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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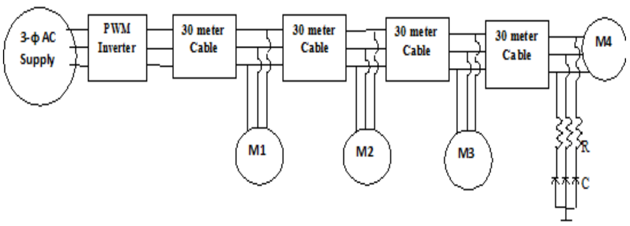


Fig.1.Block diagram of multiple motors fed by single PWM inverter

There are various configurations for connecting multiple motors to the inverter. One method is 'daisy-chain' configuration in which, the inverter is connected to the first motor (M1) through 30m cable. The second motor (M2) is tapped at the terminals of motor M1, the motor M3 is tapped at the terminals of motor M2 and so on as shown in fig.1.The length of the motor cable used in between the motors is 30m. Even though this may create the most economical installation, it may also result in high reflected voltage waves. Voltage overshoot is due to the impedance mismatch between the motors and cable, and between the individual motor themselves. The use of multiple motors with a single control can result in a higher motor terminal voltage and may exceed double the inverter DC bus voltage, and prolonged exposure to them can permanently damage a motor's insulation and motor bearings due bearing current caused by common mode voltage. The occurrence of bearing currents in an Induction Motor (IM) has been known for several years. Asymmetric flux distribution is the basis that causes bearing current (I_b) inside the I.M [1]. It has been productively solved using advanced motor design and manufacturing methods. The high dv/dt of PWM ASD has undesirable effects on bearing life caused by I_b due to common mode voltage (V_{cm}).The long cable increases V_{cm} and hence I_b [2],[3]. When the bearing voltage (V_b) exceeds insulating strength of lubricating grease (15Vpk/µm), grease breaks down, thereby causing the Electric Discharge Machining (EDM) bearing current pulses and destroys the bearing within 1-6 months of installation [4]. The level of V_b even in small machine can reach a value upto 20V. According to IEEE 112 standard, allowable value of V_b is 0.5mV, as well as the manufacturer's allowable voltage of 1 to 2V for Variable Frequency Drives (VFDs). 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 (1)

$$V_{cm} = \frac{V_{an} + V_{bn} + V_{cn}}{3} \quad (1)$$

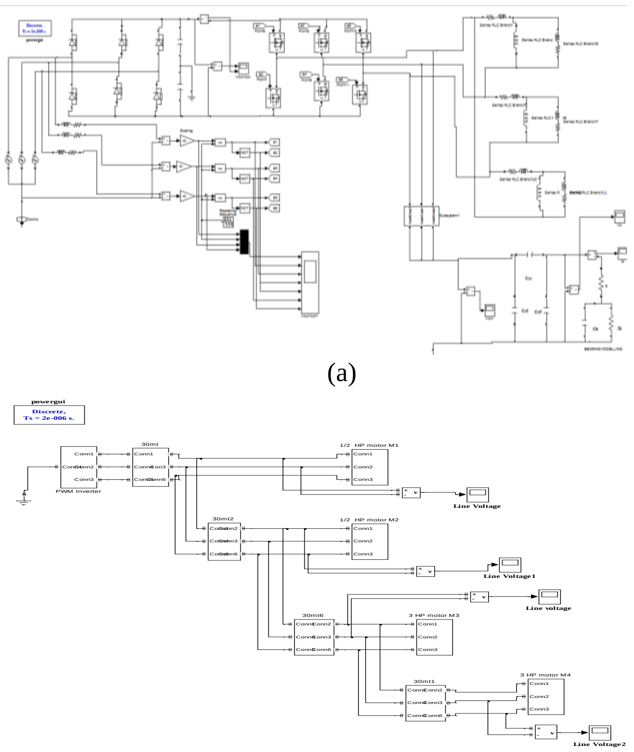
V_{an}, V_{bn} and V_{cn} are phase voltages. The difference of potential between inner and outer race of a bearing is known as bearing voltage (V_b) and is given by equation (2) [11] [12].

$$V_b = \frac{C_{wr}}{C_{wr} + C_{rs} + C_b} V_{cm} \quad (2)$$

Where C_{wr} is capacitance between stator winding and rotor, C_{rs} 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) I.M 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.



(a)

(b)

Fig.2. Simulink models (a) 2-level VFD (b) multiple motors fed by single PWM VFD

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.

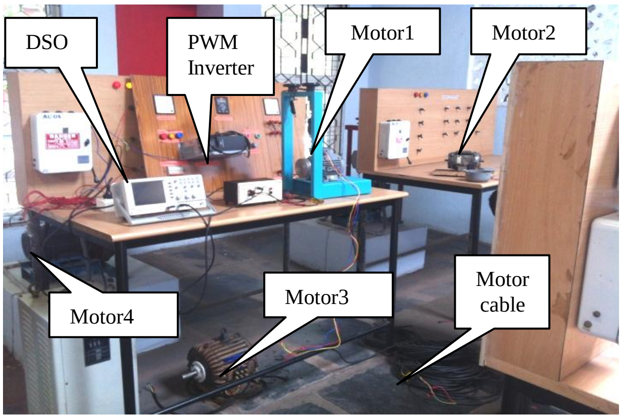


Fig.3. Experimental setup

The high frequency PVC cable of 1.0 mm[2] type that is divided into four lengths each of 30m 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.

