MITIGATION OF OVER-VOLTAGES OF PWM INVERTER FED INDUCTION MOTOR DRIVES

A PROJECT REPORT

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ABSTRACT

The phenomenon of over-voltage at motor terminals in long-cable-fed PWM AC drives poses a severe stress on motor insulation systems. The over-voltage is typically caused by the high rate of change of the inverter output voltage (dv/dt) and the surge impedance mismatch between the inverter, connecting power cable and the motor. This report presents a survey of the existing methods of over-voltage suppression, which includes optimization of cable length and implementation of passive filters at both motor terminals and inverter terminals. An RC filter at the terminals of the electrical machine and an inverter output filter designed to reduce the rise and fall times of voltage pulses are presented as a solution to the over-voltage problem. The design methodologies and effectiveness of these passive filters are discussed through computer simulations based on Matlab Simulink, and the promising approaches are recommended for researchers and industrial users.
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<td>Pulse Width Modulation</td>
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<td>AFD</td>
<td>Adjustable Frequency Drives</td>
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<td>AC</td>
<td>Alternating Current</td>
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<td>R</td>
<td>Resistance</td>
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<td>Capacitance</td>
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<td>IGBT</td>
<td>Insulated Gate Bipolar Thyristor</td>
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<td>ESP</td>
<td>Electric Submersible Pump</td>
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<tr>
<td>ASD</td>
<td>Adjustable Speed Drives</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>SPWM</td>
<td>Sinusoidal Pulse Width Modulation</td>
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<tr>
<td>kHz</td>
<td>Kilo Hertz</td>
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<tr>
<td>HP</td>
<td>Horse Power</td>
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<tr>
<td>$C_g$</td>
<td>Line to ground capacitance</td>
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<td>$C_m$</td>
<td>Line to line capacitance</td>
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<tr>
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<td>Motor frame resistance</td>
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<td>$R_t$</td>
<td>Turn resistance</td>
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<td>$L_t$</td>
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\( Z_2 \)  
Impedance of motor

\( Z_1 \)  
Impedance of source

\( E_{ref} \)  
Reflected voltage magnitude

\( E_{inc} \)  
Incident voltage magnitude

\( L_{critical} \)  
Critical cable length

\( S \)  
Wave propagation velocity

\( T_r \)  
Rise time

\( CAT \)  
Conductive armour type

\( PD \)  
Partial discharge

\( K_G \)  
Reflection co-efficient at the Inverter terminals

\( Z_o \)  
Surge Impedance of the Cable

\( L \)  
Cable length

\( Db \)  
Decibel

\( R_{filter} \)  
Filter resistance

\( L_{filter} \)  
Filter Inductance

\( C_{filter} \)  
Filter Capacitance

\( U_{DC} \)  
DC bus voltage

\( f_{res} \)  
Filter resonance frequency

\( f_{sw} \)  
Switching frequency

\( f_r \)  
Fundamental frequency

\( f_c \)  
Cut-off frequency

\( A \)  
Attenuation

\( H \)  
Output filter transfer function

\( MSO \)  
Mixed Signal Oscilloscope

\( FFT \)  
Fast Fourier Transform

\( kW \)  
Kilowatt

xvi
CHAPTER 1

INTRODUCTION

1.1 Present Scenario

Standard induction motors that have been designed to operate from fixed frequency sinusoidal power, are being used with adjustable frequency drives (AFDs) in an increasing number. Application of AC induction motors to Pulse Width Modulated (PWM) drives continues at a rate of approximately 250,000, per year. The output voltage waveform of today’s PWM adjustable frequency drive is not a sine wave, but a series of square wave pulses that produces a reasonable approximation of sine wave current. Although there is an extensive history of successful use of standard motors on this type of waveform, the possible effects on the motor insulation should be carefully considered.

One of the remarkable advancements in power switching devices has been the increased switching speeds and related switching frequencies, in addition to the associated high-frequency operation of PWM AC drives. This results in a more sinusoidal motor current waveform with less ripple, less copper losses, and less switching losses. However, the consequent high rate of voltage rise, $dv/dt$, has adverse effects on motor insulation systems and contributes to bearing current problems.

Moreover, in some industrial applications like artificial lift systems in off-shore oil operations, fan drives in underground mines which employ portable motors, constraints are such that the motor and the PWM inverter have to be placed at separate locations. Thus long interconnecting cables are often required between them. Narrow PWM pulses traveling on long cables from the inverter to the motor
behave like traveling waves on transmission lines, in which a phenomenon of voltage reflection and possibly successive voltage reflection leading to overvoltage at the motor terminals will occur. Actually, the associated voltage reflection is a function of the inverter output pulse rise time, and the length of the motor cables as well as the surge impedances of the motor and cable systems. In this case, if no mitigation measures are implemented, the motor would be likely to suffer from serious insulation damage leading ultimately to failure.

The scope of this report is to study different mitigation techniques for the above mentioned industrial applications. Detailed review of the passive filter at motor and inverter terminals, and evaluation of critical cable length is done.

1.2 Literature Survey

Standard motors are commonly used successfully with PWM drives but high switching frequencies of the IGBTs place higher levels of dielectric stress on the motor insulation. If the motor insulation is nearing the end of its useful life, connecting the motor to a PWM drive may lead to more rapid insulation failure. Annette von Jouanne stated in her paper that impedance mismatch between the inverter, cable and induction motor is one of the major causes of over-voltage. Erik Persson (1992) has investigated that if the inverter output pulses take longer than half the rise time to travel from inverter to motor, then a full reflection will happen at the motor; thus the pulse amplitude will approximately double[11]. According to Akagi(2010), when the motor is at a long distance from the inverter, the conductors connecting them act like a transmission line leading to successive voltage reflections causing over-voltage[1]. Alessandro F. Moreira (2002) has suggested that high frequency simulation models for power cables and motors are key tools to aid a better understanding of the over-voltage problem in pulse width modulation
drives with long feeders[10]. Davide Fabiani(2003) in his thesis has suggested that the inverter in AFD generates a quasi-sine wave instead of a perfect sine wave, whose characteristics depends on the switching technique, motor design and the length of the cable used for interconnection[4]. Nabeel A.O. Demerdash(2011) that various passive filter topologies for the mitigation of over-voltage[6].

