Simulation and Experimental Analysis of Common Mode Voltage and Bearing Voltage in Multiple Motors Fed by Single PWM Inverter for Long Cable Applications

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Abstract: This paper presents the influence of the motor cable length on the occurrence of over voltage at the motor terminals in multiple induction motors fed by single PWM inverter for long cable applications. Further, paper also discusses the effect of overvoltage at the motor terminals on the magnitude of the common mode voltage and the bearing voltage. Two 1/2-HP, 3-Ø induction motors (M1 and M2) and two 3HP induction motors (M3 and M4). These motors are installed at distance of 30m, 60m, 90m and 120 m respectively from inverter terminals in daisy chain configuration. As the motor cable length increases, the motor terminal voltage, common mode voltage and bearing voltage increases due to voltage reflection phenomenon and interaction between the individual motors. To suppress the over-voltage at all the motor terminals, thereby reducing the common mode voltage and bearing voltage, the RC passive filter have been installed at the motor terminals M4 to match with the cable surge impedance. The simulation results are compared with the experimental results. According to these results, the over-voltages at the motor terminal, common mode voltage and bearing voltage reduced more than 70% in all the motors with long cables.

Index Terms: Bearing Voltage, multiple motors, PWM Inverter, Voltage Reflection phenomenon

I. INTRODUCTION

It is economical in some applications the use of one large Pulse Width Modulation (PWM) inverter to drive multiple 3-Ø motors, instead of driving each motor separately from its own small inverter. In such applications, the same voltage and frequency is applied to all the motors to control the operation. Typical multiple motor applications include conveyors, steel mills, and modular air conditioning condenser systems.

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A passive R-C filter installed at the motor side reduces the over voltage and $I_b$ in a PWM ASD with long motor cable feeding only one motor. The work carried out only considering one particular HP rating of motor [5]. From experimental results the 3-level inverter topology gives lower $V_{cm}$, $V_b$ and $I_b$ compared to 2-level inverter [6]. The experimental measurement of $V_{cm}$, $V_b$ and $I_b$ in a 3-level inverter using Sinusoidal PWM (SPWM) and Space Vector Modulation (SVM) topologies were carried out. The magnitude of $V_b$ is less for SVM technique compared to the SPWM; the influence of motor cable length was not considered [7]. Simulation analysis $V_{cm}$ and $I_b$ in 2 and 3-level PWM ASD with long motor cable was carried out, there is lack of experimental work [8]. With increase in length of cable between inverter and motor, voltage at motor terminal increases. Higher the motor HP rating, smaller the winding impedance. The paper didn’t deal with the effect of motor cable length on the magnitude of $V_{cm}$, $V_b$ and $I_b$ [9], [10]. When one inverter driving multiple motors, if the parallel point is at the inverter terminals, the performance of multiple motor systems is same as that of single motor systems. The parallel point at the motor terminals will reduce the overvoltage. The paper not presented the overvoltage effect on $V_{cm}$ and $V_b$ [13]. Various configurations for connecting multiple motors to the single inverter are discussed including pros and cons of each case, but no evidence of experimental results [14].

This paper presents simulation and experimental analysis of motor terminal voltage, common mode voltage and bearing voltage. The following cases are considered:

a) Single inverter driving single motor without long cable
b) Single inverter driving single motor with long cable
c) Single inverter driving multiple motor without filter for long cable applications
d) Single inverter driving multiple motor with RC filter for long cable applications

II. COMMON MODE VOLTAGE AND BEARING VOLTAGE

In a PWM inverter fed induction motor, an average voltage in a neutral point w.r.t ground is non zero and is known as common mode voltage, it is given by the equation

$$V_{cm} = \frac{V_{an} + V_{bn} + V_{cn}}{3}$$

(1)

$V_{an}$, $V_{bn}$ and $V_{cn}$ are phase voltages. The difference of potential between inner and outer race of a bearing is known as bearing voltage ($V_b$) and is given by equation (2) [11] [12].

$$V_b = \frac{C_{sr}}{C_{sr} + C_{sr} + C_b} V_{cm}$$

(2)

Where $C_{sr}$ is capacitance between stator winding and rotor, $C_b$ is the capacitance between stator winding and rotor and $C_b$ is the bearing capacitance.

