International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-2 Issue-2, December 2012

Simulation and Analysis of Common Mode Voltage in 2-level and Multilevel Inverter Fed Induction Motor Drive with Long Cable

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Abstract— The development of high frequency, Pulse Width Modulation (PWM), based Adjustable Speed Drives (ASDs) has increased the energy efficiency, performance and controllability in the induction motor applications. But high speed switching device such as Insulated Gate Bipolar Transistors (IGBTs) used in ASDs having rise time of 0.1µSec.,that generate fast switching transients (high dv/dt) about 6000V/µSec for 400V system and common mode voltage. This common mode voltage causes unwanted shaft voltage and resulting bearing currents. Parasitic capacitive couplings create a path to discharge current in the rotor and bearings results in premature bearing failure. In many new and retrofit industrial applications the PWM inverters and motors must be at separate locations thus requiring long motor cable, which contributes over voltage at the motor terminal due to voltage reflection phenomenon. In 480V application, inverter output common mode dv/dt can be as high as 7000V/µsec. and at motor terminals in the presence of long cable (20ft) can reach11000V/µSec. Higher common mode dv/dt (nearly double) at the motor terminals results in higher induced shaft voltage and bearing currents. Multilevel inverter generates smaller Common-Mode (CM) voltage, thus reducing the stress in the motor bearings. In addition, using sophisticated modulation methods, common mode voltage can be eliminated.

Index Terms-Common mode voltage, induction motor drive, multilevel inverter, voltage reflection.

I. INTRODUCTION

The phenomenon of bearing currents in induction motors has been known for decades. It has been reported by Alger [1] in the 1920's that the basic reason for these currents is asymmetric flux distribution inside of the motor .This problem has been effectively solved with modern motor designing and manufacturing practices. However unexpectedly the problem has returned since power electronic devices are becoming common in an Adjustable Speed Drives (ASD) shown in Fig.1.

Manuscript published on 30 December 2012.
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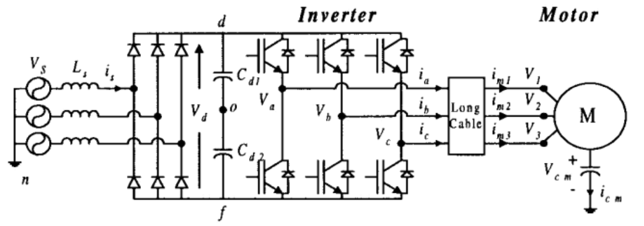

Fig.1.Two level PWM inverter fed induction motor with long motor cable

PWM inverters with IGBT operate at switching frequencies of 2 to 20kHz and rise time of 0.1µsec with voltage rise of 6000V/µsec for 400V system. The high dv/dt has adverse effects on bearing damage caused by bearing currents due to common mode voltage. Motor Insulation stress due to motor terminal over voltages (exacerbated by long cable lengths) and contributes to Electromagnetic Interference (EMI). In 480V applications, inverter output common mode dv/dt can be as high as 7000V/µsec. However at the motor terminals in the presence of long cable (>20 feet) and above can easily double. [3]-[6].

The bearing current faults are most frequent in PWM fed ASDs, nearly 30% according to an IEEE motor reliability studies. The bearing currents cause premature bearing failure within 1-6 months of installation. In order to protect ASD investment, predictive maintenance is highly recommended for early detection and schedulable replacement of defective bearing to avoid the hidden costs involved in downtime and lost product.

There are mainly two types of Inverter induced bearing currents: High frequency circulating bearing current and Electric Discharge Machining (EDM) bearing current. The high dv/dt common mode voltage rate at the motor terminals causes circulating currents through parasitic capacitor (C_{sf}) in closed loop consisting of shaft, both bearings and the frame. An electrically insulated lubrication film normally has thickness ranging from 2-3 microns, the bearing voltage V_b mirrors the common mode voltage V_{com} at the stator terminals via capacitor voltage divider i.e Bearing Voltage Ratio (BVR).The electrically loaded oil film between balls and races breaks down when threshold voltage of the film exceeds dielectric strength of lubricating oil 15Vpk/µm (approx.5-30V) ,thereby causing the EDM current pulses and results in premature bearing failure [2].

