram of the studied three-phase wind wound-rotor induction generator (WIG) fed to a three-phase three-wire load. The Δ-connected stator windings of the WIG is connected to the load through a Y-connected capacitor bank. The Y-connected rotor windings of the WIG are short-circuited together. Each phase of the capacitor bank is represented by a parallel circuit with an excitation capacitor C and an equivalent discharge resistance R_L. Each phase load impedance is represented by an equivalent series circuit with a resistance R_t and an inductance L_t.

The studied machine driven by a 500 [W] brushless DC motor has the following specifications: 0.5 hp (300 [W]), 220(Δ)/380(Y) [V], 1.5(Δ)/0.8(Y) [A], 60 [Hz], 4 poles, rated speed of 1760 [rpm]. The excitation capacitor bank is with phase capacitance of 20 [μF]. When the studied WIG operated as a SEIG, its rotor speed is kept at about 1500 [rpm].

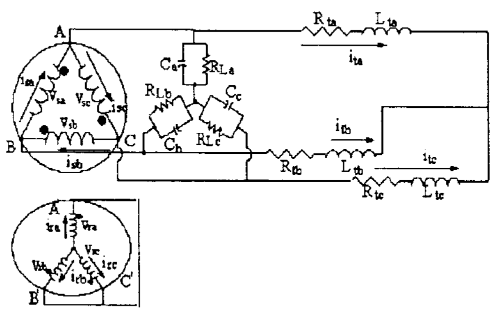
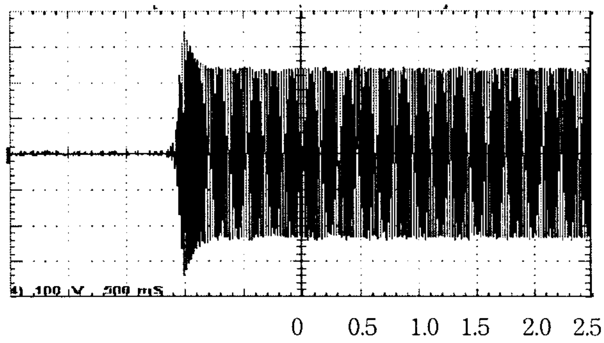
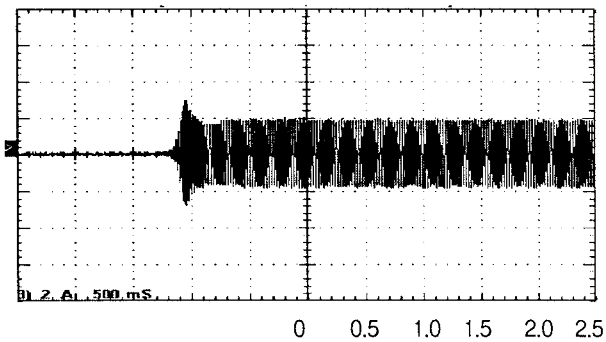


Fig. 1 Three-phase connection diagram of the studied wind SEIG.

Before performing 5-minute measurement in the next section, Fig. 2 shows the measured transient responses of the generated voltage and current during voltage build-up process using an oscilloscope. It is found from Fig. 2 (a) that the excitation capacitor bank is connected to the stator windings of the studied WIG at t = 1.25 [s] and the transient terminal peak voltage jumps as high as about 350 [V] and drops to about steady-state 240 [V]. From Fig. 2 (b), the peak current of the studied WIG also jumps to as high as 3 [A] at t = 1.25 [s] and drops to about steady-state 1.9 [A].



