Evaluation of Winding Insulation of IGBT PWM Inverter-Fed Low-Voltage Induction Motors

Doh-Young Park, Don-Ha Hwang, Yong-Joo Kim, Do-Hyun Kang — Mechatronics Research Group, Korea Electrotechnology Research Institute (KERI), P.O. Box 20, Changwon, Kyungnam, 641-600, Korea

Young-Hoon Lee, Dong-Hee Kim — School of Electrical & Electronic Eng., Yeungnam University, Kyongsan, Kyongbuk, Korea

In-Woo Lee — Industrial Performance Group, Hyosung Corporation, Changwon, Kyungnam, Korea

Abstract

IGBT inverters have switching rise times of 0.2-2 μ sec, and have been believed to cause insulation stresses and premature motor failures. Inverter driven induction motors with high speed switching and advanced PWM techniques are widely used for variable speed applications. Recently, the insulation failures of stator winding have attracted many concerns due to high dv/dt of IGBT PWM inverter output. In this paper, the detailed insulation test results of 19 low-voltage induction motors are presented. Different types of insulation techniques are applied to 19 motors. The insulation characteristics are analyzed with partial discharge, discharge inception voltage, and dissipation factor tests. Also, breakdown tests by high voltage pulses are performed, and the corresponding breakdown voltages are obtained.

Keywords - Induction motor, stator winding, insulation failure, pulse-width modulated inverter, partial discharge

I. INTTRODUCTION

The development of advanced power electronic switching devices has enabled high frequency switching operation and has improved the performance of pulse width modulated (PWM) inverters for driving induction motors. 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 waveform. But wire insulation failures of the random wound stator windings of induction motors have been reported due to the voltage surges having fast rise time of switching devices of PWM inverter such as IGBT devices whose switching frequency range is 2-20 [kHz]. In addition, these voltage surges at high switching frequencies cause over-voltages associated with complex reflection phenomena due to impedance mismatches between the inverter, the cable, and the motor [1-3].

In this paper, the test results for evaluation on the stator winding insulation of induction motors 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. Nineteen induction motors of different insulation techniques were built and thoroughly tested. The maximum partial discharge (PD) magnitude (Qm) and the discharge inception voltage (DIV) were obtained by PD test. Also the dissipation factor tip-up ($\Delta\tan\delta$) are measured [5].

From the above test data, the effects due to different insulation techniques on the insulation characteristics of low-voltage induction motors are compared and analyzed. An effective impregnation method 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.

II. IGBT PWM-INVERTER-FED INDUCTION MOTOR

A. Insulation System

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 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, there is a likelihood 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.

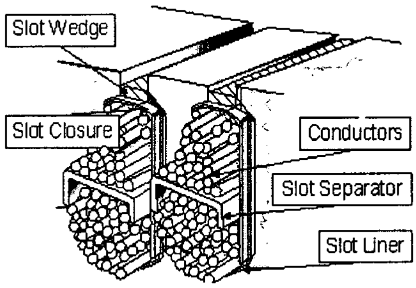

Fig. 1. Insulation system of stator winding

B. Voltage Waveforms

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), multiple reflections at both ends of the motor cable lead 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) [6-8].

