Design of Filters for PWM Inverter Fed AC Drivers Using Simulation Program

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Abstract: Combined use of power electronics devices and ac induction motors, made IM use as an adjustable speed drives has been increased drastically. Of these, induction motors are widely used in industrial and domestic applications due to the advantages like simple construction, ruggedness, flexible control, good efficiency and low cost. In order to control the stator voltage and speed, PWM inverters are used. But the usage of PWM inverters has the effects like non-uniform voltage distribution and increase in the temperature. Recent advances in power electronic switching device technology have resulted in dramatic improvements and cost reduction of pulse-width modulated AC adjustable speed drives. Concomitant with the better performance enabled by the high switching speed and increased switching frequency they have also raised several concerns related to the consequences of high speed switching one of these concerns is the over-voltage that appears at the motor terminals due to the impedance mismatch between the power cable and the motor. In this paper, accurate simulation models for power cables and motors that allow a better understanding of the over-voltage problem are developed. The models can be readily implemented using computational tools like Matlab, thereby providing a convenient method to develop the best dv/dt filter solution for a particular drive. Simulation results are presented for analyzing the over-voltage problem for a range of pulse rise times and cable lengths for 3hp 7hp and 15hp motors. Simulation program is used for the investigating the filter network solution

Keywords: **Four to six keywords are to be provided for indexing purposes.**

I. INTRODUCTION

As high switching speed and frequency are enabling adjustable speed drives with better performance, concerns have arisen related to certain unintended consequences of the same. One of these concerns, the over-voltage problem due to steep voltage fronts and short pulse rise time from the inverter traveling along long power cable feeding the motors. The overvoltage is explained as a voltage pulse, initiated at the inverter, traveling along the cable and being reflected at the motor terminal due to the mis-match between the surge impedance of the motor and the cable. Its behavior is dependent, however, on the characteristics of voltage pulse rise time and of the cable. The objective of this paper is to present a definitive study of the motor over-voltage phenomena by developing accurate and fast simulation models for power cables and motors that allow a better understanding of the over-voltage problem. The models can also be used to provide a convenient tool to benchmark the best dv/dt filter solution for a particular drive. The use of distortion-less line representation is a much better approximation than the loss less line. However, it is still not sufficiently accurate to investigate the over-voltage problem, especially for drives with long feeders, when the distortion of the line becomes more important. In this paper, it is shown that representing the industrial power cable as a lossy transmission line, better results can be achieved. The induction motor model for the purpose of studying the over-voltage phenomenon has been modeled using a simple RL circuit.

The simulation program developed in Matlab including the aforementioned cable and motor models are described in the subsequent sections. Several simulation results are presented showing the suitability of the simulation program in the overvoltage calculation. The most interesting dv/dt filter topologies, including RC and RLC filters at the motor terminals and RLC filters at the inverter output, are evaluated in the simulation program.

II. SYSTEM REPRESENTATION

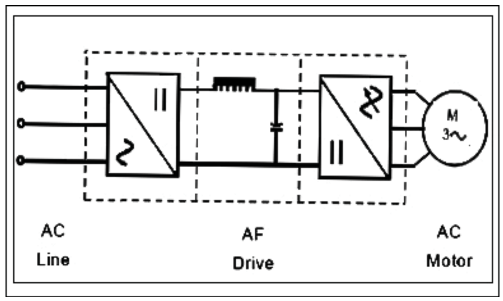

Figure 1 Principle of operation of AC drive

Adjustable Speed Drives (ASDs) are Pulse Width Modulated (PWM) drives. Fig.1 illustrates the basic principles of a PWM drive. The rectifier converts input line power, which has a nominally fixed voltage and frequency, to fixed voltage DC power. The fixed voltage DC power is then filtered to reduce the ripple voltage resulting from the rectification of the AC line. The inverter then changes the fixed voltage DC power to AC output power, with adjustable voltage and frequency. The output waveform consists of a series of rectangular pulses with a fixed height and adjustable width. The overall pattern of positive vs. negative pulses is adjusted to control the output frequency. The width of the individual pulses is modulated so that the effective voltage of the fundamental frequency is regulated in proportion to the fundamental frequency. One cycle of the output waveform at a given output voltage can be made from many narrow pulses or fewer wider pulses. To generate a waveform containing more pulses, the transistors or other switching devices in the inverter must switch more often. The rate at which the switches operate is called the switching frequency or carrier frequency. By varying switching frequency variable voltage can be obtained at the inverter output. This voltage is applied to the AC motor to control speed.

