Analysis of Voltage Stress in Stator Windings of IGBT PWM Inverter-Fed Induction Motor Systems

Don-Ha Hwang†, Ki-Chang Lee*, Jeong-Woo Jeon*, Yong-Joo Kim*, In-Woo Lee and Dong-Hee Kim*****

Abstract - The high rate of voltage rise (dv/dt) in motor terminals caused by high-frequency switching and impedance mismatches between inverter and motor are known as the primary causes of irregular voltage distributions and insulation breakdowns on stator windings in IGBT PWM inverter-driven induction motors. In this paper, voltage distributions in the stator windings of an induction motor driven by an IGBT PWM inverter are studied. To analyze the irregular voltages of stator windings, high frequency parameters are derived from the finite element (FE) analysis of stator slots. An equivalent circuit composed of distributed capacitances, inductance, and resistance is derived from these parameters. This equivalent circuit is then used for simulation in order to predict the voltage distributions among the turns and coils. The effects of various rising times in motor terminal voltages and cable lengths on the stator voltage distribution are also presented. For a comparison with simulations, an induction motor with taps in the stator turns was made and driven by a variable-rising time switching surge generator. The test results are shown.

Keywords: equivalent circuit, finite-element analysis, IGBT PWM inverter-fed induction motor, insulation breakdown, stator winding, switching surge, voltage stress

1. Introduction

An insulated gate bipolar transistor (IGBT) device can perform high frequency switching operation so that it not only has improved efficiency and current waveform due to the high carrier frequency, but also has reduced audible noise. But the IGBT PWM inverter can cause insulation breakdowns and irregular voltage distributions on the stator windings of the motor due to the high rising rate of voltage (dv/dt) caused by high-frequency switching and impedance mismatch between the inverter and the motor. The steep pulses and irregular voltages of the stator windings lead to partial discharge occurrence and eventually premature breakdowns [1-4].

In this paper, the voltage distributions at each turn of the stator windings of the induction motor driven by the IGBT PWM inverter are studied. To calculate the parameters of equivalent circuit model, i.e. turn-to-turn resistances, inductances and capacitances of stator winding, high frequency equivalent circuit models of the inverter-fed motor system are proposed and analyzed using 2-dimensional electromagnetic field analysis software. The resistance, inductance, and capacitance according to frequency variation are also computed to examine the effects of high frequency switching operation on the voltage distributions of stator winding. Furthermore, by utilizing the electro-magnetic program (EMTP), all stator windings of the PWM inverter-fed induction motor are modeled and analyzed. As well, voltage pulses with various magnitudes and rising-times are applied to the stator windings of the motor through various lengths of cable. Finally, for the measurement of voltage distributions in stator windings, five taps are made in each phase turn of the test induction motor. This motor was then driven by a switching surge generator with various rising times and magnitudes, and the test results are shown.

2. The Stator Windings of IGBT PWM Inverter-Fed Induction Motors

2.1 Insulation System of the Stator Winding

The induction motor stator winding insulation system chiefly consists of main, phase, and turn insulation. The main or slot insulation separates the slot-windings from the stator core and the phase insulation (phase separation) causes different potentials of the individual phases. The turn insulation among adjacent turns inside the coils consists of

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enamel wire and an impregnating resin or varnish.

Due to the random-wound windings of low-voltage induction motors and the fact that coils of larger machines are usually wound from several parallel wires, there exists the strong possibility that the starting and ending turns of one coil would be adjacent. In this case, the entire coil voltage can appear between two adjacent turns. Under unfavorable conditions, the turn insulation can even be subjected to a voltage drop over multiple coils or coil groups.