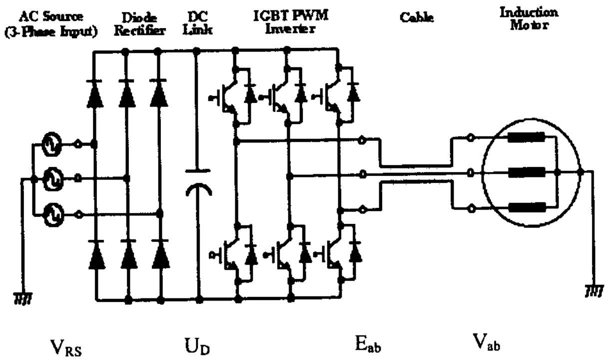

Fig. 2. Block diagram of the IGBT PWM inverter drive systems

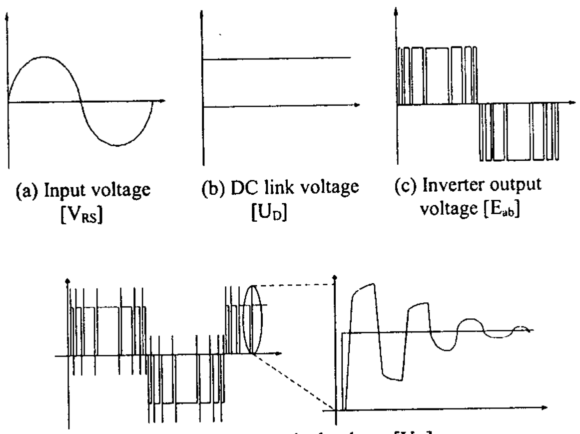

Fig. 3. Voltage waveforms

Also, due to the effect of cable impedance, the voltage at the motor terminal can increase more than 2 [pu]. This switching impulse voltage decreases the insulation strength of stator wire and causes the insulation breakdown eventually.

C. Enhancement of Insulation Performance of Induction Motors

Recently, many incidents of premature breakdown of low-voltage induction motor driven by IGBT PWM inverter have been reported. To prevent those insulation breakdowns of inverter driven induction motor, many research activities have been performed. These activities 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 [8-9].

The following methods are introduced for the improvement of insulation capability of the wires and impregnation methods for induction motors.

- Use ISR (Inverter Spike Resistant) grade magnet wire capable of with standing surge voltage by PWM inverters
- Apply Dip and Bake impregnation at least two times
- Adopt Trickle impregnation for a small quantity production of motors
- Use insulation paper with high insulation capability for the protection of insulation breakdown between phases

III. INSULATION TEST METHODS

A. Specifications of Tested Motors

Nineteen stators of induction motor for the insulation characteristics test are built as shown in Table I. Two different impregnation methods are used. One is standard impregnation (SI) and another is vacuum pressure impregnation (VPI).

The rating of the motor is three phase, 4 poles, 380 [V], 20 [HP] (15 kW), F-class (155 °C). Polyester enameled wires (PEW) whose diameters are 1.0 and 1.1 [mm] with an insulation thickness of 0.077 [mm] are used for the stator winding.

Table I. Specifications of the induction motors

Impregnation Method	Iteration of Impregnation	Motor Symbol	Number
Standard Impregnation	1	S1#1~S1#5	3
	2	S2#1~S2#5	5
	3	S3#1~S3#5	5
Vacuum Pressure Impregnation	1	V1#1~V1#5	3
	2	V2#1~V2#	3

B. AC Current and Dissipation Factor Test

To measure AC current, capacitance and dissipation factor (tanδ) simultaneously, automatic insulation test system of Haefely Trench Tettex (Type 2818-QA) is used.

The rate of change in AC current (ΔI) and capacitance (ΔC/Co) that shows current and capacitance characteristics according to the applied voltage is calculated by AC current test. From the dissipation factor test, the dissipation factor tip-up (Δtanδ) that is the difference between tanδ at the rated phase to ground voltage and tanδ at the low voltage with no PD occurrence is measured.

C. Partial Discharge Test

The maximum partial discharge magnitude (Qm) and the discharge inception voltage (DIV) are measured by partial discharge detector (Model TE571) of Haefely Trench Tettex. The initial discharge inception voltage is believed to be 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 a radio frequency shield room with noise-free power supply.

D. Breakdown Test

An insulation breakdown test with simulated switching pulses applied to motor windings is performed in order to analyze the insulation breakdown of windings impacted by transient switching pulse voltage while the motor is in operation. The test circuit consists of an isolation transformer, a diode rectifier, DC link, IGBT PWM inverter, a high-frequency transformer, and high voltage pulse generator up to 20 [kV] [8].