1.3 Areas of application

Subsea applications like artificial lift systems in off-shore oil and gas operations often require the use of AFD for increased efficiency. Long cables and high starting torque are characteristics of subsea pump and compressor applications. A typical subsea application consists of a topside installed AFD and a submerged AC motor pump that are connected by long cable, in some case in excess of 25 km. Long cable runs when combined with standard topology AFDs have proven to dramatically reduce motor lifetime due to peak voltage stress on the motor winding insulation when compared with fixed speed ESP motors.

Fan drives play an important role in underground mines, providing fresh air flow in very long galleries. In this application, for controlled starting as well as air flow regulation adjustable speed fan drives are applied. Usage of ASD may result in the failure of the winding insulation of induction motors which reveal the existence of motor terminal over-voltages. The possible causes of these over-voltages are related to the long cables, incorporating capacitances and inductances, which together with the other impedance of the system could generate resonances which may be excited by the inverter fast commutations.

In wind turbine applications, the generator and power converter can be located in the nacelle of the mast. However, typically the converter is installed at the bottom, which makes maintenance and access to the drive system easier.
Because the height of the mast can be a hundred metres, long cables are required leading to over-voltage phenomenon. Fig. 1.1 shows the structure of a wind power station where the drive and the motor are at different places.

Figure 1.1 Wind power station structure
1.4 Objective

The over-voltage observed in the PWM inverter fed induction motor drives has been proven detrimental to insulation of the induction motors and thereby reduces the life time of the motor. Hence this over-voltage has to be suppressed. The objective of our project is to mitigate this over-voltage by optimizing the cable length and employing suitable passive filters at the inverter and motor terminals.

1.5 Organization of the Report

In this report, the various causes of over-voltage occurring in inverter fed induction motor drives and its mitigation methods have been discussed. Chapter 1 gives an introduction to the problem and its areas of applications. In Chapter 2, the model of the system which consists of the PWM inverter, IGBT devices, three core cable and a three phase induction motor has been explained. The simulation model of the system and the need for high frequency modelling of the cable and induction motor is analysed in Chapter 3. Chapter 4 deals with the various causes of over-voltage at the motor terminals viz., impedance mismatch between the inverter, cable and the induction motor, high switching frequencies and long cables. The various methods adopted for the design of filters and the subsequent reduction of over-voltage in each case have been dealt with in detail in Chapter 5. Chapter 6 outlines the experimental procedure, observation and inference of the results obtained. Chapter 7 summarises the project and also gives a scope for future work.
CHAPTER 2

SYSTEM MODEL

2.1 Block diagram

The block diagram of the system is shown in figure 2.1.

![Block diagram of the system](image)

**Figure 2.1** Block diagram

2.2 PWM Inverter

A device that converts dc power into ac power at desired output voltage and frequency is called an inverter. Output voltage from an inverter can be adjusted by exercising a control within the inverter itself. The most efficient method of doing this is by Pulse Width Modulation control used within the inverter. In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of inverter components. This is the most popular method of controlling the output voltage. The advantages possessed by PWM technique are as under:

(a) The output voltage control with this method can be obtained without any additional components.
(b) With this method, lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily, the filtering requirements are minimized.

**Sinusoidal PWM Inverter:**

In SPWM, the pulse width is a sinusoidal function of the angular position of the pulse in a cycle. For realizing SPWM, a high frequency triangular carrier wave is compared with a sinusoidal reference wave of the desired frequency. The interaction of these two waves determines the switching instants and commutation of the modulated pulse. The carrier and reference waves are mixed in a comparator. When the sinusoidal wave has magnitude higher than the triangular wave, the comparator output is high, otherwise it is low. The comparator output is processed in a trigger pulse generator in such a manner that the output voltage wave of the inverter has a pulse width in agreement with the comparator output pulse width. Fig. 2.2 shows the generation of pulses for IGBTs. Fig. 2.3(a) shows the comparison of reference and carrier signals and fig. 2.3(b) shows the IGBT gate pulses.

![Figure 2.2 Generation of gate pulses for IGBTs](image)

Figure 2.2 Generation of gate pulses for IGBTs
The low switching loss feature of the IGBT is advantageous to both drive and motor. Reduced semiconductor switching loss results in smaller heat sinks and ultimately lower drive package cost. The IGBT being a voltage rather than current controlled gate device has a lower base drive circuit cost that also results in lower drive package cost. The low switching loss, along with fast transition times, may now allow higher carrier or switching frequencies in the 6 to 12 kHz region.

Higher switching frequencies of IGBT drives produce less peak current ripple, thus producing less current harmonic motor heating and allowing rated motor torque with lower peak current. IGBT drives with high switching frequency values have substantially reduced motor ripple current and better torque
performance. The higher switching frequency now obtainable also reduces motor lamination noise in the audible range.

2.4 Cables and Three phase induction motor

A cable can be considered as an electrical network with lumped electrical elements R, L and C. Two methods are used for modelling the cable viz., lumped parameter model and distributed model. In the distributed model, the parameters are distributed over the length of the cable and it gives a more accurate analysis of over-voltage phenomenon than a lumped parameter model. Fig. 2.4 shows a typical three core cable.

![Figure 2.4 A typical three core cable](image)

1. Conductor (Cu/Al)  
2. Insulation (XLPE)  
3. Bedding (PVC)  
4. Armouring (Al/Steel)  
5. Sheath (PVC)

An induction motor is a type of AC motor which operates on the principle of electromagnetic induction. Its advantages are its simple and rugged design, low cost, low maintenance and direct connection to an AC power source. Three phase induction motors are widely used in AFD drives. Over-voltage problem is predominant in motors with HP < 20.
CHAPTER 3

SIMULATION MODEL OF THE SYSTEM

3.1 Power frequency model

The computer simulations are based on MATLAB SIMULINK MODEL of the entire system. For the purpose of analysis, 230V DC supply is used as the inverter input. SPWM inverter is used in 180 degree conduction mode. A 10 HP 220V 3 phase induction motor is used. The simulation model is shown in fig. 3.1.

