

EXPERIMENTAL DESIGN OF LOW LOSS FILTER TO MITIGATE OVERVOLTAGE FOR LONG CABLE FED INDUCTION MOTOR DRIVE

KANCHANA KADIRVEL

Department of Electrical and Electronics Engineering,
Saveetha Engineering College, Chennai, India.
Email: kanchana.anoop@gmail.com

RAJINI V

Department of Electrical and Electronics Engineering,
SSN College of Engineering, Chennai, India
Email: rajini@ssn.edu.in

Abstract—Overvoltage stress in long cable drive can dramatically reduce the reliability of insulation systems without suitable protection. This paper investigates the overvoltage mitigation and controlling techniques at motor terminal of Pulse Width Modulated (PWM) inverter fed induction motor for long cable lengths. A new approach to the high frequency model of power cable using T-network is depicted in the proposed work. Using proposed high frequency model of T network helps to predict over voltage compared to other cable model and give more accurate validation with experimental results. Detailed design equations for different types of passive filters such as RC, RLC and LC filters are presented. Simulation results indicate that LC filter contributes better performance compared to other filters. Simulation and experimental results are compared to verify the design of the proposed LC filter for three phase 1 HP induction motor connected to commercial AC motor drive through different lengths of three-core cable.

Keywords - filter, induction motors, pulse inverters, simulation, switching frequency.

I. INTRODUCTION

The Pulse Width Modulated (PWM) inverter has been widely used to control induction motors since it performs superior V/f control for medium range of induction motors. Further, in many industries, it is essential that inverter and induction motor must be placed separately and connected through long cable. Nowadays PWM inverters use high frequency switching devices and repetitive voltage pulses for enhanced performance. However, these inverter pulse travels through long cable and reflected back at the motor terminal and causes overvoltage [1]. In addition,

reflected voltage depends on difference between cable and motor surge impedance, fast switching frequency, cable length, cable size and shorter distance between consecutive pulses. These over voltages are extremely dangerous to motor insulation. Moreover, if these voltages create partial discharge (PD) activity, the life time of the induction motor is reduced rapidly. For example, the organically insulated magnetic wires in small motors may seriously be damaged by PD activity [2]-[3]. To overcome the above problem, either filtering techniques or strengthening the insulation of the induction motor can be adopted.

The study of rise time of overvoltage with either active or passive filters is essential for the implementation of suitable filters for preventing premature failure of PWM inverter fed Induction motor. Several authors have been designed passive filters to mitigate overvoltage and alter the rise time of voltage pulse [4]-[7]. But, passive filters are bulky size and have more power loss. So Chen, W, Yang [8] has designed an active filter for compensating the drawbacks of passive filters. However, active filters are rarely used in industrial application due to additional switches and complex algorithms. So, low loss passive filters are preferred because of their simplicity and availability. In this paper, different types of passive filters (RC, RLC and LC) with low power loss are designed for mitigation of overvoltage and augmentation of the rise time of the voltage at motor terminal. In few underwater applications, the motor terminals may not be available and hence, RLC and LC filters are connected at the inverter terminals to overcome the above challenge. These filters are

designed and simulated using Simulink / MATLAB and the results are compared for different cable lengths. Furthermore, experimental results of LC filter show superior performance to diminish overvoltage.

II. VOLTAGE REFLECTION ANALYSIS AND WAVE PROPAGATION THEORY

High frequency voltage pulse travels from inverter to motor through long cable. After reaching motor terminal it reflects back and the reflected voltage added with instantaneous voltage. Hence, the voltage at the motor terminals is increased. The reflected voltage magnitude is multiple of reflection coefficient (Γ) expressed in eqn. (1) which is proportional to the difference between surge impedance of cable Z_1 as in eqn. (2) and induction motor Z_2 .

$$\Gamma = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} \quad (1)$$

$$Z_1 = \sqrt{\frac{L}{C}} \quad (2)$$

Where, L and C are cable parameters. Due to high value of winding inductance, the surge impedance of the motor Z_2 is greater than 10 to 100 times of Z_1 .

$$v = \frac{1}{\sqrt{LC}} = \frac{c_0}{\sqrt{\epsilon_r}} \quad (3)$$

v is wave velocity, c_0 is speed of light and ϵ_r is relative permittivity of cable insulation material. Moreover, The speed of the travelling wave is approximately equal to half of light speed as per eqn. (3) because ϵ_r values for cable dielectrics is around 4 to 5. Therefore, the velocity of travelling wave is $150(m/\mu sec)$ and takes time (t_t in μs) expressed in eqn. (4) to travel between inverter to motor terminal.

$$t_t = \frac{l(m)}{150(m/\mu sec)} \quad (4)$$

Where l = length of the cable in meter.

t_t = time taken to travel the voltage pulse from inverter to motor terminal once (μsec).