IV. TEST RESULTS

A. Dissipation Factor and AC Current Tests

Figs. 4 to 6 show the test results of dissipation factor, AC current, and capacitance tests for induction motor stator windings of five different types, respectively. The dissipation factor tip-up, Delta Tan Delta (Δtanδ), is illustrated in Fig. 4, where Δtanδ is the differences of tanδ between at 1, 400 [V], 1,500 [V] and at 600 [V]. Δtanδ of S3 motors is less than that of other motors.

The rate of change in AC current (ΔI) and capacitance (ΔC/Co) were obtained as shown in Fig. 5 and Fig. 6 at 1,400 [V] and at 1,500 [V]. S1 motor (SI once) has the maximum ΔI and ΔC/Co values. It can be seen that the more times the motors are impregnated, the less Δtanδ, ΔI, and ΔC/Co are obtained.

B. Partial Discharge Test

Fig. 7 shows the maximum partial discharge (PD) magnitude (Qm) of all 19 induction motors. Also shown is the average PD magnitude, which shows that PD increases as the applied voltage increases. Qm of V2 motor has the lowest value over all the applied voltages. Also, it can be seen that Qm of V1 and S3 motors at 1,500 [V] increase rapidly compared to those at 1,300 [V].

Fig. 8 shows test results of discharge inception voltage (DIV) of the motors. DIV is the applied voltage when maximum PD magnitude becomes 10 [pC]. Figs. 8 and 9 show that V2 motors have the largest DIV, and S1 motors have the lowest DIV. Therefore PD occurs at the highest applied voltage with V2 motor.

Figs. 8 and 9 indicate that, in order to reduce the PD less than 10 [pC], the switching over-voltage of IGBT PWM inverter must be kept under 1,000 [V]. Therefore, the insulation is assessed poor when the PD is detected over 10 [pC] at 1,000 ~ 1,200 [V] considering the external noise at the shop.

C. Breakdown Test

Fig. 10 shows insulation breakdown voltage (V_{BD}) by the switching surge. V2 motors by VPI process have relatively strong insulation strength under breakdown voltage around 14 [kV]. Insulation of other motors is failed under 13 [kV]. V_{BD} of S2 and S3 motors is in the range of 12 ~ 13 [kV] with one exception of S3 motor. In addition, the tendency is that the more times the motors are impregnated, the higher V_{BD} is obtained.

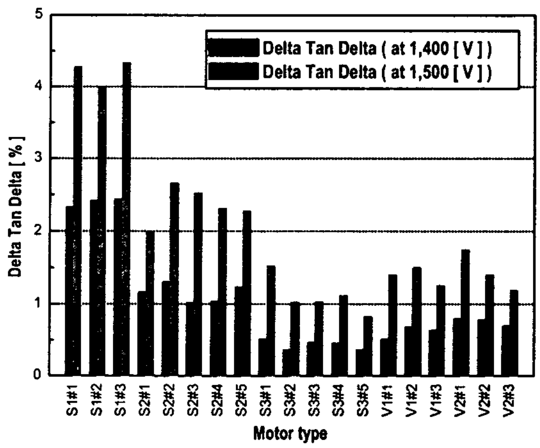

Fig. 4. Test results of tan delta (Δtanδ)

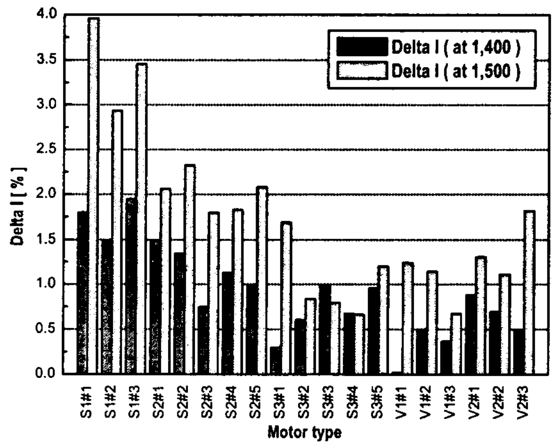

Fig. 5. Test results of AC current (ΔI)

