

Shaft voltage and bearing current - a common phenomenon in electric machines

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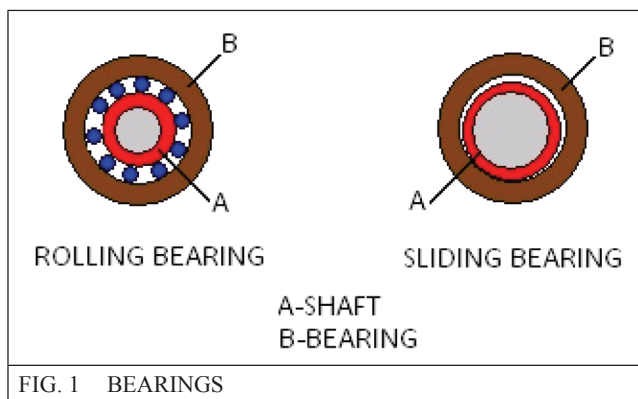
Presence of shaft voltage & bearing currents were noticed probably after the invention of electric rotating machines. Pittings on the bearing surfaces, changes in the chemical composition of bearing lubricants and premature bearing failures were some of the evidences of these phenomena. This paper discusses about the bearing mechanism and its failure causes. Origination of shaft voltage is elaborately presented here. Types of bearing currents and its mitigation techniques are also discussed briefly.

Keywords: Shaft voltage, bearing currents, circulating current, variable frequency drive, pulse width modulation, common mode voltage.

1.0 INTRODUCTION

1.1 Bearings in Machines

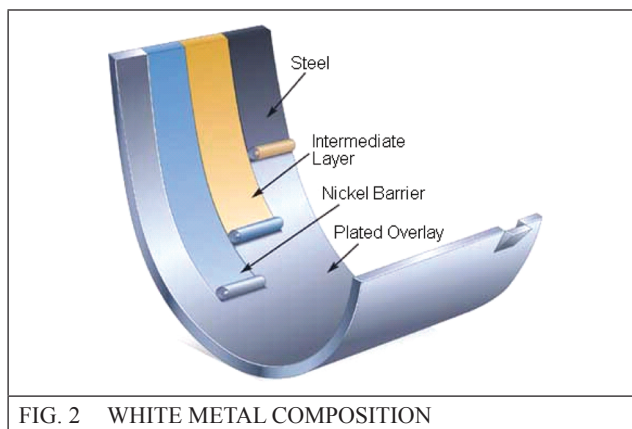
In a rotating machine, bearing plays an important role to separate the moving part from the fixed one. Maximum wear & tear takes place due to rubbing in contact surfaces. Depending on their type of friction bearings form two major groups: Rolling bearings & sliding bearings (Figure 1).



1.2 Bearings Materials

Journal bearing surface (Figure 2) is an alloy called Babbitt metal or White metal. It is used

as a thin surface layer (0.025 to 2.5 mm) in a complex, multi-metal structure, coated over the bore.



Babbitt bearings are designed not to damage the journal during direct contact and to collect any contaminants in the lubrication.

1.3 Bearings Lubrication

Grease Lubrication -Grease is used to lubricate ball bearings (Figure 3) and sometimes in journal bearings when cooling of the bearing is not a factor, typically if the bearing operates at relatively low speeds. Grease is also beneficial if

shock loading occurs or if the bearing frequently starts and stops or reverses direction.

in a supporting metal sleeve or shell (Figure 5). Their design and construction may be relatively simple, but the theory and operation of these bearings can be complex.

