VOL. 7, NO. 9, SEPTEMBER 2012 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

HIGH FREQUENCY MODEL OF INVERTER FED INDUCTION MOTOR DRIVE FOR INVESTIGATION OF OVER VOLTAGE PHENOMENA

K. Kanchana[1] and V. Rajini[2]
[1]Department of EEE, Saveetha Engineering College, Chennai, Tamil Nadu, India
[2]Department of EEE, SSN college of Engineering, Chennai, Tamil Nadu, India
E-Mail: kanchana.anoop@gmail.com

ABSTRACT

This paper describes the analysis of the over voltage phenomena at the motor terminal of an inverter fed induction motor. The high frequency model for a three phase cable and induction motor is simulated using Simulink and analyzed for the over voltage for different cable length. The results indicate that the over voltage is a function of cable length and it also depends on gauge of the cable.

Keywords: High frequency model, over voltage, PWM, IGBT.

1. INTRODUCTION

The number of industry applications in which induction motors are fed by static frequency inverters is growing fast. An increasing part of low voltage standard induction motors operate with PWM voltage source inverters using IGBT transistors. The supply of these induction motors by PWM inverters through cables leads to undesire over voltages at the motor terminals. The rapid switching speed of the IGBT generates voltage transients with very short rise times which propagate to the motor terminals and reflect, causing a large voltage across the terminals, as much as 80% of which can appear across the first turn of the motor. Modern IGBT-based adjustable speed drives (ASD) have modulation frequencies in the range of 2 to 20 kHz with typical switching times of 50 ns or about 13 V/ns for a 460 V system, As the impedance of a motor is generally much greater than the impedance of the cable which connects the ASD to the motor, the short rise time pulses incident on the motor terminals reflect, causing substantial over voltages at the motor terminals. [1] - [4]. Depending on the cable parameters like the length of the cable, these over voltages may reach 3 or 4 p.u, and may lead to a failure of the insulation of the motor windings. The high magnitude and short rise time of the over voltage is potentially hazardous for motor insulation, motor bearings, etc.

When pulse width modulation is used as a switching technique, repetitive voltage impulses due to motor-cable-converter impedance mismatch are generated, which can greatly exceed the amplitude of the fundamental voltage. Moreover, uneven voltage distribution along the motor windings can cause a large overstress of the inter turn insulation of the first coils. In this way a new unconventional electrical stress is applied to the insulation systems, which can cause premature failure in service if not taken into account in the design phase. Depending on the type of PWM employed, the switching frequency and cable length, the motor suffer from over voltage, temperature rise and noise. Over voltage depends on several factors like rise time of the voltage pulse, cable length, type of cable, cable gauge, minimum time between successive pulses and switching frequency.

The problems become much more severe if the overstresses can initiate or enhance partial discharge (PD) activity, e.g., low-voltage motors supplied by Power electronic converter. These motors are usually manufactured with organically insulated magnetic wires like polyamide, which may be seriously damaged by PD activity. Thus, improved insulating materials, capable of resisting PD activity are essential. Corona-resistant insulation consists of mixed organic and inorganic materials, the latter being more resistant to PD activity [2], [3]. So it is necessary to model the inverter fed induction motor and analyze the over voltage phenomena by using various parameters as mentioned above. This paper aims to investigate the effect of the cable length and the cable gauge as parameter to analyze the over voltage of inverter fed induction motor drive system. The problem and the importance of predicting peak over voltages to determine the appropriate insulation to be used by cables is addressed. Frequency-domain characterization of cables and induction motor is considered.

2. REFLECTED VOLTAGE PULSES

When ripples travel across a pond and strike a barrier, they reflect back from the barrier and combine with the incoming ripples. In a similar way, a voltage wave travelling down a transmission line is reflected back from the transition between the line impedance and the load impedance at the end of the line. If the load impedance is equal to the characteristic impedance of the line, there is no reflected wave. If there is a large difference in impedance, the amplitude of the reflected wave will approach the amplitude of the original or incident wave. A positive reflection occurs if the load impedance is greater than the line impedance. The conductors that connect a motor to a PWM controller act as a transmission line. Since the characteristic impedance of a motor cable is typically less than the characteristic impedance of a motor, classical transmission line theory predicts that a voltage reflection will occur at the end of a motor cable [1], [4]. The characteristic impedance is significantly less for larger motors than for smaller motors while there is a smaller range of values for typical cable impedances. This means that the magnitude of the reflected voltage is significantly less for larger motors as compared to smaller motors. Although the output pulse travels from the PWM controller to the motor at about half the speed of light, it is possible that the time required for a pulse to reach the motor may be more than half the rise time of the pulse. This is the case when the length of the motor cable is greater than or equal to the critical length. The critical length can be estimated as one half (1/2) of the speed that the pulse travels from the drive to the motor multiplied by the rise time.

$$L_{critical} = \frac{Vcable * tr(\mu s)}{2}$$

V_{cable} (sometimes referred to as propagation factor) is the speed that the pulse travels from the drive to the motor in feet per µsec. The value of V_{cable} depends on the type of cable, the type of conduit or cable tray and other details of the cable installation. V_{cable} is often estimated as 500 feet per sec.