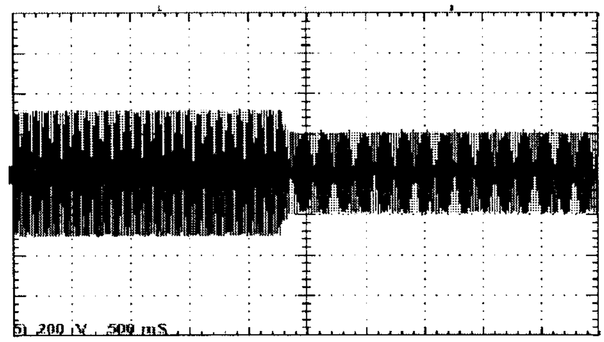
(a) Voltage waveform



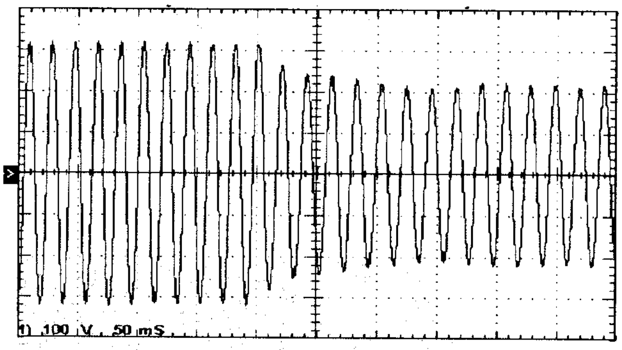
(b) Current waveform

Fig. 2 Measured transient responses of the studied WIG during voltage buildup process.

Fig. 3 shows the transient responses of the studied WIG subject to a sudden connection of a three-phase 420 [Ω](2.6 [pu] under WIG's base) resistive load at t = 2.25 [s] after the voltage buildup process. It is found from Fig. 3 (a) that the peak terminal voltage drops from 320 [V] to as low as 200 [V] which is equal to about 37.5% voltage variation. Fig. 3 (b) is the time-scale extension of Fig. 3 (a) before and after the sudden connection of the resistive load. It is found that the generated frequency drops from 50 [Hz] to as low as 43 [Hz].



(a) Voltage waveform



(b) Extended voltage waveform

Fig. 3 Measured transient voltage responses of the studied WIG during sudden connection of a resistive load.

3. Results and Discussion

3.1 Measurement of Electrical Quantities

Figs. 4 and 5 respectively show the measured results of electrical quantities at generator and load terminals of the studied WIG subject to sudden connection of 420 [Ω] resistive load at t = 2 [min]. Sections (a) and (b) in both figures are respectively the results of the studied WIG without and with the resistive load. The measured quantities are voltage (Vs in Vrms), current (I in Arms), active power (P in W), reactive power (Q in VAR), apparent power (S in VA), power factor (PF lagging or leading), and frequency (f in Hz) using an intelligent power-system recorder/monitor from three-phase voltages and currents. Minor measured differences shown below are due to the connecting lines among the studied WIG, the excitation capacitors and the resistive load. Due to measured errors in both PCs and CTs connected to the measured terminals, random variation can be observed.

From the results in Fig. 4, it is found that the terminal voltage of the studied WIG drops from 200 [V] to 122 [V] with 39% voltage variation and the stator current drops from 1.65 [A] (no-load current) to 1 [A]. The total average active power of connecting the resistive load is about 40 [W] but the active power in section (a) is randomly varied. The reactive power of the studied WIG is about -500 [VAR] before connecting the load since the stator windings of the WIG must absorb reactive power. When the load is connected, the reactive power drops to as low as -100 [VA]R. Since the studied WIG supplied positive active power and negative reactive power, the power factor at the WIG's terminal is kept to be leading. The power factor of the studied WIG with a resistive load is higher than the one without load. The frequency at WIG's terminals drops from 50 to 47 [H]z with 6% frequency variation.

From the results shown in Fig. 5 it is found that the load voltage drops from 205 [V] to 127 [V] with 38% voltage variation and the stator current jumps from 0 [A] to 0.3 [A]. The total average active power of connecting the resistive load is about 30 W but the active power in section (b) is randomly varied. The reactive power of the load is changed from 0 [VAR] to be randomly varied waveform with average value of 0 [VAR] since the load is resistive. The power factor of the load is changed from 1.0 unity to be a randomly varied waveform with average value of 1.0. The frequency at load drops also from 50 to 47 [Hz] with 6% frequency variation.

