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A Study on the Insulation Characteristics for Stator Windings of IGBT PWM Inverter-Fed Induction Motors

[1]Don-Ha Hwang*, [1]Dong-Sik Kang, [1]Yong-Joo Kim, [2]Tae-Hoon Lim, [2]Sung-Woo Bae, [2]Dong-Hee Kim, and [2]Chae-Gyun Ro

[1]Industry Applications Research Lab., Korea Electro-technology Research Institute (KERI), Changwon, Korea
[2]School of Electrical & Electronic Eng., Yeungnam Univ., Kyongsan, Korea

ABSTRACT

The winding insulation of low-voltage induction motors in adjustable-speed drive system with voltage-fed inverters is substantially stressed due to the uneven voltage distribution and excessive voltage stress (dv/dt), which result in the premature insulation breakdown In this paper, the detailed insulation test results of 26 low-voltage induction motors are presented. Six different types of insulation techniques are applied to 26 motors. The insulation characteristics are analyzed with partial discharge, discharge inception voltage, AC current, and dissipation factor tests Also, insulation breakdown tests by high voltage pulses are performed, and the corresponding breakdown voltages obtained.

Keywords: Induction motor, IGBT PWM inverter, dv/dt, stator winding, partial discharge, electrical breakdown

1. Introduction

The inverter driven induction motors are applied in the various fields of industry where the variable speed drive is needed Induction motors driven by PWM inverters have capabilities of variable speed operation and accurate speed control by the control of voltage and frequency. The application of theses motors have been rapidly increasing due to the progress of power electronics technologies including power semiconductors and digital control techniques[1-4].

Recently the switching frequencies of inverters have been increasing due to the application of IGBT devices whose switching frequency range is 2~20[kHz] The faster switching frequency allows the higher rate of voltage increase, which in turn contributes to the reduction of switching losses, reduction of audible noise, easiness of heat dissipation, and better current waveforms. But some adverse effects on the stator winding insulation are reported due to the uneven voltage distribution and excessive voltage stress, which result in the premature insulation breakdown[1-6].

In the variable-sped induction motor drive system with IGBT PWM inverter, insulation breakdown has become serious problem and lots of research works have been attempted to solve this problem, including design of filter or reactor suppressing transient surge voltage[7-9], adoption of insulation strengthened magnet wire[10], improvement of insulation class in stator winding[11], and so on. However, these methods cause manufacturing and insulation costs to be increased and especially studies

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Corresponding Author: dhhwang@keri re kr Tel +82-55-280-1544, Fax: +82-55-280-1547

about insulation design, impregnation and insulation characteristics do not widely reported even though they are very important factors in the design of induction motor.

In this paper, the test results for evaluation on the stator winding insulation of 310[V], 5 5[kW] induction motors for elevator applications are presented Also, the insulation characteristics are presented in order to analyze the insulation strength under high voltage pulse due to high switching speed of IGBT PWM inverter.

Twenty-six induction motors of six types with different wires and insulation techniques are built and thoroughly tested. The maximum partial discharge (PD) magnitude (Qm) and the discharge inception voltage (DIV) are obtained by PD test Under AC current test, the rate of change in AC current (ΔI) and the dissipation factor tip-up (Δtanδ) are measured

A single phase IGBT PWM inverter is built and used for the insulation breakdown test to compare and analyze the breakdown voltages of motors with different wires and insulation techniques. This single-phase inverter has the same switching surges in magnitude and dv/dt of one phase of the three-phase inverter which is used for driving the motors

From the above test data, the effects due to different wires and insulation techniques on the insulation characteristics of low-voltage induction motors are compared and analyzed The insulation technique to enhance the insulation strength is suggested from the test results Also, the criterion to assess the insulation strength for quality assurance test at the shop is proposed

2. IGBT PWM Inverter-Fed Induction Motor

2.1 Insulation System of Stator Winding

The insulation system of stator windings consists of the main and phase insulation as shown in Fig. 1 The main or slot insulation separates the winding from the stator core The different potentials of the individual phases are separated from each other by the phase insulation The slot insulation is composed of slot separator to separate phase to phase, slot closure to separate phase to ground, and slot liners to separate phase to ground Motor varnish is used for various reasons, one of its primary purposes is to