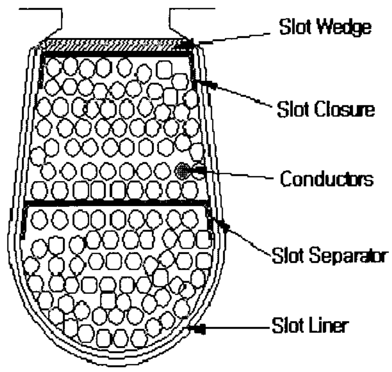


Fig. 1 Insulation system of stator winding

2.2 Voltage Waveforms of IGBT PWM Inverter-Fed Motor

A typical configuration of an induction motor system driven by an IGBT PWM inverter and its voltage waveforms are shown in Fig. 2 and Fig. 3, respectively. Fig. 3 (a) presents an AC source (VRS) of the 3-phase input. The dc-link voltage (U_D) of the voltage-fed inverter supplied by an ideal power line rectifier is illustrated in Fig. 3 (b). At the inverter output terminals, voltage pulses can be created with amplitudes corresponding to the voltage of the dc-link circuit as shown in Fig. 3 (c). Caused by voltage drops, the dc-link voltage depends upon the load conditions and can exceed or fall below its nominal value, according to the direction of the power flow. The short rise times of the voltage impulses at the inverter output result in traveling waves on the motor cable. As indicated in Fig. 3 (d), multiple reflections at both ends of the motor cable guide oscillating impulse voltages at the motor terminals. The voltage at the motor terminal has switched over-voltage with high rate of voltage rise (dv/dt). Furthermore, elongated cable lengths contribute to a damaged high-frequency ringing at the motor terminals due to the distributed nature of the cable leakage inductance and coupling capacitance (L–C), which result in over-voltages and further stress on the motor insulation [1–5].

3. Computation of Induction Motor Parameter in High Frequency Region

In this paper, a 50 [HP], 3-phase, squirrel-cage induction motor is applied. In order to compute the distributed high frequency parameters of the motor, electromagnetic field analysis is performed using an ANSOFT package [6].

For computing turn resistances and inductances, the eddy current solver available in the package is used and for computing the capacitance matrix, electrostatic analysis is used [5-8]. This is because of the fact that the capacitance values change little with the frequency change. Each conductor is defined as a current source in the eddy current analysis and a voltage source in the electrostatic analysis.

3.1 The Slot Modeling of a 50 [HP] Induction Motor

To analyze voltage distributions in the stator winding of low voltage induction motors fed by an IGBT PWM inverter, the induction motor of 50 [HP] and 380 [V] is applied.

A single slot out of 48 stator slots is modeled and the inner part of a slot consists of 1.2 [mm]×3 and 1.1 [mm]×1, connected in parallel fashion. Other same strands are connected in parallel manner and hence, the total number of conductors is 96.

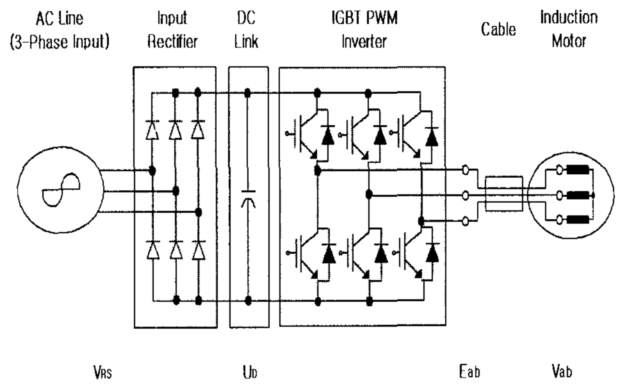
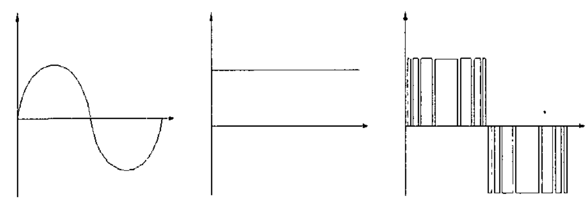
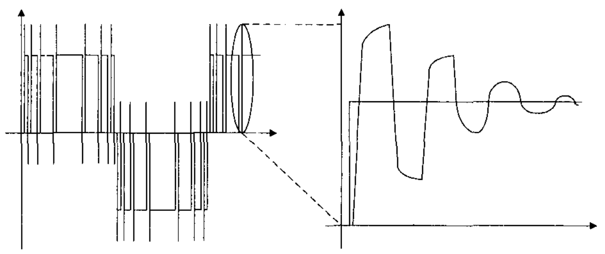


Fig. 2 Block diagram of the IGBT PWM inverter-fed induction motor system



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



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

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

For exact computation of this model, slot cell and top wedge are included as shown in Fig. 4. The value of resistance from the first to the fifth turn is calculated into an average value and the other turns are calculated by multiplying the number of turns to an average value, because it is almost constant without relating to position.

Fig. 5 presents parameters computed at various frequencies. It can be known that the resistance increases and the inductance decreases as frequency rises due to skin effect.

