새로운 파라메타인 부분방전 변화지수에 의한 발전기 고정자 권선의 절연상태 평가

論 文
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The Assessment on the Insulation Condition of Generator Stator Windings by a Novel Parameter PDI(Partial Discharge Index)

黃 敦 夏[*] · 朴 都 永[*] · 金 容 柱[**] · 金 鎭 峰[***] · 朱 榮 鎬[§]
(Don-Ha Hwang · Doh-Young Park · Yong-Joo Kim · Jin-Bong Kim · Young-Ho Ju)

Abstract - The monitoring and assessment on the insulation condition of generator stator windings have been an important task of utility companies. The interest for the assessment of insulation condition has been increasing due to the need to keep old generating equipment reliable in order to extend the equipment life and to increase the generating capacity. Even though many developments and research activities for the condition assessment of generator insulation have been performed for decades, the assessment criterion in order to consistently predict the actual insulation condition is still in question. In this paper, the correlation between the parameters and the insulation condition is analyzed through the various non-destructive diagnostic tests in order to establish the assessment criterion on insulation deterioration of generator stator windings. By analyzing the correlation, PDI(Partial Discharge Index) as a novel parameter for the assessment criterion on insulation diagnosis of stator windings is proposed and verified.

Key Words : Generator Stator Winding, Insulation Condition, PDI(Partial Discharge Index), Assessment Criterion

1. Introduction

Presently, there are many diagnostic tests available, which may provide important information on the insulation condition of generator stator windings. Some diagnostic parameters, such as partial discharge magnitude, give indication of the relative condition of generator stator insulation. The parameters indicating the absolute condition of generator stator insulation have been sought [1].

Recently partial discharge measurements have been considered as the most important diagnostic technology for maintenance of stator windings based on insulation condition. Though the partial discharge measurements are an important diagnostic test, it can not be used as the only means for objectively assessing the actual insulation condition. For that purpose, a correlation between the breakdown strength and various combinations of the results from diagnostic measurements, e.g., partial discharges, capacitance, and dissipation factor, should be considered [1-2].

As it is difficult to obtain a single effective diagnostic test, the assessment on the condition of generator stator winding has attracted many discussions. Numerous experiments have been reported to ensure that old generating plants continue to be reliable power producers and to avoid in-service failures all over the world, utilizing various diagnostic tests. Many studies have attempted to identify new calibration technique [3], eliminating external noise [4] and predicting remaining life of machine insulation [5-7]. The absolute magnitude of partial discharge has been the decision criteria of the insulation condition in Japan [6-8]. In North America [1], [10-11], the trend of partial discharge activities over time with the on/off-line scheme has been the common practice.

This paper reports the investigation of factors which can estimate the insulation condition. A new parameter, PDI (Partial Discharge Index), is introduced as the realistic diagnostic measure for the assessment of insulation condition. The ratio between partial discharge increment and stepwise voltage increment from discharge inception voltage at characteristic or resonant frequency band showed the high correlation between breakdown voltage and PDI.

2. Methods of the diagnostic tests

2.1 Sample bars and windings

Four different types of stator bars are tested to destruction in order to evaluate the conventional diagnostic

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[*] 正 會 員 : 韓國電氣研究所 Mechatronics研究그룹 先任研究員
[**] 正 會 員 : 韓國電氣研究所 産業電氣研究團 責任研究員 團長
[***] 正 會 員 : 韓瑞大學校 航空機械學科 助敎授
[§] 正 會 員 : 韓電 電力研究院 發電計電그룹 責任研究員 部長

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tests. Three out of four types (generators A, B, and C) have been operated more than 20 years and the rest of them (generator G) is aged up to 7,000 [hours] in the laboratory. In the accelerated aging tests, the new stator bars are subjected to the enhanced voltage stresses at 420 [Hz]. In addition, three different types of complete stator windings (generators D, E, and F) are tested on-site. The details of the bars and windings are outlined in Table 1.