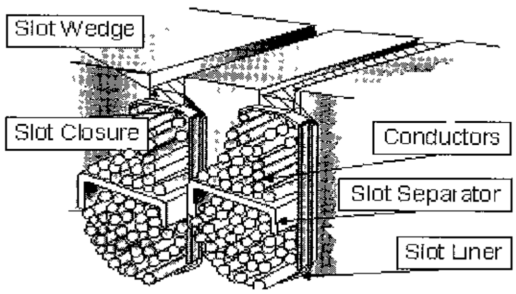


Fig 1 Insulation system of stator winding

increase the dielectric withstand capability of the insulation system[2][4][5]

The turn insulation between adjacent turns inside the coils consists of the wire enamel and an impregnating resin or varnish Due to the random nature of conductor placement of low-voltage wound winding induction motors, it is possible that the starting and end turn of a coil would be adjacent Thus, the entire coil voltage would appear between two adjacent turns Under very unfavorable conditions, the turn insulation may even be subjected to the voltage drop over multiple coils or coil groups [2-6]

2.2 Voltage Waveforms of IGBT PWM Inverter Driven Induction Motor System

The typical configuration of induction motor system driven by IGBT PWM inverter and its voltage waveforms are shown in Fig. 2 and Fig 3, respectively. Fig 3(a) shows an AC source (V_{RS}) of the 3-phase input A power line rectifier supplies the dc-link voltage (U_D) of the intermediate circuit of a voltage-fed inverter as shown in Fig 3(b). At the inverter output terminals, voltage impulses are created with amplitudes corresponding to the voltage of the dc-link circuit as shown in Fig. 3(c).

The short rise times of the voltage impulses at the inverter output result in traveling waves on the motor cable As shown in Fig 3(d) and (e), multiple reflections at both ends of the motor cable led to oscillating impulse voltages at the motor terminals. The voltage at the motor terminal has switching over-voltage with high rate of voltage rise (dv/dt). This switching surge voltage gradually decreases insulation strength of stator wire and causes the insulation breakdown eventually

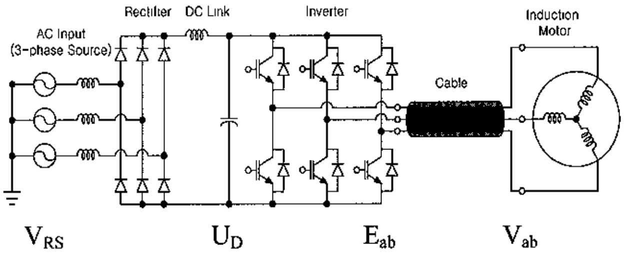
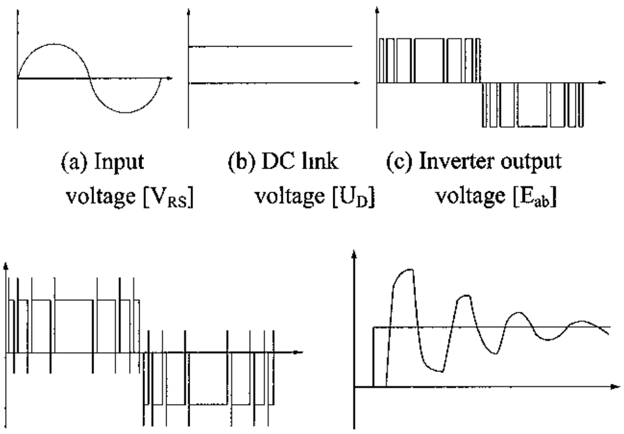


Fig 2 Configuration of induction motor system driven by IGBT PWM inverter.



(a) Input voltage [V_{RS}] (b) DC link voltage [U_D] (c) Inverter output voltage [E_{ab}]

(d) Motor terminal voltage [V_{ab}] (e) Actual motor terminal voltage

Fig 3 Voltage waveforms of IGBT PWM inverter-fed induction motor system

To prevent the premature insulation breakdown are centered on the enhancement of insulation strength of stator winding, suppression of surge voltage magnitude produced by inverter switching, restraint of the rate of voltage rise (dv/dt) applied to motor terminal, and so on[7-11].