In order to compute capacitance between the conductor and the ground, the 1 [V] voltage source has to be substituted in a conductor required computation and the 0 [V] voltage source has to be substituted in the other conductors, stator, and rotor.

3.2 High Frequency Equivalent Circuit Including Cable

While the PWM inverter-fed induction motor is in the transient states, the switching frequency is very high and the disposition of coil within a slot is irregular due to the rapid switching operation. Therefore, it is essential that the equivalent circuit model of the stator should be expressed as a distributed parameter circuit just as in Fig. 4.

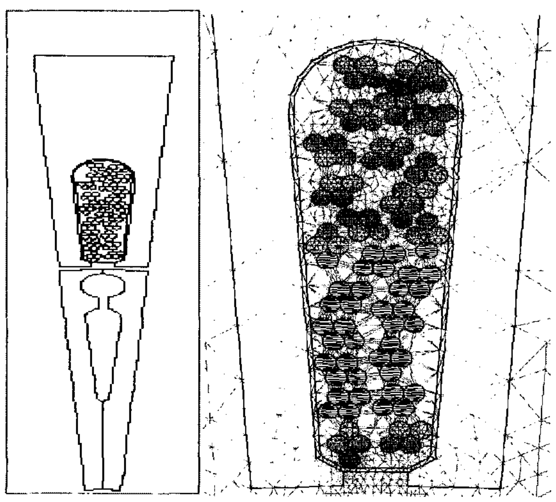


Fig. 4 Cross sectional view of slot model and mesh diagram for FEM analysis

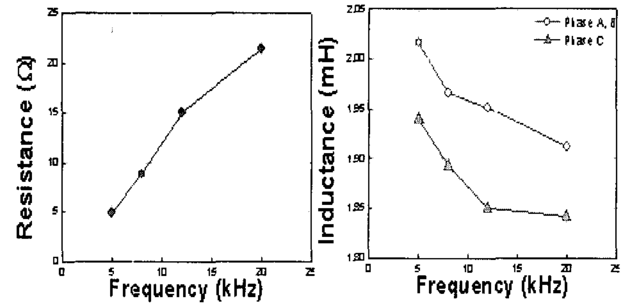


Fig. 5 Parameter computation at various frequencies

The first to fifth turns of a coil are modeled as distributed circuit parameters and the other turns of each phase are modeled as concentrated constant circuits. The distributed parameter circuit is composed of resistance, self-inductance, mutual inductance, and capacitance.

Fig. 6 illustrates the equivalent circuit applied distributed parameter from the first turn to the fifth turn. Leakage conductance can be ignored due to its very small value. Mutual capacitance between the conductor and ground has a very small value, which can be ignored. However, mutual capacitance of closely adjacent conductors is high, and therefore cannot be ignored. Capacitance is not greatly affected by frequency, but rather by the position of the conductor.

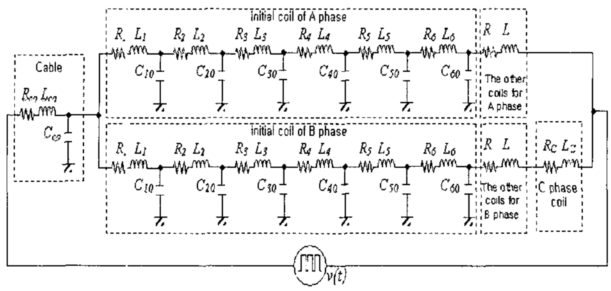


Fig. 6 Equivalent circuit of one coil for stator winding

4. EMTP Simulation

In order to analyze voltage distributions in the stator winding of a low-voltage induction motor driven by an IGBT PWM inverter, electromagnetic transient program (EMTP) analysis is performed, because voltage distributions of the stator appear as unbalanced voltage. The EMTP can analyze voltage, current, and power consisted of a concentrated constant circuit, distributed parameter circuit, and nonlinear factor [9, 10]. Fig. 7 shows a model of EMTP analysis systems. The equivalent pulse voltage source and cable model parameter is indicated in Table 1.