Table 1 The specification of generators

Generator	Type	Rating (Capacity /Voltage)	Insulation system	Operating time	Quantity of bars (or phases)
A	Turbine Generator (Fossil)	300 MVA 17 kV	Polyester	25 years	20 ea
B	Hydro Generator	27 MVA 11 kV	Polyester	23 years	15 ea
C	Hydro Generator	22.6 MVA 6 kV	Polyester	22 years	16 ea
D	Turbine Generator (Gas)	72 MVA 13.8 kV	Polyester	20 years	3 phases
E	Pumped Storage Generator	33.6 MVA 18 kV	Epoxy	10 years	3 phases
F	Nuclear Generator	500 MVA 22 kV	Epoxy	New	3 phases
G	Turbine Generator (Fossil)	500 MVA 22 kV	Epoxy	7,000 hours (aged in lab.)	10 ea

2.2 Test methods

2.2.1 Diagnostic test

Prior to the destructive breakdown test, the sample bars are subjected to a variety of non-destructive diagnostic tests to assess their insulation conditions. All the diagnostic tests are performed on the individual bars of generators A, B, C, and G, which are removed from the generator and installed into the simulated slots. For the case of generators D, E, and F, each phase is tested within the stator core, as the normal practice for diagnostic tests on generator.

Standard test procedures, such as the measurements of capacitance, dissipation factor, and partial discharge intensity at several voltages up to 1.25 times the rated phase to ground voltage ($1.25 \times E/\sqrt{3}$ [kV], E ; rated voltage), are applied.

Tettex 9124 Partial Discharge Measuring System with both the conventional amplifier of 40 [kHz] to 200 [kHz] frequency bandwidth and the narrow band amplifier of 30 [kHz] to 2 [MHz] frequency bandwidth is used to measure partial discharge.

2.2.2 Destructive test

After completion of the diagnostic tests on individual bars of generators A, B, C, and G, the groundwall insulation of each bar is subjected to the gradually increasing AC voltages until the insulation failed. The 60 [Hz] AC voltage is linearly increased by about 1 [kV/sec]. AC dielectric test system (100 [kV], 1 [A], Hipotronics) is used for the destructive test.

In the case of generator E, the destructive test is also performed using DC power supply. The test voltage ($2 \times E$ [kV]), derived from IEEE standard 95 [12], is maintained for one minute. For generator F, AC breakdown voltage ($1.5 \times E$ [kV]) is maintained for one minute.

3. Results and discussions

3.1 Relationship between the diagnostic parameters and breakdown voltage

Prior to destructive test, various diagnostic tests are performed on the bars. In general, the percentage change in bar capacitance ($\Delta C/C_O$) and the change in dissipation factor ($\Delta \tan\delta$) are the quality of the insulation system. $\Delta C/C_O$ versus $\Delta \tan\delta$ from 1 [kV] to 1.25 times the rated phase to ground voltage for generator A is found highly correlated as shown in Fig. 1. Physically, both parameters are measures of the void content in the insulation, and if the system has a large number of voids, then $\Delta \tan\delta$ and $\Delta C/C_O$ would increase as the voltage is increased. However, as $\Delta \tan\delta$ and $\Delta C/C_O$ measurements are averaging type measurements, they will not identify a coil or a bar that has a single large void. Partial discharge magnitude (Qm), on the other hand, will identify this coil or bar as it is a specific event measurement. Fig. 2 shows that there has been no correlation between Qm and $\Delta \tan\delta$ or $\Delta C/C_O$.

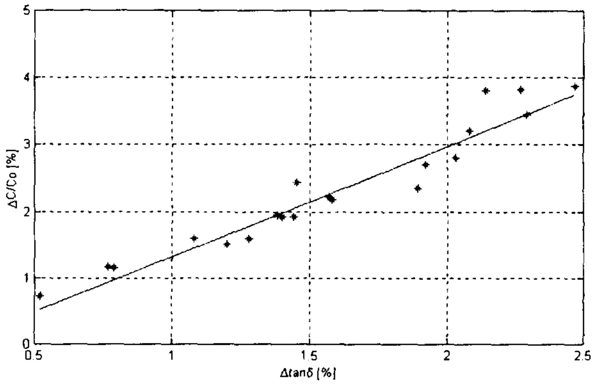


Fig. 1 Comparison of diagnostic quantities $\Delta C/C_O$ vs. $\Delta \tan\delta$ measured at 1 [kV] to 12.3 [kV] (Sample bars of generator A).

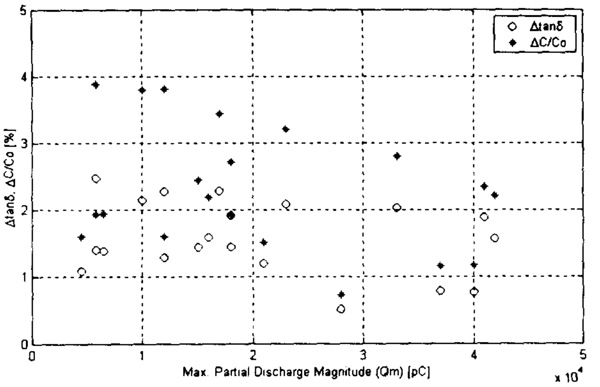


Fig. 2 Relationship between Qm and $\Delta\tan\delta$, $\Delta C/C_0$ (Sample bars of generator A).