The voltage pulse at time t_t , will be reflected back and will have a magnitude of V_R given by eqns. (5) and (6).

$$V_R(t_t) = \frac{t_t V_i \Gamma}{t_r} \quad \text{for } t_t < t_r \quad (5)$$

$$V_R(t_t) = V_i \Gamma \quad \text{for } t_t \geq t_r \quad (6)$$

Where V_i = inverter output voltage.

t_r = rise time of the inverter pulse.

Eqn. (6), shows that when $t_t \geq t_r$, the rise time of inverter pulse is not influencing the magnitude of the reflected voltage. The block diagram of the inverter fed induction motor is shown in Fig.1.

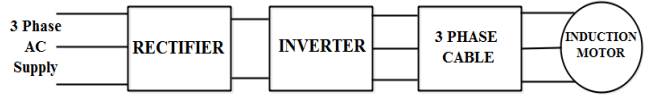


Fig. 1. Block diagram inverter fed induction motor

III. HIGH FREQUENCY MODEL

For longer cable lengths and/or fast rising times, reduction of overvoltage becomes challenging. The design of filtering techniques is needed to overcome the above problem. Hence, it is required to precisely calculate over voltage in order to design filters. So accurate simulation models of cable and induction motor are essential [9]-[11]. In addition, the parameters of cable and induction motor in the model should depend over a wide frequency response to get precise results. Therefore, the cable parameters are obtained by conducting measurement of short-circuit (Z_{sc}) and open-circuit impedances (Z_{oc}) from the frequency range of 100Hz to 2MHz using LCR meter. The high frequency cable model using T network in Fig.2 contains the series inductance (L_s), series resistance (R_s) which are obtained from the behavior of Z_{sc} , and parallel capacitances (C_{p1} , C_{p2}) and resistances (R_{p1} , R_{p2}) which are obtained from the behavior of Z_{oc} .

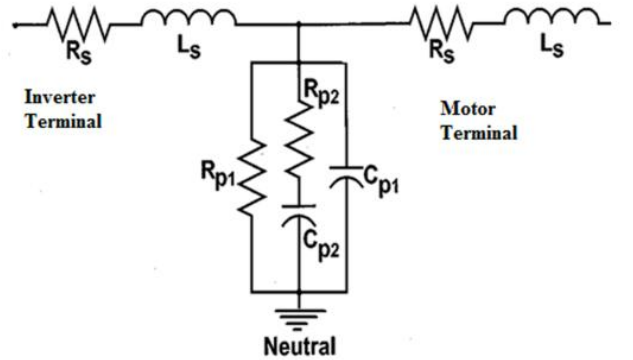


Fig. 2. High-frequency model of the cable using T network

The high frequency model of the induction motor is obtained using the frequency response of the phase-to-neutral impedances (Z_{PN}) and phase-to-ground impedances (Z_{PG}). The high-frequency induction motor model is shown in Fig.3 can be calculated using Z_{PG} and Z_{PN} which are measured from range of the 1 kHz to 2 MHz.

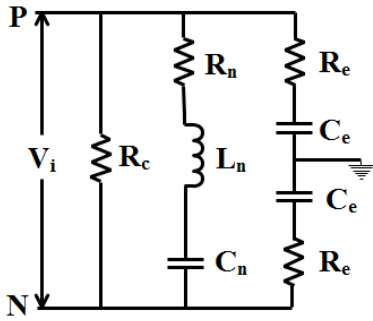


Fig. 3. High frequency model of induction motor.

Here, C_e is capacitance between motor winding and ground, R_e is the resistance of the motor winding, R_n , is turn to turn resistance, L_n is the turn to turn inductance, C_n is the turn to turn capacitance and R_c - parallel resistance.