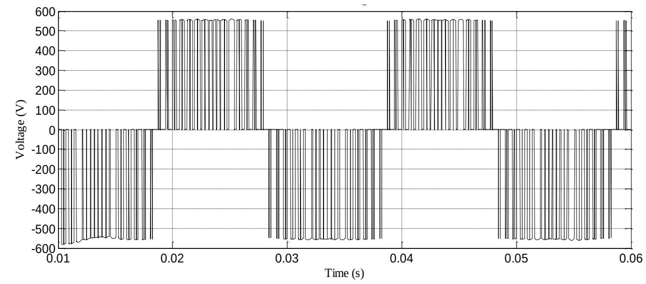
The space around bearing outer race on both sides of an end plate of all the four motors are slightly enlarged by machining. The insulation is placed around the outer race of the bearings at both drive and non drive ends.

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 30m, 60m, 90m and 120m 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 (V_T), V_{cm} and V_b waveforms without long motor cable. Figs. 5(a)-5(c) show the experimental peak values of V_T, V_{cm} and V_b results without long motor cable. The motor terminal voltage is the same as inverter output voltage. The magnitude of V_{cm} and V_b of the motor remains the same.



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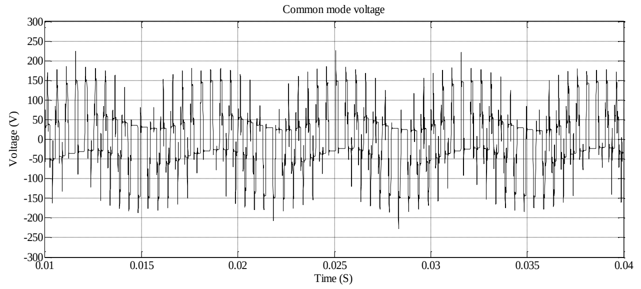

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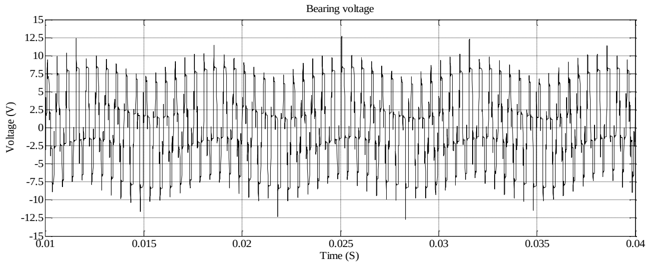
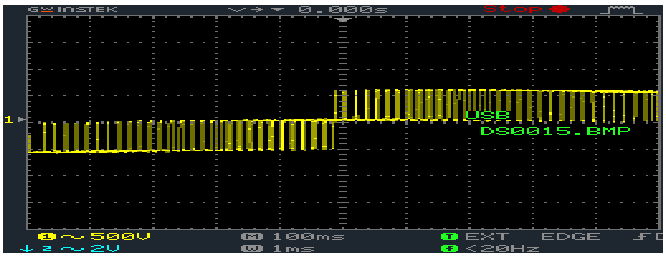
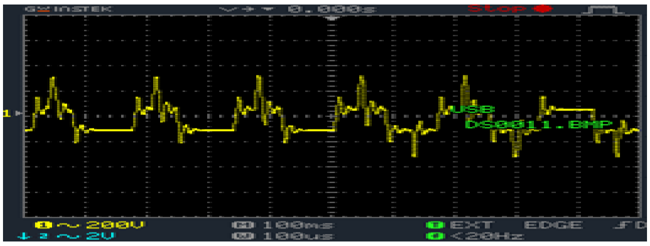


(c)

Fig.4. Simulation results a) Motor terminal voltage b) Common mode voltage c) Bearing voltage



(a)



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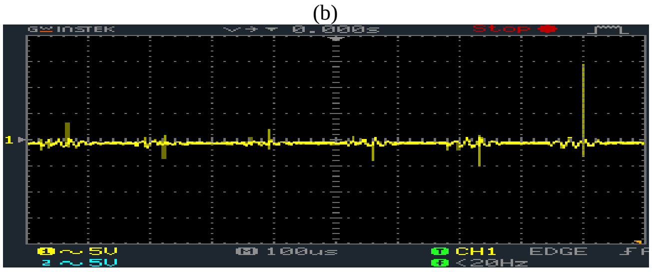
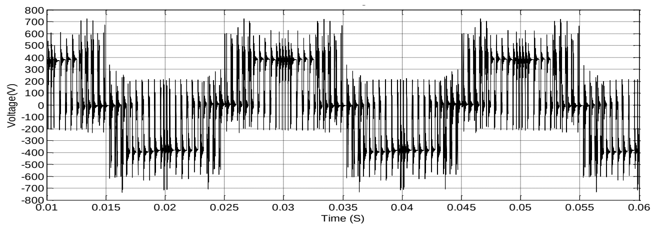


(c)

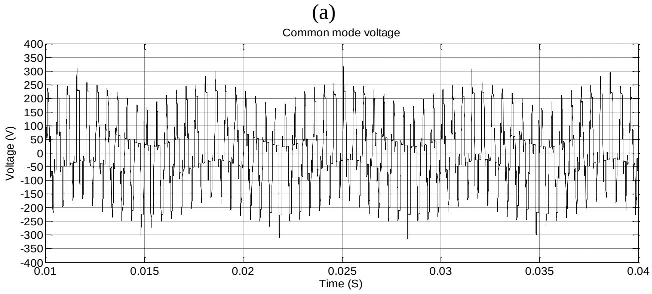
Fig.5. Experimental results a) Motor terminal voltage b) Common mode voltage c) Bearing voltage