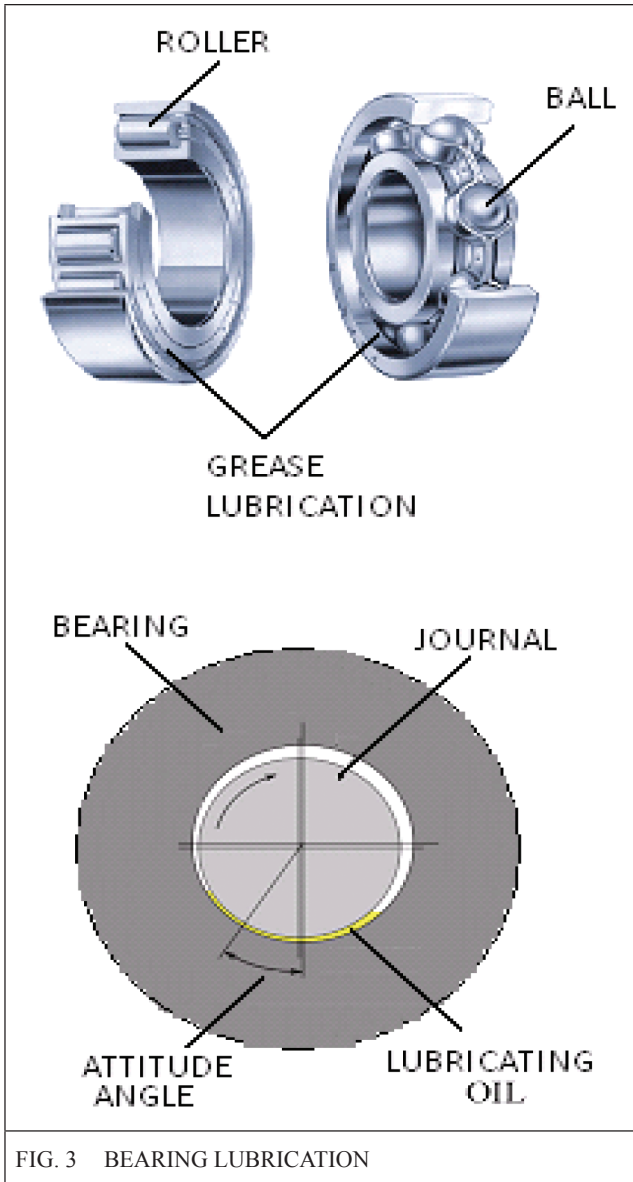


FIG. 3 BEARING LUBRICATION

Oil Lubrication - Oils are used in journal bearings when cooling is required or contaminants or debris need to be flushed away from the bearing. High-speed journal bearings are always lubricated with oil rather than grease. Oil is supplied to the bearing by a pressurized oil pump system, an oil ring or collar or a wick. Grooves in the bearing shell are used to distribute the oil throughout the bearings' surfaces.

1.4 Journal Bearings Mechanism

Journal bearing (also called plain bearing) consist of a shaft or journal (Figure 4) which rotates freely

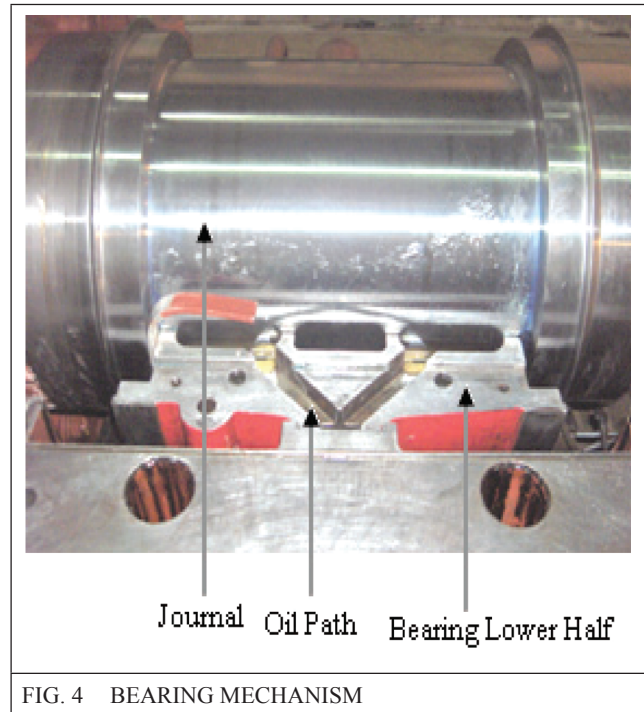


FIG. 4 BEARING MECHANISM

During starting, bearing surface is separated from the journal surface by a high pressure (jacking) oil pump thus creating a lubricant film around the periphery. The same film is maintained naturally during running also.



FIG. 5 BEARING MECHANISM

2.0 BEARING FAILURE

Potential causes of bearing failures in electric motors and electric motor-driven equipment are mechanical, thermal and electrical. Bearing failure can be broadly classified as:

2.1 Mechanical / Thermal Causes

Causes of this failure are listed as:

- Normal fatigue
- Overloading
- Reverse loading
- Overheating
- Contamination
- Lubricant failure
- Corrosion
- Misalignment
- Loose/Tight fit
- Inadequate maintenance.

2.2 Electrical causes

Flow of current through the bearing surfaces is the main reason behind this failure. Figure 6 and 7 shows a typical failure called pittings due to the presence of bearing current. Three different formats of bearing currents are observed. Each of these formats happens under certain conditions:

- Circulating currents due to shaft voltages.
- Currents due to dv/dt .
- The discharge currents (EDM).



