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EXPERIMENTAL ANALYSIS OF EFFECTS OF MECHANICAL PARAMETERS ON BEARING VOLTAGE IN A PWM VOLTAGE SOURCE INVERTER FED INDUCTION MOTOR DRIVE

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Abstract— Pulse Width Modulated (PWM) inverters are one of the major causes of electrically induced bearing damage in an inverter fed induction motor drive. These inverters uses high speed switching devices such as the IGBT's, with faster switching times. On one side improved the performance, efficiency and controllability of Adjustable Speed Drives (ASDs) but, on the other side, have brought some relevant disadvantages. In fact, the output voltage from an inverter is non-sinusoidal and associated with high frequency harmonics, producing common mode voltage in the stator windings of an induction motor. Due to capacitor voltage divider action inside the motor, a part of common mode voltage appears across the inner and outer race of the bearings as bearing voltage. When bearing voltage exceeds the dielectric strength of lubricating film, breakdown of lubricating film takes place and generates high frequency Electric Discharge Machining (EDM) bearing current. The EDM bearing current causes fluting of the bearing races and results in premature bearing failure within few months of installation. In this paper, experimental analysis of influence of mechanical parameters such as speed, load, bearing temperature, lubricant viscosity on the magnitude of bearing voltage is carried out. In addition to that, viscosity index improver using high polymer machine oil has been presented. The experimental work is carried out on specially modified induction motor (insulated bearings).

Keywords--PWM inverter, bearing voltage, electric discharge machining, lubricant film thickness, bearing temperature, viscosity.

I. INTRODUCTION

The occurrence of bearing currents in an induction motor has been known for decades. It has been reported by Alger [1] that, the basic reason for these currents is asymmetric flux distribution inside the motor. This problem has been effectively solved with modern motor designing and manufacturing practices. However, unexpectedly the problem has returned since power electronic devices are becoming common in Adjustable Speed Drives (ASDs).The bearing current faults are most frequent in PWM fed ASDs, nearly 30% according to an IEEE motor reliability studies.

The bearing voltage (V_b) mirrors common mode voltage (V_{cm}). When V_b exceeds dielectric strength of lubricating oil film (15Vpk/μm),oil film breaks down, thereby causing the Electric Discharge Machining (EDM) bearing current pulses and results in premature bearing failure within 1-6 months of installation [2][3][4][5].

The level of bearing voltage even in small machine can reach a value up to 20V. According to IEEE 112 standard, allowable value of bearing voltage is 0.5mV, as well as the manufacturer's allowable voltage of 1 to 2V for Variable Frequency Drives (VFDs).

The effect of mechanical load, temperature, speed and lubricant viscosity on the bearing capacitance C_b has been reviewed [4]. C_b is the critical mechanical component influencing the magnitude of bearing voltage and EDM current. Bearing contact area establishes the current density at the point of contact between bearing race and balls. The contact area increases with increase in bearing load, the current density through the bearing decreases, reducing the intensity of EDM bearing current damage. Minimum oil film thickness 'H' is given by equation (1).

$$H=2.65^{-0.7}\, g^{0.54} / Q_z^{0.13} \qquad (1)$$

Lubricant film thickness decreases with increasing load 'Q' and breakdown occurs at lower bearing voltage. Mitigating effect of bearing current occurs with increasing mechanical load [4] [6].

The influence of different motor operating parameters such as speed, temperature, inverter switching frequency and DC bus voltage on discharge activity inside the bearings have been analyzed [7].

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As the load increases, the lubricant film thickness decreases, momentarily balls makes contact with outer race hence, less chance of EDM bearing current occurrence. As the temperature increases viscosity decreases and hence reducing film thickness, breakdown occurs at lower bearing voltage. At low speed (<100rpm) balls make quasi contact with races [8].The breakdown voltage for all lubricants under consideration shows strong reduction, when temperature increases from 30°C to 60°C,where as, it doesn't change appreciably if the temperature reaches 90° C [9].

Below 10% of rated speed there may be a partially metallic contact between inner and outer race. The constant speed operation increases the risk of bearing current damage. Bearing capacitance depends on the lubricant temperature, speed, load and value of bearings voltage. Experimental study conducted on modified induction motor supplied by AC, DC and PWM inverter output voltage. But only the effect of viscosity on V_b is carried out under PWM inverter output voltage [10].