The root cause of bearing current is the common mode voltage, in order to minimize the common mode voltage and hence shaft voltage and bearing current, advanced mitigation technique such as multilevel inverter can be used. This paper presents simulation and analysis of common mode voltage in two level and diode clamped multilevel inverter fed induction motor drive with long cable.

Also presented common mode voltage minimization for higher HP ratings of induction motor with long motor cable.

This paper is organized as follows: Section I gives introduction about bearing current, its causes, types and one of advanced mitigation technique. Section II deals with common mode voltage and multilevel inverters helps to understand background of related work and simulink modeling. Section III explains voltage reflection analysis .Section IV deals with simulink modeling of inverter with long cable, HF induction motor with common mode equivalent circuit. Section V gives the simulation results and discussion. Section VI includes the conclusion about the paper and followed by reference and bibliography.

II. COMMON MODE VOLTAGE IN INVERTER DRIVEN AC MACHINE

A. Common Mode Voltage

At the PWM inverter output, instantaneous summation of all the three phase voltages is non zero, an average voltage in a neutral point w.r.t ground create so called common mode voltage.

$$V_{cm} = \frac{[V_{an} + V_{bn} + V_{cn}]}{3} \qquad (1)$$

In the above equation V_{an},V_{bn} and V_{cn} are the phase voltages generated by the PWM inverter. The common mode voltage is a stair case function of amplitude equal to the DC bus voltage and the frequency equal to the inverter switching frequency. The waveform of common mode voltage is schematically shown on Fig.2.

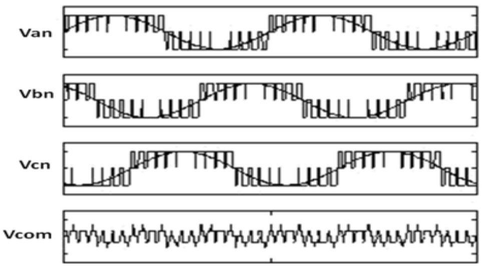

Fig.2. Common Mode Voltage

The common mode voltage can be measured between star point of stator winding of an induction motor and the ground In case if the motor is delta connected, artificial neutral is created using three high value of resistance (1MΩ) connected in star at the motor terminals [8].

B. Shaft Voltage and Bearing Voltage Ratio (BVR)

The shaft voltage has the same shape as the common mode voltage, because the shaft voltage is formed as a result of common mode voltage and capacitive voltage divider circuit. The source of common mode voltage at the output of inverter is the cause of a voltage emerging on shaft, because of the distribution of parasitic capacitances inside of the motor. These create an internal capacitive divider and the shaft voltage can be expressed [3][4].

$$BVR = \frac{V_{sh}}{V_{cm}} = \frac{C_{sr}}{C_{sr} + C_{rf} + C_b} \qquad (2)$$

Where, V_{sh} is shaft voltage, C_{cr} is capacitance between stator winding and rotor, C_{rf} is capacitance between stator frame and rotor/air gap capacitor (C_g) and C_b is bearing capacitance.

The ratio V_{sh} /V_{com} is typically in the range of 1:10 because the value of the C_g is much larger than that of C_{sr}. The C_{sr} value is small when compared with other capacitances because of the relatively large distance and small area between stator and rotor. However it has significant influence on the value of BVR . Figure.3. Shows the various parasitic capacitances in an AC motor that become relevant when the motor is driven by PWM voltage source inverter[3][4].

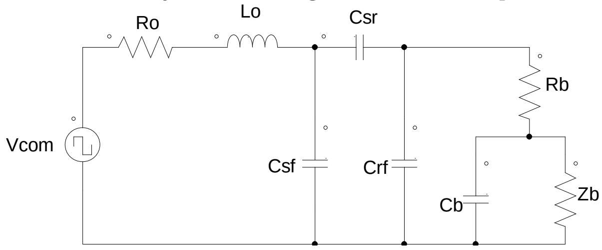

Fig.3. Common Mode Equivalent Circuit

C. Multilevel Inverter

Several multilevel inverter topologies and modulation technologies have been developed and applied to high power and high voltage systems. The main motivation for multilevel inverter topologies is the reduction of voltage stress on the semiconductor devices used in the inverter bridge and the generation of high quality output voltages. They generate smaller common-mode voltage, thus reducing the stress in the motor bearings. In addition, using sophisticated modulation methods, CM voltages can be eliminated [7] presently there are three kinds of multilevel inverters: (1) Neutral Point Clamped inverter (NPC) (2) Flying Capacitor inverter and (3) Cascaded inverter. This paper presents modeling, simulation and analysis of Neutral point clamped multilevel inverter fed induction motor drive.