III. PROBLEMS ASSOCIATED WITH PWM FED A.C. DRIVES

A High switching frequencies (2–20 kHz) are common with insulated gate bipolar transistor (IGBT) technology for power levels over 500 kW. While the high switching speeds and advanced PWM schemes significantly improve the performance of the PWM-inverter-fed induction motors, the high rate of voltage rise (dv/dt) of 0–650 V in less than 0.1 s has adverse effects on the motor insulation. These steep rising and falling pulses lead to an uneven distribution of voltages within the motor, especially during switching transitions. This contributes to insulation deterioration and subsequent failure of the motor. In addition, the dv/dt contributes to damaging bearing currents and electromagnetic interference (EMI). If a long cable is employed between the inverter and the motor,damped high frequency ringing at the motor terminals occurs resulting in excessive over voltage which further stresses the motor insulation. Also, the motor impedance, which is dominated by the winding inductance, presents an effective open circuit at high frequencies at the end of the long cable. This produces a reflected voltage at the end of the cable approximately equal in magnitude and with the same sign, resulting in twice the magnitude of the incident voltage at the motor terminals. The primary means of reducing the motor insulation stresses due to motor terminal over-voltages are

1) Filtering techniques.
2) Increasing the insulation strength of the magnet wire to withstand a high dv/dt.

IV. MODELLING OF THE SYSTEM PARAMETERS

4.1 High Frequency Model of the Induction Motor

Another key factor for an accurate over-voltage analysis is the high frequency representation of the ac motor input impedance, which must be valid over a broad range of frequency. It is not necessary to verify how voltage will distribute inside the AC machine winding in order to calculate the over voltage at the terminals. It is important, rather, to know the value of the ac motor input impedance and how it varies as a function of frequency. The fig.2 shows the schematic of the proposed model that is implemented in the simulation program to evaluate the over-voltage analysis. The model conjugates low and high frequency representations of the motor. The suggested model is a lumped-parameter representation of the motor input impedance. The low frequency equivalent model parameters, r1, r2, l1, l2 and lm is partly responsible for capturing the low frequency transients, while the remaining RL-C network is responsible to represent the high frequency phenomena. Winding-to-ground capacitance and winding turnto- turn capacitance play the major role in the high frequency phenomena. Their relation with the leakage inductance forms the dominant poles in the frequency response. The parameter Cg represents the winding-to-ground capacitance. The parameter Rg is added in the circuit to represent the dissipative effects that are present in the motor frame resistance. The circuit formed by the parameters Rt, Lt, and Ct is the part of the network responsible to capture the second resonance in the frequency response, which is related to the winding turn-toturn capacitance. The parameter Re is responsible to account for the losses introduced by eddy current inside the magnetic core.

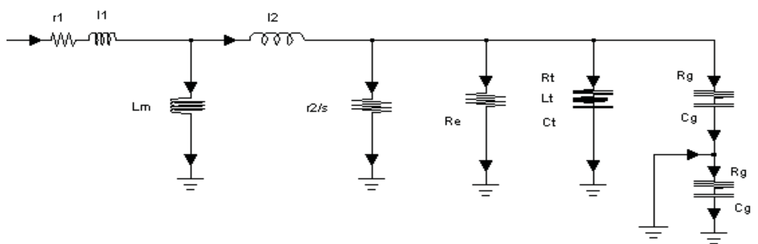

Figure 2 High Frequency Model of the Induction Motor

4.2. *High Frequency Model of the Power Cable*

An adequate estimation of the power cable parameters is needed in order to have an accurate computation of the over voltage. Long cable lengths contribute to a damped high frequency ringing at the motor terminals due to the distributed nature of the power cable leakage inductance and coupling capacitance which results in over voltages and further stress the motor insulation. In addition, voltage reflection is a function of inverter output pulse rise time and the length of the motor cables, which behave as a transmission line for the inverter output pulses. So the cable representation resembles like lumped parameter model of the transmission line.

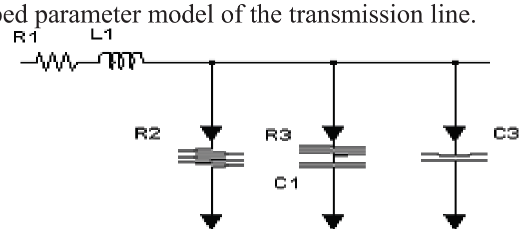

Figure 3 High Frequency Model of the Power Cable

The Figure3 shown above is the per phase representation of one lumped –segment of the power cable used in the Matlab Simulation .The model conjugates low and high frequency representations of the power cable.R1,R2,C3 are responsible to represent the low frequency and remaining for the high frequency phenomena.