3. HIGH FREQUENCY MODEL OF CABLE

A combination of high switching frequencies, fast rising and falling times of pulses, and long cables results in serious application problems, especially for low to medium HP machines. The reflected voltage waveforms generate significant over voltage peaks, RFI, EMI and bearing currents. When cable lengths and/or fast rising times become excessive, mitigation becomes difficult. These conditions require techniques like filtering at the motor terminals, filtering at the inverter terminals or considerations for cable design for VFD to help solve such problems. These solutions add cost and can be prohibitive for low HP applications. In such cases, it is desirable to accurately predict voltage peaks, current peaks and ringing frequency at the terminals of the motor driven by a VFD in order to determine the appropriate electric cable to use, the appropriate insulation to consider.

Peak voltage prediction depends on accurate cable and load models. High frequency motor models have been refined with good correlation to test data. Cables are modeled with segments and transport delay approximations. High frequency effects (skin and proximity effects) are modeled using r-l ladder networks. However, ladder networks incorrectly add phase and take more and more simulation time as accuracy is increased.

The model that provide a sufficiently accurate frequency response for the short and open circuit measurements, and thus for the cable surge impedance is given in Figure-1. It includes the line inductance and resistance per unit length Ls and Rs, the adjacent line-to-neutral capacitance and conductance per unit length Cp2 and Rp2, and the difference-mode capacitance per unit length Cp1 [5].

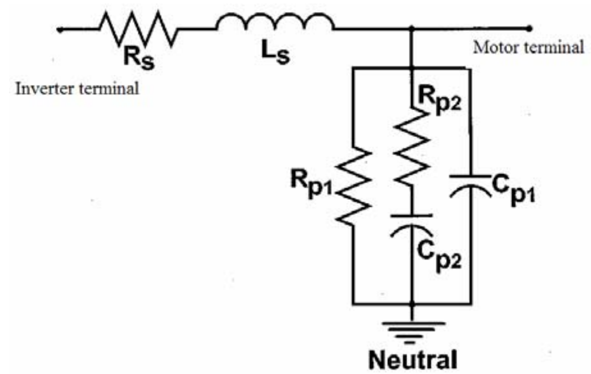

Figure-1. Per-phase high-frequency model of the power cable per-unit length.

4. HIGH FREQUENCY MODEL OF INDUCTION MOTOR

The proposed model for the ac motor input impedance is based on the high-frequency model [5] - [8], which has been successfully used in calculating the over voltage. The parameters of the model are the phase-to-neutral impedance (Z_{pn}) and phase-to-ground impedance (Z_{pg}). Figure-2 shows the proposed per-phase high-frequency motor model that is used in the calculation of the over voltage analysis. Accurate modeling of induction motors in high-frequency range plays an important role in investigating the motor drive over voltage.

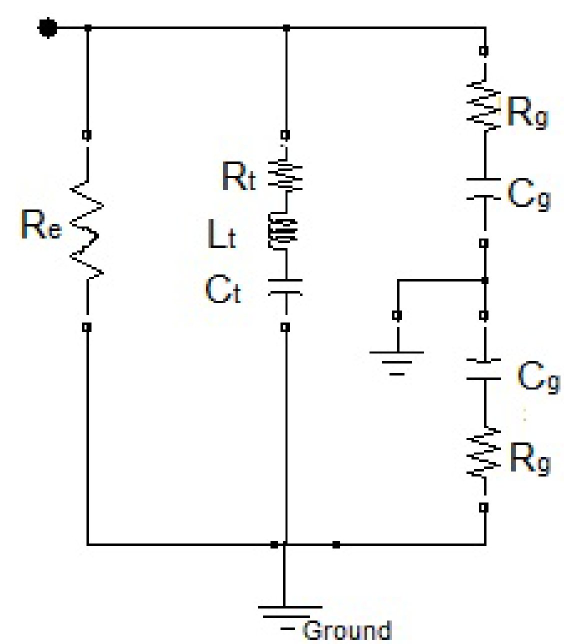

Figure-2. Per-phase representation of the high frequency induction motor.