III. VOLTAGE REFLECTION ANALYSIS

PWM pulses traveling in a cable between the inverter and the motor behave like traveling waves on transmission lines. Over voltage at the motor terminal depends on rise time of the PWM pulses, the cable length and the impedance mismatch between the power cable and motor. The reflection co-efficient at the motor terminals Γ_m and at inverter terminals Γ_s, respectively are given by [9]

$$\Gamma_M = \frac{Z_M + Z_C}{Z_M - Z_C} \qquad (3)$$

$$\Gamma_S = \frac{Z_S + Z_C}{Z_S - Z_C} \qquad (4)$$

Z_M is the motor surge impedance (0.9 for motor upto 20HP) ,Z_S is the source impedance (typically Z_S=0) and Z_C is the cable surge impedance and it is given by

$$Z_c = \sqrt{\frac{L_c}{C_c}} \qquad (5)$$

Where L_c is the cable inductance per unit length and C_c is the cable capacitance per unit length. If Z_S=0,it follows that Γ_{S}= -1,and the over voltage magnitude is primarily determined by Γ_m. Propagation delay for an inverter output PWM pulses to travel from the inverter terminals to the motor terminals can be expressed as.

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$$t_p = l_c / v_p \tag{6}$$

where l_c is cable length and v_p is pulse propagation velocity, propagation velocity is given by

$$v_p = \frac{1}{\sqrt{L_c C_c}} \text{ m/s} \tag{7}$$

The impedance of smaller motors is dominated by winding inductance, thus in comparison to the low surge impedance of the cable, the motor impedance is high and is equivalent to an open circuit at high frequencies.

The forward-travelling inverter output pulses will be reflected at the motor terminals after propagation delay t_p, and then the resulting backward traveling wave, which is a function of Γ_M, moving towards the inverter, will also be reflected at the inverter terminals in the same manner. Hence, after the PWM pulses has travelled the cable length three times, the peak voltage, $V_{LL,p}$ can be shown to be [9]

$$V_{LL,p} = \frac{3 l_c V_{dc} \Gamma_M}{v_p t_r} + V_{dc} \text{ , for } t_p < t_r/3 \tag{8}$$

$$V_{LL,p} = V_{dc} \Gamma_M + V_{dc} \text{ , for } t_p > t_r/3 \tag{9}$$

where, V_{dc} and t_r represent the dc-bus voltage and rise time of PWM pulses respectively.

A. Common mode voltage analysis without long cable

The terminal voltages at the motor would be same as at the inverter output.

The common mode voltage

$$V_{cm} = \frac{V_a + V_b + V_c}{3} \tag{10}$$

$$V_a = V_{a,o} + V_{o.n} \tag{11}$$

$$V_b = V_{b,o} + V_{o.n} \tag{12}$$

$$V_c = V_{c,o} + V_{o.n} \tag{13}$$

Substituting eqns.(11)-(13) into eqn.(10),we have

$$V_{cm} = \frac{V_{a,o} + V_{b.o} + V_{c,o}}{3} + V_{o.n} \tag{14}$$

Summation of inverter output voltage (when 3 upper or 3 lower switches ON)

$$V_{cm,inst} = \pm \frac{Vd}{6} + (V_{o,n})_{inst} \tag{15}$$

B. Common mode voltage analysis with long cable

Common mode voltage at the motor terminal

$$Vcm = \frac{V_1 + V_2 + V_3}{3} \tag{16}$$

Motor terminal voltage also expressed as

$$V_1 = V_{1,o} + V_{o.n} \tag{17}$$

$$V_2 = V_{2,o} + V_{o.n} \tag{18}$$

$$V_3 = V_{3,o} + V_{o.n} \tag{19}$$

From eqns.(17)-(19) and eqn.(16),we have,

$$V_{cm} = \frac{V_{1,o} + V_{2.o} + V_{3,o}}{3} + V_{o.n} \tag{20}$$

With long motor cables the motor terminal voltage is nearly double than the inverter output due to transmission line effect. The instantaneous summation is

$$V_{1,o} + V_{2,o} + V_{3,o} = \pm V_d \tag{21}$$

Substituting in eqn.(21) in eqn.(20) yields

$$V_{cm,inst} = \pm \frac{Vd}{3} + (V_{o,n})_{inst} \tag{22}$$

Comparing eqn.(15) to eqn.(22) shows that instantaneous common mode voltage and dv/dt is nearly double in the presence of a long cable.