To obtain correlation of Qm, $\Delta C/C_0$, $\Delta\tan\delta$, and breakdown voltage, the destructive tests are performed on the sample bars of generator A, B, C, and G. The data of sample bars punctured only at the slot region as shown in Fig. 3 are selected to compare the relationship between diagnostic parameters and breakdown voltage.

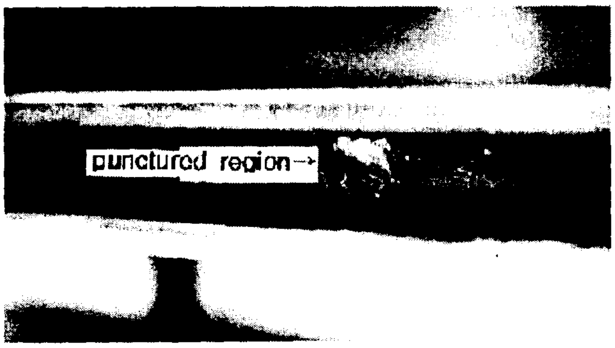


Fig. 3 Punctured region (No. 31 sample bar of generator A).

Fig. 4 & 5 are the plots of AC breakdown voltage (V_{BD}) versus some of these measured or derived diagnostic parameters. The figures clearly show a lack of correlation between the diagnostic parameters and breakdown voltage as reported in [11], [13]. The test result is similar to the ones reported by G. Anders [11], while contrary to the result by H. Yoshida [14].

In case of generator G, as there is no evidence of degradation during accelerated aging up to 7,000 [hours], the destructive test is performed. Only one out of eight bars is failed and it is concluded that the accelerated aging only by electric stress can not degrade the insulation. Therefore, the mechanical or thermal cycling stress should be applied to cause the progressive deterioration of stator winding insulation.

Fig. 6 shows Qm measured from the sample bars of generator A at $E/\sqrt{3}$ [kV]. According to a certain criterion [7], four sample bars of generator A (No. 17, 18, 20, and 21) whose Qms were higher than 30,000 [pC] should have been in the relatively poor insulation condition. However, the bars did not fail over 80 [kV], but only result in surface flashover. On the other hand, the other sample bars such as No. 31, which did not have high Qm (28,000 [pC]) and could be judged to be in the relatively moderate insulation condition, unexpectedly failed at 15 [kV].

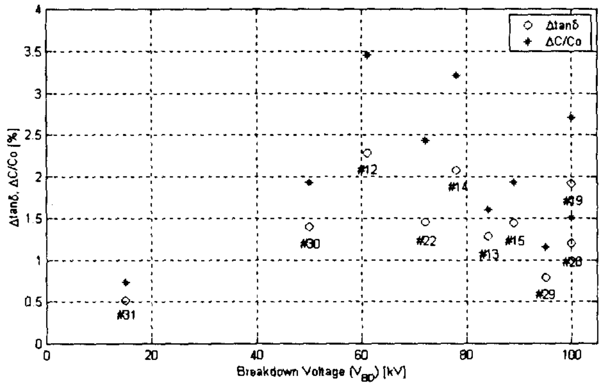


Fig. 4 Relationship between V_{BD} and $\Delta\tan\delta$, $\Delta C/C_0$ (Generator A).

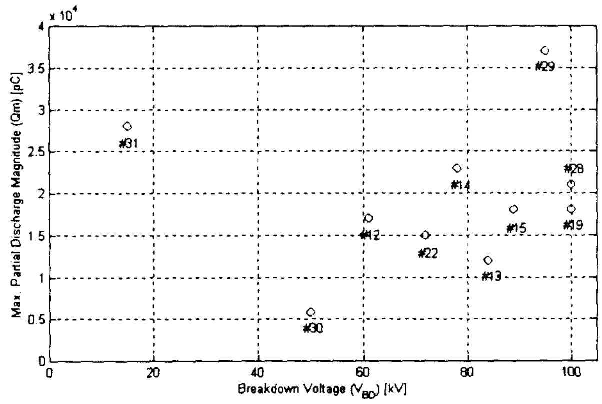


Fig. 5 Relationship between V_{BD} and Qm at $E/\sqrt{3}$ [kV] (Generator A).