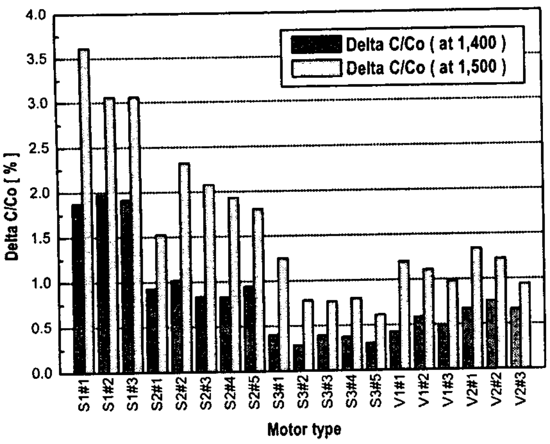

Fig . 6. Test results of capacitance (ΔC/Co)

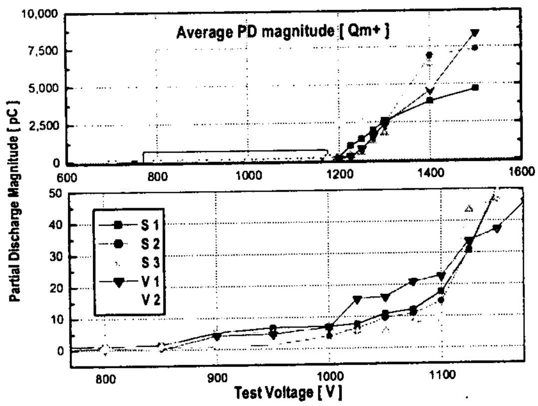

Fig. 9. Average PD magnitude (Qm+)

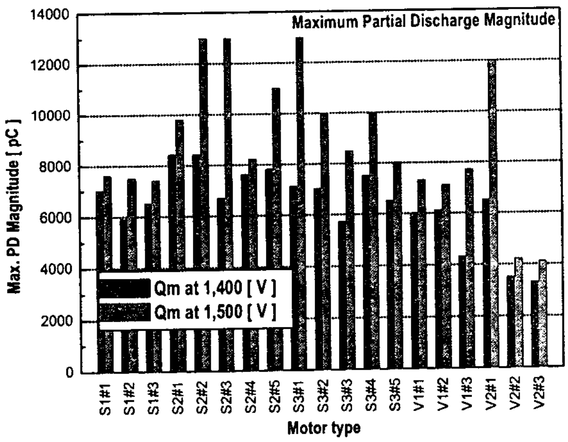

Fig. 7. Test results of the maximum PD magnitude (Qm)

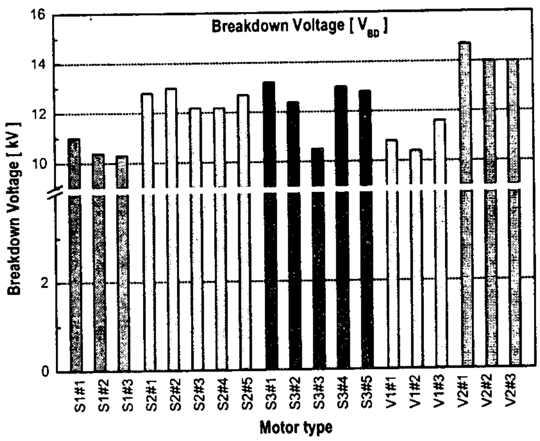

Fig. 10. Test results of breakdown voltage (V_{BD})

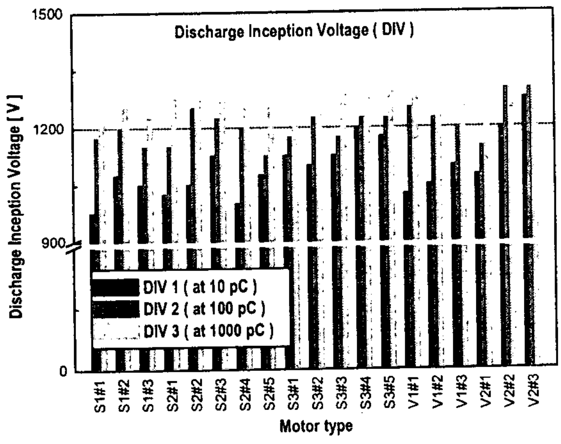

Fig. 8 . Test results of discharge inception voltage (DIV)

V. CONCLUSION

In this paper, the insulation test results of the stator winding of nineteen 380 [V] 20 [HP] induction motors for IGBT PWM inverter applications are presented. The motors are built with five different types of insulation techniques.