B. Single Inverter Driving Single Motor with Long Cable

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



(a)



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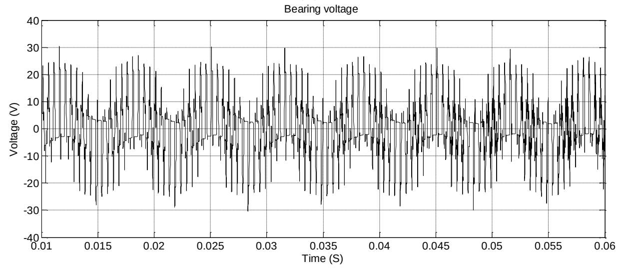

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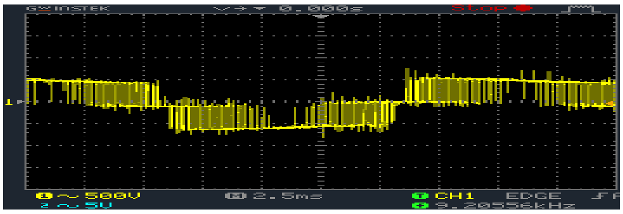
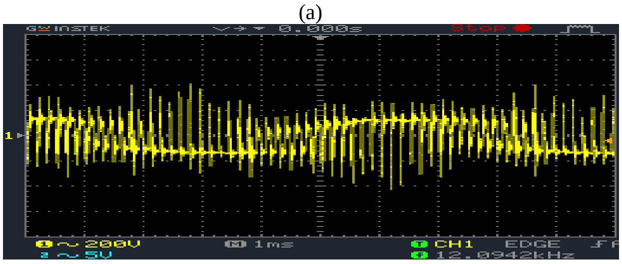
Fig.6. Simulation results a) Motor terminal voltage b) Common mode voltage c) Bearing voltage



(a)



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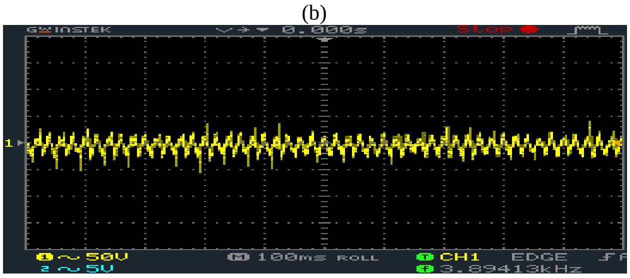

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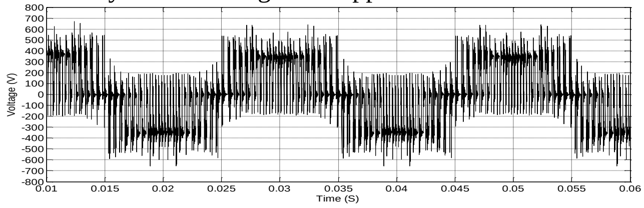
Fig.7. Experimental results a) Motor terminal voltage b) Common mode voltage c) Bearing voltage

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

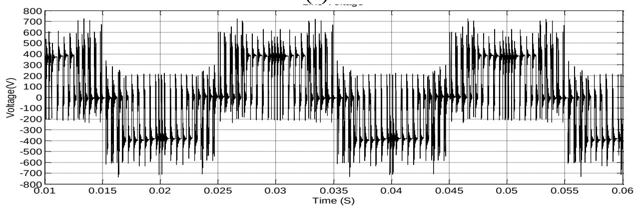
Parameters	Simulation			Experimental		
	Motor terminal voltage (V_T) (pk) V	V_{cm} (pk) V	V_b (pk) V	V_T (pk)V	V_{cm} (pk) V	V_b (pk) V
Without long cable	535	221	12.5	540	288	13.6
With 120m cable	701	315	30	744	408	44

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, 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 increase, 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.



(a)



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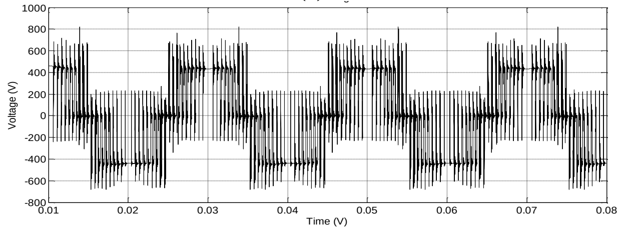