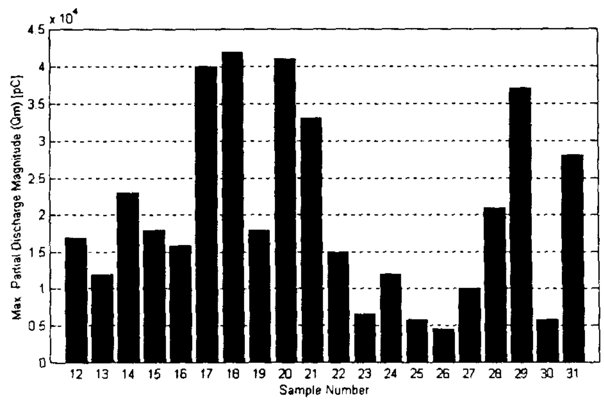


Fig. 6 Qm of each sample for generator A.

Table 2 represents similar information as in Fig. 6. After diagnostic tests are completed, a bundle of phases of generator E and each phase of generator F are subjected to breakdown test. In spite of high partial discharge activities, neither of the insulation of generator E nor generator F are punctured except one phase of generator F. In case of punctured phase of generator F, the groundwall insulation is not punctured, but the end winding insulation near the slot exit has flashover and it is concluded that the flashover is caused by poor surface treatment. From the results shown in Fig. 6 and Table 2, it can be concluded that the condition of insulation can not be assessed by the single parameter, such as Qm. Therefore, a novel parameter is needed to judge the condition of the machine whether it is near to its end of life or not.

Table 2 Results of diagnostic and destructive tests for generators E and F.

Generator	Phase / Parameter	U	V	W
E	Maximum PD magnitude (Qm)	60,000 [pC]	51,000 [pC]	61,000 [pC]
	Breakdown	Not failed		
F	Maximum PD magnitude (Qm)	40,000 [pC]	42,000 [pC]	41,000 [pC]
	Breakdown	2 Phases : Not failed		
		1 Phase : Failed at the end winding near slot exit		

3.2 Novel parameter for condition assessment of stator windings

Based on the test results of sample bars, it is clear that the diagnostic tests alone can not judge the absolute condition of stator windings, especially when the tests are performed only once. However, some diagnostic parameters, such as partial discharge magnitude, indeed give an indication of relative condition [14]. Thus, the information from such diagnostic tests is very useful when it is taken over time, so that a history of winding can be referred to judge the condition of insulation.

As off-line diagnostic tests are performed at an interval of four or five years, it is difficult to judge the condition of insulation of the machine whether it is near to its end of life or not. Thus, a novel diagnostic parameter or a criterion is needed to identify the condition of insulation.

The Partial Discharge Index(PDI) defined by Eq. (1) is proposed as a novel assessment criterion in order to overcome the previously mentioned difficulties [15].

$$PDI = \frac{(Q_m - 1,000)}{(V_n - V_i)} \quad [\text{pC/kV}] \tag{1}$$

In Eq. (1), V_n is the applied voltage, V_i is the voltage when the apparent maximum partial discharge magnitude is 1,000 [pC], and Qm is the apparent maximum partial discharge magnitude at V_n.

3.3 Criteria for condition assessment of stator insulation by PDI

The shape of measured partial discharge is dependent on the coupling impedance between the partial discharge measurement circuit and the detector. Resonant frequency of partial discharge pulse is reported to be varying according to the number of connected coils or windings [16]. The resonant frequency ($R.F.$) can be simplified as

$$R.F. = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

where L and C are the coil inductance and capacitance.

Because the propagation modes and attenuation rates of partial discharge pulse cause difference in the measurement of its magnitude, the choice of detector frequency range is important in partial discharge measurement. It is reported that the detection of series mode pulses leads to the accurate measurements of partial discharge [17].

Fig. 7 shows the frequency response of partial discharge of the sample bars of generators A, B, and D. The resonant frequency for each sample of generators A and B is 0.57 [MHz]. On the other hand, the resonant frequency is lower than 100 [kHz] for each phase winding of generator D which has 26 windings per phase.