![Simulation model diagram](image)

**Figure 3.1** Simulation model
Simulations are carried out to observe the over-voltage at the motor terminals. Fig. 3.2 shows the over-voltage in the conventional model of the machine.

![Figure 3.2 Over-voltage in conventional model of induction motor](image)

High dv/dt spikes of the order of around 1000V can be observed from the above simulation result. This leads to heavy stress on the motor insulation leading to partial discharge which in turn deteriorates insulation and thereby reduces the lifetime of the motor.

### 3.2 High frequency modeling of cable and induction motor

The motivation for the work presented here is the lack of good simulation approaches that can be used to accurately investigate the over-voltage phenomena in conventional model of motor. Therefore, the objective is to study the motor over-voltage phenomena in a definitive manner by developing accurate and fast simulation models for power cables and motors that allow a better understanding of the over-voltage problem. Conventional model of the motor does not take into account the effect of inter-turn capacitance and leakage inductance. The effect of inductive and capacitive reactance is predominant only at high frequencies. Hence we use high frequency modeling of the induction motor and the cable.
3.2.1 High Frequency Modeling of the Cable

For the power cable, it is well known that distributed-parameter representation provides more accurate results in the study of high-frequency transients than the lumped-parameter models. This model is shown in fig.3.3.

![Distributed parameter model of the cable](image)

**Figure 3.3** Distributed parameter model of the cable (one section shown).

The cable parameters per meter are:

- R (line resistance) = 12.96 mΩ/m
- L (line inductance) = 0.34 μH/m
- Cg (line-to-ground capacitance) = 181 pF/m
- Cm (line-to-line capacitance) = 32.5 pF/m

3.2.2 High frequency modeling of the induction motor

It is not necessary to verify how voltage distributes inside the ac machine winding in order to calculate the over-voltage. It is important, rather, to know the value of the ac motor input impedance and how it varies as a function of frequency. This model is shown in fig.3.4.
**Fig.3.4** High Frequency Model of the Induction Motor.

- $C_g = 704 \text{ pF}$
- $R_g = 23.2 \Omega$
- $R_t = 0.086 \text{ k}\Omega$
- $L_t = 0.09 \text{ mH}$
- $C_t = 70.4 \text{ pF}$
- $R_e = 1.4 \text{ k}\Omega$

$C_g$ denotes the winding-to-ground capacitance. $R_g$ represents the dissipative effects present in the motor frame resistance. The circuit formed by the parameters $R_t$, $C_t$ and $L_t$ is the part of the network responsible to capture the second resonance in the frequency response, which is related to the winding turn-to-turn capacitance. $R_e$ accounts for the losses due to eddy currents present inside the magnetic core.

### 3.2.3 Over-voltage in high frequency model of induction motor:

The suggested model is a lumped-parameter representation of the motor input impedance. The RLC network is responsible to represent the high-frequency phenomena. Winding-to-ground capacitance and winding turn-to-turn capacitance play the major role in the high-frequency phenomena. Over-voltage at the motor terminals for high frequency model is shown in fig.3.5.
Figure 3.5 Over-voltage at the motor terminals for high frequency model.

From the above figure it can be seen that the over-voltage is reduced to 450V when the high frequency model of the induction motor is employed and also the waveform is more accurate compared to the conventional model of the motor.
CHAPTER 4

ANALYSIS OF OVERVOLTAGE AT MOTOR TERMINALS

Over-voltages at motor terminals are determined by three main aspects, namely, the rise time of the PWM pulses, the cable length, and the impedance mismatch between the inverter, power cable, and the motor.

4.1 Voltage reflection analysis

On long cables, PWM pulses traveling between the inverter and the motor behave like traveling waves on transmission lines. Forward-traveling waves, or PWM pulses, travel from the inverter to the motor, while backward-traveling waves move toward the inverter due to voltage reflection. The reflection mechanism can be viewed as a mirror that produces a reflected wave $V^-$ which is a replica of $V^+$ that is “flipped around” such that all points on the $V^-$ waveform are the corresponding points of the $V^+$ waveform multiplied by the voltage reflection coefficient. The voltage reflection coefficient $K_L$, at the motor terminals is determined by the surge impedance ratio at the junction point. The incident wave voltage reflections under three extreme conditions are given below:

(i) If the cable is shorted at the end, the reflected voltage at the end of the cable will be equal in magnitude but with a negative sign resulting in zero voltage at the motor terminals.
(ii) If the cable is open at the end, the reflected voltage at the end of the cable will be equal in magnitude with the same sign, resulting in two times the magnitude of the incident voltage at the motor terminals.
(iii) If the cable is terminated by an impedance that matches the characteristic impedance of the cable, the incident voltage will not be reflected.

\[ K_L = \frac{z_2 - z_1}{z_2 + z_1} \]  \hspace{1cm} (4.1)

\[ E_{\text{ref}} = K_L \cdot E_{\text{inc}} \]  \hspace{1cm} (4.2)

The impedance of smaller motors is dominated by the 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. Thus voltage doubling occurs as shown in the figure 4.1.

![Figure 4.1 Voltage doubling due to reflection process](image)

To better understand the repeated reflections on a finite length of cable with infinite dv/dt, one reflection of an incident wave will be considered. Figure 4.1(a) shows the equivalent circuit of a PWM inverter at the sending end of the line. The
motor terminal is treated as an open circuit, due to the large impedance at high frequencies. Figure 4.1(b) shows the incident wave traveling to the right after the switch is turned on. The voltage wave traveling to the right is accompanied by the current wave of the same shape but different amplitude. Figure 4.1(c) shows the incident wave being reflected on arrival at the receiving end of the line. The current at the open line must equal zero at any time (open circuit), therefore, the reflected current will have the same amplitude, but with opposite sign. The incident voltage will be reflected as a positive voltage traveling to the left toward the sending end (dashed line). The reflected wave plus the incident wave will cause the voltage to double at the terminal of the motor (solid line).