Here, C_g is the winding-to-ground capacitance, R_g is the winding to ground resistance, R_t, is Turn to turn resistance, L_t is the turn to turn inductance, C_t is the Turn-to-turn capacitance and R_e-parallel resistance.

VOL. 7, NO. 9, SEPTEMBER 2012 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

5. MATLAB MODEL OF AN INVERTER FED INDUCTION MOTOR

In MATLAB, the three phase high frequency model of inverter fed induction motor is designed using the above mentioned high frequency model of cable and induction motor as shown in Figure-3. In inverter model, we used pulse width modulation technique and IGBT as a switch. In this model different cable gauges: #6, #8, #10, #12, and #14 AWG type of cable [5] per meter is connected in between the inverter and the motor of 3HP, and a 400V pulse voltage is applied to the motor through the cable and observed the voltages and oscillations at motor and inverter terminals.

Similarly the length of the cable is varied for 10m, 20m, 30m, 40m and 50m and observed the voltages and oscillations at motor and inverter terminals. Figure-4 shows the voltage wave form at inverter and motor terminal for 6 Gauge per meter cable length with time period of 10^{-6} sec. Figure-5 shows oscillation of voltage waveform at inverter and motor terminal for 6 Gauge per meter cable length with time period of 0.03s. Figure-6 shows the terminal voltages at motor and inverter for a 8 gauge cable length of 20m for a time period of 10^{-6} sec. Figure-7 shows the terminal voltages at motor and inverter for a 8 gauge cable of length 20m for a time period of 0.03s

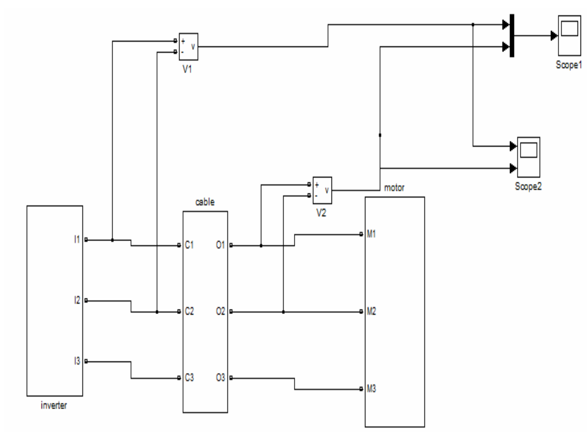

Figure-3. Simulation model of high frequency inverter fed induction motor.

6. ANALYSIS OF OVERVOLTAGES

The simulation results show the over voltage at motor terminal for different gauges. This is listed in Table-1. Graphically the variations in terminal voltage of motor for various cable gauges are represented in Figure-8. It shows that over voltage at 12 gauges is minimum compared to other gauges. The over voltage at motor terminal for different cable length is listed in Table-2. Graphically the variations in terminal voltage of motor for various cable lengths are represented in Figure-9. It clearly shows that peak voltage value increases with cable length.

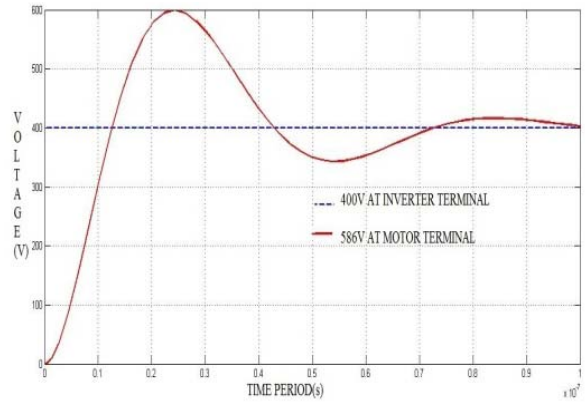

Figure-4. Voltages at motor and inverter terminal for a 6 gauge per meter cable length for a time period of 10^{-6} sec.

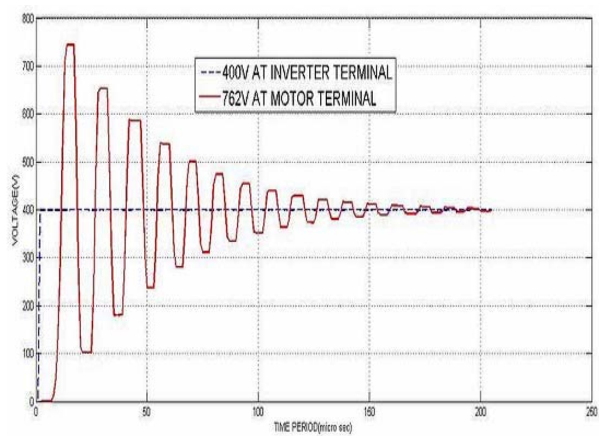

Figure-5. Voltage at inverter and motor terminal for 6 Gauge cable length of 20m with time period of 0.0002sec.