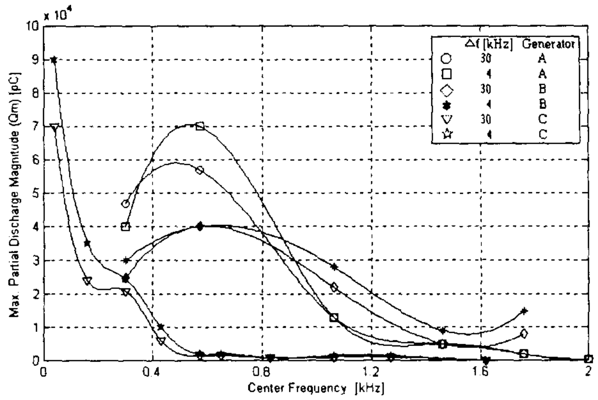
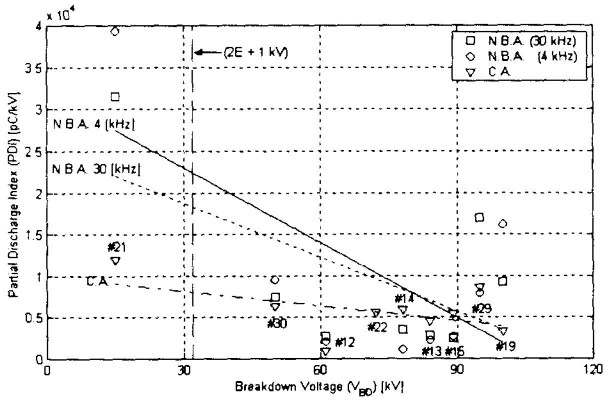
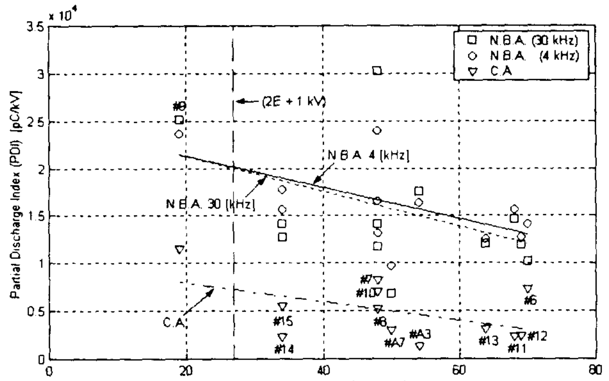


Fig. 7 Frequency response of Qm ($E/\sqrt{3}$ [kV]).

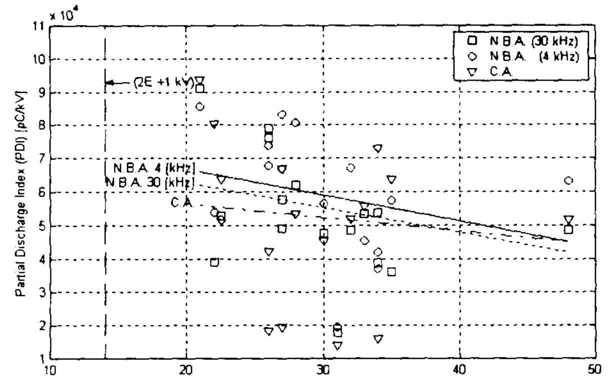
The partial discharge is measured with two different amplifier to identify the influence of the detector's frequency range : conventional amplifier (40 [kHz] to 200 [kHz]) and narrow band amplifier (30 [kHz] to 1 [MHz]) at resonant frequency (0.57 [MHz]) with two bandwidths (Δf : 4 [kHz] and 30 [kHz]). It is measured at stepwise voltages up to $E/\sqrt{3}$ [kV].



(a) Sample bars of generator A ($0.5\times E/\sqrt{3}$ [kV]).



(b) Sample bars of generator B ($E/\sqrt{3}$ [kV]).



(c) Sample bars of generator C ($E/\sqrt{3}$ [kV]).

Fig. 8 Correlation between PDI and breakdown voltage. (C.A. ; Conventional Amplifier, N.B.A. ; Narrow Band Amplifier)

The maximum PDI is used to judge the condition of sample bar. The voltages which produce the maximum PDI are $0.5\times E/\sqrt{3}$ [kV] for the bars of generator A and $E/\sqrt{3}$ [kV] for the bars of generator B.