4.2 Over-voltage due to rise-time

The rise time of the inverter voltage influences the magnitude of the over-voltage produced. If the turn-on time of the output device is slow, the capacitance of the motor has an opportunity to charge and discharge with the IGBT. However, if the output device’s turn-on time is fast, the capacitance of the motor is not able to keep up with the charge and discharge. Instead, the voltage applied across the lead increases. Therefore, more energy is stored, resulting in more overshoot voltage. At the beginning of the pulse, the voltage rises rapidly from zero, overshoots to a peak and then settles back to the normal pulse height. The voltage may not oscillate at all or may oscillate or “ring” before settling back to the normal pulse height as shown in figure 4.2.
Rise Time, is usually defined as the time required for the voltage to rise from 10% to 90% of the peak voltage. The dv/dt is the slope of the voltage rise in volts per microsecond. The dv/dt can be approximated as 80% of the peak voltage divided by the rise time. If the time required for a pulse to travel from the controller to the motor is more than half the rise time of the pulse, the reflected pulse will combine with the incident pulse to increase the amplitude of the pulse at the motor. If the motor impedance is much greater than the cable impedance, the amplitude of the reflected pulse can equal the amplitude of the incident pulse resulting in a peak voltage at the motor that is twice the peak voltage at the controller.

4.2.1 Ringing

The inductance and capacitance of the cable, the motor and the output circuit of the drive may constitute a resonant circuit that can cause the edges of the voltage pulses to assume an under-damped ringing waveform. Combined with the voltage reflection phenomena, this ringing can result in voltage peaks that are significantly more than twice the bus voltage of the drive. The ringing frequency is
determined by the cable length and the velocity of the incident and reflection waves traveling inside the cable. It is known that the ringing frequency is in inverse proportion to the cable length. So in the following work, the over-voltage at the input terminals of the induction motor are investigated for various cable lengths keeping the switching frequency of the inverter constant.

Figure 4.3 shows the effect of ringing and voltage reflections on the output pulse shape at the motor.

![Figure 4.3 Reflected Voltage at the motor terminals with ringing](image)

**4.2.2 Simulation results**

To study the effect of rise-time on over-voltage, cable-length is fixed to 50m and inverter output is approximated to triangular waveforms to vary the rise-time. Figures 4.4 to 4.8 show the voltages waveforms at the motor terminals for increasing rise times.
Figure 4.4 Voltage waveform for rise-time = 0.1μs

Figure 4.5 Voltage waveform for rise-time =1μs
**Figure 4.6** Voltage waveform for rise-time = 3μs

**Figure 4.7** Voltage waveform for rise-time = 5.31μs
Figure 4.8 Voltage waveform for rise-time = 6μs

From the above simulations, it can be observed that as the rise time of the PWM voltage pulses increases, the over-voltage at motor terminals decreases. This inference is tabulated in the following table 4.1.

Table 4.1 Variation of over-voltage for various rise times

<table>
<thead>
<tr>
<th>Rise Time(μs)</th>
<th>Over-voltage produced (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1417.668</td>
</tr>
<tr>
<td>1</td>
<td>495.5</td>
</tr>
<tr>
<td>3</td>
<td>335</td>
</tr>
<tr>
<td>5.31</td>
<td>276</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
</tr>
</tbody>
</table>
4.3 Over-voltage due to cable-length

Long cable lengths contribute to a damped high frequency ringing at the motor terminals due to the distributed nature of the cable leakage inductance and coupling capacitance (LC) which result in over-voltages and further stress the motor insulation. Fig. 4.9 shows the equivalent circuit of the cable.

![Equivalent Circuit of the Cable.](image)

Figure 4.9 Equivalent Circuit of the Cable.

As the energy wave moves to the motor end of the cable, the last capacitor, \( C_n \), becomes charged to voltage \( V \) but current is still flowing through the last inductor, \( L_n \). Since the impedance of the motor is very large compared to the cable impedance, the current from \( L_n \) continues to flow into \( C_n \) until most of the stored energy has been transferred to \( C_n \). This results in an overcharge of voltage on \( C_n \) up to a theoretical maximum of \( 2V \). As \( C_n \) becomes charged to its maximum value, \( 2E \), the current reverses and flows back toward the source, charging each capacitor along the way to a higher voltage.

This creates a reflected travelling wave that moves along the cable toward the inverter terminals, where it is reflected once again, but this time with an inverter reflection factor that is always -1. A new traveling wave, but one that is now negative, is created and moves once more to the motor end. If this negative second wave reaches the motor while the first reflection is still building up, it will subtract from the first reflection and result in less of an over-voltage at the motor terminals. This leads to the "critical cable length" statement that says that "if the
propagation time of the travelling wave from the inverter to the motor is greater than 1/2 the pulse rise time, a full voltage reflection will take place”.

4.3.1 Simulation results

To study the effect of cable-length on over-voltage, rise time is kept constant to 0.5 µs and cable-length is varied. Figure 4.10 to 4.12 show the voltage waveforms at the motor terminals for increasing cable lengths.

Figure 4.10 Voltage Waveform for a cable of length 15m
From the above simulations, it can be observed that as the length of the cable increases, the over-voltage at motor terminals also increases. This inference is tabulated as follows in table 4.2.
Table 4.2 Variation of over-voltage for various cable lengths

<table>
<thead>
<tr>
<th>Length of the Cable (m)</th>
<th>Over-voltage produced (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1417.668</td>
</tr>
<tr>
<td>25</td>
<td>495.5</td>
</tr>
<tr>
<td>30</td>
<td>335</td>
</tr>
</tbody>
</table>

4.3.2 Critical cable length

In some applications, long distances are forced between motor and control. This has an adverse effect because of increased power transistor switching frequencies and reflected voltage waveforms. Therefore it is essential to optimize the cable length used in such applications.