Viscosity is the property of a fluid that resist for its flow, viscosity may be visualized as a result of interaction of molecules when subjected to flow. Viscosity is the most significant property for establishing the film thickness, pressure and temperature of a film in hydrodynamic lubrication. Viscosity Index (VI) is commonly referred as change in viscosity with temperature. The higher the value of VI,the smaller the relative change in viscosity with temperature[11]

This paper is organized as follows: section. I gives introduction. Section. II deals with common mode voltage and bearing voltage. Experimental set up described in section.III. Section.IV deals with results and discussion.Section.V includes conclusion followed by references and acknowledgement.

II. COMMON MODE VOLTAGE AND BEARING VOLTAGE

At the PWM inverter output, instantaneous summation of all the three phase voltages is non zero, an average voltage in a neutral point with the reference to the ground create common mode voltage given by equation (2).

$$V_{cm} = \frac{[V_{an} + V_{bn} + V_{cn}]}{3} \qquad (2)$$

In equation (2), V_{cm} is common mode voltage. V_{an}, V_{bn} and V_{cn} are the phase voltages generated by the PWM inverter. The bearing voltage has the same shape as the common mode voltage because, the bearing voltage is formed as a result of common mode voltage and capacitive voltage divider circuit.An internal capacitive divider and the bearing voltage are given by equation (3)[3] [4].

$$V_b = \frac{C_{sr}}{C_{sr} + C_{rf} + C_b} V_{cm} \qquad (3)$$

Where, V_b is bearing voltage, C_{sr} is capacitance between stator winding and rotor, C_{rf} is capacitance between stator frame and rotor (air gap capacitor) and C_b is bearing capacitance.

III. EXPIRIMENTAL SETUP

The experimental set up shown in fig.1 consists of a three-phase, 415 V, 50 Hz, star-connected, 4-pole, 3HP induction motor with mechanical loading arrangement. The motor is fed by a three-phase 440V, 50 Hz inverter (Danfoss make) with 2 kHz switching frequency and sinusoidal PWM technique is used. Also consists of Digital Storage Oscilloscope (DSO), high frequency cable, power scope, tachometer and Infra Red (IR) thermometer. The space around bearing outer race on both sides of an end plate of a standard induction motor is slightly increased by machining. The proper insulation is placed around the outer race of the bearings at both drive end and non drive end. Hence the whole rotor is isolated from the main body of the induction motor and ground. With this modification, the rotor is floating. The continuity can be checked between stator body and rotor using multimeter under running condition to ensure electrical isolation between stator and rotor. Ball bearings were used on both drive end and non drive end of motor.

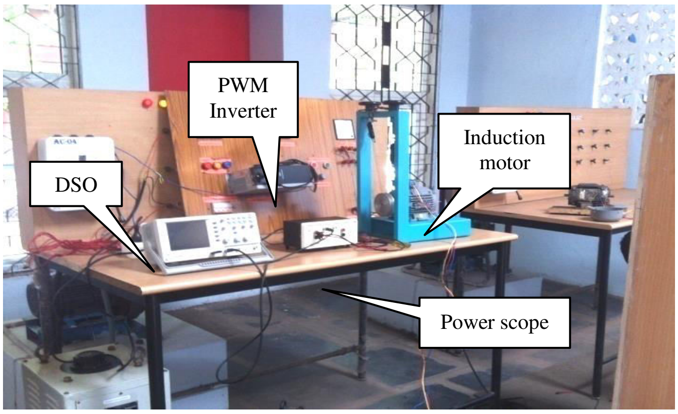


Fig.1 Experimental set up

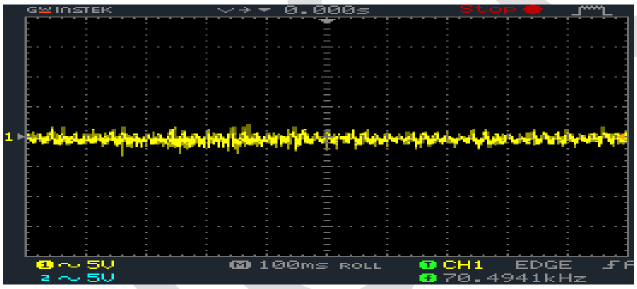
The influence of speed on the magnitude of bearing voltage has been performed experimentally under no load. The speed of the motor is gradually increased by changing the supply voltage (V/f control) fed by PWM inverter. The bearing voltage is recorded across the outer and inner race of the bearing at drive end using DSO.