IV. INVESTIGATION OF OVERVOLTAGE

A simulation model is implemented in SIMULINK which consists of three phase inverter, connected to high frequency cable and induction motor which is described in section III. In Three phase inverter model comprises of six IGBT (Insulated Gate Bipolar Transistor) switches. PWM pulses are generated and given to the IGBT switches. In this model, the inverter output of 400V is applied to a 1HP Induction Motor through a cable and the voltage at motor and inverter terminals are observed. The length of the cable is varied from 10m to 100m. Fig. 4 clearly indicates that the overvoltage waveform at the motor terminal takes much time to settle down as the length of the cable increases. Fig. 5 shows the voltage waves (zoomed in) measured between two Lines at both inverter and motor side which is connected between 100m cable. Fig.6 (a) and (b) show the terminal voltages (Expanded) at inverter and motor respectively with a cable length of 100m.

Fig.5 and 6 illustrate that the over voltage and high frequency oscillation occur at the motor terminal due to voltage reflection which in turn stress the motor insulation. The simulation results show that the magnitude of overvoltage depends on cable length. As in a longer cable, the forward inverter voltage wave takes greater time to reach motor terminal than the rise time of the inverter. So the magnitude of reflected voltage is increased and that are described in section II.

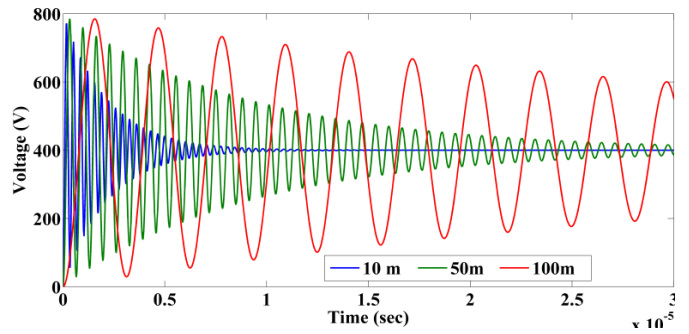


Fig. 4. Voltage wave forms (Zoomed in) at motor terminal for a cable of length 10m, 50m and 100m.

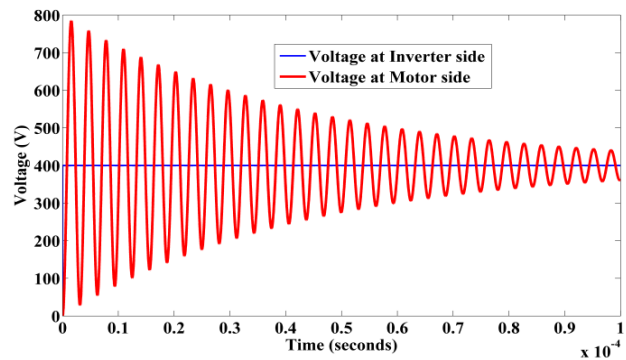


Fig. 5. Voltage wave forms (Zoomed in) at motor and inverter terminal for a cable of length 100m.

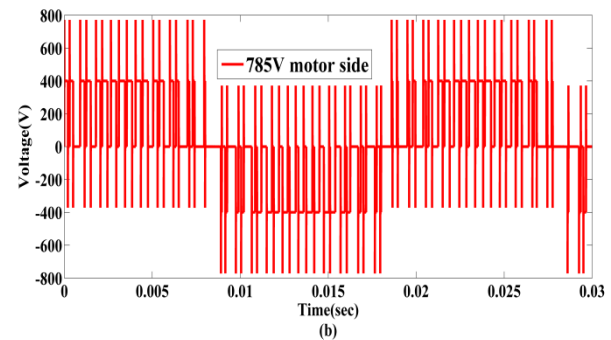
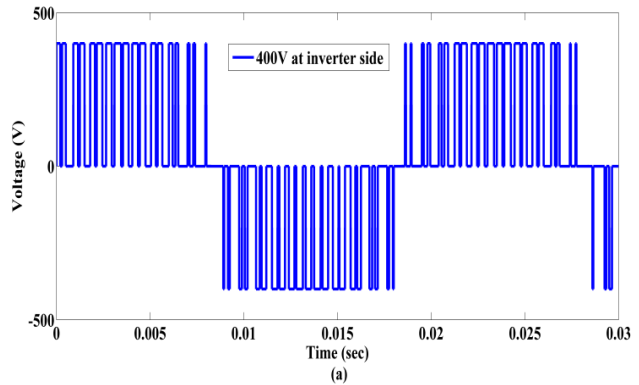


Fig. 6. Voltage wave form (Expanded) at (a) inverter output and (b) motor terminal for a cable length of 100m.