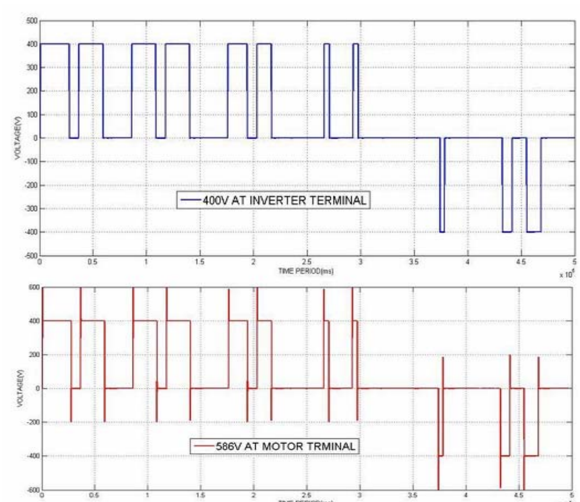

Figure-6. Voltage at inverter and motor terminal for 8 gauge per meter cable length with time period of 0.03 sec.

VOL. 7, NO. 9, SEPTEMBER 2012 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

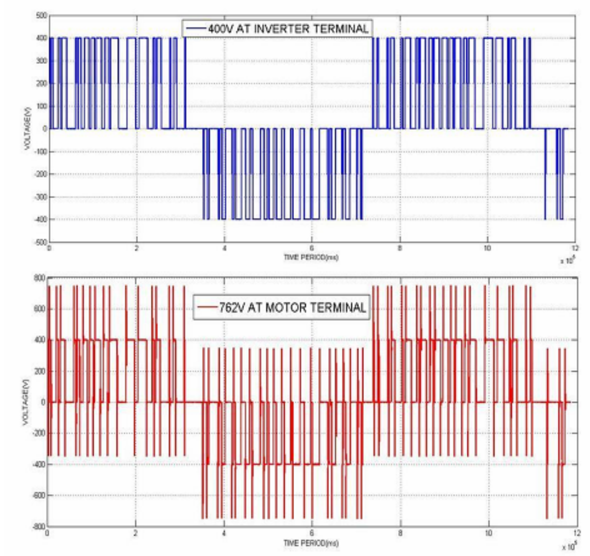

Figure-7. Voltage at inverter and motor terminal for 8 Gauge cable of length 20m with time period of 0.03 sec.

Table-1. Terminal voltages for various gauges for a 3hp motor.

S. NO	GAUGE OF THE CABLE	VOLTAGE AT INVERTER TERMINAL (V)	VOLTAGE AT MOTOR TERMINAL (V)
1	6	400	586
2	8	400	585.5
3	10	400	585.4
4	12	400	570
5	14	400	575

Table-2. Terminal voltages for various cable lengths of a 8 gauge cable.

S. NO	LENGTH OF THE CABLE(m)	VOLTAGE AT INVERTER TERMINAL(V)	VOLTAGE AT MOTOR TERMINAL(V)
1	10	400	734
2	20	400	762
3	30	400	773
4	40	400	778
5	50	400	781

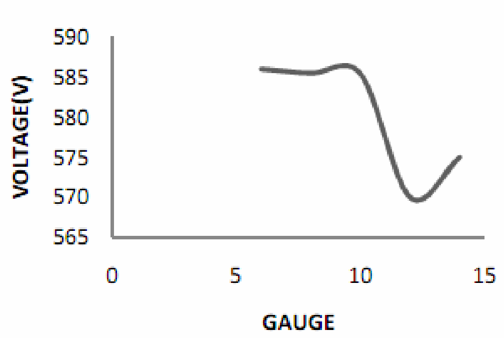

Figure-8. Peak voltage at motor terminal versus cable gauges.

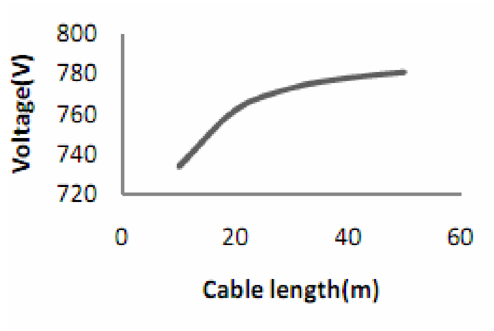

Figure-9. Peak voltage at motor terminal versus cable length.