Mechanical loading effect on the magnitude of V_b is carried out by direct loading method, consists of applying brake to a water cooled pulley and spring balance $S_1$and S_2 mounted on the shaft. Initially the motor is operated on no load and then the load is increased in steps till it carries full load current.

A small hole is created near the outer race of bearing such that infra red rays can be applied on the bearing surface to record the bearing temperature using contactless IR thermometer.

IV. RESULTS AND DISCUSSION

Motor Speed Figs.2(a)-2(e) show experimental results, indicating the peak values of bearing voltage waveforms for different motor speed. It is observed that, a minimum peak value of bearing voltage at low speed (100 rpm) under no load operation is 4V, while it is running at rated speed (1500rpm) the max.value of V_b is 38Vpeak. It can be seen that, the V_b increasing with increase in speed of the motor. As motor speed increased, the balls float in thin film of lubricant grease and forming bearing capacitance C_b. Bearing capacitance is a function of the shaft speed, at constant temperature and constant radial load C_b decreases as speed increases. C_b is the critical mechanical component influencing the magnitude of bearing impedance Z_b, thereby V_b and EDM current (I_b=V_b/Z_b). Bearing voltage greater than 2V is sufficient to cause bearing damage. Table I present peak values of V_b at different speed. It can be inferred that, constant speed operation under no load and light load increases the risk of EDM bearing current.



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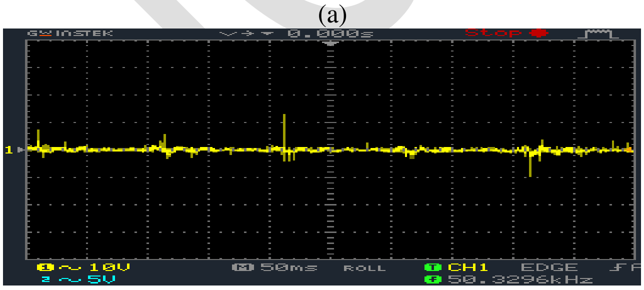

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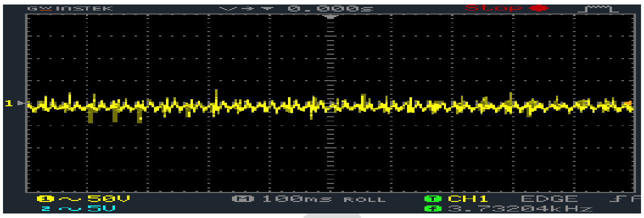

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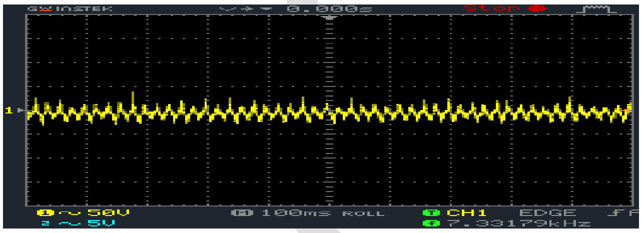

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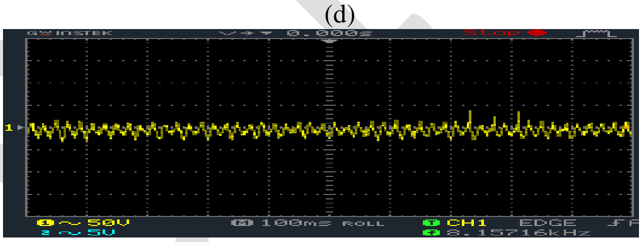

(e)

Fig.2 Bearing voltage at different motor speed (a) speed N=100rpm (b) N=520rpm (c) N=850rpm (d) N=1200rpm (e) N=1500rpm

TABLE I BEARING VOLTAGE AT DIFFERENT MOTOR SPEED

Speed in N (rpm)	**Frequency f (Hz)**	**Bearing voltage (V_b) (V)**
100	3.33	4
520	17.16	12.8
850	28.05	24
1200	39.6	28
1500	50	38