4.3. PWM Inverter Modeling Sine-triangle technique is adopted to model the PWM inverter:

In this, to obtain balanced three phase output voltages, the triangular voltage wave form (carrier wave Vc, freq fc) is compared with three sinusoidal control voltages (reference wave Vr, freq f) that are 120 degrees out of phase. The inter section of Vc and Vr waves determines the switching instants and commutation of the modulated pulse. The carrier and reference waves are mixed in a comparator. When sinusoidal wave has magnitude higher than the triangular wave, the comparator output is high, otherwise it is low. The Figure4 shows the simulation circuit in MATLAB.

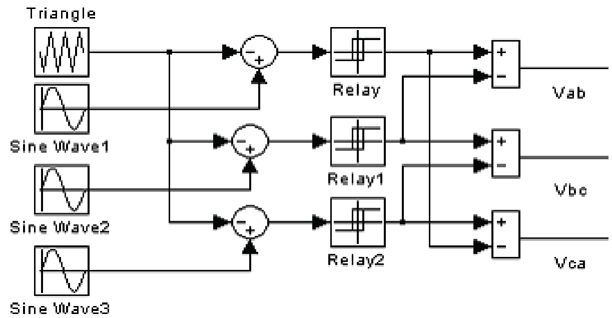

Figure 4 PWM Inverter modeling

The ratio of Vr / Vc is called the modulation index (MI) and it controls the harmonic content of the output voltage waveform. The magnitude of fundamental component of output voltage is proportional to MI, but MI can never be more than unity. Thus the output voltage is controlled by varying MI. 1. For MI<1, largest harmonic amplitudes in the output voltage are associated with harmonics of order fc/f ± 1 or 2N ± 1, where N is the no. of pulses per half cycle. Thus by increasing the number of pulses per half cycle, the order dominant harmonic frequency can be raised, which can then be filtered out easily. But higher value of N entails the higher switching frequency. This amounts to more switching losses and therefore an impaired inverter efficiency. 2. For MI>1, lower order harmonics appear, since for MI>1, pulse width is no longer a sinusoidal function of the angular position of the pulse. For low values of frequency modulation index (MF= fc/f) to eliminate the even harmonics, a synchronized PWM should be used and MF should be an odd integer. More ever MF should be a multiple of 3 to cancel out the most dominant harmonics in the line to line voltage.