IV. SIMULINK MODELING

This paper presents modeling and simulation of 2-level and diode clamped multilevel inverter fed induction motor drive using MATLAB/Simulink software.PWM signals are generated using a high frequency triangular wave, called the carrier wave, is compared to a sinusoidal signal representing the desired output, called the reference wave. Whenever the carrier wave is less than the reference, a comparator produces a high output signal, which turns the upper switch in one leg of the inverter ON the lower switch OFF. In the other case the comparator sets the firing signal low, which turns the lower switch ON and upper switch OFF. Model also includes common mode equivalent circuit for CM voltage measurement.

The induction motor equivalent electrical circuit parameters are determined by two wattmeter's method i.e, no-load and the blocked-rotor tests. These tests were performed at the frequency of 50Hz. Using characteristic equations and curves for determining the motor high frequency parasite capacitances of the high frequency model of the induction motor for different HP ratings [6].Table I. Shows the no-load and blocked rotor test results of 3HP, 400V induction motor. The equivalent electrical circuit parameters are determined (per phase) and presented in the Table II. HF cable parameters are determined as in the reference [10]. Fig.4.Shows the complete simulink model consists of converter-dc link–inverter, HF cable and induction motor.

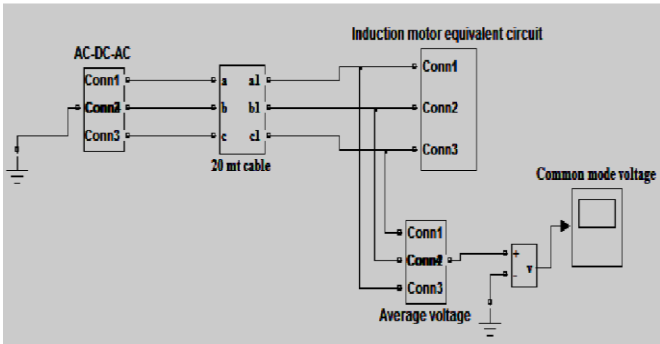

Fig.4.MATLAB Simulink model

TABLE I - Induction motor test results

Vo(V)	Io(A)	Wo (W)	No (rpm)
440	2.2	350	1500
Vb(V)	Ib(A)	Pb (W)	R_1 (Ω)
150	5	540	0.72

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TABLE II - Equivalent circuit parameters

R_1 (Ω)	R_2 (Ω)	$L1=L_2$ (mH)	L_m (mH)
0.72	13.4	6.36	268.63

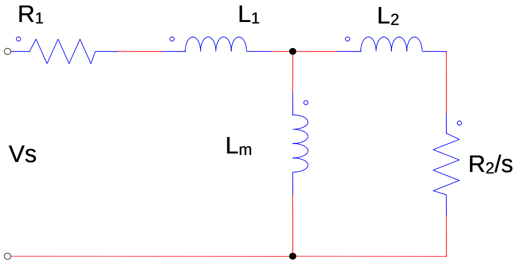

Fig. 5. Per phase motor equivalent electrical circuit.

V. RESULTS AND DISCUSSION

From Fig.6, 7, and 8 and from Table. III, it is observed that reduction of common mode voltage with higher levels of PWM inverter in the presence of long cable connected between the inverter and motor. It is also observed from Fig.9.and from Table. IV with higher motor HP ratings, the magnitude of over voltage at the motor terminal decreases and hence the common mode voltage, it is due to impedance matching between motor and the cable characteristic impedance.