A. Mechanical load

Figs.3 (a)-3(e) show experimental results, representing the peak values of bearing voltage waveforms for different mechanical loading on motor. When the mechanical load on motor is small (1A), bearing voltage is 24V peak and at full load (5A) the max. Bearing voltage is 2.24V peak. As the load increases V_b decreases. With increased mechanical load, the balls make momentary contact with bearing races. Hence, reduces possibility of voltage build up across the bearing races. The current density through the bearing decreases,

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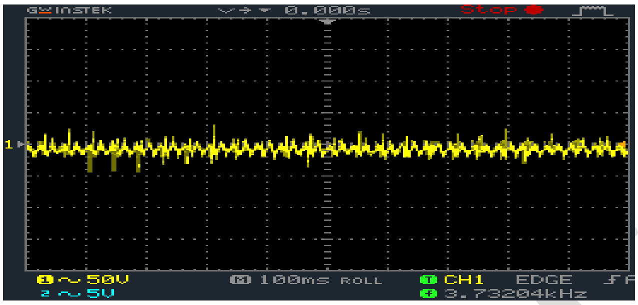
reducing the intensity of EDM current. For smaller bearing loads, the supporting lubricant film thickness increases. Under these situations, significantly higher bearing voltages can be established. As a result, EDM current pulses are much more intensive. For higher loads, the possible voltage before the lubricant breaks down is significantly lower. Discharges in this range result in lower bearing currents. Table II provide the bearing voltage for different mechanical loading. When the motor operating at full load prevents V_b build up and provide the mitigating effect (positive effect) of bearing current damage. Operating motor under no load or light load condition is more prone to increased V_b level and results in high discharge bearing currents.



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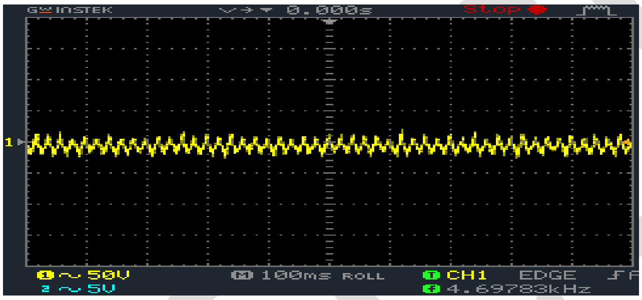

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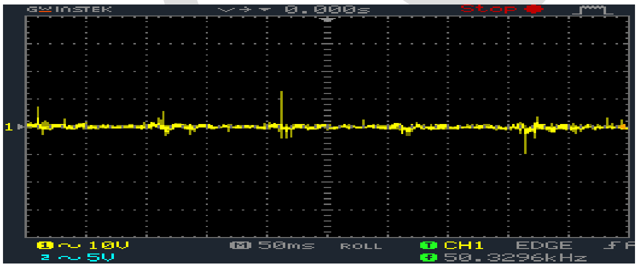

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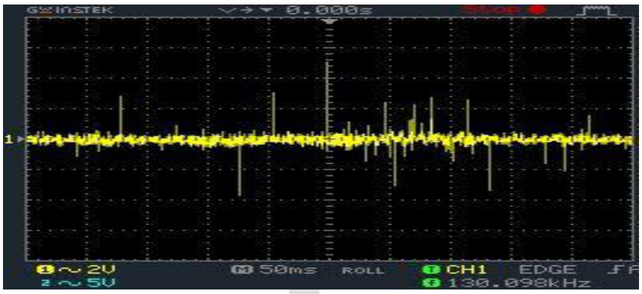

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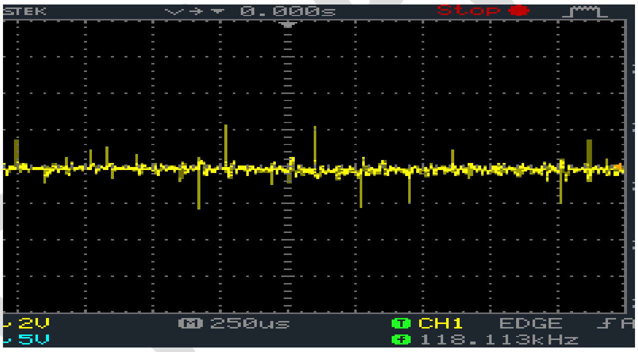


(e)