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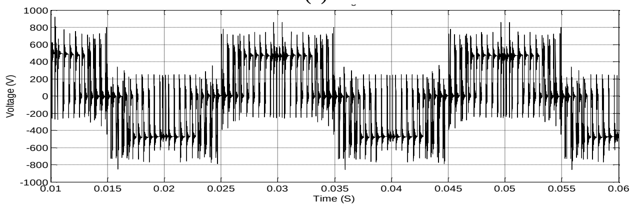
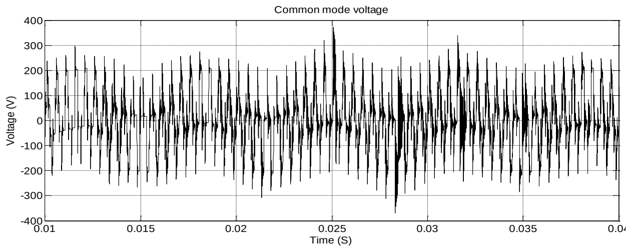
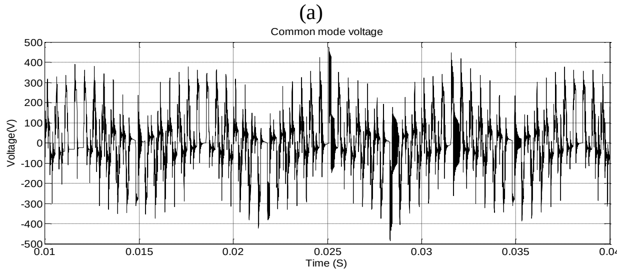


(d)

Fig.8.Simulation results of motor terminal voltage at a) M1 b) M2 c) M3 d) M4



(a)



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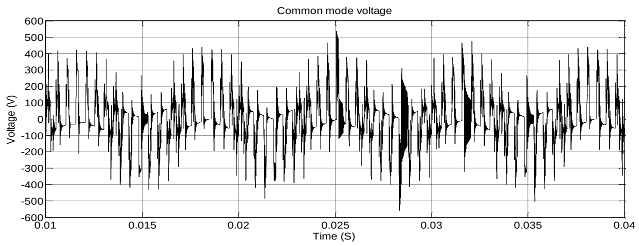

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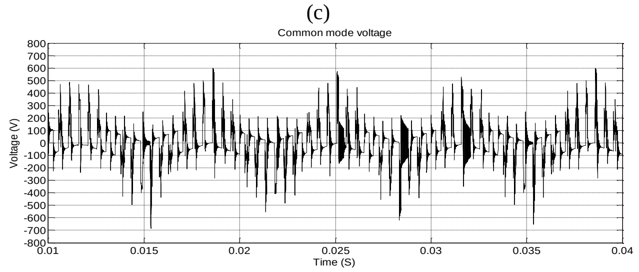

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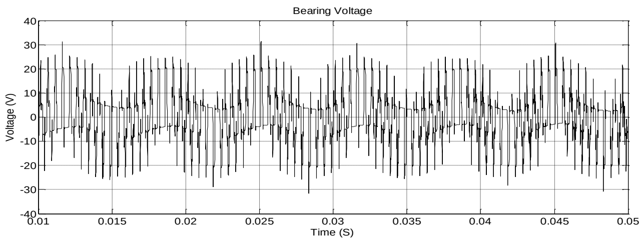
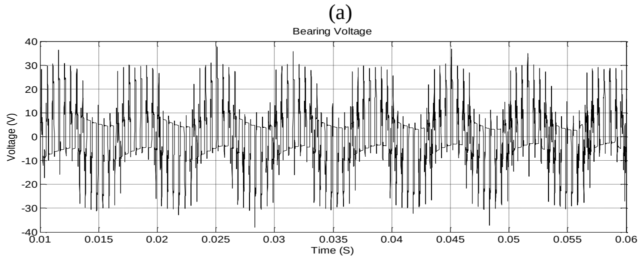
Fig.9.Simulation results of common mode voltage at the motor terminals a) M1 b) M2 c) M3 d) M4



(a)



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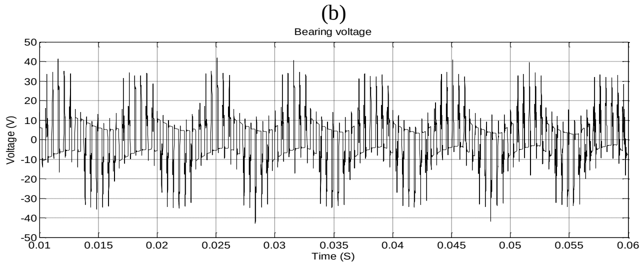

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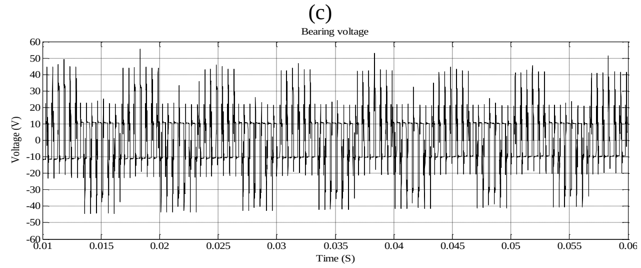
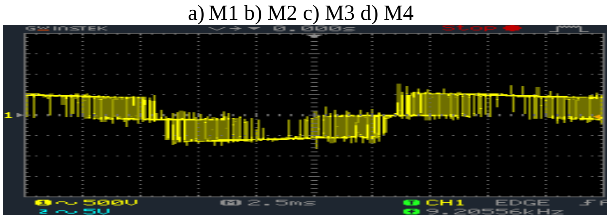


(d)

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



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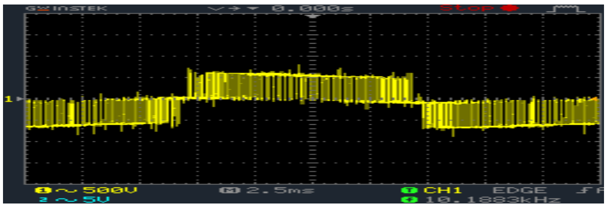