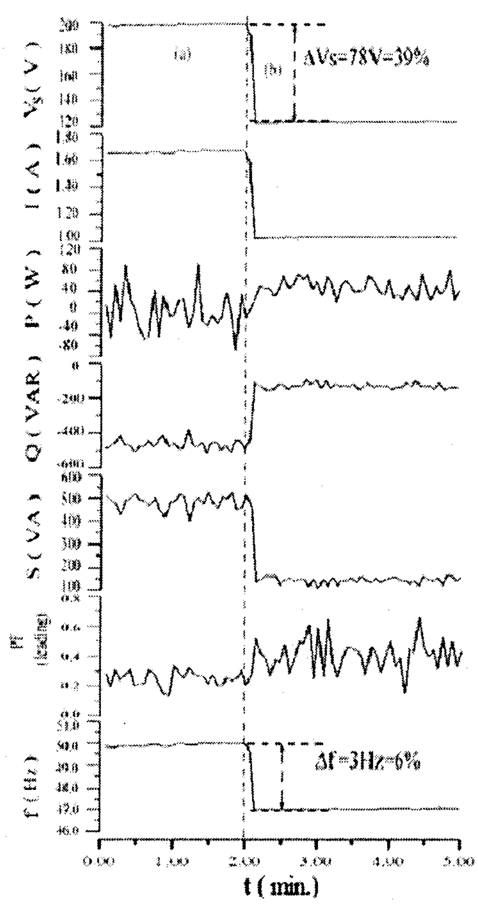


Fig. 4 Measured results at terminals of the studied WIG.

3.2 Amplification of Current Harmonics Due to Excitation Capacitors

This section compares the total harmonic distortion (THD) of the current generated at terminals of the studied WIG and the load. The top plot shown in Fig. 6 (a) is the stator current waveform at WIG's terminals, which is identical to the current waveform shown in Fig. 4. The bottom plot in Fig. 6 (a) shows the THD variation during the 5 [min.]. Before connecting the load, the average value of THD is as low as about 25% average value. However, the value of THD jumps to as high as about 70% average value when the resistive load is connected. The left plot of Fig. 6 (b) shows the probability distribution of THD and it is found the highest probability of 40% is on THD ranging from 19% to 33.8% and the probability of 30% is on THD ranging from 75.8% to 82.8%. The right plot of Fig. 6 (b) shows that the 95% cumulative probability distribution of THD is about 83.241%.

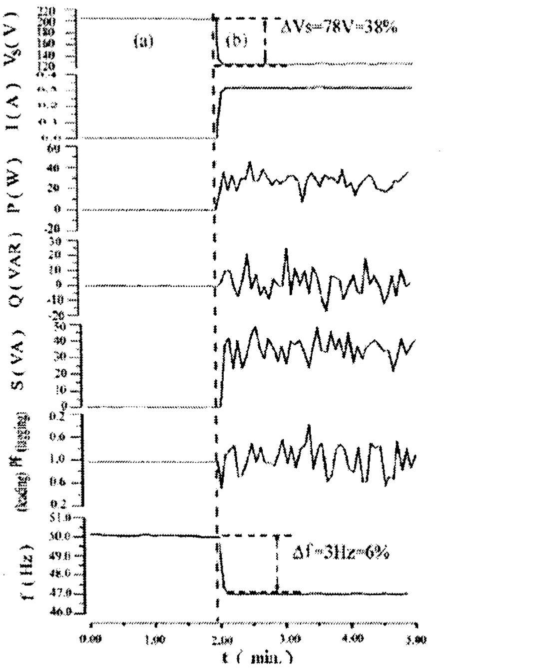
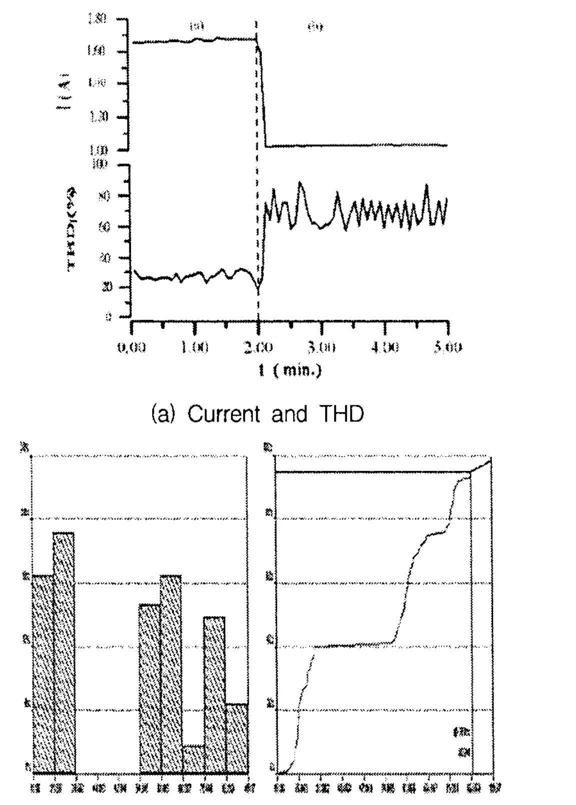


Fig. 5 Measured results at terminals of the connected load.