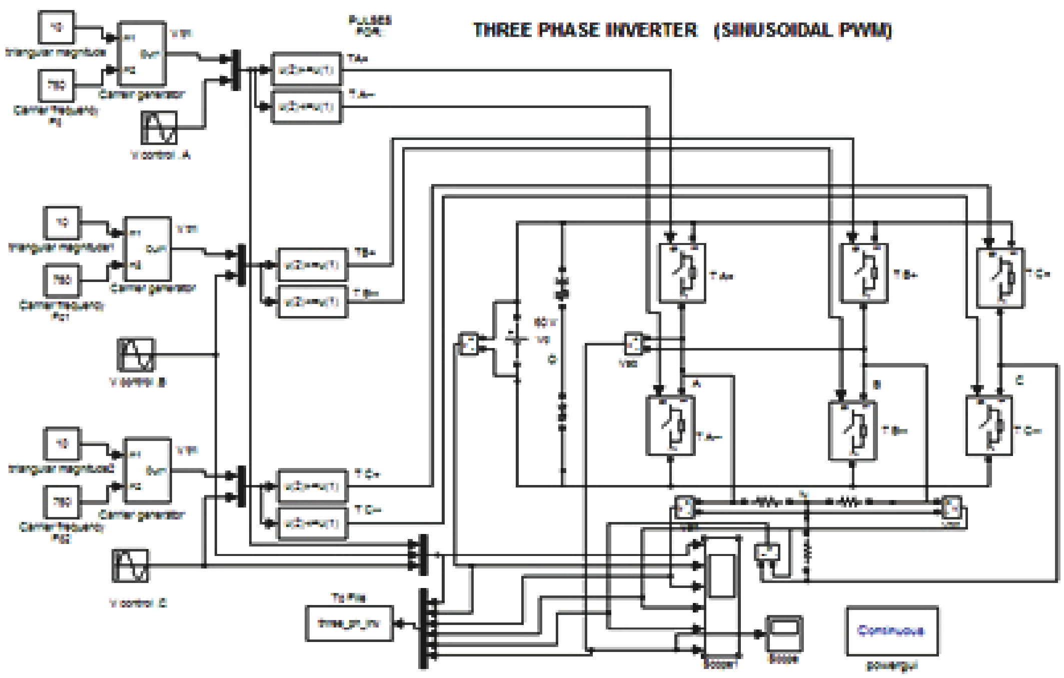

Figure 5 PWM INVERTER SIMULINK BLOCK

V. SIMULATION ANALYSIS OF THE OVERVOLTAGE AT MOTOR TERMINAL

Using the high frequency models presented in the preceding sections, a simulation program has been developed in MATLAB to calculate the over voltage, driving three different induction motor power ratings (3hp, 15hp and 40 hp). The following figure show the maximum line-to-line voltage at the motor as a function of terminal voltage pulse rise times for different cable lengths (4m, 10m ,14m and 20m) for a 3hp motor.

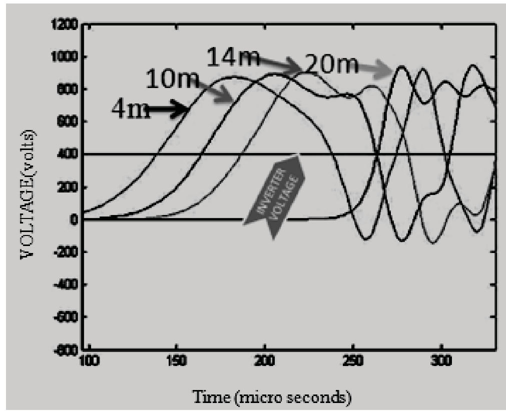

Figure 6 Voltage profile without filter for 3HP Motor with 4m, 10m, 14m and 20m Cable.

From the waveforms, it is observed that the voltage at the motor terminals becoming higher as the length of the cable increases for the same rise time and as the rise time increases the over voltage reduces for the same length of cable. The overvoltage also depends up on HP rating of motor, because impedance of the motor changes with rating. Hence, if HP changes, motor impedance matching with cable impedance also changes. The figures show the over voltage at the motor terminals for 3 hp and 15hp ratings of the motor for the same cable length and rise time.

Cable length (m)	Peak Voltage (volts)
4	**790**
10	**920**
14	**940**
20	**960**

Table 4.1

Table 4.1.shows the value of delay time, rise time of both inverter output and motor output voltage and peak voltage for different cable length for 3 HP motor From the waveforms and the table1, it is observed that the voltage at the motor terminals becoming higher as the length of the cable increase for the same rise time and as the rise time increases the over voltage reduces for the same length of cable.