We define a quantity called critical length for choosing the appropriate cable length. The critical cable length is the maximum cable length at which voltage amplification does not occur. It is the length at which the sum of the reflected and incident waves is equal to the peak value of the incident wave.

If the propagation speed of the voltage wave is $S$ and the rise time of the PWM wave front is $T_r$, then the critical lead length is given by:

$$L_{\text{critical}} = S \times T_r / 2$$

(4.3)

$$S = 1/ \sqrt{LC}$$

(4.4)

$$= 1/ \sqrt{(0.34 \times 10^{-6} \times 181 \times 10^{-12})}$$

$$S = 127 \text{ m/µs}$$

Typical rise time of IGBT = 0.1 µs

$$L_{\text{critical}} = 6 \text{ m}$$
Figure 4.13 Voltage waveform at critical cable length = 200V

From figure 4.13 it is evident that at critical cable length of 6m, there is no voltage amplification.

4.4 Variation of Over-voltage with Rise time and Cable length

The figure 4.14 shows the variation of over-voltage with both rise time and cable length. It can be observed from the graph that as the cable length increases, over-voltage increases and as the rise time decreases, over-voltage increases.

Figure 4.14 Variation of Over-voltage with Rise time and Cable length
4.5 Effect on motor insulation

Motor coils are subjected to high thermal stress due to the application of repetitive fast pulses i.e. PWM voltage waveforms. This type of complex voltage waveform may increase the dielectric heating in the stress grading tape (SGT) and the conductive armour type (CAT) of the insulation system. Under such circumstances, hot-spots are developed in the coils due to joule heating and dielectric losses. These hotspots can deteriorate the coil insulation, eventually leading to motor failure.

4.5.1 Partial Discharge

Each voltage peak can cause a small breakdown called a partial discharge (PD) in any air-filled voids in the insulation material. Repeated PD breakdowns gradually destroy the insulation. Reducing the inverter switching frequency slows the rate of deterioration but does not eliminate it, because deterioration is more a function of rise time versus repetition. Deterioration is eliminated only by assuring that the amplitude of the voltage peaks is less than the PD inception voltage of the motor insulation. Insulation deterioration and failure can also be caused by dielectric stress of the wire insulating coating.

4.5.2 Corona Discharge

Corona discharge occurs when the air is ionized by the electric field between the windings. Current will not flow through the ionized air as long as the insulating materials remain intact, but the ionized air can cause the insulating materials to deteriorate. Thus, the life of the motor is reduced due to voltage over-shoot.
CHAPTER 5

PASSIVE FILTERS FOR OVER-VOLTAGE MITIGATION

From the point of view of flattening $dv/dt$ of the PWM pulses, there are mainly two mitigation methods: one is using active filters, but this method is seldom employed in industrial motor drives since additional switches and complex algorithms are required. In the other approach, passive filters based on resistors, inductors and capacitors are used. The latter one is much more popular because of its simplicity and availability.

Passive filters, such as RC and RLC filters, have been proposed to be installed at the motor terminals to match the surge impedance of the cable, which could significantly attenuate the overvoltage at the motor terminals. On the other hand, for some special applications, such as submarine situations or deep well pumps, filters have to be installed at the inverter cabinet, because of the lack of accessibility for installing such devices at the motor terminals. The following subsections will elaborate the common passive filters both at the motor terminals and at inverter terminals.

5.1 RC filter at the motor terminal

To match the surge impedance of the cable and provide proper level of damping to control the voltage overshoot, an RC filter, as shown in Fig.5.1, has been proposed.
30

Figure 5.1 RC Filter at the motor terminal

An RC filter can be designed by the following four methods:

1. Transfer Function approach with inverter terminal as reference
2. Transfer Function approach with motor terminal as reference
3. Design using Voltage Pulse Rise Time
4. Design using impedance matching

5.1.1 Transfer Function approach to design with inverter terminal as reference

In choosing the parameters of the RC filter, the reflection coefficient is regarded as a transfer function between the incident and reflected voltages, and the capacitance is chosen so that cancellation occurs between the reflected voltage and its resulting incident voltage.

\[ Z_1 = Z_0 \text{ (Surge Impedance of the Cable)} \]  \hspace{1cm} (5.1) \\
\[ Z_2 = R_f + C_s \text{ (Impedance of the Filter)} \]  \hspace{1cm} (5.2)

Reflection co-efficient at the inverter terminals is \( K_G \).
Reflection co-efficient at the motor terminals $K_L$

\[ K_L = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (5.3) \]

\[ K_L = \frac{R_f + \frac{1}{C_f} - Z_0}{R_f + \frac{1}{C_f} + Z_0} \quad (5.4) \]

\[ K_L = \frac{1 + C_S (R_f - Z_0)}{1 + C_S (R_f + Z_0)} \quad (5.5) \]

$R_f$ is chosen so that $K_L$ becomes negative which implies there is no reflection.

\[ R_f = 0.5Z_0. \quad (5.6) \]

Assuming step input for $u_{inc}(t)$,

\[ u_{inc}(s) = U/s \quad (5.7) \]

\[ u_{ref}(s) = K_L \cdot u_{inc}(s) \quad (5.8) \]

\[ = \frac{R_f + C_S - Z_0}{R_f + C_S + Z_0} \]

Resolving into partial fractions and applying $Z_0 = R_f$,

\[ u_{ref}(t) = 1 - \frac{2Z_0 e^{-\frac{t}{(R_f+Z_0)C_f}}}{R_f + Z_0} \quad (5.9) \]

Considering the inverter terminal, after a time delay $\tau$ first reflection occurs at the inverter side. And a second incident voltage comes back to the motor side after another delay time resulting in $u_{inc}(t)$.

\[ u_{inc}(t) = K_G - \frac{2K_G Z_0 e^{-\frac{\tau-2\tau}{(R_f+Z_0)C_f}}}{(R_f+Z_0)} \quad (5.10) \]
Adding the first reflected voltage to its corresponding second incident voltage after delay time \(2\tau\) gives us:

\[
\begin{align*}
u_{\text{ref}}(t) + u_{\text{inc}}(t) &= (1 + K_G) - \frac{2Z_0}{(R_f + Z_0)} (1 + K_G e^{(R_f + Z_0)c_f} e^{- \frac{-t}{R_f + Z_0}c_f})
\end{align*}
\] (5.11)

Here \(1 + K_G = 0\).