The top plot shown in Fig. 7 (a) is the load-current waveform at load terminals. The bottom plot in Fig. 7 (a) shows the THD variation during the studied 5 [min.]. Before connecting the load, the average value of THD is as high as about 400% average value. This no-current section with high THD should be neglected since very low current results in very large and meaningless THD. However, the value of THD drops to as low as about average value of 200% when the load is connected. The left plot of Fig. 7 (b) shows the probability distribution of THD and it is found the highest probability of 50% is on THD ranging from 153% to 246% and the probability of 24% is on THD ranging from 339% to 433%. The right plot of Fig. 7 (b) shows that the 95% cumulative probability distribution of THD is about 496.478%. Since the currents in Figs. 6 and 7 are very small, the obtained values on THD are very high.

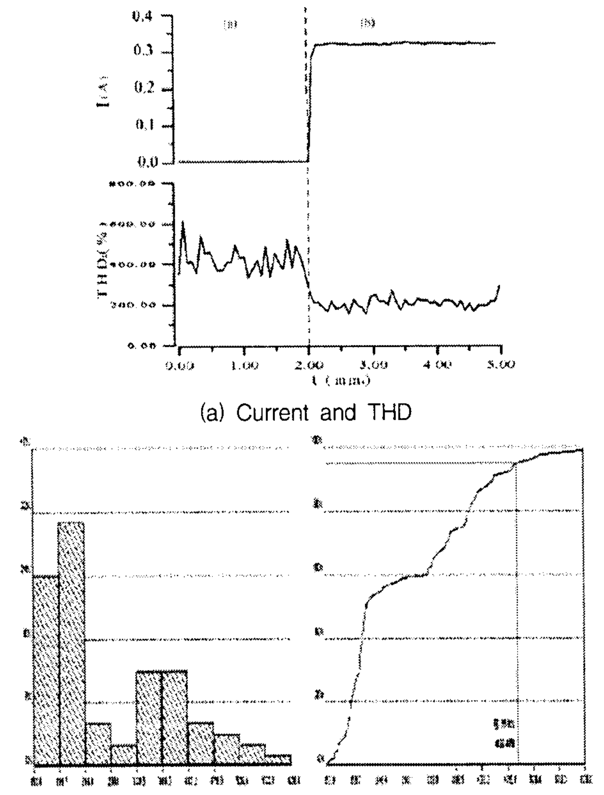
Because the three-phase excitation capacitors are located at the terminals just between the WIG and the load, it can be concluded from the measured results shown above that the excitation capacitors contributed severe current harmonics to the load due to their inherent low impedance at high frequency. In other words, the excitation capacitors amplify the high-frequency current harmonics generated from the studied WIG and send them to the connected load.



(a) Current and THD

(b) Probability distribution and cumulative distribution function

Fig. 6 Current and THD at the terminals of the connected WIG.



(a) Current and THD

(b) Probability distribution and cumulative distribution function

Fig. 7 Current and THD at the terminals of the connected WIG.

4. Conclusions

This paper has presented the measured electrical quantities of a three-phase Δ-connected wind induction generator (WIG) under sudden connection and disconnection of resistive loads. An intelligent power-system recorder/monitor has been employed to measure three-phase voltages and currents of the studied system at the terminals of the studied WIG and the load. The measured electrical quantities have been analyzed. Total harmonic distortion (THD) of current using cumulative probability density function has been employed to determine the penetration of harmonic distortion at load side. The results show that the harmonic currents generated by the studied WIG can be severely amplified by the connected self-excited capacitance at the stator's terminals.

Acknowledgement

This work was financially supported by MOCIE program (R-2007-2-234-01).

References

[1] E. D. Basset and F. M. Potter, "Capacitive excitation of induction generators", Trans. American Institute Electrical Engineering, Vol. 54, pp.540-545, 1935.

[2] T. Thiringer, "Power quality measurements performed on a low-voltage grid equipped with two wind turbines", IEEE Trans. Energy Conversion, Vol. 11, no. 3, September, pp.601-606, 1996.

[3] M. G. Ioannides, "A new approach for the prediction and identification of generated harmonics by induction generators in transient state", IEEE/PES 1994 Summer Meeting, Paper 94 SM 360-8 EC, San Francisco, CA, 1994.

[4] S. S. Yegna Narayanan, B. K. Murthy, and G. S. Rao, "Dynamic analysis of a grid-connected induction generator driven by a wave-energy turbine through hunting networks", IEEE Trans. Energy Conversion, Vol. 14, no. 1, pp.115-121, 1999.