The insulation characteristics are analyzed with partial discharge (Qm and DIV), dissipation factor (Δtanδ), ac current (ΔI), and capacitance (ΔC/Co) tests for each motor. Also, insulation breakdown tests by switching pulse voltage are performed. From the test results the tendency is that the more times the motors are impregnated, the better insulation characteristics are obtained. The results of the insulation characteristics test are as follows;

1. V2 motors (VPI twice) have good overall insulation characteristics over standard impregnation motors.

2. The breakdown voltage by switching pulse suggests having a relationship with PD characteristics. Hence, it may be concluded that the maximum PD magnitude (Qm) and DIV are the most important parameters in the insulation life of low-voltage induction motors.
3. It can be said that three times of standard impregnation provide the most effective insulation strength for this specific type of 20 [HP] motor considering the manufacturing cost and efforts.
4. In order to reduce the PD less than 10 [pC], the switching voltage at the motor terminal must be kept under 1,000 [V].
5. The variations in the parameters for the analysis of insulation characteristics may be attributed to the uneven manufacturing conditions such as the degree of vacuum in VPI process, baking time and temperature in standard impregnation process.

REFERENCE

[1] A.H. Bonnett, "Available insulation systems for PWM inverter-fed motors", *IEEE Industry Applications Magazine*, Vol. 4, No. 1, pp. 14-26, Jan./Feb. 1998.

[2] E. Persson, "Transient effects in application of PWM inverters to induction motors", *IEEE Transactions on Industry Applications*, Vol. 28, No. 5, pp. 1095-1101, Sep./Oct. 1992.

[3] J.P. Bellom, et al., "The effect of Pulsed Voltages on Dielectric Material Properties", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 6, No. 6, pp. 20-26, Feb. 1999.

[4] M. Kaufhold, et al., "Electrical stress and failure mechanism of the winding insulation in PWM-inverter-fed low-voltage induction motors", *IEEE Transactions on Industrial Electronics*, Vol. 47, No. 2, pp. 396-402, Apr. 2000.

[5] D.H. Hwang, et al., "Analysis of insulation characteristics of low-voltage induction motor driven by IGBT PWM inverter", *Conf. Record of the 2000 IEEE International Symposium on Electrical Insulation (IEEE ISEI-2000), Anaheim, USA*, pp. 17-20, Apr. 2000.

[6] J.M. Bentley and P.J Link, "Evaluation of Motor Power Cables for PWM AC Drives", *IEEE Transactions on Industry Applications*, Vol. 33, No. 2. pp 342-358. Mar./Apr.1997.

[7] A. Mabaye, et al, "Electrical Stresses Applied to Stator Insulation in Low-Voltage Induction Motors Fed by PWM Drives", *IEE Proceedings of Electrical Power Applications*, Vol. 144, No. 3, pp. 191-198, May 1997.

[8] D.H. Hwang, et al., "Analysis of insulation characteristics of PWM Inverter-Fed Induction Motors", *2001 IEEE International Symposium on Industrial Electronics (IEEE ISIE-2001), Pusan, KOREA*, pp. 477-481, June 2001.

[9] H. Brandes and J.A. Allison, "Insulating systems for inverter-driven motors ; Status and developments", *Power Engineering Journal*, Vol. 14, No.4, pp. 164-168, Aug. 2000.

[10] W.Yin, "Dielectric Properties of an Improved Magnet Wire for Inverter-Fed Motors", *IEEE Electrical Insulation Magazine*, Vol. 13, No.4, pp. 17-23, Jul./Aug. 1997.