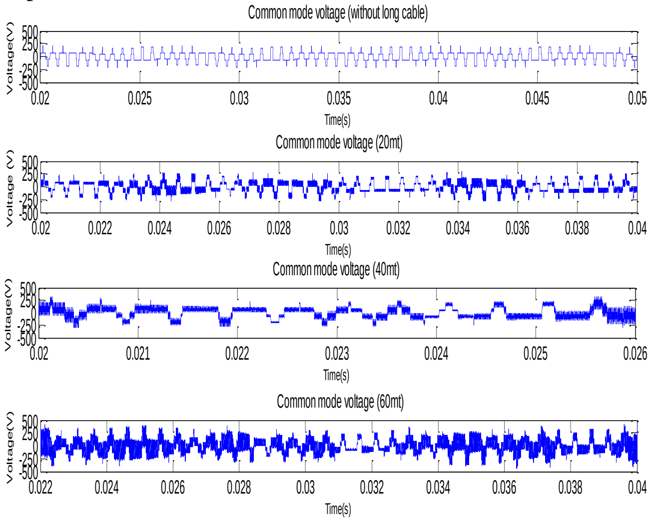

Fig.6. Common mode voltage (2-LEVEL)

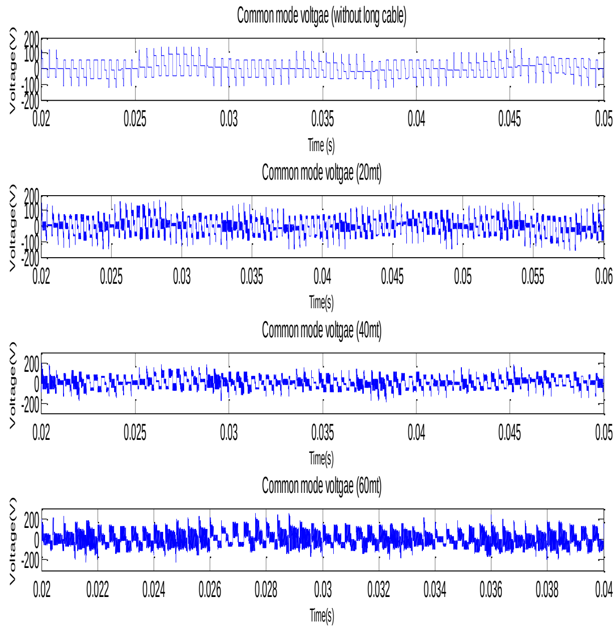

Fig.7 Common mode voltage (3-LEVEL)

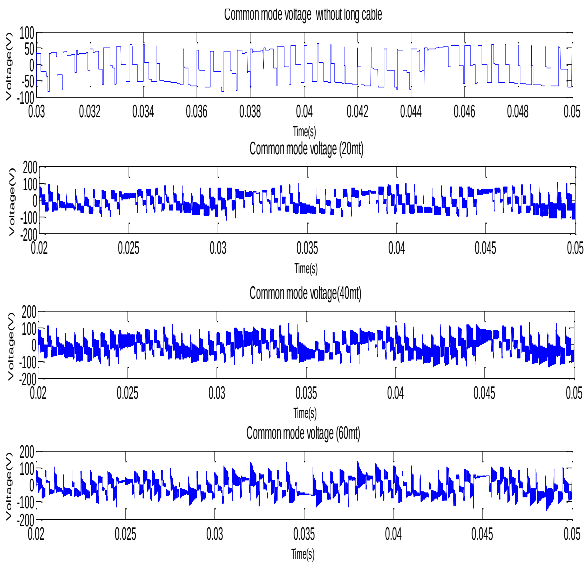

Fig.8.Common mode voltage (5-LEVEL)

TABLE III – Common mode voltage for 2,3 and 5 level inverter fed induction motor with different cable length

Level\ length	Without long cable	With 20mt long cable	With 0mt long cable	With 60mt long cable
2-level	200V	270V	390V	450V
3-level	140V	170V	190V	250V
5-level	60V	100V	130V	150V

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International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-2 Issue-2, December 2012