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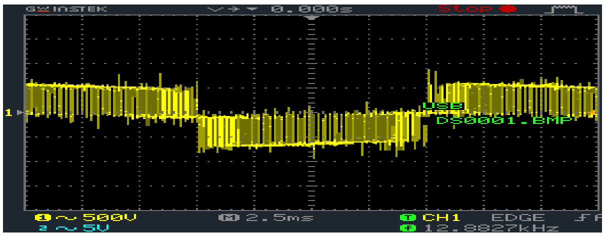

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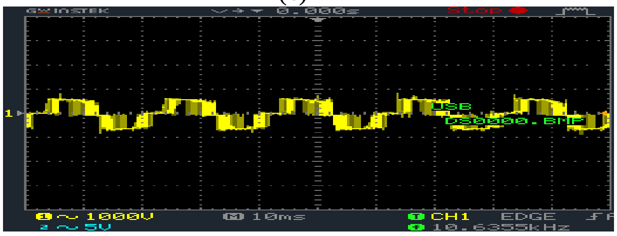

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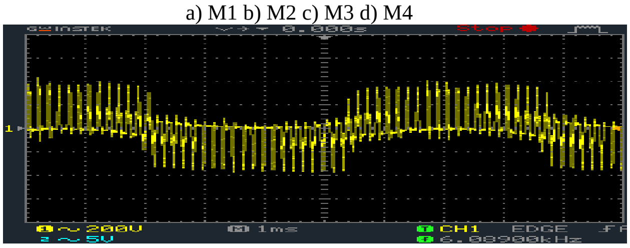
Fig.11.Experimental results of motor terminal voltage at a) M1 b) M2 c) M3 d) M4



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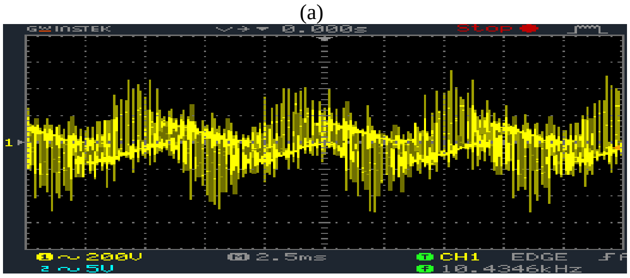

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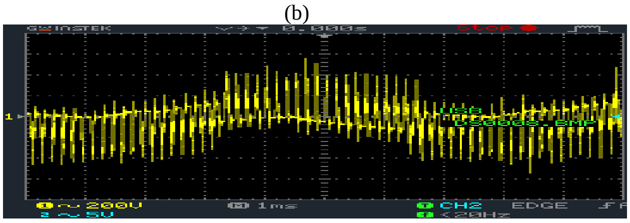

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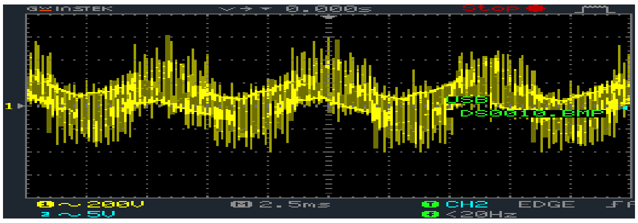

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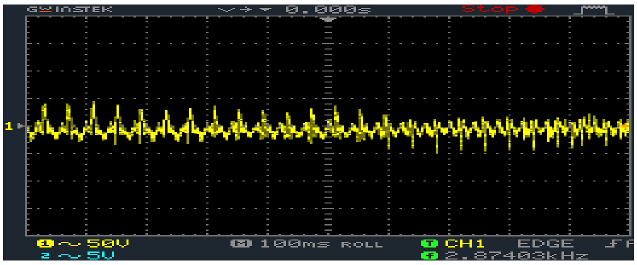
Fig.12.Experimental results of common mode voltage at the motor terminals a) M1 b) M2 c) M3 d) M4



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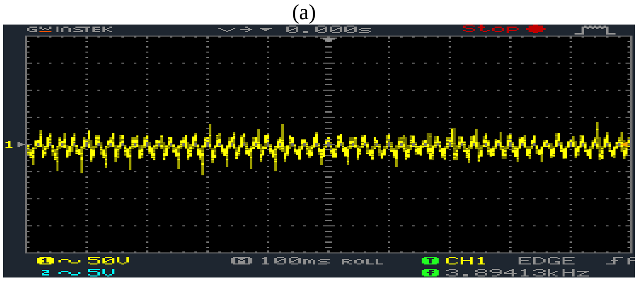

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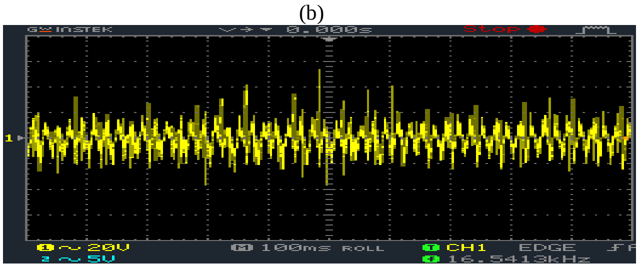

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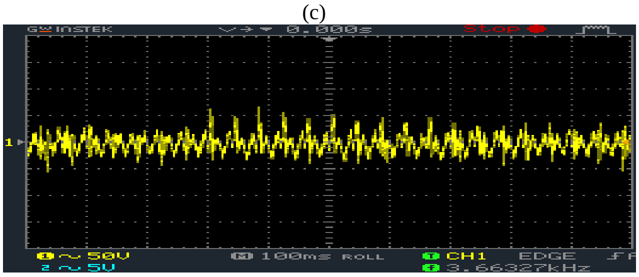


(d)

Fig.13.Experimental results of bearing voltage of the motors a) M1 b) M2 c) M3 d) M4.