3. Test Methods

3.1 Specification of Tested Motors

Twenty-six stators of induction motor for the insulation characteristics test are manufactured as shown in Table 1. The rating of the motor is three phase, 4 poles, 310/380 [V], 5.5/7.5[kW], F-class (155 °C)

Two different impregnation methods are used. One is standard impregnation (SI) applied vanish dipping & bake and another is vacuum pressure impregnation (VPI). The number of impregnation is differently applied from one to two. Three different wires of stator windings are used; coil A (standard coil, polyester enameled wire; PEW), coil B (polyester-amide), coil C (mica-film taped coil).

Diameter of coil A (PEW) is 0.95[mm] with insulation thickness of 0.033[mm]. Coil C has the insulation thickness of 0 16[mm]. T0.25 NTN is used for slot and phase insulation, and T0.35 NTN is used for turn insulation paper Varnish of solvent DVB-2328 is used.

3.2 Dissipation Factor and AC Current Test Methods

To measure dissipation factor (tanδ) and AC current simultaneously, Automatic Insulation Test System (Tettex, Type. 2818-QA) is used. The rate of change in AC current (ΔI) that shows current characteristics according to applied voltage is calculated by AC current test From the dissipation factor, Δtanδ (the dissipation factor tip-up) which is the difference between tanδ at the rated phase to ground voltage and $\tan\delta_0$ at the low voltage with no PD occurrence is measured[12] .

3.3 Partial Discharge Test Method

The maximum partial discharge magnitude (Qm) and discharge inception voltage (DIV) are measured by Partial Discharge Detector (Model. TE571) of Haefely Trench Tettex. The initial discharge inception voltage is an important factor for the low-voltage motor with enamel wires, therefore, noise cancellation method and sensitivity of below 1[pC] are necessary. To eliminate external noise, the measurement of PD is performed in radio frequency shield room with noise-free power supply[4], [12].

3.4 Breakdown Test Method

To analyze the insulation breakdown of windings impacted by transient switching pulse voltage while the motor is in operation, an insulation breakdown test with simulated switching pulse applied to motor windings is performed.

Fig. 4 shows the block diagram of insulation breakdown test with IGBT PWM inverter. Isolation transformer is used not to affect power sources, and the main circuit consists of diode rectifier, DC link, and IGBT PWM inverter. High-frequency (HF) step-up transformer is used to apply high-frequency switching surge voltage to the motor[4].

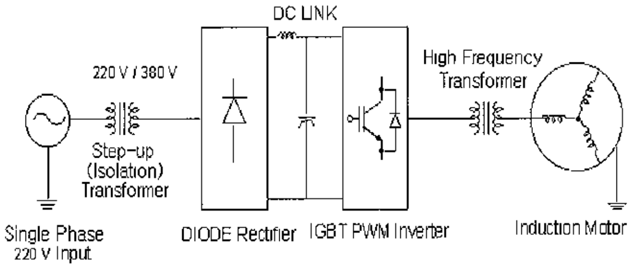


Fig 4 Block diagram of breakdown test with IGBT PWM inverter for simulated switching surge

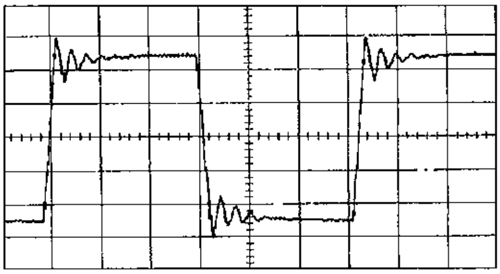


Fig 5 Example of inverter output voltage at HF transformer output terminal (20 μs/div., 2 kV/div , V_{p-p} 12 kV)

Fig 5 shows an example of inverter output voltage waveform at HF transformer output terminal, and bipolar pulse voltage is generated up to maximum of 13[kV] (peak to peak)

4. Test Results

4.1 Dissipation Factor and AC Current Tests

Fig. 6 and Fig 7 show the test results of dissipation factor and AC current tests for induction motor stator windings of six different types as shown in Table 1

Table 1 Specifications of the induction motors.
(4 pole, 310/380 V, 5 5/7 5 kW)