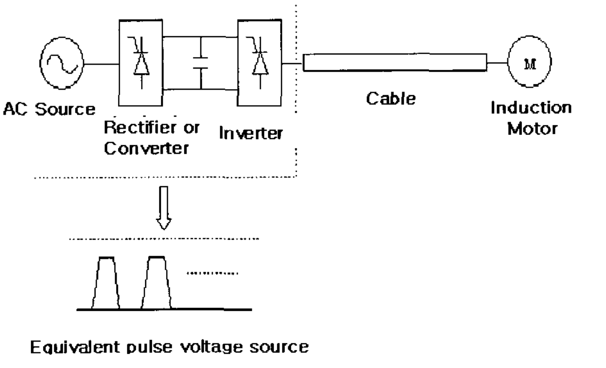


Fig. 7 Model of EMTP analysis system

Table 1 Equivalent pulse voltage source and cable model parameter

Equivalent pulse voltage source	Cable model parameter (UL3321 AWG10)
• Single step pulse model • Pulse magnitude: 380 [V] • Rise-time: 1 [μs], 400 [ns], 300 [ns], 200 [ns]	• The frequency independence distributed parameter circuit • Surge impedance: 70 [Ω] • Ratio wave speed: 200 [m/μs] • Cable length: 5, 10, 30, 50, 100 [m]

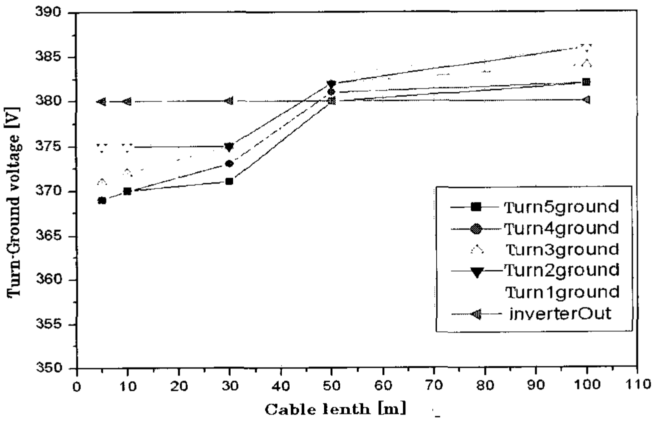


Fig. 8 Magnitude of turn to ground voltage(Rise-time: 200 [ns])

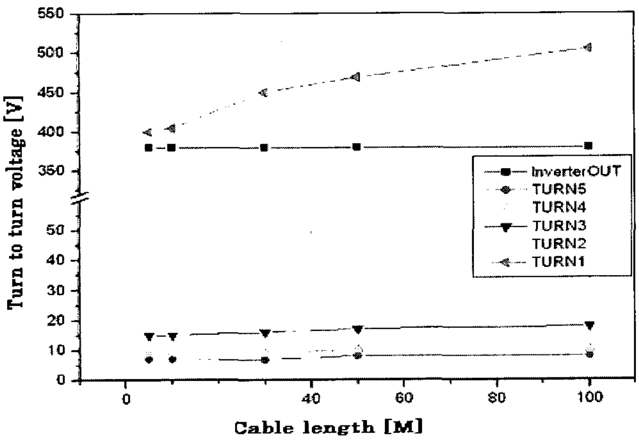


Fig. 9 Magnitude of turn to turn voltage(Rise-time: 200 [ns])

In this paper, various rise-times and cable lengths are applied to analyze the relation of rise-time of the PWM inverter and the length of cable between PWM inverter output and induction motor input. Rise-times of 1 [μs], 400 [ns], 300 [ns], and 200 [ns], and cable lengths of 5, 10, 30, 50, and 100 [m] are applied.

Turn to ground voltage distribution of stator winding by EMTP simulation is shown in Fig. 8. Turn to ground voltage relates to the voltage between turn of stator and slot. Turn to ground voltage is similar to inverter output voltage.

The voltage distributions between one turn and the other turns are as presented in Fig. 9. As the cable length increases, the magnitude of voltage increases. Especially, the first turn voltage is much higher than the others.

5. Experimental Results

In order to measure voltage distributions in the stator windings of an induction motor, a test motor of 50 [HP] rating, was made. Stator windings were insulated by standard varnish impregnation and the first turn to fifth turn of each phase were tapped to measure voltage distributions in each coil as shown in Fig. 10 and Fig. 11. The extracted five wires were single wires of 0.2 [mm^2] and each joint of extracted taps was welded. To prevent insulation breakdowns from occurring in the welded parts, KAPTON insulation, a type that has superior insulation characteristics, even at over 200°[C] was used.