TABLE II
SIMULATION AND EXPERIMENTAL RESULTS OF MULTIPLE MOTORS FED BY SINGLE INVERTER WITHOUT FILTER

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.

$$R_f = Z_{cable} = \sqrt{\frac{L}{C}} \quad (3)$$

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 'C_f' estimated using the RC charge equation given by

$$V_{cf} = V_{bus}\left(1 - e^{\frac{trise}{R_f C_f}}\right) \quad (4)$$

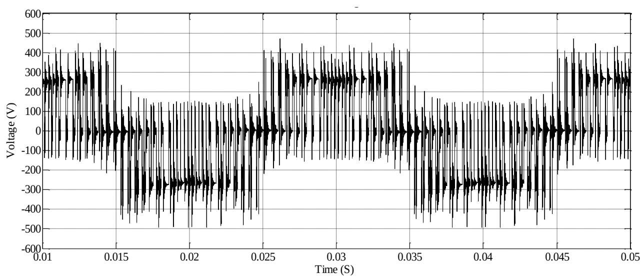
$$C_f = \frac{t_r}{0.1625 R_f} \quad (5)$$

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

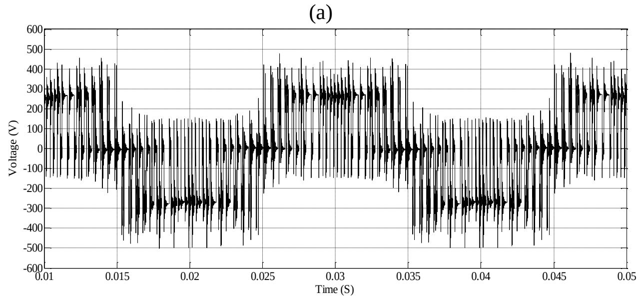
Figs.14(a)-14(d) and figs.17 (a)-17(d) show simulation and experimental waveforms respectively, are indicating peak values of motor terminal voltage at the motors M1-M4 with the RC filter. It is observed from results; the terminal voltage gets reduced significantly more than 80% at all the motor terminals.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

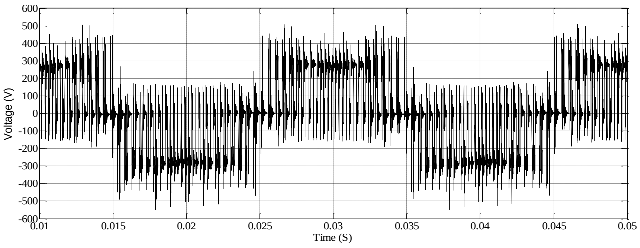


(a)



(b)

		Simulation			Experimental		
MOTORS	Length of cable from inverter in (m)	V_T (pk) V	V_{cm} (pk) V	V_b (pk) V	V_T (pk) V	V_{cm} (pk) V	V_b (pk) V
M1	30	640	370	30	760	432	36
M2	60	750	416	36	800	536	40.5
M3	90	815	532	40	880	585	53.6
M4	120	832	585	55	900	620	56.5



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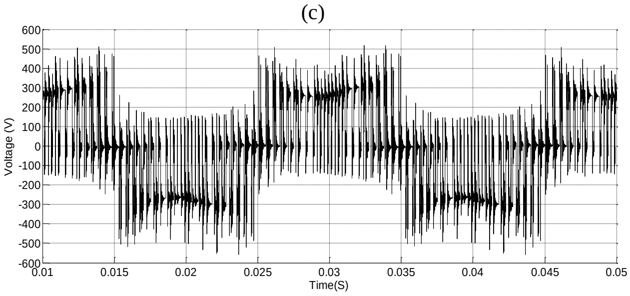
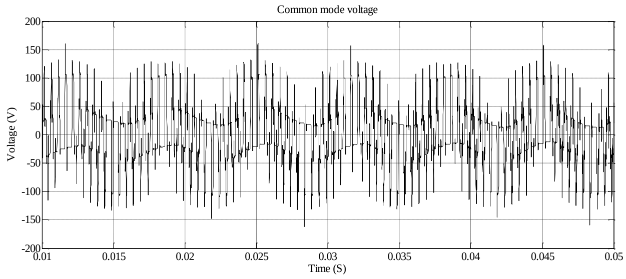
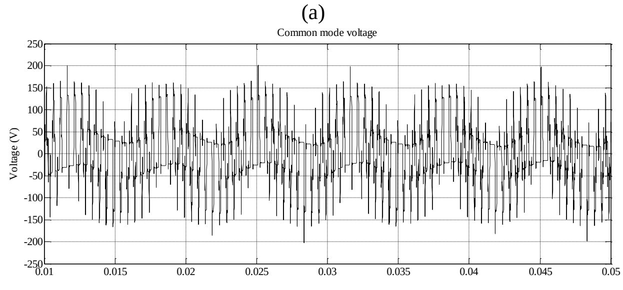


(d)