III. SIMULATION MODELING

The MATLAB simulink model of multiple motors fed by single PWM inverter is as shown in fig.2(b) and fig.2(a) shows 2-level PWM VFD. It includes common mode equivalent circuit and bearing model. High Frequency (HF) IM modeling is obtained as in [15]. The HF cable modeling is carried out as in [16]. The SPWM technique with a switching frequency of 2 kHz is used.

IV. EXPERIMENTAL SETUP

The experimental set up shown in fig.3 consists of a 3-Ø, 415 V, 50 Hz, star-connected, 4-pole, two ½ HP and two 3HP induction motors. The Motors M1 and M2 are 1/2HP, M3 and M4 are 3HP.

![Experimental Setup Image]
The high frequency PVC cable of 1.0 mm² type that is divided into four lengths each of 30 m long were used. The motors are fed by a 3-Ø 440V, 50 Hz inverter (Danfoss make) with 2 kHz switching frequency SPWM technique, Digital Storage Oscilloscope (DSO) and power scope. The space around bearing outer race on both sides of an end plate of all the four motors are slightly enlarged by machining. The insulation is placed around the outer race of the bearings at both drive and non drive ends. Hence the whole rotor is isolated from the main body of the I.M. The motors M1, M2, M3 and M4 are at a distance of 30 m, 60 m, 90 m and 120 m respectively from the inverter terminals.

V. RESULTS AND DISCUSSIONS

A. Single Inverter Driving Single Motor without Long Cable

Figs. 4(a)-4(c) depict simulation results indicating the peak values of Motor terminal voltage (Vₜ), Vₐₗ and Vₖ waveforms without long motor cable. Figs. 5(a)-5(c) show the experimental peak values of Vₜ, Vₐₗ and Vₖ results without long motor cable. The motor terminal voltage is the same as inverter output voltage. The magnitude of Vₐₗ and Vₖ of the motor remains the same.

![Graphs showing simulation results](image1)

B. Single Inverter Driving Single Motor with Long Cable

Figs. 6(a)-6(c) show simulation results of Vₜ, Vₐₗ and Vₖ with 120 m of motor cable. The experimental waveforms are presented in Figs. 7(a)-7(c), indicating the peak values of the Vₜ, Vₐₗ and Vₖ for a 3 HP motor fed by single PWM inverter via 120 m of cable. As the length of the cable increases, the Vₜ, Vₐₗ and Vₖ increases due to transmission line effect. Table I gives the simulation and experimental results, is indicating the peak values of Vₜ, Vₐₗ and Vₖ without long cable and with 120 m motor cable.

![Graphs showing experimental results](image2)
Simulation and Experimental Analysis of Common Mode Voltage and Bearing Voltage in Multiple Motors Fed by Single PWM Inverter for Long Cable Applications

particularly it is significant at the terminating motor M4, compare to at the motor M1. The over voltage at the motor terminal results in higher values of the \( V_{cm} \) and \( V_b \). Figs.9(a)-9(d) and figs.12(a)-12(d) show simulation and experimental waveforms respectively, are representing peak values of common mode voltage at the motor terminals M1-M4 without any filter. The \( V_{cm} \) increases as the length of the cable increases, due to increase in motor terminal voltage, which primarily depends on DC bus voltage. Figs.10(a)-10(d) and figs.13(a)-13(d) show simulation and experimental waveforms respectively, are indicating peak values of bearing voltage in the motors M1-M4 without any filter. The \( V_b \) depends on \( V_{cm} \) as the length of the cable increases, the motor terminal voltage and \( V_{cm} \) increases. With increase in the magnitude of \( V_{cm} \), the \( V_b \) and hence, the EDM bearing current increases and leads to premature bearing damage. Table-II gives simulation and experimental results of the motor terminal voltage, \( V_{cm} \) and \( V_b \) of the motors M1-M4 without any filter for long cable applications.