Fig.3 Bearing voltage for different mechanical load a) 1A b) 2 A

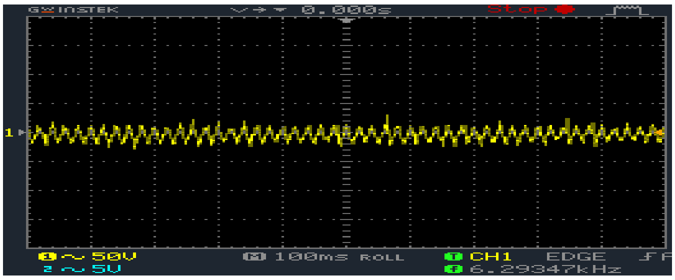
c) 3.5 A d) 4.5A e) 5A

TABLE II BEARING VOLTAGE FOR DIFFERENT MECHANICAL LOAD

Mechanical load (A)	1	2	3.5	4.5	5
Bearing voltage V_b (V)	24	20	12.8	5.02	2.24

B. Temperature

The effect of bearing temperature (T_b) on bearing voltage at constant speed and load are shown in figs. 4(a)-4(e).The peak value of V_b is 30V at 35°C,While it is 4V peak at 60°C.The influence T_b on the magnitude of bearing voltage is significant, affects the lubricant film thickness. From table III and figs. 4(a)-4(e) it is observed that, as the bearing temperature increases, the bearing voltage decreases due to decrease in viscosity of the lubricant grease. Hence breakdown of lubricant occurs at lower values of bearing voltage, which results in high discharge EDM current flow. The EDM current creates craters on bearing surfaces. With increasing bearing temperature, the bearing voltage no longer mirrors the common mode voltage but, lubricating film frequently builds up the voltage and discharges.



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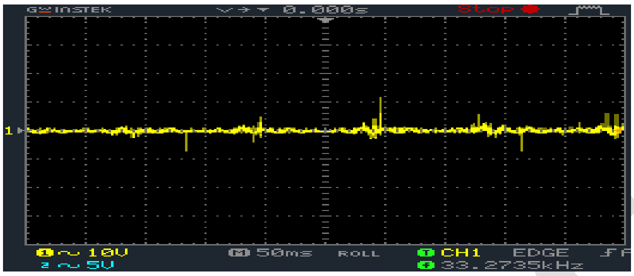

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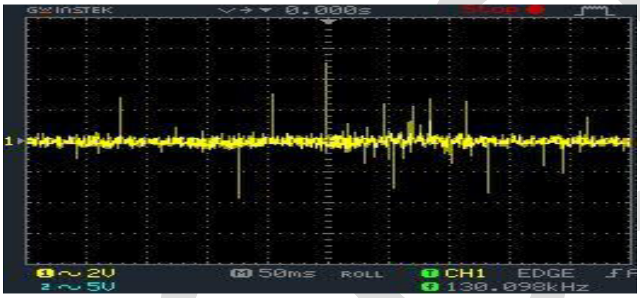

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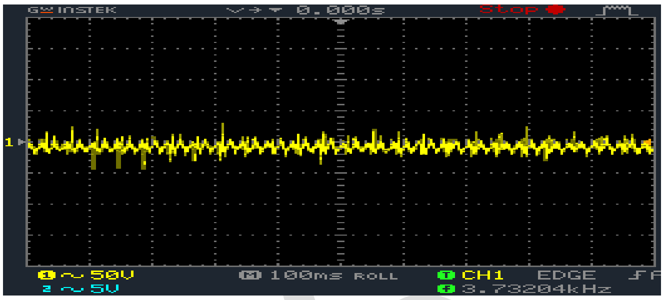
Bearing temperature T_b (°C)	35	38	47	55	60
Bearing voltage V_b(V)	30	24	11.6	5.04	4



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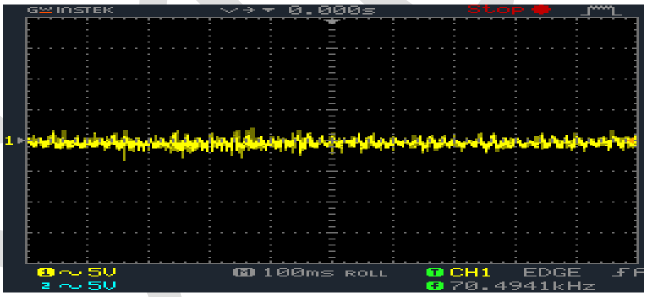