Fig.14.Simulation results of motor terminal voltage at the motors a) M1 b) M2 c) M3 d) M4



(a)



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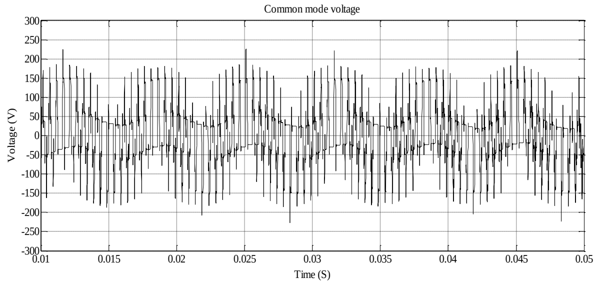

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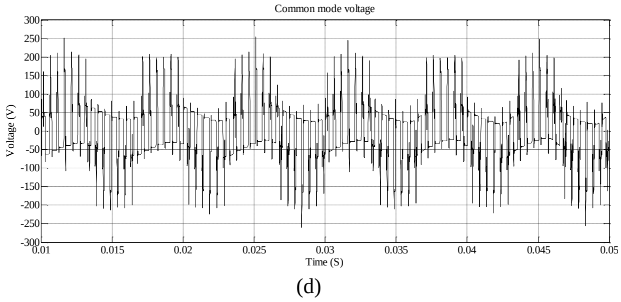
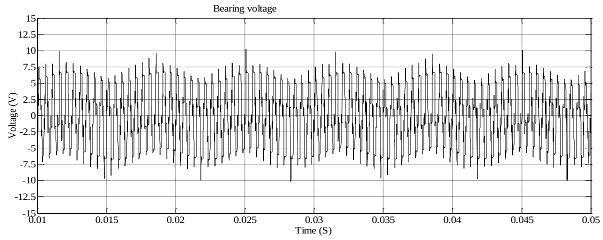
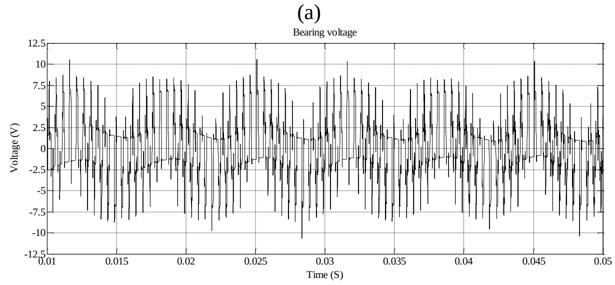


(d)

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



(a)



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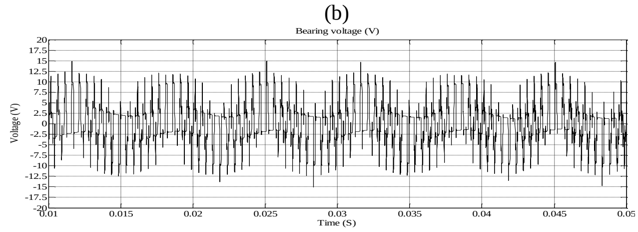

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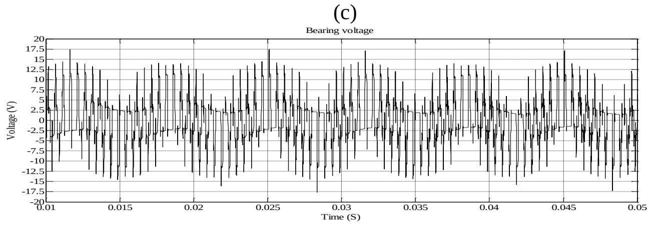
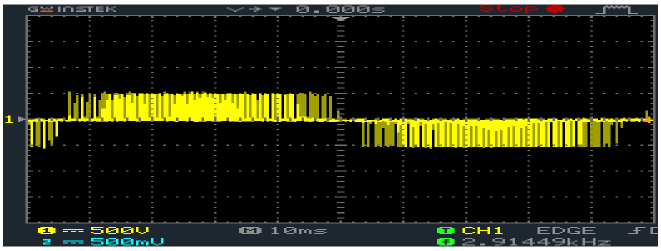
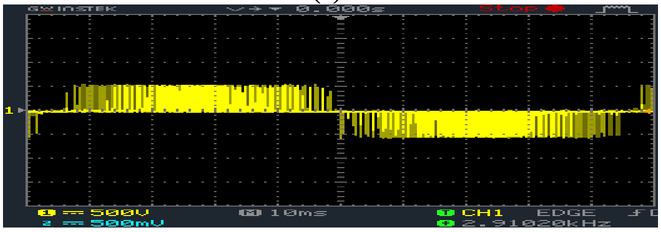


(d)

Fig.16.Simulation results of bearing voltage for the motors a) M1 b) M2 c) M3 d) M4



(a)



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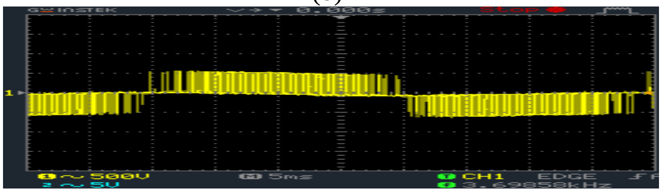