Enamel wire	Impregnation method	Motor symbol	No	Output [kW]	Voltage [V]	Lamination length [mm]
Coil A	SI once	LG#1 ~ LG#7	7	5 5	310	150
	SI twice	LS#1 ~ LS#3	3	5 5	310	150
	VPI once	LV#1 ~ LV#3	3	5 5	310	150
	VPI twice	LV#4 ~ LV#6	3	5 5	310	150
Coil B	SI once	LC#1 ~ LC#3	3	7 5	220/380	120
Coil C	SI once	LI#1 ~ LI#7	7	5 5	310	150

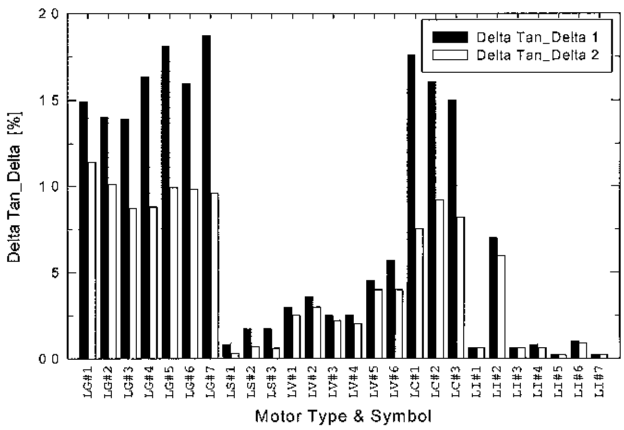


Fig 6 Test results of tan delta (Δtanδ)

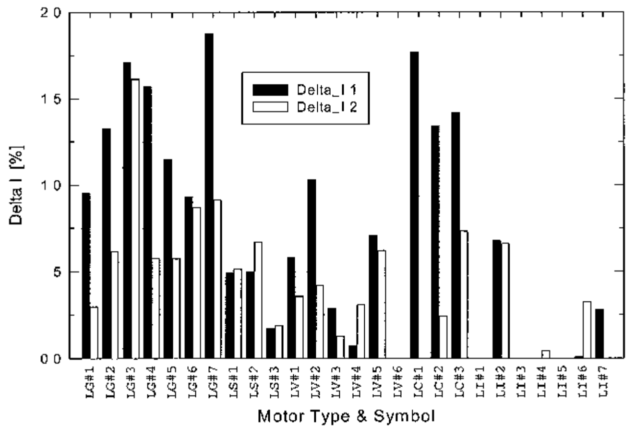


Fig 7 Test results of AC current (ΔI)

The dissipation factor tip-up (Δtanδ) is illustrated in Fig 6, where Δtanδ1 and Δtanδ2 are the differences of tanδ between 1,300[V] and 310[V], and between 1,250[V] and 310[V], respectively Δtanδ of LI motor (coil C, SI once) has the minimum value and LS motor (coil A, SI twice) has relatively low value. On the other hand, Δtanδ is very high for LG (coil A, SI once) and LV (coil A, VPI once/twice) motors Particularly, Δtanδ of LV #4, #5, and #6 motors with VPI twice is rather higher than that of LV#1, #2, and #3 motors with VPI once

The rates of change in AC current, ΔI_1 and ΔI_2 are obtained as shown in Fig 7 at 1,300[V] and 1,250[V], respectively ΔI of LG and LC motor (coil B, SI once) has the maximum value LI motor has the minimum ΔI value Also, ΔI value is relatively low for LS and LV motors.

4.2 Partial Discharge Test

Fig. 8 shows test results of discharge inception voltage (DIV) of all 26 induction motors. DIV1, DIV2, and DIV3 are the applied voltage when maximum PD magnitude becomes 10, 100, and 1,000[pC], respectively. DIV of LI motor is the highest, whereas LV motor with VPI has the lowest DIV. Therefore PD occurs at the lowest applied voltage with LV motor. The other motors have similar DIV levels.

Fig. 9 shows the maximum PD magnitude (Qm) of all the motors. The left vertical axis corresponds to black bar (■) and the right one corresponds to white bar (□). Qm1, Qm2, and Qm3 show the maximum PD magnitude when applied voltage is 900, 1,000, and 1,200[V], respectively. Qm of LI motor has the lowest value over all the applied voltages. Qm1 and Qm2 values of LV motor are the highest. LC motor has relatively low Qm1 and Qm2, but Qm3 becomes considerably high. In case of LG & LS motors, the Qm of LG motor with VPI twice is relatively low until 1,000[V], but Qm3 shows little difference at 1,200[V].