FIG. 6 PITTINGS ON THE BEARING



FIG. 7 PITTINGS ON THE SHAFT

3.0 SHAFT VOLTAGE

When machine is in operation its shaft is charged with significant potential above the ground by some internal or external means; this is called shaft voltage. A representative value of shaft voltage is shown in Figure 8.

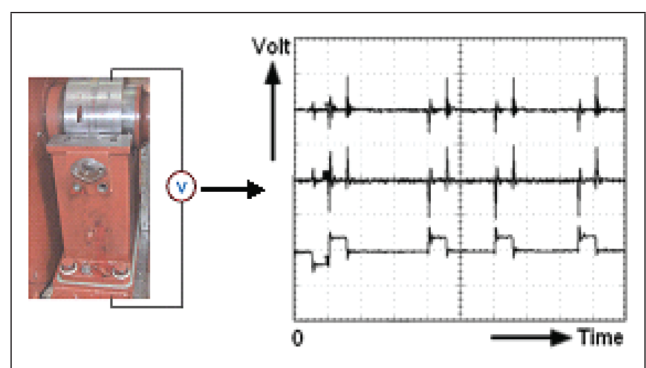


FIG. 8 SHAFT VOLTAGE

3.1 The history of shaft voltage

German and French engineers were pioneer in manufacturing electrical rotating machines. They studied the cases of bearing failure. Such studies were mostly published in their own languages from 1907 to 1915. In the year 1924 Alger and Samson compiled all these scattered information and presented nicely [11]. According to them, the possible ways by which shaft voltage can appear are:

- By a direct or alternating flux flowing in the shaft due to asymmetrical windings or uneven air gap.
- By a difference of potential between shaft and ground due to electrostatic effects, or to grounding of rotor conductor to the core.
- By an alternating flux linking the shaft e.g., clockwise flux is not equal to the counterclockwise flux.

Other than the above there are many more reasons for origination of the shaft voltages; which will be discussed further.

3.2 Past concept

3.2.1 Operation under Sine wave (Figure 9)

- Electromagnetic and electrostatic are the main two reason for all the bearing currents.
- Mineral oil field strength is 10^6 V/m. A typical bearing oil film is 0.2 microns and there are two films in series. Hence the bearing breakdown voltage threshold is 0.4 V.
- If the bearing capacitor voltage, charged by the shaft voltage, becomes high (>0.4 V) to break down oil, a short (nanoseconds) high current impulse flows from the charged oil film capacitor within the bearing. The discharge current pulse is a prime source of bearing erosion and is commonly known as fluting or Electric Discharge Machining (EDM).

- EDM currents causing oil film breakdown, and chemical changes within the lubrication. Several authors suggest that shaft voltage <0.3 V is safe, while 0.5 V-1.0 V may develop harmful bearing currents and shaft voltages >2 V may destroy the bearing.
- End to end axial shaft voltages >200 m Vrms on sine wave excitation indicate magnetic dissymmetry, creating high localized bearing current.

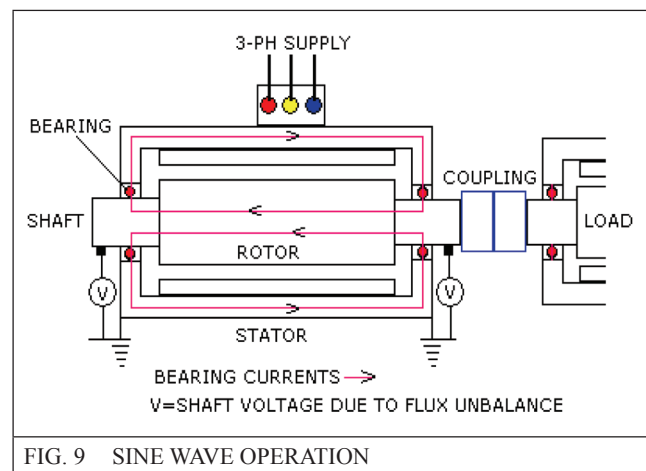
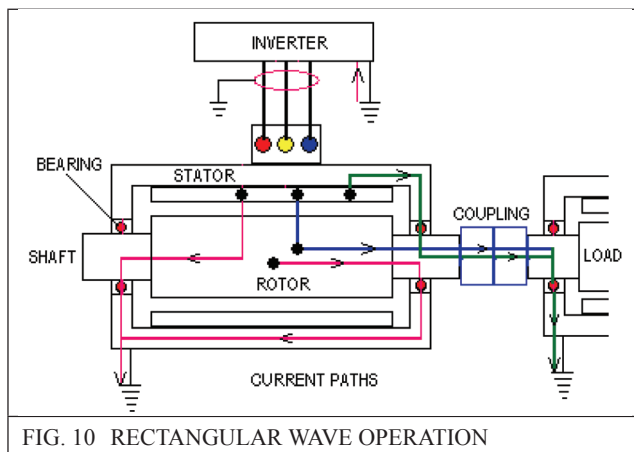