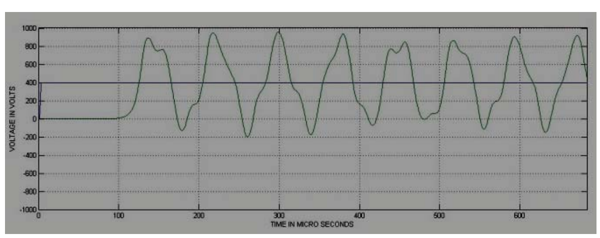

Figure 6

VI. MODELLING AND SIMLATION OF FILTERS TO REDUCE TERMINAL OVERVOLTAGE

6.1 RC filter at motor terminal

As explained in RC filter design the equations are reduce to

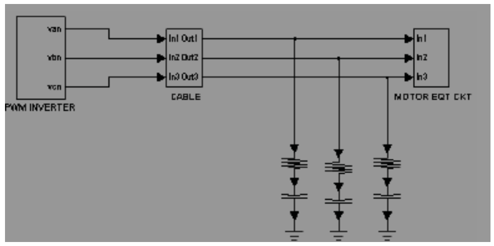

Figure 7 (a).Block diagram for RC filter at 3HP motor terminal

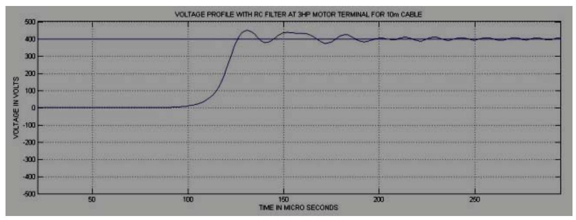

Figure 7(b). Voltage profile of RC filter at 3HP motor terminal

6.2 RLC filter at motor terminal

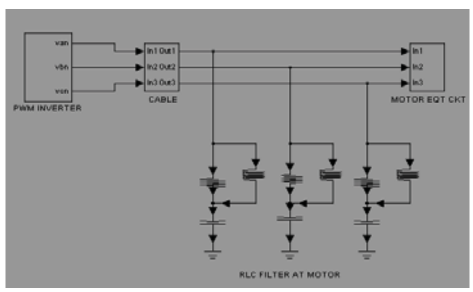

Figure 7(c).Block diagram for RLC filter at 3HP motor terminal

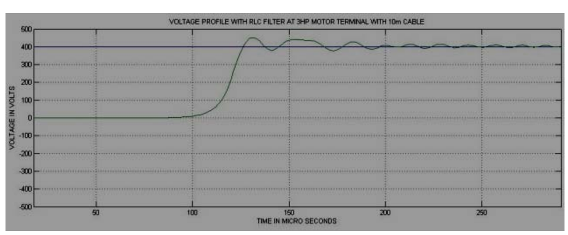

Figure 7(d). Voltage profile of RC filter at 3HP motor terminal

6.3 RLC filter at Inverter terminal

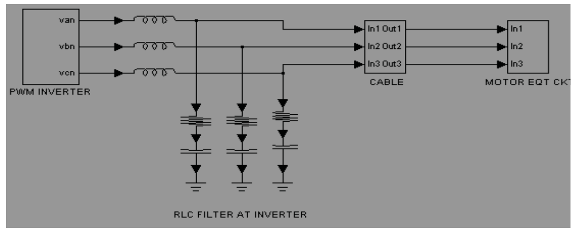

Figure 7(e).Block diagram for RLC filter at 3HP Inverter terminal.

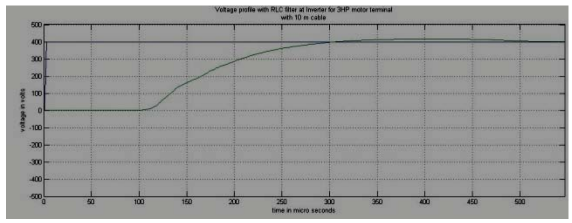

Figure 7(f). Voltage profile of RLC filter at 3HP Inverter terminal.

6.4 Voltage profile with all filters included (with out filter, RC at motor, RLC at motor, RLC inverter)

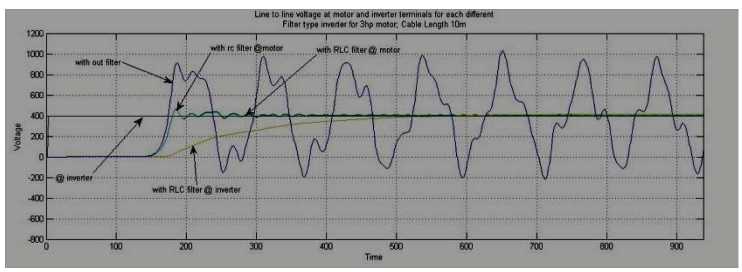

Figure 7(g). Voltage profile with all filters included (with out filter, RC at motor, RLC at motor, RLC inverter)

Table 6.1.comparison of over voltages without and with all type of filters for different cable lengths

CABLE LENGTH (m)	WITH/ WITHOUT FILTER	PEAK OVER VOLTAGE (v) FOR		
		3 HP IM	7 HP IM	15 HP IM
10	With NO Filter	920	893	870
	With RC Filter @ Motor	487	480	482
	With RLC Filter @ Motor	460	459	460
	With RLC Filter @ Inverter	418	412	410
20	With NO Filter	1030	1025	1010
	With RC Filter @ Motor	510	522	529
	With RLC Filter @ Motor	480	481	485
	With RLC Filter @ Inverter	425	425	426
30	With NO Filter	1140	1140	1141
	With RC Filter @ Motor	540	541	541
	With RLC Filter @ Motor	500	500	501
	With RLC Filter @ Inverter	430	430	430

VII. CONCLUSION

In this Paper, a MATLAB based program is proposed. It can be used for the analysis of the over voltage phenomena in long cable PWM drives. This project has proposed first, the analysis of the over-voltage phenomena in long cable PWM drives. In next case, the over-voltage concepts were analyzed by taking different HP Rating of an Induction motor. So conclusion for over voltage phenomena are, as cable length increases the over voltage increases. Finally the most common dv/dt filter topologies for mitigating over voltage problems were analyzed. The main conclusion from this analysis is that the solutions placed at the motor terminals are not able to reduce the dv/dt as much as the filters placed at the inverter terminals. This occurs because the filters at the motor terminals, which match the cable surge impedance, can only reduce the voltage to the dc bus level but are not capable of reducing the pulse rise time.

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