To verify simulation result, experimentation is carried out by a DELTA inverter (Model:VFD007L21A) connected to a three phase 1HP induction motor using different length of three-core cable (10m, 20m and 30m). The voltage waveforms are measured using DSO (Digital Signal Oscilloscope).

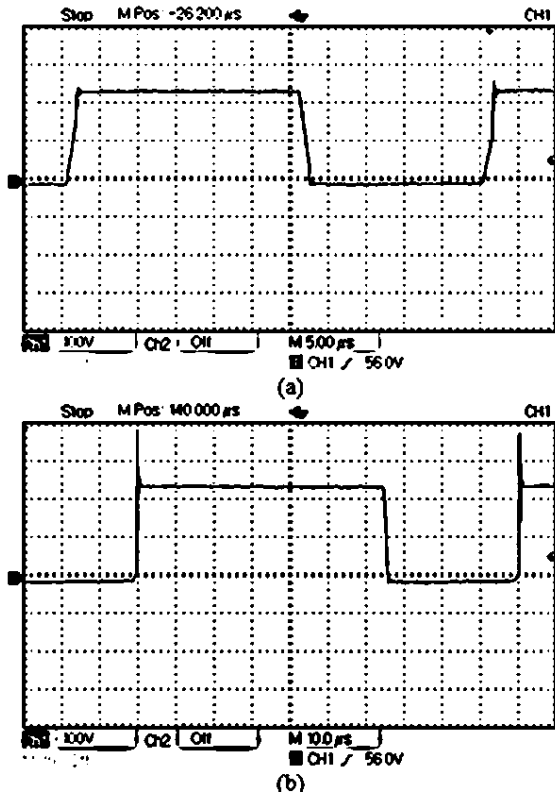


Fig. 7. Experimental line voltage waveform at (a) inverter side (b) motor side for a cable length of 10m

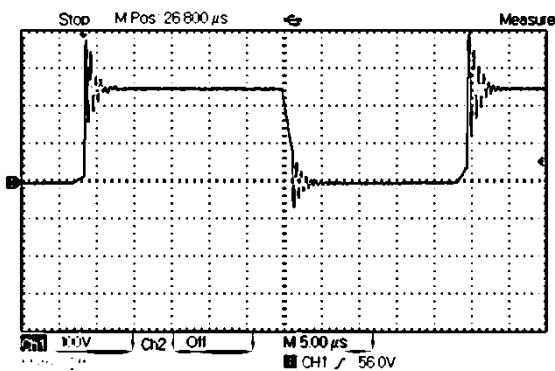


Fig. 8. Experimental line to line voltage waveform at motor side for a cable length of 20m

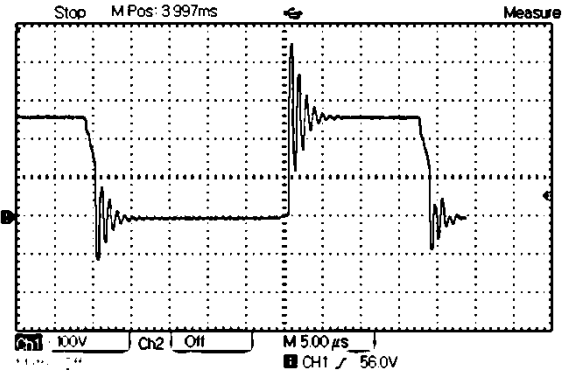


Fig. 9. Experimental line to line voltage waveform at motor side for a cable length of 30m

Fig.7 to 9 represent the recorded line to line voltage waveform at the inverter output and motor input terminals respectively using DSO. Voltage waveform at inverter side shown in Fig.7 contains lesser spikes compared to motor side because of the reflection wave generated at motor terminal which are discussed in section II. Moreover, Fig.8 and 9, show that the line to line voltage peaks are high and contain more number of spikes since travelling wave takes longer time (eqn.5) for long cable and clearly indicates that the ringing increases with cable length.