Fig. 8 and Fig. 9 indicate that, in order to reduce the PD less than 5[pC], the switching over-voltage of IGBT PWM inverter must be kept under 850[V]. Therefore, the insulation is assessed poor when the PD is detected over 10[pC] at 900[V] considering the external noise at the shop.

4.3 Breakdown Test

Fig. 10 shows insulation breakdown voltage by the switching surge. LI motor has relatively strong insulation strength under breakdown voltage over 10[kV].

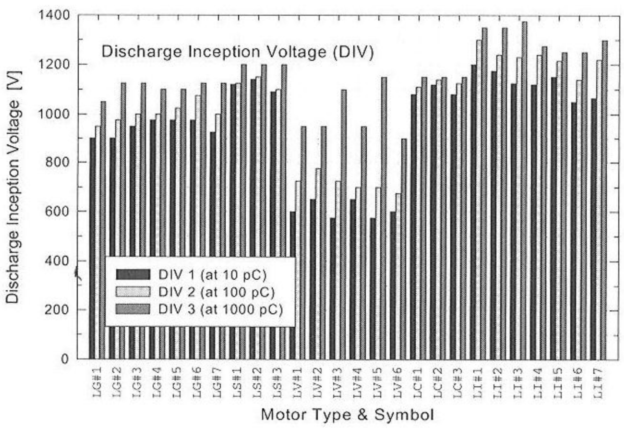
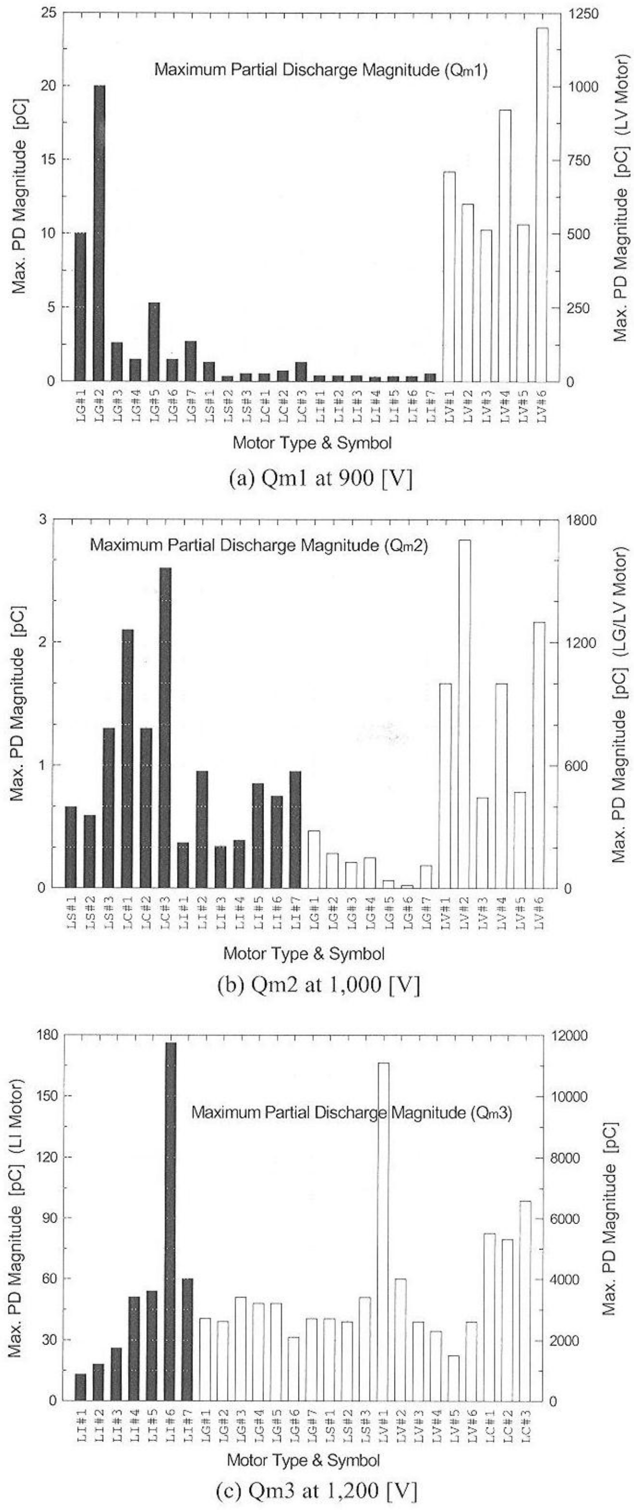


Fig. 8. Test results of discharge inception voltage (DIV).