Fig. 12 shows experimental voltage distributions as cable lengths change among the turns of winding corresponding to 300 [ns] rise-time and 5 [kHz] switching frequency. The first turn voltage is very similar to the inverter output voltage of the 5 [m] cable. However, the magnitude of first turn voltage is 1.3 times higher than that of the inverter output voltage indicated at Fig. 12 (b). The surge voltage occurred in the initial part of the waveform.

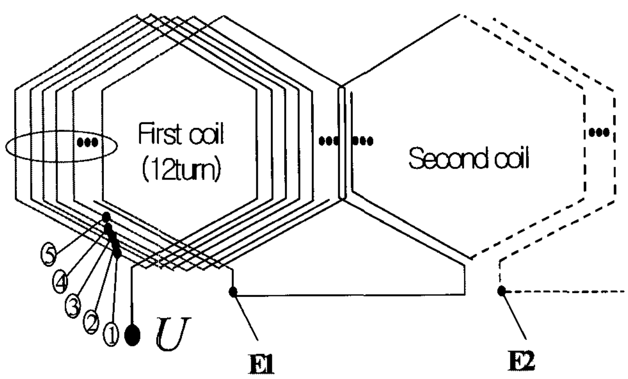


Fig. 10 Taps for the measurement of voltage distributions

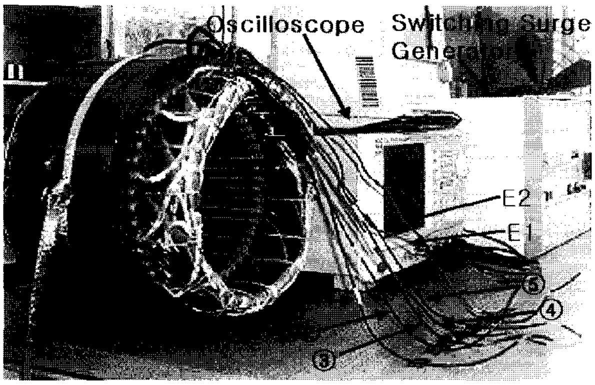
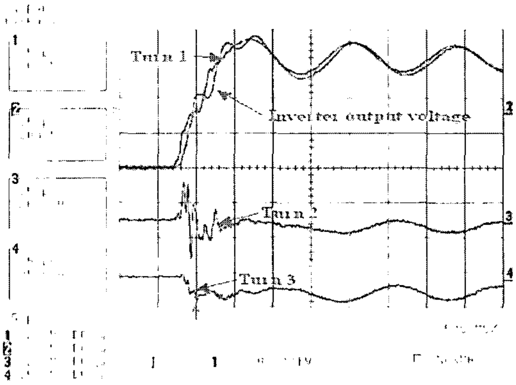
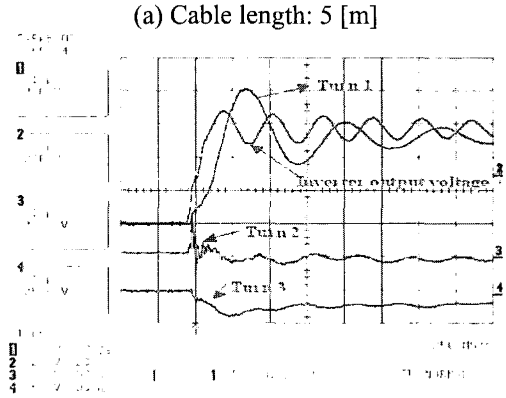


Fig. 11 The stator of 50 [HP] induction motor with conducts tapped for voltage measurement

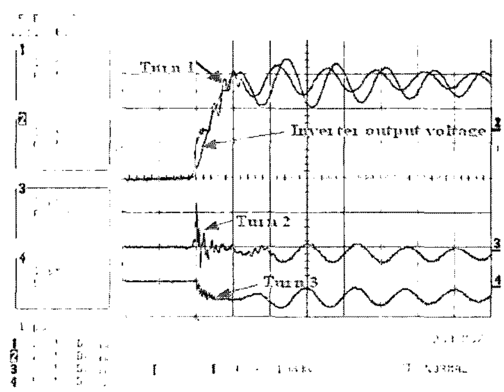


(a) Cable length: 5 [m]