V. DESIGN OF PASSIVE FILTERS

A number of filtering methods have been recommended to eliminate the over-voltage in inverter drive fed by long cable. In this section, design equations of RC filter, RLC filter at motor terminal and RLC filter at inverter side are derived based on impedance matching of motor and cable during the rise and fall time of the inverter voltage pulse.

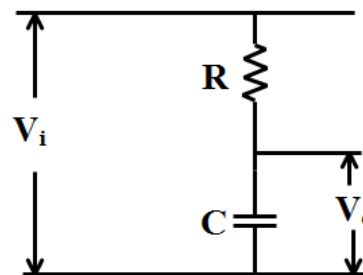


Fig. 10. RC low pass filter at motor side

The RC filter shown in Fig.10 is used to reduce the reflection coefficient by inserting a line to line resistance termination during rise and fall time of the inverter pulse. Hence eqns. (7) and (8) are derived in which voltage across the capacitor is equated to 10% of maximum value of the inverter voltage. Therefore,

almost full travelling voltage initially appears across the resistance during the transient period of the inverter voltage pulse. The value of R is fixed to the surge impedance of the cable in eqn. (10) to reduce the over voltage. The value of capacitor is designed according to the eqn. (9) which is derived from eqn. (8). The major constraint of choosing C value is that $3RC$ (three times of time constant of the capacitor) should be less than the inverter pulse time, to confirm that the capacitor is initially at zero before the next pulse.

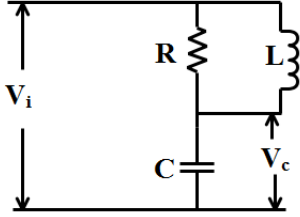


Fig. 11. RLC filter at motor side

$$V_c(S) = \frac{V_i}{RC S(s + \frac{1}{RC})} \quad (7)$$

$$V_c(t) = 0.1V_i = V_i \left(1 - e^{-\frac{t}{RC}}\right) \quad (8)$$

$$C = \frac{t_r}{0.1054 R} \quad (9)$$

$$R = \sqrt{\frac{L_s}{C_{p1}}} \quad (10)$$

The design of RLC filter (Fig.11) at the motor terminals is based on voltage across the capacitor as in eqn. (11) during the switching period of voltage pulse is made equal to 10% of inverter voltage, as in eqn. (12). The values of the filter capacitance and inductance are determined by using eqns. (13), (14) and (15) which are derived from eqns. (11) and (12).

$$V_c(S) = \frac{V_i(s + \frac{R}{L})}{RC S(s^2 + \frac{s}{RC} + \frac{1}{LC})} \quad (11)$$

$$V_c(t) = 0.1V_i = V_i(1 - e^{-\omega_n t} + \omega_n t e^{-\omega_n t}) \quad (12)$$

$$2\omega_n = \frac{1}{RC} \quad (13)$$

$$\omega_n^2 = \frac{1}{LC} \quad (14)$$

$$e^{-\omega_n t_r}(1 - \omega_n t_r) = 0.1 \quad (15)$$

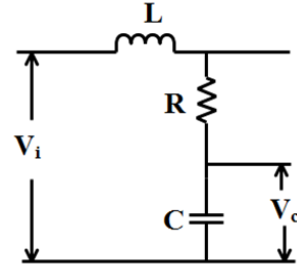


Fig. 12. RLC filter at inverter output

The voltage across capacitor of RLC circuit shown in Fig.12 is expressed using eqn. (16). The capacitor voltage is equated to 10% of input voltage described in eqn. (17) to design the values of R, L and C in order to suppress the over voltage during rise and fall time. The values of the filter capacitance and inductance are determined by using eqns. (18), (19) and (20) which are derived from eqns. (16) and (17).

$$V_c(S) = \frac{V_i Z_C}{(2RLC + Z_C LC) s(s^2 + \frac{s(Z_C RC + 2L)}{(2RL + Z_C LC)} + \frac{Z_C}{(2RLC + Z_C LC)})} \quad (16)$$

$$V_c(t) = 0.1V_i = V_i(1 - e^{-\omega_n t} + \omega_n t e^{-\omega_n t}) \quad (17)$$