[5] W. E. Feero and W. B. Gish, "Overvoltages caused by DSG operation: Synchronous and induction generators", IEEE Trans. Power Delivery, Vol. 1, no. 1, pp.258-264, 1986.

[6] W. B. Gish, W. E. Feero, and S. Greuel, "Ferroresonance and loading relationships for DSG installations", IEEE Trans. Power Delivery, Vol. 2, no. 3, pp.953-959, 1987.

[7] A. H. Ghorashi, S. S. Murthy, B. P. Singh, and B. Singh, "Analysis of wind driven grid connected induction generators under unbalanced grid conditions", IEEE Trans. Energy Conversion, Vol. 9, no. 2, pp.217-223, 1994.

[8] S. D. Rubira and M. D. McCulloch, "Control method comparison of doubly fed wind generators connected to the grid by asymmetric transmission lines", IEEE Trans. Industry Applications, Vol. 36, no. 4, pp.986-991, 2000.

[9] O. J. M. Smith, "Three-phase induction generator for single-phase line", IEEE Trans. Energy Conversion, Vol. 2, no. 3, pp.382-387, 1987.

[10] Å. Larsson, "Flicker emission of wind turbines during continuous operation", IEEE Trans. Energy Conversion, Vol. 17, no. 1, pp.114-118, 2002.

[11] Å. Larsson, "Flicker emission of wind turbines caused by switching operations", IEEE Trans. Energy Conversion, Vol. 17, no. 1, pp.119-123, 2002.

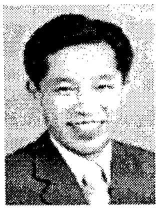
[12] G. Saccomando, J. Svensson, and A. Sannino, "Improving voltage disturbance rejection for variable-speed wind turbines", IEEE Trans. Energy Conversion, Vol. 17, no. 3, pp.422-428, 2002.

저 자 소 개

오 용 (吳 鏞)

1964년 8월 2일생. 1987년 전남대학교 졸업 (학사). 1989년 동 대학원 졸업 (석사). 2007년~현재 동신대학교 대학원 전기공학과 박사과정.

E-mail : hanelc@chol.com



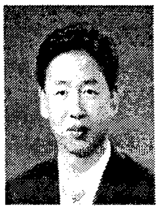
황 종 선 (黃 宗 善)

1953년 12월 13일생. 1977년 2월 한양교 전기공학과 졸업(공학사). 1979년 동 대학원 졸업(석사). 1995년 전북대학교 전기공학과 졸업(박사). 1987-1998 한국원자력연구원 책임연구원. 1998~현재 전남도립대학 컴퓨터응용전기과 교수. 2001~현재 한국직업능력개발원 평가위원. 1999~2002 국제기능올림픽 국제심사위원 Commercial Wiring Trade. 1998~2002 한국기능올림픽위원회 옥내배선 전국대회 심사위원. 1999~2002 한국산업단지공단 자문위원.

Tel : 061-380-8621

Fax : 061-380-8466

E-mail : hlepw@hanmail.net



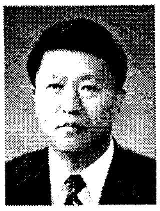
최 용 성 (崔 龍 成)

1967년 11월 14일생. 1991년 동아대학교 전기공학과 졸업 (학사). 1993년 동 대학원 전기공학과 졸업 (석사). 1998년 동 대학원 전기공학과 졸업 (공박). 1999년~2001년 JAIST Post-Doc.. 2001년~2003년 Osaka Univ. Post-Doc.. 2002년~2005년 원광대학교 연구교수. 2006년~현재 동신대학교 전기공학과 교수. 2006년~현재 전력산업인력양성사업단 기획운영부장.

Tel : 061-330-3204

Fax : 061-330-3103

E-mail : yschoi67@dsu.ac.kr



이 경 섭 (李 炅 燮)

1956년 11월 09일생. 1983년 조선대학교 전기공학과 졸업(학사). 1986 동 대학원 전기공학과 졸업(석사). 1991년 동 대학원 전기공학과 졸업(공박). 1988년~현재 동신대학교 전기공학과 교수. 1994년~ 1995년 동경공업대학 객원연구원. 2006년~현재 전력산업인력양성사업단 단장.

Tel : 061-330-3203

Fax : 061-330-3103

E-mail : kslee@dsu.ac.kr