FIG. 9 SINE WAVE OPERATION

3.2.2 Operation under rectangular wave (Figure 10)

- The early concept was based on sine wave operation.
- After the invention of semiconductor devices rotating exciter of large synchronous generators were replaced by static excitation system in the year 1961 [1].
- Impact of the static controller came to notice many years later, after the premature failure of bearings.
- This created a new source of shaft voltages [2] due to static excitation systems have a rectangular wave shape of three times the fundamental frequency (for 6-pulse converter) with high frequency voltage peaks superimposed.
- The sources of these voltages are the common mode voltage (CMV) in the converter, and the steep voltage step during commutation.



3.3 Present concept

- In the beginning of 1990 another reason for the shaft voltage was noticed.
- Power electronics components became cheaper.
- World market is flooded with variable frequency drive (VFD).
- VFD / soft starter became popular because of low starting current with controlled torque, smooth speed control, emergency braking etc.
- Conventional starters were replaced by VFDs.
- Drawback of VFD came to notice after a long days. Cases of bearing failure were increased.
- After investigation it was found that pulse width modulation (PWM) switching used in VFDs was generating high dv/dt or electro-statically induced currents.
- Under PWM operation earlier electromagnetic problems are now predominantly an electrostatic phenomenon [12].
- Experimental results with PWM voltage source inverters and typical system components demonstrated possible rotor voltages in excess of the nominal 30 Vpk. The EDM currents produced current densities of over 5.0 Apk/mm².

4.0 BEARING CURRENTS

- Bearing currents are theoretically two types; non-circulating & circulating currents (Figure 11).
- The non-circulating type of bearing current includes the air-gap capacitor related discharge mode current and the dv/dt related conduction mode current [4].
- A small portion of the common mode currents flows from the windings through parasitic capacitors to the rotor and then finds its path via the conductive bearings back to the grounded motor case.
- Since this type of current passes through the bearings unidirectionally from rotor iron to the stator iron, rather than circulating in the conductive loop formed by the stator case, rotor shaft, and bearings, it is termed the non-circulating type of bearing current.
- Although bearing currents of both circulating and non-circulating types can be simply attributed to common mode coupling currents, the generation of circulating type currents is a far more intricate process, which involves not only capacitive coupling but also inductive coupling or magnetic induction.
- Currents in the two coil sides of a phase winding will never be equal. With unbalanced currents in the winding, a net flux with a high frequency will be produced surrounding the motor shaft.
- This will induce shaft voltages and circulating currents in shorted or low impedance bearings [16].
- It is this flux that links the conductive loop formed by the stator case, rotor shaft, and bearings and induces the circulating currents.

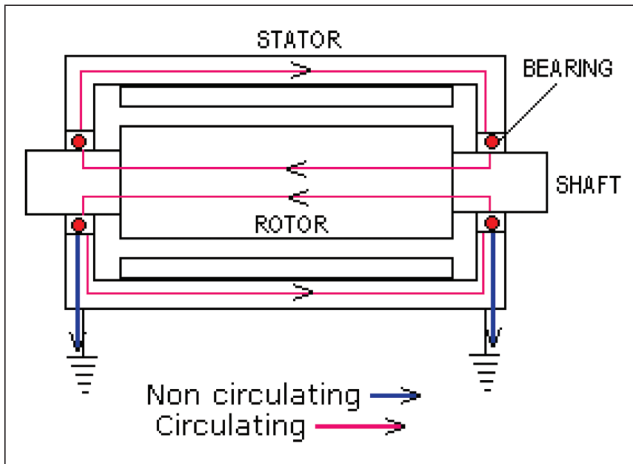


FIG. 11 NON-CIRCULATING & CIRCULATING CURRENTS

5.0 COMMON MODE VOLTAGE

Inverter (Figure 12) output voltages (V_a, V_b, V_c in Figure 13) are not the phase voltages. The load phase voltages and a common mode voltage (V_n) can be derived based on the inverter voltages [16].