Fig. 8 shows the linear relationship between PDI and breakdown voltage. It shows a strong correlation among them in the whole frequency range. The vertical dashed line($2E+1$ [kV]) in the each plot means the endurance voltage. The breakdown voltages of No. 31 bar of generator A and No. 9 bar of generator B are lower than the endurance voltage, and their PDIs are higher than those of any other bars in the whole frequency range.

Table 3 shows the PDI level which the winding can not withstand the voltage over $2E+1$ [kV]. From the results, it can be suggested that the windings, whose PDIs at each frequency band are above the critical level, are judged not to withstand the endurance voltage and to be in severely deteriorated condition.

In addition, PDI level for deteriorated insulation is not unique for every insulation but depends on the rated voltage of insulation or other factors. Therefore, further study is needed to apply PDI parameter to assess the various types of insulation system.

Table 3 PDI criteria for deteriorated insulation of generators A, B, and C.

Amplifier (Frequency range)	PDI criteria [pC/kV]		
	Generator A	Generator B	Generator C
Conventional amplifier (40~200 kHz)	≥ 7,500	≥ 7,500	≥ 60,000
Narrow band amplifier (570±30 kHz)	≥ 20,000	≥ 20,000	≥ 70,000
Narrow band amplifier (570±4 kHz)	≥ 20,000	≥ 20,000	≥ 70,000

4. Conclusions

A novel method on assessing the insulation condition of generator stator windings has been investigated. Even though only a limited number of sample bars with specific systems have been under investigation, it is shown that PDI has strong correlation with breakdown voltage and it has been successfully applied to three types of stator bars. The conclusions can be summarized as follows ;

(1) $\Delta C/C_0$ versus $\Delta\tan\delta$, which represents the void content in the stator insulation, is highly correlated.

(2) Qm, $\Delta\tan\delta$, and $\Delta C/C_0$ show a lack of correlation with breakdown voltage.

(3) A novel diagnostic parameter PDI is highly correlated with breakdown voltage. It can be used as a reliable criterion in order to assess the condition of windings.
(4) As resonant frequency of partial discharge pulse of generator windings is lower than 100 [kHz], the low frequency measuring system with noise elimination is needed.
(5) PDI level for deteriorated insulation is not unique for every insulation but depends on the rated voltage of insulation or other factors.

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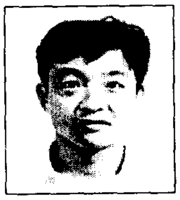
저자소개

황 돈 하 (黃 敦 夏)

1969년 2월 10일생. 1991년 영남대 전기공학과 졸업. 1993년 동 대학원 전기공학과 졸업(석사). 1993년~현재 한국전기연구소 Mechatronics연구그룹 선임연구원

Tel : (0551) 280-1544
Fax : (0551) 280-1547
E-mail : dhhwang@keri.re.kr



박 도 영 (朴 都 永)

1962년 3월 19일생. 1984년 서울대 전기공학과 졸업. 1986년 동 대학원 전기공학과 졸업(석사). 1997년 Queen's University 졸업(공박). 1987년~현재 한국전기연구소 Mechatronics연구그룹 선임연구원

Tel : (0551) 280-1545
Fax : (0551) 280-1547
E-mail : dypark@keri.re.kr

김 용 주 (金 容 柱)

1953년 11월 12일생. 1975년 서울대 전기공학과 졸업. 1984년 R.P.I. 전기공학과 졸업(석사). 1987년 동 대학원 전기공학과 졸업(박사). 1988년~1993년 한국전기연구소 전력기기연구실장. 1993년~1999년 한국전기연구소 발전기진단연구팀장. 1996~1999년 한국전기연구소 고속전철사업그룹장 겸임. 1999년 ~ 현재 한국전기연구소 산업전기연구단장

Tel : (0551) 280-1400, Fax : (0551) 280-1547

E-mail : yjkim@keri.re.kr

김 진 봉 (金 鎭 峰)

1958년 7월 17일생. 1981년 고려대 기계공학과 졸업. 1985년 부산대 대학원 기계공학과 졸업(석사). 1992년 고려대 대학원 기계공학과 졸업(박사). 1982~ 1998년 한국전기연구소 발전기진단연구팀 선임연구원, 1998년~현재 한서대학교 항공기계학과 조교수

Tel : (0455) 660-1463, Fax : (0455) 660-1119

E-mail : jbkim@hanseo.ac.kr

주 영 호 (朱 榮 鎬)

전기학회논문지 제48권 제3호 참조

Tel : (042) 865-5260, Fax : (042) 865-5214

E-mail : juyh@kepri.re.kr