

## Application Note

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### Motor Bearing Current Phenomenon

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<b>Subject: Application Note</b>	Product: E7, F7, P7	Doc#: AN.AFD.17
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## INTRODUCTION

Since the introduction of PWM inverters, it has been recognized that PWM inverters introduce motor shaft voltages and bearing currents. The bearing damage in inverter-driven motors is mainly caused by the shaft voltage and bearing currents created by the common-mode voltage and its sharp edges [1]. All inverters generate common-mode voltages relative to the power source ground that cause coupling currents through the parasitic capacitances inside the motor. The main source of bearing currents is the capacitance-coupling currents that return via the motor bearings back to the ground.

This paper discusses the relationship among common-mode voltage, motor shaft voltage, and bearing currents using parasitic capacitances and its mathematical representation inside the motor.

## COMMON-MODE VOLTAGE IN INVERTER-DRIVEN AC MACHINES

### Common-mode Voltage

In a three-phase AC system, the common-mode voltage can be defined as the voltage difference between the power source ground and the neutral point of a three-phase load. If the load is an AC motor, the neutral point of the load means the stator neutral of the motor. It is important to define the common-mode voltage in mathematical terms in order to compare its characteristics among different types of source and load combinations.

In three-phase AC loads, the phase to ground voltages ( $V_{a-G}$ ,  $V_{b-G}$ , and  $V_{c-G}$ ) can be written as the sum of the voltage from phase to the neutral point of the load and the neutral point of the load to system ground ( $V_{N-G}$ ). As per the definition, the common mode voltage is the voltage across the neutral point of the load and the system ground. Since in a balanced system, the sum of all three phase-to-neutral voltages is zero, the voltage from neutral to ground (common-mode voltage) can be defined in terms of phase to ground voltage as shown below.

$$V_{a-G} = V_{a-N} + V_{N-G}, \quad V_{b-G} = V_{b-N} + V_{N-G}, \quad \text{and} \quad V_{c-G} = V_{c-N} + V_{N-G}$$

$$\text{From above, } V_{N-G} = \frac{V_{a-G} + V_{b-G} + V_{c-G}}{3} - \frac{V_{a-N} + V_{b-N} + V_{c-N}}{3} = \frac{V_{a-G} + V_{b-G} + V_{c-G}}{3} \quad (1)$$

*0 (in balanced three phase AC loads)*

<b>Subject: Application Note</b>	Product: E7, F7, P7	Doc#: AN.AFD.17
Title: Motor Bearing Current Phenomenon		

In equation (1), it is assumed that the load is balanced so that the sum of all three phase-to-neutral voltages is zero ( $\sum V_{a,b,c-N} = 0$ ). If the source voltage is assumed to be balanced and ideal, then the sum of all three phase-to-ground voltages is zero ( $\sum V_{a,b,c-G} = 0$ ). In that case,  $V_{N-G}$ , will be zero from equation (1).

However, in the case of an inverter-driven AC machine, there exists a common-mode voltage because the voltage source inverter does not constitute an ideal balanced source. Figure 1 shows a typical 2-level voltage source inverter-fed AC machine.