Insulation of the other motors is failed near 7[kV]. In addition, breakdown voltage of the motor with SI twice and VPI twice are relatively higher than the others.



(a) Qm1 at 900 [V]

(b) Qm2 at 1,000 [V]

(c) Qm3 at 1,200 [V]

Fig. 9. Test results of the maximum PD magnitude (Qm).

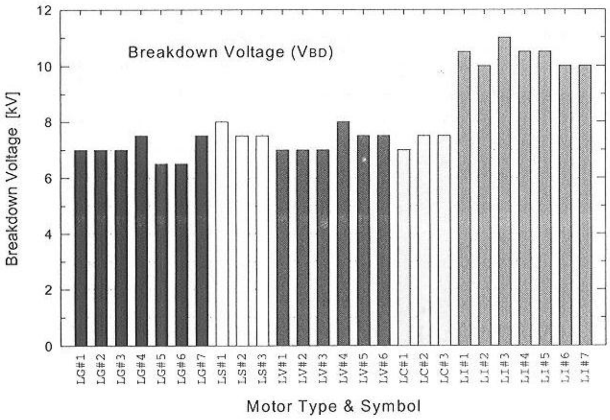


Fig. 10. Test result of breakdown voltage (V_{BD}).

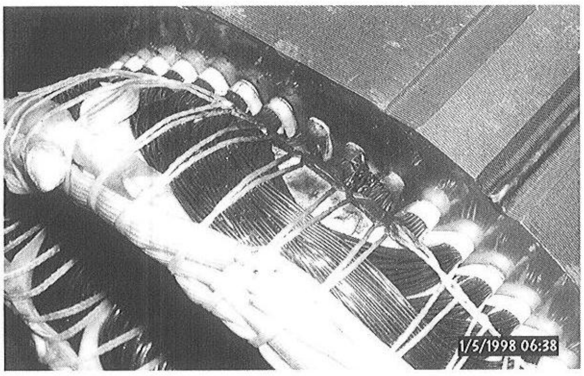


Fig. 11. Failed position of the stator.

Fig. 11 shows the failed position of stator windings. The breakdown occurred at the slot exit for all the motors under breakdown test. Therefore, in order to prevent the breakdown at the slot exit, the electric field intensity must be reduced at the slot exit.

5. Conclusions

In this paper, the insulation test results of the stator winding of twenty-six low-voltage induction motors for elevator applications are presented. Six different types of insulation techniques are applied to 26 motors. Partial discharge (Qm and DIV), AC current (ΔI), and dissipation factor tip-up ($\Delta\tan\delta$) tests are performed for each motors. Also, breakdown tests by switching pulse voltage are performed. The following conclusions can be drawn from the insulation characteristic tests for IGBT PWM inverter driven induction motors.

Table 2. The insulation characteristics of the induction motors. (1; Best, 6; Worst)

Parameter / Motor		Change in AC current (ΔI)		Change in dissipation factor ($\Delta\tan\delta$)		Discharge inception voltage (DIV)			Maximum PD magnitude (Qm)			Break-down voltage (V_{BD})	Manu-factur-ing cost
Wires and Insulation Techniques	Sym-bol	ΔI 1	ΔI 2	ΔT 1	ΔT 2	DIV 1	DIV 2	DIV 3	Qm 1	Qm 2	Qm 3	V_{BD}	Cost
Coil A, SI Once	LG (7ea)	5	6	5	6	4	4	4	4	4	3	6	6
Coil A, SI Twice	LS (3ea)	2	5	2	2	2	2	2	2	2	2	2	5
Coil A, VPI Once	LV (3ea)	4	4	3	3	5	5	6	5	5	5	5	4
Coil A, VPI Twice	LV (3ea)	3	2	4	4	6	6	5	6	6	4	3	3
Coil B, SI Once	LC (3ea)	6	3	6	5	3	3	3	3	3	6	4	2
Coil C, SI Once	LI (7ea)	1	1	1	1	1	1	1	1	1	1	1	1