(e)

Fig.4 Bearing voltages for different bearing temperature (T_b)

a) 35° C b) 38° C c) 47° C d) 55° C e) 60° C

TABLE III BEARING VOLTAGES FOR DIFFERENT BEARING TEMPERATURE

C. Viscosity

Figs. 5(a)-5(b) show experimental results representing the peak values of bearing voltage waveforms for low viscosity lubricant (65cSt) and high viscosity lubricant (128cSt) at 55°C respectively. It is observed that, the bearing voltage for low viscosity lubricant is 6.6V peak at 55°C and for high viscosity lubricant 24V peak at same bearing temperature. As the temperature increases viscosity decreases, but the decrease in viscosity for high viscosity lubricant is insignificant. The breakdown voltage in bearing with low and high viscosity lubricants is listed in Table IV. We can observe a big difference between the values of breakdown voltage in bearing with low viscosity lubricant and bearing with high viscosity lubricant.

As the temperature increases the viscosity of lubricating film decreases and the breakdown occurs at lower value of V_b. Damage due to bearing current can be considerably reduced by utilizing low viscosity grease.

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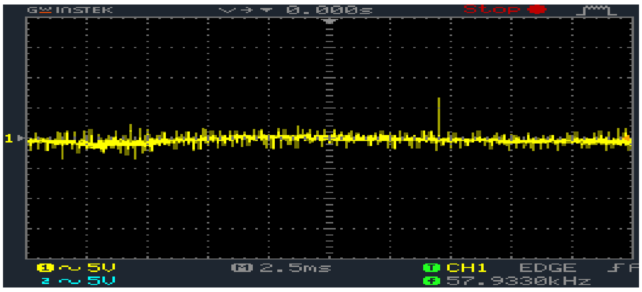

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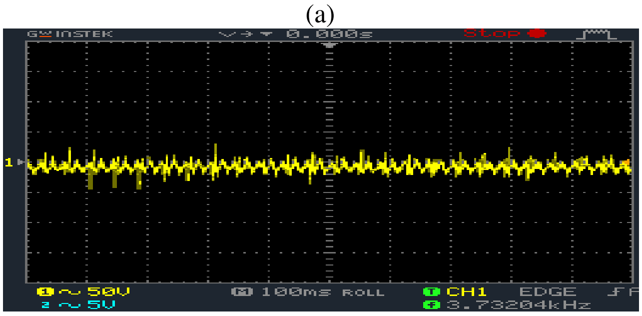


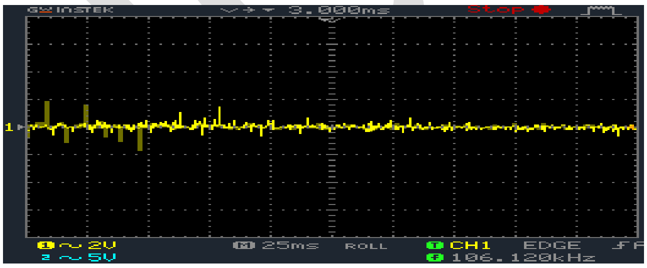
(b)

Fig.5 Bearing voltage at a) viscosity 65cSt b) viscosity 128cSt

TABLE.IV BEARING VOLTAGE FOR DIFFERENT VISCOSITY

D. Viscosity Index (VI) and VI Improvers

Viscosity Index (VI) is commonly referred as change in viscosity with temperature. Higher molecular weight polymers known as multigrade oils, they reduce change in viscosity with the temperature.Fig.6 (a)-(b) show the peak values of bearing voltage waveforms when high polymer machine oil (2ml) mixed with grease (20gm) at constant speed and load. It is observed that, at temperature 26.8 ^{o}C the V_b is 4V and at 64 ^{o}C the V_b is 1.6V.Eventhough the increase in bearing temperature is large, the variation of bearing voltage is very small.