### TABLE I
SIMULATION AND EXPERIMENTAL RESULTS OF SINGLE INVERTER DRIVING SINGLE MOTOR WITHOUT AND WITH LONG CABLE

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Simulation</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor terminal voltage (( V_T ) (pk)) V</td>
<td>( V_{cm} ) (pk) V</td>
<td>( V_b ) (pk) V</td>
</tr>
<tr>
<td>Without long cable</td>
<td>535</td>
<td>221</td>
</tr>
<tr>
<td>With 120m cable</td>
<td>701</td>
<td>315</td>
</tr>
</tbody>
</table>

C. Single Inverter Driving Multiple Motors without Filter for Long Cable Applications

Figs. 8(a)-8(d) and figs.11(a)-11(d) show simulation and experimental waveforms respectively, are representing the peak values of motor terminal voltage at motors M1-M4 without any filter. It is notice that, long motor cable increases motor terminal voltage significantly due to transmission line effect, interactions between the motors, cable, inverter and between the individual motor themselves. The over voltage,
Fig. 9. Simulation results of common mode voltage at the motor terminals
a) M1 b) M2 c) M3 d) M4

Fig. 10. Simulation results of bearing voltage of the motors
a) M1 b) M2 c) M3 d) M4

Fig. 11. Experimental results of motor terminal voltage at
a) M1 b) M2 c) M3 d) M4
D. Single Inverter Driving Multiple Motors with RC Filter for Long Cable Applications

In this case the cable is terminated by a first order filter consisting of a capacitor in series with the resistor to match with the cable impedance and provide the proper level of damping to control the voltage overshoot. The optimum value of filter resistor \( R_f \) is equal to characteristic impedance of the cable.

\[
R_f = Z_{cable} = \sqrt{\frac{L}{C}}
\]

Where \( L \) and \( C \) are the inductance and capacitance of the cable per meter length. A design goal is to make \( C_f \) voltage < 15% of DC bus voltage. The value of filter capacitance \( \text{'} C_f \text{'} \) estimated using the RC charge equation given by

\[
V_{cf} = V_{bus} \left( 1 - e^{-\frac{t_{rise}}{R_f C_f}} \right)
\]

(4)

\[
C_f = \frac{t_{rise}}{0.1625 R_f}
\]

(5)

By solving equations (3), (4) and (5) for 0.1µSec rise time, \( R_f = 42\Omega \) and \( C_f = 14.65\text{nF} \).

Figs.14(a)-14(d) and figs.17 (a)-17(d) show simulation and experimental waveforms respectively, are indicating peak values of motor terminal voltage at the motors M1-M4 with the RC filter. It is observed from results; the terminal voltage gets reduced significantly more than 80% at all the motor terminals. The RC Filter connected at the motor terminal M4 matches with the cable characteristic impedance.

Figs.15(a)-15(d) and figs.18(a)-18(d) show simulation and experimental waveforms respectively. These waveforms indicate the peak values of the common mode voltage at the motor terminals M1-M4 with RC filter. The \( V_{cm} \) decreases due to decrease in the motor terminal over voltage.

Figs.16(a)-16(d) and figs.19(a)-19(d) show simulation and experimental waveforms respectively, are representing peak value of the bearing voltage of the motors M1-M4 with RC filter. The \( V_b \) depends on \( V_{cm} \) with decrease in \( V_{cm} \) reduces \( V_b \). Reduction in the \( V_b \) minimizes the EDM bearing current damage. Table-III gives simulation and experimental results of motor terminal voltage, \( V_{cm} \) and \( V_b \) of the motors M1-M4 with RC filter for long cable applications.