1. The insulation characteristics of LI motor with mica-film taped coil (coil C) is better than the others as shown in Table 2. In case of LC motor with polyester-amide wire (coil B), PD characteristics are good but the others are not.
2. Motors through standard impregnation (SI) process twice show good general insulation characteristics. It is recommended that, when a standard coil (PEW) is used, two times SI be applied to random winding low-voltage induction motors considering the cost, manufacturing process, and general insulation characteristics as shown in Table 2.
3. The insulation characteristics of vacuum pressure impregnated (VPI) motors show unexpected results, which may suggest that VPI is not very effective for random winding low-voltage motors. It shall be investigated whether VPI process is correctly applied.
4. In order to reduce the PD less than 5[pC], the switching over-voltage of IGBT PWM inverter must be kept under 850[V]. Also, the test results recommend that DIV is the most prominent factor for insulation life of IGBT PWM inverter driven motor.
5. The insulation is assessed poor when the PD is detected over 10[pC] at 900[V] considering the external noise at the shop.
6. LI and LS motors with PD magnitude (Qm) of less

than 1[pC] are acceptable in practical field applications. Therefore, it is recommended to suppress the surge voltage between 800[V] and 1,000[V].

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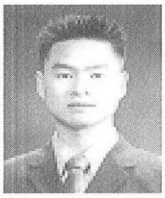
Don-Ha Hwang received the B.S. and M.S. degrees in Electrical Engineering from Yeungnam University, Korea, in 1991 and 1993, respectively, where he is currently working toward the Ph.D. degree. Since 1993, he has been with the Industry Applications Research Lab., Korea Electro-technology Research Institute (KERI), Korea, as a senior researcher. His main research interests are design, analysis, monitoring, and diagnosis of electric machines.

Dong-Sik Kang received his B.S., M.S. and Ph.D. degree in Electrical Engineering from the Busan National University, Busan, Korea, in 1983, 1992 and 2002 respectively. Since joining the Research Division of Korea Electro-technology Research Institute (KERI) in 1987, he has been active in developing on-line diagnostic techniques for rotating machines. Presently he is technical leader of partial discharge diagnosis team in KERI.

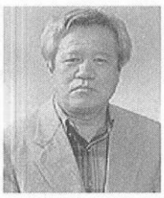
Yong-Joo Kim received his B.S. degree in Electrical Engineering from the Seoul National University, Seoul, Korea, in 1975, and M.S. and Ph.D. degrees in Electric Power Engineering from the Rensselaer Polytechnic Institute, New York, USA, in 1984 and 1987, respectively. Since joining the Research Division of Korea Electro-technology Research Institute (KERI) in 1979, he has been active in developing on-line diagnostic techniques for rotating machines. Presently he is Director of the Machine Control and Application Research Group in KERI.



Tae-Hoon Lim received the B.S. degree in Electrical Engineering from Yeungnam University, Kyongsan, Korea, in 2003, where he is currently working toward the M.S. degree. His primary research interests are design, analysis and diagnosis of electric machines.

Sung-Woo Bae received the B.S. degree in Electrical Engineering from Yeungnam University, Kyongsan, Korea, in 2002, where he is currently working toward the M.S. degree. His primary research interests are design and analysis of rotating machines.

Dong-Hee Kim received the B.S. and M.S. degrees in Electrical Engineering from Yeungnam University, Korea, in 1973 and 1975, respectively, and Ph.D. degree from the Kobe University, Japan in 1987. From 1987 to 1989, he was a general manager of Power Electronics Research Division, Korea Electro-technology Research Institute (KERI), Korea. He joined the School of Electronic & Information Engineering, Yeungnam University, Korea in 1990, where he is a professor. His main research interests include circuit and control systems of power electronics, especially in soft-switching areas.



Chae-Gyun Ro received the B.S. degree in Electrical Engineering from Seoul National University, Korea, in 1961, M.S. and Ph.D. degrees in Electrical Engineering from Yeungnam University, Korea in 1975 and 1978, respectively. Since 1970, he has been a professor in the School of Electronic & Information of Yeungnam University, Korea. His main research interests are design, analysis and control of rotating machines.