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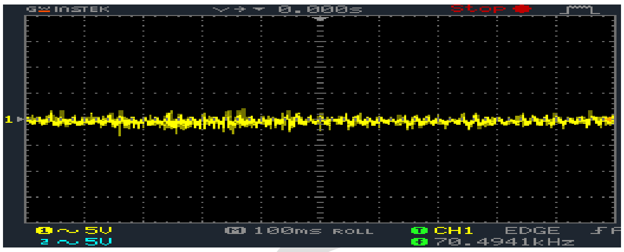

(b)

Fig.6 Bearing voltage at temperature a) T_b=26.8 ^{o}C b) T_b=64 ^{o}C

TABLE V BEARING VOLTAGE FOR DIFFERENT TEMPERATURE WITH VI IMPROVER

Bearing temperature (^{o}C)	**Bearing voltage (V_b)**
26.8	4
64	1.6

Thereby enhancing the bearing life. Table V gives the variation of bearing voltage V_b verses bearing temperature with VI improver.

V.CONCLUSION

Parameters	**Viscosity (65cSt)**	**Viscosity (128cSt)**
Bearing Temperature T_b (^{o}C)	55	55
Bearing voltage V_b (V)	6.6	24

In this paper, experimental analysis of influence of mechanical parameters viz. speed, load, temperature and lubricant viscosity on the magnitude of bearing voltage is carried out. At low speed, less than 100rpm bearing balls makes contact with the races, less scope for bearing voltage build up. As the speed increases the balls floats in the grease and forms bearing capacitor, V_b starts increasing .Constant speed operation at no load or light load associated with risk of EDM bearing current.

Mechanical load on an induction motor has significant influence on V_b, as the load increases the, balls makes contact with bearing races, which provides mitigating effect of EDM bearing current damage. Operating the motor under no load or light load condition is more prone to increase in peak value of bearing voltage and causes high discharge bearing currents.

Increase in bearing temperature, viscosity of lubricant decreases and hence breakdown occurs at smaller values of V_b. Higher the value of VI, the smaller the relative change in viscosity with temperature. When an induction motor fed

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from PWM inverter, the influence of motor speed, load, temperature, viscosity and VI are taken into consideration for reliable operation without causing down time and product lost.

REFERENCES

[1] Alger P., Samson H., "Shaft Currents in Electric Machines" A.I.R.E. Conference., Feb. 1924

[2] Annette Muetze, Andreas Binder, "Techniques for Measurement of Parameters Related to Inverter Induced Bearing Currents",IEEE transactions on industry applications,vol.43,No5,September/October 2007.

[3] J. Erdman, R. J. Kerkman, D. Schlegel, and G. Skibinski, "Effect of PWM inverters on AC motor bearing currents and shaft voltages," in IEEE, APEC-95,10th An Applied Power Electronics Conference and Exposition, vol. 1, pp. 24 - 33, Mar. 5-9, 1995

[4] Doyle Busse, Jay Erdman, Russel J. Kerkman, Dave Schlegel, and Gary Skibinski "System Electrical Parameters and Their Effects on Bearing Currents", IEEE, transactions, 0-7803-3044-719, 1996.

[5] D. Busse, J. M. Erdman, R. J. Kerkman, D. W. Schlegel, and G. L. Skibinski, "Bearing currents and their relationship to PWM drives," in Conf. Record IEEE ,IECON '95, Nov. 1995.

[6] D. Busse, J. Erdman, R. J. Kerkman, D. Schlegel, and G. Skibinski, "The effects of PWM voltage source inverters on the mechanical performance of rolling bearings," IEEE Applied Power Electronics Conf., pp. 561–569, Mar.3–7, 1996.

[7] Annette Muetze, Jussi Tamminen, and Jero Ahola," Influence of Motor Operating Parameters on Discharge Bearing Current Activity". IEEE transactions on industry applications, vol. 47, no. 4, July/August 2011 .pp 1767-1777.

[8] H. Tischmacher, S. Gattermann, M. Kriese E and Wittek,"Bearing Wear Caused by Converter-Induced Bearing Currents",IEEE conf. 2010,pp-778-785.

[9] G.Costabile, B.De Vivo,L.Egiziano, P.Lamberti, and V. Tucci," Performances of dielectric greases for rolling bearings employed in high power induction motors fed by PWM inverters", Annual Report Conference on Electrical Insulation and Dielectric Phenomena 2007.

[10] Zdzislaw Krzemien," Phenomena appearing in oil film of bearings in induction motors supplied from PWM inverters ".pp 293-296.

[11] Douglas Godfrey and William R.Hergut, "Physical and Chemical Properties of Industrial Mineral Oils Affecting Lubrication", Back to basics ,Herguth laborites, society of tribologists, California.

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