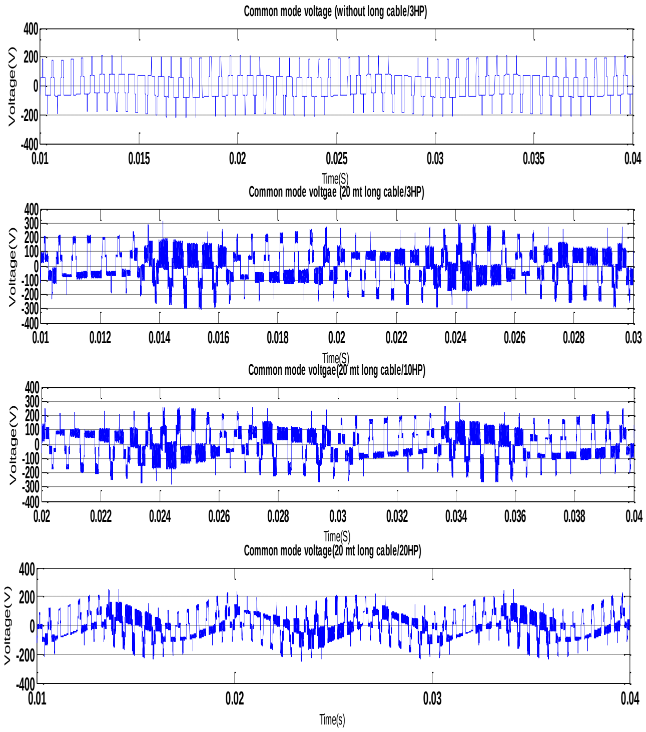

Fig.9. Common mode voltage for different HP ratings of motor.

TABLE IV – Common mode voltage for different HP ratings of Induction motor

HP rating of induction motor	Common mode voltage without long cable	Common mode voltage with 20mt long cable
3HP	200V	300V
10HP	200V	250V
20HP	200V	210V

VI. CONCLUSION

In this paper simulation and analysis of the common mode voltage in 2-level SPWM inverter and diode clamped multilevel inverters fed induction motor with long cable has been presented. A simplified high frequency modeling of induction motor and HF power cable is carried out. It is observed from simulation results, reduction in common mode voltage with long motor cable for 3 and 5 level inverter fed induction motor compared to 2-level inverter fed induction motor. It is also observed that with higher motor HP ratings, the magnitude of common mode voltage decreases. Reduction in common mode voltage reduces shaft voltage and bearing current, avoiding premature bearing failure. Hence increases the life of the motors as well as reduces many more hidden problems in the motors.

REFERENCES

[1] Alger P., Samson H., "Shaft Currents in Electric Machines" A.I.R.E. Conference .,Feb. 1924

[2] Annette Muetze, Andreas Binder, "Techniques for Measurement of Parameters Related to Inverter Induced Bearing Currents",IEEE transactions on industry applications,vol.43,No5,September/October 2007.

[3] J. Erdman, R. J. Kerkman, D. Schlegel, and G. Skibinski, "Effect of PWM inverters on AC motor bearing currents and shaft voltages," in IEEE, APEC-95,10th An Applied Power Electronics Conference and Exposition, vol. 1, Mar. 5-9, 1995, pp. 24 - 33.

[4] Doyle Busse, Jay Erdman, Russel J. Kerkman, Dave Schlegel, and Gary Skibinski "System Electrical Parameters and Their Effects on Bearing Currents", IEEE, transactions ,0-7803-3044-719, 1996.

[5] D. Busse, J. M. Erdman, R. J. Kerkman, D. W. Schlegel, and G. L. Skibinski, "Bearing currents and their relationship to PWM drives," in Conf. Record IEEE ,IECON '95, Nov. 1995.

[6] A. Muetze, A. Binder, "Calculation of motor capacitances for prediction of discharge bearing currents in machines of inverter-based drive systems," Proceedings of the 5th International Electric Machines and Drives Conference (IEMDC), San Antonio, TX, May 15- 18, 2005, pp. 264-270.

[7] José Rodríguez, Jih-Sheng Lai, Fang Zheng Peng "Multilevel Inverters: A Survey of Topologies, Controls, and Applications,". IEEE transactions on industrial electronics, vol. 49, no. 4,PP 724-734,August 2002.

[8] A.Ramachandran, M.Channa Reddy, Ranjan Moodithaya, "Minimization and identification of conducted emission bearing current in variable speed induction motor drives using PWM inverter," Sadhana, Vol.33,Part5,October 2008.

[9] B.Basavaraja and D.V.S.S.Siva Sarma "Modeling, Simulation and Experimental Analysis of Transient Terminal Overvoltage in PWM-Inverter fed Induction Motors," Proceedings of International Conference on PES General Meeting held in 333 S. Franklin Street Tampa, Florida,3602 USA, 2007.

[10] A. F. Moreira T. A. Lipo G. Venkataraman and S. Bernet "High Frequency Modeling for Cable and Induction Motor Over-voltage Studies in Long Cable Drives." IEEE Industrial Application Society 36th Annual Meeting Chicago, Illinois, USA, September 30 – October 5, pp 1-8, 2001.

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