$$2\omega_n = \frac{(2L + Z_C RC)}{LC(2R + Z_C)} \quad (18)$$

$$\omega_n^2 = \frac{Z_C}{LC(2R + Z_C)} \quad (19)$$

$$e^{-\omega_n t_r}(1 + \omega_n t_r) = 0.1 \quad (20)$$

VI. EXPERIMENTAL AND SIMULATION RESULTS

A new proposed model of inverter fed induction motor with passive filters is simulated in MATLAB. The simulation model is created with RC filter at motor side, RLC filter at both inverter output side and motor side and LC filter at inverter side. Fig.13 shows that all the three types of the filters effectively mitigate the overvoltage and reduce ringing. It also clearly shows that rise time of the voltage is more in RLC filter at inverter side compared to other two types. Furthermore, it demonstrates that the magnitude of overvoltage is reduced more in RLC filter at inverter output side as compared with RC filter and RLC filter at motor side because the RLC filter at inverter side decreases the pulse rise time before the pulse travels through the cable. Fig.14 illustrates the wave form at motor side using an LC filter. It gives pure sinewave without any overshoot.

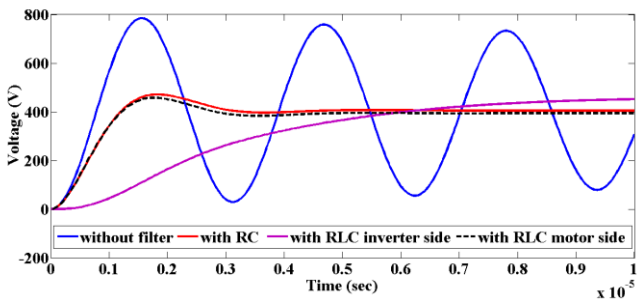


Fig. 13. Line Voltage waveforms at motor side without filter and with RC filter, RLC filter at motor side and RLC filter at inverter side for 1HP PWM Induction Motor

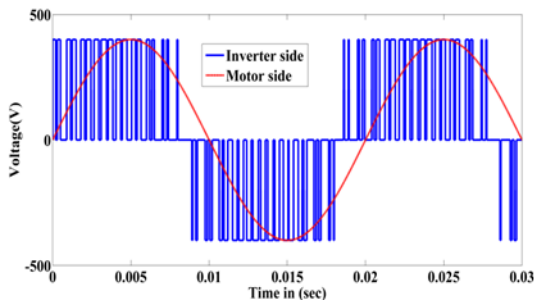


Fig. 14. Voltage waveforms with LC filter

LC filter is connected to inverter side of three phase 1HP induction motor connected to a DELTA inverter (Model: VFD007L21A) through a three-core cable as shown in Fig.15. The voltage waveforms are recorded using DSO (Digital Storage Oscilloscope) at motor and inverter terminal with and without LC filter. The voltage waveform at inverter side shown in Fig.16 does not have spikes compared to motor side. Fig. 17(a) and (b) present the overvoltage waveforms at motor side which clearly shows that the number spikes are more as cable length increases. Fig.18, the enlarged form of Fig.17 (a), indicates the waveform contains ringing which shows the acceptability of the simulation results. The inclusion of LC filter at either motor side or inverter side gives pure sine voltage waveform at both inverter and motor side and null overshoot which is displayed in Fig.19. In addition, the wave form remains same irrespective of the length of the cable.

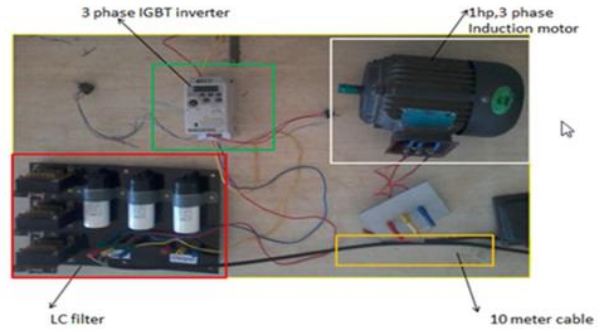


Fig. 15. Photo of the setup for inverter fed induction motor with LC Filter.