\(C_f\) is chosen so that the remaining part of the equation becomes zero.

\[
C_f = \frac{4}{3} \times \frac{1 \times C}{\ln \left( \frac{1}{|K_G|} \right)}
\] (5.12)

1 – Cable length,

\(C\) - Cable capacitance,

\(K_G = 0.9\), where \(K_G\) is the Reflection Co-efficient at inverter terminals.

The filter parameters are as follows:

Resistance – 21.67 \(\Omega\)

Capacitance - 0.229nF

The simulation result for the above filter is shown in figure 5.2 and the overshoot voltage is 349.7V.

![Output Waveform of RC Filter by Transfer Function approach with inverter terminal as reference](image)

**Figure 5.2** Output Waveform of RC Filter by Transfer Function approach with inverter terminal as reference
The cut-off frequency of this filter is obtained from a bode plot shown in fig 5.3. The cut-off frequency corresponds to -3db in the magnitude plot. For this filter, the cut-off frequency is 412 KHz.

![Bode Diagram](image)

Figure 5.3 Bode Plot of the RC Filter

5.1.2 Transfer Function Approach with motor terminal as reference

With this design method, the main principle in selecting the values of R and C is to make the first incident reflected wave result in a leading front magnitude of zero. This is accomplished if \( R_f = Z_0 \).

The capacitance value is selected so that when the second incident wave reaches the machine terminals (after \( t = 3 \)), the magnitude of the reflected voltage \( u_{ref}(t) \) is less than 0.2 U, if 20 per cent overvoltage is allowed. This results in

\[
u_{ref}(t) = 0.2u = u(1 - e^{-\frac{2\pi}{(2\pi f_0 C_f)}})
\]  

(5.13)

The filter capacitance \( C_f \) can now be solved by

\[
C_f = \frac{-3\sqrt{L_C C_f}}{2Z_0 \ln(0.8)} = \frac{-3\sqrt{L_C C_0}}{2\ln(0.8)}
\]  

(5.14)
The value of $R = 43.34\Omega$ and $C = 0.121\,\text{nF}$

The simulation result for the above filter is shown in fig. 5.4 and the over-voltage is 380V.

![Figure 5.4 Output Waveform of RC Filter by Transfer Function approach with motor terminal as reference](image)

The cut-off frequency for this filter is 388 kHz as found from figure 5.5.

![Figure 5.5 Bode Plot of RC Filter](image)
5.1.3 Design of Filter using Voltage Pulse Rise Time

If the filter is designed using the voltage pulse rise time, the filter resistance $R_f$ is again chosen equal to the cable characteristic impedance $Z_0$.

Factors affecting the selection of the filter capacitor $C_f$ value are inverter pulse rise time. When the travelling voltage pulse wave reaches the machine terminals, the purpose of the capacitor is to make the cable seem optimally terminated for long enough to make the load reflection coefficient zero, and also to make the filter appear as an open circuit to prevent power losses. An uncharged capacitor represents an equivalent short circuit to fast rising pulse edges, and an open circuit to DC bus values.

The capacitor seems like a line-to-line resistor termination as the pulse is propagating into the machine, if the voltage across the capacitor is less than 10 per cent of the DC bus voltage at the end of the pulse rise time. Initially, the voltage across the resistor is approximately the same as the DC bus voltage, and the peak current in the filter network is given by

\[ I_{\text{filter}} = \frac{U_{\text{DC}}}{R_{\text{filter}}} \] (5.15)

The voltage across the filter capacitor can be calculated by the RC charge equation

\[ U_{\text{G,filter}} = 0.10 \times U_{\text{DC}} = U_{\text{DC}} \cdot (1 - e^{-\frac{t_{\text{rise}}}{R_{\text{filter}}C_{\text{filter}}}}) \] (5.16)

The optimum filter capacitor value can therefore be calculated using equation

\[ C_{\text{filter}} = -\frac{t_{\text{rise}}}{R_{\text{filter}} \cdot \ln(0.90)} \] (5.17)

The parameters are as follows: $R = 43.34 \ \Omega$ and $C = 0.218nF$
The simulation result for this filter is shown in figure 5.6 and the over-voltage is 372V.

![Figure 5.6 Output Waveform of RC Filter by Voltage Pulse Rise-time approach](image)

From bode plot in figure 5.7, the cut-off frequency for this filter = 168 KHz.

![Figure 5.7 Bode Plot of RC Filter](image)
5.1.4 Design using impedance matching

The equivalent impedance of the first-order RC filter should be closely matched with the cable surge impedance as given in

\[ Z_{eq} = Z_C = \sqrt{R_f^2 + \left(1 + \frac{1}{j\omega C_f}\right)^2} = \sqrt{\frac{L}{C_f}} \]  \hspace{1cm} (5.18)

where \( R_f \) and \( C_f \) filter resistance and capacitance respectively.

Moreover, \( R_f \) should be designed to provide an over-damped circuit to ensure the minimization of the overvoltage at the motor terminals, as given below:

\[ R_f > 2 \sqrt{\frac{L}{C_f}} \]  \hspace{1cm} (5.19)

where \( L \) is the cable inductance.

By solving the above two equations, the values of \( R \) and \( C \) are determined to be 43 \( \Omega \) and 0.22\( \mu \)F respectively. The output waveform for RC filter is shown through simulation result in fig 5.8. The over-voltage is observed to be 300V.