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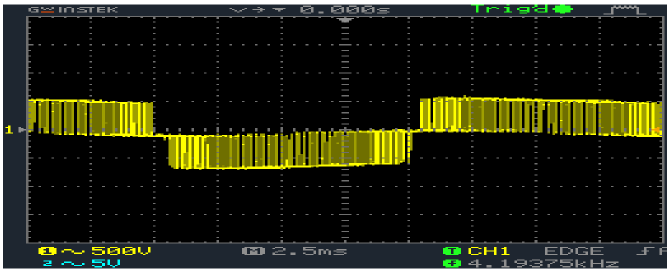
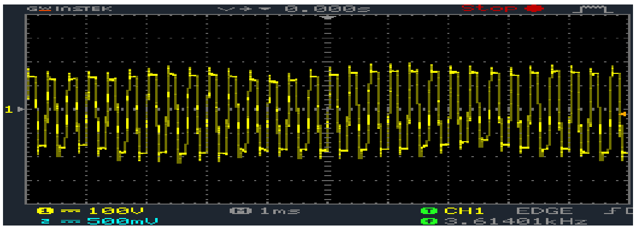
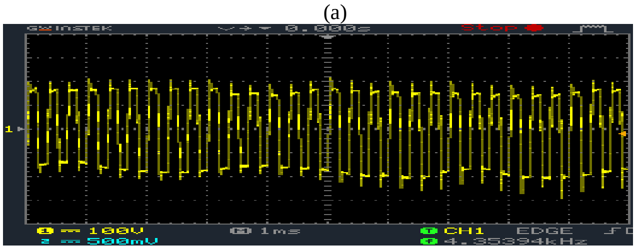


(d)

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



(a)



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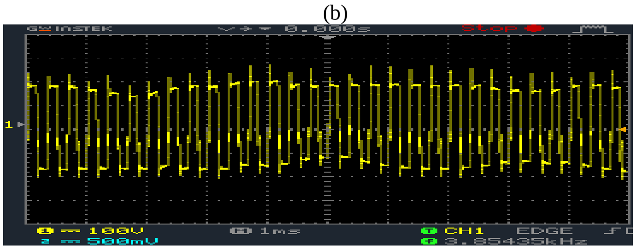

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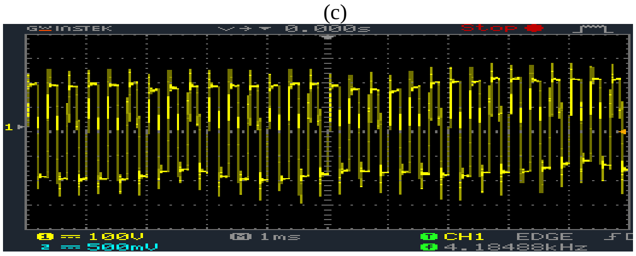
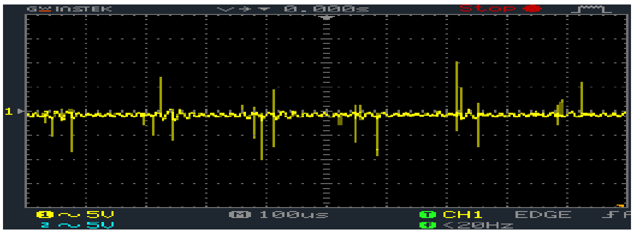
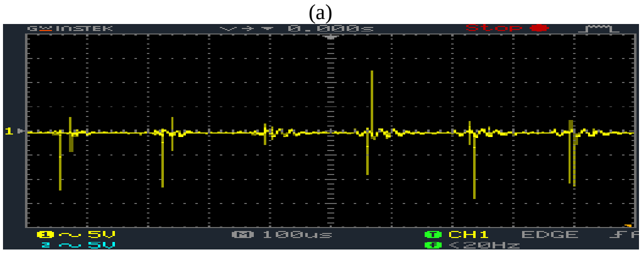


(d)

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



(a)



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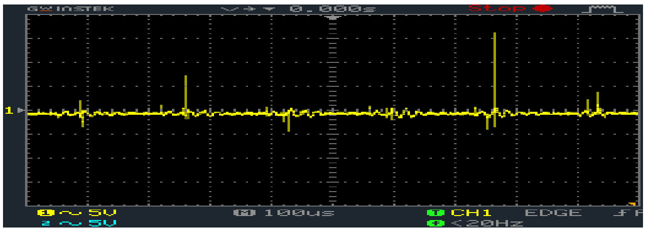

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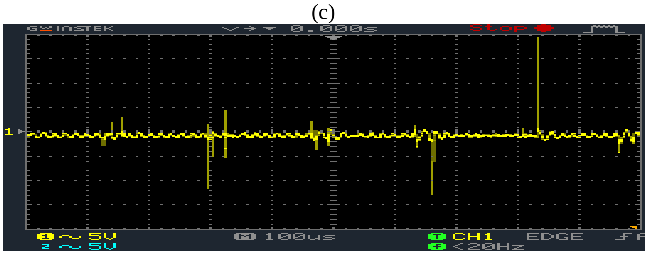

(d)

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

		Simulation			Experimental		
MOTORS	Length of cable from inverter in (m)	V_T (pk)V	V_{cm} (pk) V	V_b (pk) V	V_T (pk)V	V_{cm} (pk) V	V_b (pk) V
M 1	30	472	157.5	10	521	196	10.5
M 2	60	480	200	11.5	542	216	12.4
M 3	90	510	228.5	14.8	567	252	16.2
M 4	120	525	251	17.5	584	260	19.4

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 observe 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.

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