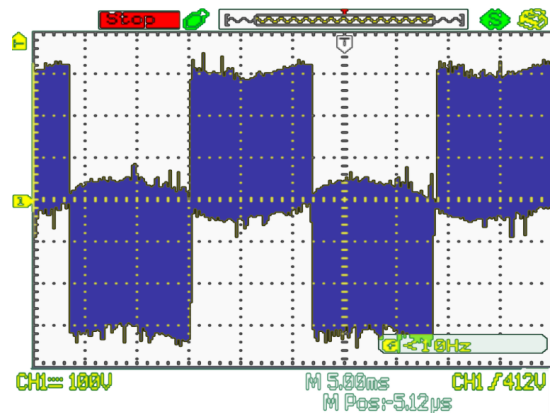


Fig. 16. Voltage waveform without filter at inverter side

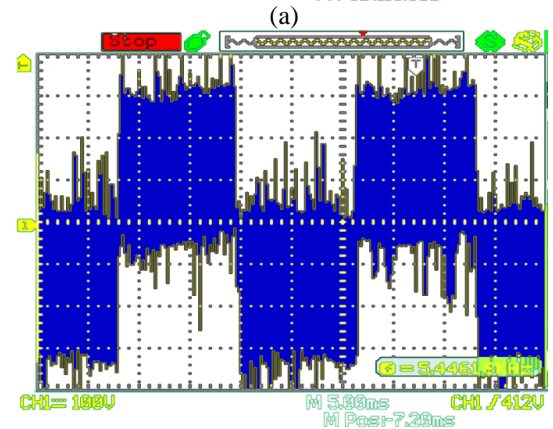
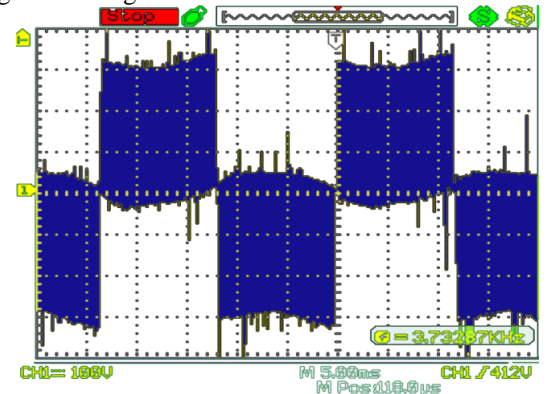


Fig. 17. Voltage waveform without filter at (a) motor side for 10m cable length (b) motor side for 50m cable length

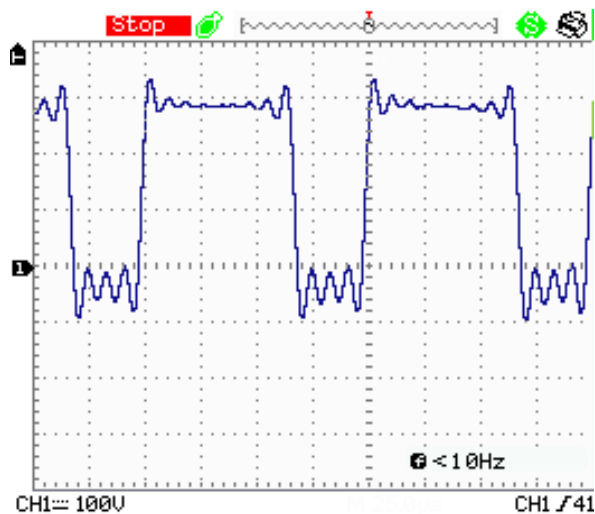


Fig. 18. Voltage waveform without filter at motor side for 10m cable length

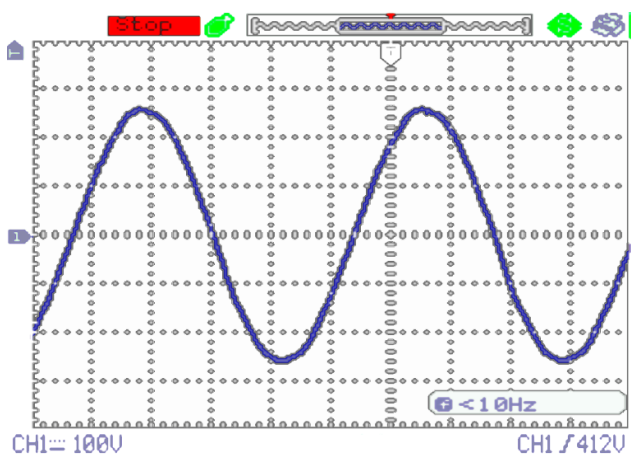


Fig. 19. Voltage waveform at motor side with LC filter

VII. CONCLUSION

The high frequency model of inverter fed induction motor in MATLAB is helpful to design filter at both at inverter and motor side. Design equations for the passive filters are derived based on characteristic impedance matching of cable and motor during switching period of the inverter voltage pulse. In this study, RC filter is not able to increase the rise time of the voltage but mitigates the magnitude of the overvoltage at the motor terminal. However, the RLC filter at inverter side gives better performance such as mitigating overvoltage and ringing than RC filter and RLC filter at motor side, since it decreases the rise time of the inverter voltage pulse. Simulation of LC filter presents more efficiency compared to all other passive filters as it gives