![Output Voltage Waveform of RC Filter by Impedance mismatch approach](image)

**Figure 5.8** Output Voltage Waveform of RC Filter by Impedance mismatch approach
The bode plot is shown in fig.5.9 and the cut-off frequency is 16.78 kHz.

![Bode Plot of RC filter](image)

**Figure 5.9** Bode Plot of RC filter

### 5.2 Output reactor at the inverter

An output reactor at the inverter may be the simplest method of conditioning the motor terminal voltage. The output reactor reduces the dv/dt of the inverter output voltage, which in turn reduces the dv/dt at the motor terminals.

However, the overvoltage suppression is almost proportional to the reactor impedance, and a high value of impedance will cause an increase in cost and weight, and it will also deteriorate the drive systems’ power factor. Besides, adding a series reactor can introduce a voltage drop at the fundamental output frequency, which reduces the ability of the motor to produce rated torque. The output reactor at the inverter output terminal is shown in fig.5.10 and the value of the reactance is chosen as 66mH.
Simulation result for the above filter is shown in fig.5.11 where output voltage is 230V.

Though there is no voltage amplification in this case, a reactor is not used because it increases the cost of the filter.

5.3 LC filter at the inverter terminal

As a very cost-efficient type, LC filters are suggested to mitigate the overvoltage at the motor terminals, and the corresponding topology is shown in Fig.5.12. However, the design of this kind of filter is complicated by the fact that overvoltage can occur due to the filter resonance. For this reason, these filters are
often designed with a resonant frequency significantly below the switching frequency, and above the output fundamental frequency to avoid resonance with the load.

\[ f_{\text{res}} = \frac{1}{2\pi\sqrt{C_f L_f}} \]  

(5.20)

\[ f_r < f_{\text{res}} < f_{\text{sw}} \]

\( f_{\text{res}}, f_{\text{sw}}, f_r \) are the filter resonance frequency, switching frequency, and fundamental frequency of the drive’s output voltage, respectively. The values of \( L \) and \( C \) used are 1mH and 2.81\( \mu \)F respectively.

**Figure 5.12** LC Filter at the Inverter terminals

The output voltage waveform is shown through simulations is given in fig.5.13 where output voltage is 230V.
5.4 Design of RLC Filter at inverter output terminals

The resonance of an LC filter makes the design of such a filter difficult, since carrier frequencies of general-purpose drives often vary between 5kHz and 20kHz. Thus, resistors are proposed to be added to the filter to dampen the resonance.

To design the values of resistance, inductance and capacitance, it is assumed that 20% over-voltage is the maximum over-voltage allowed at the motor terminals.

It follows that, the critical rise time of the PWM pulses can be calculated as

\[
\frac{3 \cdot L \cdot K_l}{v \cdot t_r} = 0.2
\]

(5.21)

\[
t_r = \frac{3 \cdot L \cdot K_l}{v \cdot 0.2}
\]

(5.22)

\[K_L = 0.9\text{ (typical value for motors of less than 20 hp)}\]

Cut-off frequency is given by,

\[
f_c = \frac{1}{2t_r}
\]

(5.23)
For $t = 10\text{m}$, $v = 162.73\text{m/s}$

- $t_r = 0.8295\mu\text{s}$
- $f_c = 602.7\text{kHz}$

Attenuation $A = 3\text{db}$ at cut-off frequency $f_c$

The output filter transfer function is

$$H = \frac{1+j\omega R_{filter} C_{filter}}{1-j\omega^2 L_{filter} C_{filter} + j\omega R_{filter} C_{filter}}$$

$$A = 20\log \left| \frac{1}{H} \right| \quad (5.26)$$

$$= 3\text{db}$$

To result in an over-damped circuit,

$$R_f > 2 \sqrt{\frac{L_f}{C_f}} \quad (5.27)$$

- $R_f = 43\Omega$  
- $L_f = 33.28\mu\text{H}$
- $C_f = 1\mu\text{F}$  
- $f_c = 602.7\text{kHz}$

The RLC filter topology is shown in fig.5.14.
**Figure 5.14** RLC filter at inverter output terminals

Simulation Result for this filter is as shown in fig.5.15 and the output voltage is 240V.

**Figure 5.15** Output Voltage Waveform of RLC Filter

From the bode plot shown in fig.5.16, the cut off frequency can be observed to be 712 kHz.

**Figure 5.16** Bode Plot of the RLC filter
5.5 Inference:

**Table 5.1** Comparison of various filters.

<table>
<thead>
<tr>
<th>Comparative factors</th>
<th>RC Filter (I)</th>
<th>RC Filter (II)</th>
<th>RC Filter (III)</th>
<th>RC Filter (IV)</th>
<th>Reactor</th>
<th>RLC filter</th>
<th>LC Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistor(Ω)</td>
<td>21.67</td>
<td>43.34</td>
<td>43.34</td>
<td>43</td>
<td>-</td>
<td>43</td>
<td>-</td>
</tr>
<tr>
<td>Capacitor</td>
<td>0.229nF</td>
<td>0.121nF</td>
<td>0.218nF</td>
<td>0.22μF</td>
<td>-</td>
<td>33.28μF</td>
<td>2.81μF</td>
</tr>
<tr>
<td>Inductor</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>66mH</td>
<td>1μH</td>
<td>1mh</td>
</tr>
<tr>
<td>Voltage overshoot</td>
<td>349.7 V</td>
<td>380V</td>
<td>372V</td>
<td>300V</td>
<td>230V</td>
<td>240V</td>
<td>250V</td>
</tr>
<tr>
<td>Cut-off frequency</td>
<td>412kHz</td>
<td>388kHz</td>
<td>168kHz</td>
<td>16.78kHz</td>
<td>-</td>
<td>712kHz</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.1 shows the RLC parameters of the filters discussed in this report and compares the output voltage of the various filters. It can be inferred that the RLC filter designed in this project is the most efficient filter.
CHAPTER 6

EXPERIMENTAL RESULTS

6.1 Requirements for Hardware

6.1.1 SPWM (Sine Pulse Width Modulated) Inverter

An experiment was conducted using an arrangement of a SPWM Inverter. SPWM technique is used to keep the output voltage of the inverter at the rated voltage (230 V/ 415 V AC) irrespective of the output load. SPWM inverter also reduces lower order harmonics. The inverter used in this experiment is a three phase, 415V, 50Hz inverter. The V/f control mechanism was adopted. The specification of the SPWM Inverter is shown in fig.6.1.