<table>
<thead>
<tr>
<th>Motor</th>
<th>Length of cable from inverter in (m)</th>
<th>( V_T ) (pk) V</th>
<th>( V_{cm} ) (pk) V</th>
<th>( V_T ) (pk) V</th>
<th>( V_{cm} ) (pk) V</th>
<th>( V_b ) (pk) V</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>30</td>
<td>640</td>
<td>370</td>
<td>30</td>
<td>760</td>
<td>432</td>
</tr>
<tr>
<td>M2</td>
<td>60</td>
<td>750</td>
<td>416</td>
<td>36</td>
<td>800</td>
<td>536</td>
</tr>
<tr>
<td>M3</td>
<td>90</td>
<td>815</td>
<td>532</td>
<td>40</td>
<td>880</td>
<td>585</td>
</tr>
<tr>
<td>M4</td>
<td>120</td>
<td>832</td>
<td>585</td>
<td>55</td>
<td>900</td>
<td>620</td>
</tr>
</tbody>
</table>

Where \( L \) and \( C \) are the inductance and capacitance of the cable per meter length. A design goal is to make \( C_f \) voltage < 15% of DC bus voltage. The value of filter capacitance \( \text{'} C_f \text{'} \) estimated using the RC charge equation given by

**TABLE II**

Simulation and Experimental Results Of Multiple Motors Fed By Single Inverter Without Filter

**Simulation and Experimental Analysis of Common Mode Voltage and Bearing Voltage in Multiple Motors Fed by Single PWM Inverter for Long Cable Applications**
Fig. 14. Simulation results of motor terminal voltage at the motors a) M1 b) M2 c) M3 d) M4

Fig. 15. Simulation results of common mode voltage at the motor terminals a) M1 b) M2 c) M3 d) M4

Fig. 16. Simulation results of bearing voltage for the motors a) M1 b) M2 c) M3 d) M4
Simulation and Experimental Analysis of Common Mode Voltage and Bearing Voltage in Multiple Motors Fed by Single PWM Inverter for Long Cable Applications

Fig. 17: Experimental results of motor terminal voltage at a) M1 b) M2 c) M3 d) M4

Fig. 18: Experimental results of common mode voltage at the motor terminals a) M1 b) M2 c) M3 d) M4

Fig. 19: Experimental results of bearing voltage for the motors a) M1 b) M2 c) M3 d) M4

TABLE III
SIMULATION AND EXPERIMENTAL RESULTS WITH RC FILTER AT THE MOTOR TERMINALS M4

<table>
<thead>
<tr>
<th>MOTOR</th>
<th>LENGTH OF CABLE FROM INVERTER (m)</th>
<th>VT (pk) V</th>
<th>VCM (pk) V</th>
<th>VB (pk) V</th>
<th>VT (pk)/V</th>
<th>VCM (pk)/V</th>
<th>VB (pk)/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>30</td>
<td>472</td>
<td>157.5</td>
<td>10</td>
<td>521</td>
<td>196</td>
<td>10.5</td>
</tr>
<tr>
<td>M2</td>
<td>60</td>
<td>480</td>
<td>200</td>
<td>11.5</td>
<td>542</td>
<td>216</td>
<td>12.4</td>
</tr>
<tr>
<td>M3</td>
<td>90</td>
<td>510</td>
<td>228.5</td>
<td>14.8</td>
<td>567</td>
<td>252</td>
<td>16.2</td>
</tr>
<tr>
<td>M4</td>
<td>120</td>
<td>525</td>
<td>251</td>
<td>17.5</td>
<td>584</td>
<td>260</td>
<td>19.4</td>
</tr>
</tbody>
</table>
VI. CONCLUSION

In this paper, simulation and experimental analysis of the motor terminal voltage, common mode voltage and the bearing voltage in multiple motors fed by single PWM inverter for long cable application has been presented. Long motor cable causes over voltage at the motor terminals due to voltage reflection. It is observed that, the effect of motor cable length on motor terminal voltage, $V_{cm}$ and $V_b$ is more in multiple motor fed by single inverter than single inverter driving single motor due to the interaction between the individual motors.

The RC passive filter installed at the motor terminals M4, suppress the over-voltage at all the motor terminals. Thus reducing the common mode voltage and bearing voltage more than 70% in all the motors with long cable. Hence, stress on the stator winding and bearing is reduced. The reliability of multiple motor control system is enhanced as well as the hidden costs involved in downtime and lost product is reduced.

REFERENCES


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