a pure sine wave with null overshoot. Thus, an experimental setup with a LC filter is constructed and the output waveforms are obtained for different cable lengths. Finally, the simulation and experimental results showed the acceptability of simulation analysis and the viability of the proposed LC filter.

REFERENCES

1. Persson E (1992) Transient effects in application of PWM inverters to induction motors. *Industry Applications, IEEE Transactions on*, 28(5), pp.1095-1101.
2. Cavallini, A.; Fabiani, D.; Montanari, G.C. (2010) "Power electronics and electrical insulation systems Part 1: Phenomenology overview," *Electrical Insulation Magazine, IEEE*, vol.26, no.3, pp.7, 15.
3. Cavallini, A.; Fabiani, D.; Montanari, G.C. (2010) "Power electronics and electrical insulation systems - part 2: life modeling for insulation design,"
4. Moreira, Alessandro F, Lipo, et al. (2002) High-frequency modeling for cable and induction motor overvoltage studies in long cable drives. *Industry Applications, IEEE Transactions on*, 38(5), pp.1297-1306.
5. Skibinski G (1996) Design methodology of a cable terminator to reduce reflected voltage on AC motors. In *Industry Applications Conference, 1996. Thirty-First IAS Annual Meeting, IAS'96., Conference Record of the 1996 IEEE* (Vol. 1, pp. 153-161).
6. Von Jouanne A and Enjeti PN (1997) Design considerations for an inverter output filter to mitigate the effects of long motor leads in ASD applications. *Industry Applications, IEEE Transactions on*, 33(5), pp.1138-1145.
7. Von Jouanne A, Rendusara, et al. (1996) Filtering techniques to minimize the effect of long motor leads on PWM inverter-fed AC motor drive systems. *Industry Applications, IEEE Transactions on*, 32(4), pp.919-926.
8. Chen, W, Yang, et al. (2014) A novel filter topology with active motor CM impedance regulator in PWM ASD system. *Industrial Electronics, IEEE Transactions on*, 61(12), pp.6938-6946. *Electrical Insulation Magazine, IEEE*, vol.26, no.4, pp.33, 39.
9. Bonnett, A.H. (1996), "Analysis of the impact of pulse-width modulated inverter voltage waveforms on AC induction motors," *Industry Applications, IEEE Transactions on*, vol.32, no.2, pp.386,392.

10. Boglietti, A.; Carpaneto, E. (1999), "Induction motor high frequency model," Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. *Conference Record of the 1999 IEEE* , vol.3, no., pp.1551,1558 vol.3.
11. Grandi,G.; Casadei, D.; Massarini .A.; "High frequency lumped-parameter Model for AC motor winding." *In: Proc. EPE'97*, Vol. 2, Trondheim, Norway. pp. 578-583.

Author biography



Ms. Kanchana K, Presently working as Assistant Professor in the Department of EEE at Saveetha Engineering College, Chennai and pursuing Doctoral Degree at SSN College of Engineering under Dr. V Rajini, Professor, Department of EEE. She received her M.E Degree in High Voltage Engineering from College of Engineering Guindy, Anna University. Currently she is doing research in over voltage control and mitigation techniques for Induction motors used in Industries



Dr.V.Rajini, Professor in the Department of Electrical and Electronics Engineering, SSN college of Engineering, has 18 years of teaching and research experience including 4 years of research experience in polymeric insulating materials in AnnaUniversity. Shereceived her B.E. and M.E. (University Rank1) degrees in Electrical Engineering from Annamalai University and Ph.D. in High Voltage Engineering from Anna University. She has published over 35 research publications in referred journals and international conferences. She is currently working on the development of novel cable insulating materials for nuclear power plants. She is a member of IEEE and Life member of ISTE.