Figure 6.1 SPWM Inverter specifications
6.1.2 Three phase Slip Ring Induction Motor

The motor used in this experiment is a three phase, 415 V, 50 Hz slip ring induction motor. A slip ring induction motor is an asynchronous motor, as the rotor never runs in synchronous speed with the stator poles. The rotor core is made up of steel laminations which have slots to accommodate formed 3-single phase windings.

The specifications for the slip ring induction motor are given in table 6.1.

Table 6.1 Slip ring induction motor specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kilowatts</td>
<td>3.7 KW</td>
</tr>
<tr>
<td>Volts</td>
<td>415 V</td>
</tr>
<tr>
<td>Amps</td>
<td>7.5 A</td>
</tr>
<tr>
<td>Speed</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>Horsepower</td>
<td>5 HP</td>
</tr>
</tbody>
</table>
6.1.3 Cable

The area of cross section of the three core cable used for the experimental analysis is 2.5 sq.mm. This is a three core round cable with a voltage capacity of 1100V and current carrying capacity of 22 A at 40°C. The thickness of the insulation is .9mm. The sheath has a thickness of 1.2mm and size 13.9x6.4 mm (width x thickness).
6.1.4 Mixed Signal Oscilloscope (MSO)

The voltage waveforms were recorded in an MSO (Agilent Technologies - MSO 6014A). A Mixed Signal Oscilloscope (MSO) can be considered a replacement for a typical digital oscilloscope because it contains the same analog analysis capabilities, such as standard time and voltage measurements such as rise/fall times, frequency and overshoot amplitude, in addition to histograms, waveform math, FFT, and eye diagrams. In our project we used the MSO to measure voltage at various points.

Figure 6.4 Mixed Signal Oscilloscope

6.2 Experimental Setup

The experiment was conducted with the apparatus mentioned above. The Sine PWM Inverter drive was connected to the three phase induction motor through a 10m long three core cable. The MSO was used to measure the voltage between the phases 1&2, 1&3 and 2&3 and obtain the corresponding voltage waveforms.

Initially, this experiment was conducted without using filters. Then, an RC filter was incorporated in the circuit at the motor terminals and the experiment was
repeated. For this three 100Ω / 5A rheostats and a capacitor bank with each capacitor unit being 2.6 μF were used. The experimental setup is shown in fig.6.5 and fig.6.6.

Figure 6.5 Experimental Setup

Figure 6.6 Filter setup
6.3 Experimental Observation

The output voltage at the inverter terminal is observed to be 415 V. The waveform was recorded using the MSO and is shown in figure 6.6.

![Output voltage waveform at the inverter terminal](image)

**Figure 6.7** Output voltage waveform at the inverter terminal

6.3.1 Experimental Observation without Using Filter:

When the experiment was conducted first without using filters, the following output voltage waveforms were observed at the input terminals of the motor. The experiment was conducted at different speeds of the motor and thereby at different frequencies. The waveforms at the motor terminal were recorded using MSO and is shown in fig.6.8 and fig.6.9 for speeds 910 rpm and 1210 rpm respectively.
Figure 6.8 Output Voltage waveform at motor terminal at 906 rpm

Figure 6.9 Output Voltage waveform at motor terminal at 1210 rpm
6.3.2 Experimental Observation Using Filter:

The experimental procedure is repeated after incorporating RC filter at the motor terminals. The following voltage waveforms were recorded using MSO at the motor input terminals for different speeds of the motor. The voltage waveform was observed for terminals 1-2, 2-3 and 1-3 of the motor and is shown in fig.6.10 and fig.6.11 for speeds 910 rpm and 1210 rpm respectively. It can be observed that the spikes have reduced remarkably as compared to the voltage waveforms obtained without using filter at the motor terminal.

![Output Voltage waveform at motor terminal at 910 rpm](image)

**Figure 6.10** Output Voltage waveform at motor terminal at 910 rpm
6.4 Inference

From the experimental observation, it can be inferred that without using filters, the over-voltage is as high as 800V for a speed of 1210 rpm and 1500V for a speed of 906 rpm. This dangerously high voltage will damage the motor’s insulation and reduce its lifetime. The RC Filter used in the circuit has been added in order to reduce this overshoot voltage to 500V for a speed of 906 rpm. It is evident from the MSO observations that over-shoot voltage has reduced significantly after using filters.

Figure 6.11 Output Voltage waveform at motor terminal at 1210 rpm
7.1 Overview of the project

- Our project deals with the analysis and mitigation of over-voltages in IGBT based SPWM fed Induction motor drives.
- Impedance mismatch between surge impedance of the cable and motor causes voltage doubling at the motor terminals. High switching frequencies and long cable lengths cause the voltage to shoot-up beyond twice the peak-supply voltage.
- At critical cable length, no voltage amplification occurs.
- High frequency modeling of the cable and induction motor is required for accurate analysis.
- Passive filters are employed at the motor and inverter terminals to slow down $dv/dt$ and hence, reduce over-voltage. Using experiment, an RC filter employed at the motor terminals reduced the over-voltage to 500V.
- Optimization of cable-length between the inverter and motor will reduce the impedance mismatch and it is done based on critical cable length calculation.

7.2 Scope for future work

The over-voltage is reduced using an RC filter at the motor terminals to certain extent. In order to eliminate voltage over-shoot completely, RLC filter at the inverter terminals has to be employed. Further the over-voltages can also be suppressed using active filters.
REFERENCES