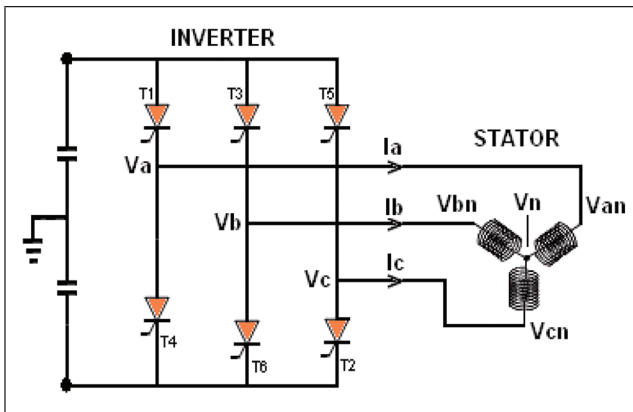


FIG. 12 INVERTER CONNECTED TO A STAR CONNECTED MOTOR LOAD

Each leg voltage of a three phase inverter (Figure 12) is:

$$V_a = V_{an} + V_n, V_b = V_{bn} + V_n, V_c = V_{cn} + V_n \dots(1)$$

And then:

$$V_a + V_b + V_c = (V_{an} + V_{bn} + V_{cn}) + 3V_n \dots(2)$$

It is understood that:

$$(V_{an} + V_{bn} + V_{cn}) = 0 \dots(3)$$

So, the common mode voltage V_n (Figure 13) can be calculated as:

$$V_n = (V_a + V_b + V_c)/3 \dots(4)$$

The common mode voltage has amplitude proportional to the inverter DC bus voltage [17]. It contains all frequencies of the inverter switching harmonics. CMV is the reason for flowing common mode current which also damages the bearings and other metal parts.

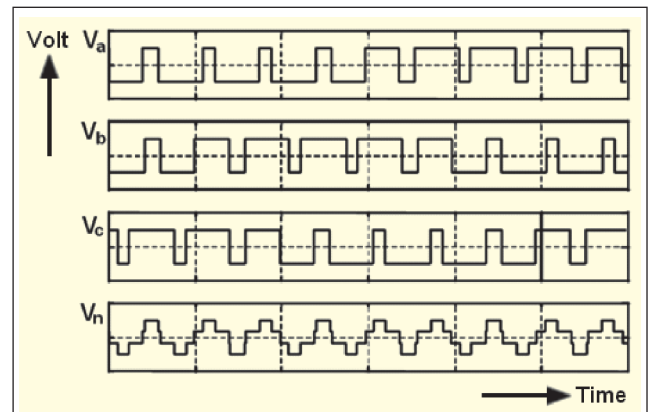


FIG. 13 INVERTER OUTPUT VOLTAGES AND CMV (V_n)

6.0 MITIGATION TECHNIQUES

Complete cancellation of common mode voltage is impossible, but it can be minimized by various techniques. Numerous topologies and modulation strategies have been reported in many papers to mitigate the CMV. A few of them are enumerated below:

- By providing an electrostatic shield or Faraday's shield in the motor winding e.g. ESIM [3].
- By using buck converter topology with two de-rated switching devices and a split inductor [5].
- Auxiliary Zero State Synthesizer (AZSS) is capable of synthesizing zero state components without generating any common mode voltage at the output. This is done by adding three switches to the conventional VSI.
- The common-mode voltage can be used for charging the energy storage

device (battery) at normal conditions of the source power [7]. That is, while driving the motor controlling common-mode voltage with a small reactor for regulating the charging current.

- CMV can also be eliminated by either active [14-15] or passive filter.
- A hybrid filter (by combining a pure active filter with a small passive filter) can also be used for effective elimination of CMV [8-10].
- By changing the switching pattern of PWM inverter [6, 13].

7.0 CONCLUSIONS

- Bearing currents are unwanted currents that flow through motor shaft and bearings.
- Reducing these bearing currents is critical to increase the life span of the motor and saving money on maintenance.
- Methods for bearing current reduction using common mode filters are possible. Another promising method is based on the concept of common mode voltage cancellation. If the total effect of the common-mode voltages can be eliminated, the bearing currents and EMI both will be reduced.
- Finally, a thorough understanding of the inverter driven system is must for designing an appropriate remediation method of bearing current.

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