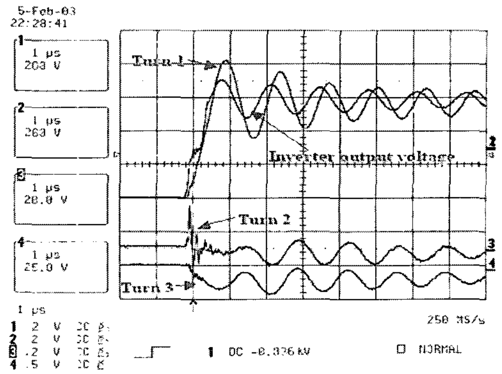


(b) Cable Length: 100 [m]

Fig. 12 The voltage distribution according to cable length (Rise-time; 300 [ns], Switching frequency; 5 [kHz])

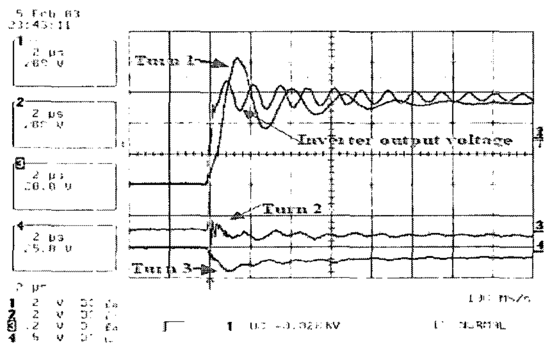


(a) Rise-time: 1 [μs]

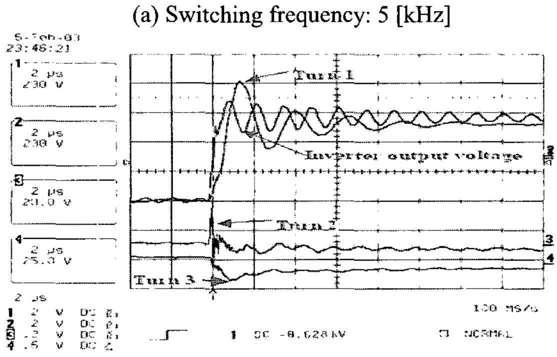


(b) Rise-time: 300 [ns]

Fig. 13 The voltage distribution according to rising time (Cable length; 30 [m], Switching frequency; 12 [kHz])



(a) Switching frequency: 5 [kHz]



(b) Switching frequency: 20 [kHz]

Fig. 14 The voltage distribution according to switching frequency(Cable length; 100 [m], Rise-time; 200 [ns])

When the rise-time is 1 [μs] as shown in Fig. 13 (a), the first turn peak to peak voltage is around 720 [V], which is very similar to inverter output voltage amplitude in Fig. 13 (b), which shows high surge voltage. The peak-to-peak value of surge voltage is 840 [V] at the first turn as the inverter output voltage is still around 700 [V]. This over-voltage causes the voltage reflection phenomena to occur due to impedance mismatches among the inverter, cable, and motor. This surge voltage results in premature failure of the induction motor driven by an IGBT PWM inverter.

Fig. 14 presents voltage distribution according to switching frequency change. The effect on switching frequency is not very high.

6. Conclusion

In this paper, the voltage distributions in the stator windings of a low-voltage induction motor driven by an IGBT PWM inverter are analyzed and shown. To examine voltage distributions in stator windings, a stator slot model and equivalent circuit of one coil are proposed. The tap for the voltage measurement experiment is built in the induction motor. The examined voltage distributions in each coil of the stator windings by the simulation and experiment indicate that the voltage of the first turn is generally higher than that of the other turns and as rise-time become smaller, the magnitude of voltage is increased. If the first turn and last turn of the line-end coil are placed near each other within the slot, which may happen in a random wound machine, then the voltage stress caused during the transients on the thin coating separating the two turns may result in dielectric breakdown over a period of time and consequently reduce the life of the insulation systems.

Furthermore, according to increase in the cable length between inverter and motor, the magnitude of terminal voltage in the induction motor is amplified. When these results are considered, it is evident that an induction motor that is able to endure surge voltage is needed.

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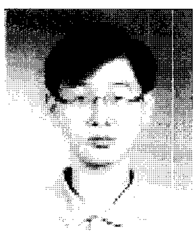

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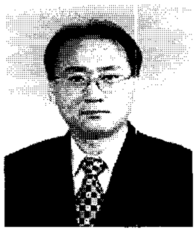

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