7. EXPERIMENTAL ANALYSIS OF THE OVER VOLTAGE

An experiment was conducted using an arrangement of a SPWM (Sine Pulse Width Modulated) inverter connected to a slip-ring induction motor through a three-core cable of length 15m. The V/f control mechanism was adopted wherein the voltage was initially set at 400V, frequency at 50Hz and speed at 1325rpm. The voltage and speed were varied keeping the V/f ratio constant and the voltage waveforms were recorded in a MSO (Mixed Signal Oscilloscope). The specifications for the slip ring induction motor are given in Table-3.

Table-3. Drive specifications.

Specifications	Values
Kilowatts	3.7KW
Volts	415V
Amps	7.5A
Speed	1410rpm
Horsepower	5HP

Figures 11 and 12 represent the recorded voltage waveform at the inverter output and motor input terminals using the MSO. The experimental set up used for the study is shown in Figure-10.

Figure-10. Experimental set up.

Figure-11. Experimental voltage waveform recorded for a cable length 15m at the inverter output terminals.

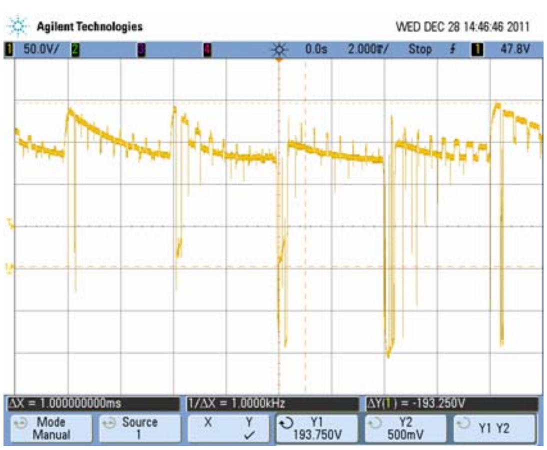

Figure-12. Experimental voltage waveform recorded for a cable length 15m at the motor input terminals.

8. CONCLUSIONS

This paper discusses the over-voltage phenomena in long cable PWM drives due to voltage reflection theory. Experimental and simulation analysis has been made. Effect of cable length and cable gauge on the over voltages are analyzed. As the cable length increase the magnitude of over voltage increases. There is a potential danger of the voltage capability of stator winding insulation recommended by existing standards being exceeded in many cases. Hence mitigation methods need to be addressed for long cable fed adjustable speed drives with PWM strategy.

REFERENCES

[1] Persson E. 1992. Transient Effects in Application of PWM Inverters to Induction Motors. IEEE Transactions on IA. 28(5): 1095-1101.

[2] A. Cavallini, D. Fabiani and G. C. Montanari. 2010. Power electronics and electrical insulation systems - Part 1: Phenomenology overview. IEEE Electr. Insul. Mag. 26(3): 7-15.

[3] Cavallini, D. Fabiani and G. C. Montanari. 2010. Power electronics and electrical insulation systems - Part 2: Life modeling for insulation design. IEEE Electr. Insul. Mag. 26(4): 33-39.

[4] H. Bonnett. 1996. Analysis of the impact of pulse-width modulated inverter voltage waveforms on AC induction motors. IEEE Trans. Ind. Applicant. 32: 386-392, Mar/Apr.

[5] A.F. Morira, T. A.Lipo, G. Venkataramanan and S. Bernet. 2001. High Frequency Modelling for Cable and Induction Motor Over-voltage Studies in Long Cable Drives. IEEE Industrial Applications Society36th Annual Meeting Chicago, Illinois, USA, September 30-October 5.

[6] Basava Raja and D.V.S.S. Siva Sarma. 2006. Modelling and Simulation of dv/dt filters for A.C Drives with fast switching Transients. Power India Conference. IEEE Publication on 10-12 April.

[7] G. Grandi, D. Casadei and A. Massarini. 1997. High frequency lumped-parameter Model for AC motor windings. In: Proc. EPE'97, Vol. 2, Trondheim, Norway. pp. 578-583.

[8] A. Boglietti and E. Carpaneto. 1999. Induction motor high frequency model. In: Conf. Rec. IEEE-IAS Annu. Meeting, Phoenix, AZ, Oct. 3-7. pp. 1551-1558.