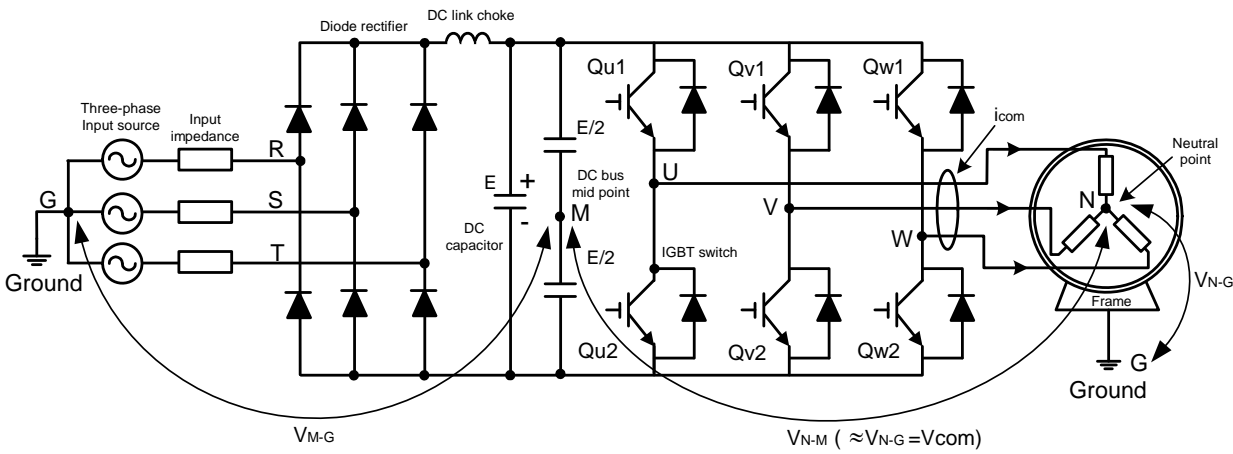


Figure 1. 2-level inverter-driven AC machine

In an inverter-driven system, the common mode voltage ( $V_{com}$  or  $V_{N-G}$ ) can also be defined as the voltage across the stator neutral (N) and the DC bus mid-point (M) because from a high-frequency viewpoint, the DC bus mid-point (M) is same as the electrical ground (G) of the system. Using this definition, the common-mode voltage can be redefined as shown in equation (2). This definition would then be valid for 3-level inverters as well.

$$V_{com} = V_{N-G} \approx V_{N-M} = \frac{V_{U-M} + V_{V-M} + V_{W-M}}{3} \tag{2}$$

In equation (2), it should be noted that the source voltage nomenclature has been changed from  $V_{a,b,c-G}$  to  $V_{u,v,w-M}$  to reflect the fact that the source now is the voltage source inverter. The common mode current ( $i_{com}$ ) is defined as the instantaneous sum-total of all the currents flowing through the output conductors. Stray capacitances of the motor cable and inside the motor are the paths of this current, and a source of EMI noise problems.

<b>Subject: Application Note</b>	Product: E7, F7, P7	Doc#: AN.AFD.17
Title: Motor Bearing Current Phenomenon		

## MOTOR SHAFT VOLTAGE AND COMMON-MODE VOLTAGE

### Parasitic Capacitances Inside the Motor

Figure 2 shows the various parasitic capacitances in an AC motor that become relevant when the motor is driven by a PWM voltage source inverter. The high  $dv/dt$  of the common mode voltage applied across the stator and grounded frame of the motor causes pulsed currents to flow through the parasitic capacitances shown in Figure 2.

The parasitic capacitances shown are:

- a. Stator to Frame capacitance or  $C_{SF}$ : This is the primary capacitance that is formed between the stator winding and the grounded frame. It is perhaps the largest single parasitic capacitance in the motor. Most of the common mode current due to the high  $dv/dt$  of the common mode voltage flows through this path.
- b. Stator to Rotor capacitance or  $C_{SR}$ : This capacitance is formed in between the stator winding and the rotor frame. The value of this capacitance is rather small but is the principal path that charges the rotor body to which the motor shaft is physically connected. Hence, the value of this capacitance is very important in evaluating the magnitude of the shaft voltage.
- c. Rotor to Frame capacitance or  $C_{RF}$ : The rotor to frame capacitance completes the charging path that started from the stator winding to the rotor surface. The value of this capacitance is typically about ten times that of the stator winding to rotor surface capacitance ( $C_{SR}$ ). Since the voltage across a capacitor is inversely proportional to its capacitance value, the most of the applied common mode voltage appears across  $C_{SR}$  and only a small voltage is developed across  $C_{RF}$  or the rotor to frame structure. This voltage is called the “shaft voltage”. Thus the rotor to frame capacitance is vital in establishing the shaft voltage.
- d. Shaft to Frame capacitance or Bearing capacitance,  $C_B$ : When the motor is rotated at or above a certain speed, the balls in a ball-bearing or rollers in a roller-bearing of the motor float up and occupy the space in between the inner and outer race of the bearing. An insulating film is formed by the lubricant medium in which the ball or roller is floating. The value of this capacitance depends on the shaft speed, type of lubricant used, the surface area of the ball or roller in the bearing, the temperature of the lubricant, and the mechanical load on the shaft. This parasitic capacitance is transient and is formed only when the motor rotates and hence it is shown to be variable in Figure 2. The value of this capacitance is important because its characteristics determine bearing current and dictates the life of the bearing.

All of the above parasitic capacitances are depicted in an electrical model shown in Figure 2(a) and its physical presence shown in Figure 2(b).

<b>Subject: Application Note</b>	Product: E7, F7, P7	Doc#: AN.AFD.17
Title: Motor Bearing Current Phenomenon		

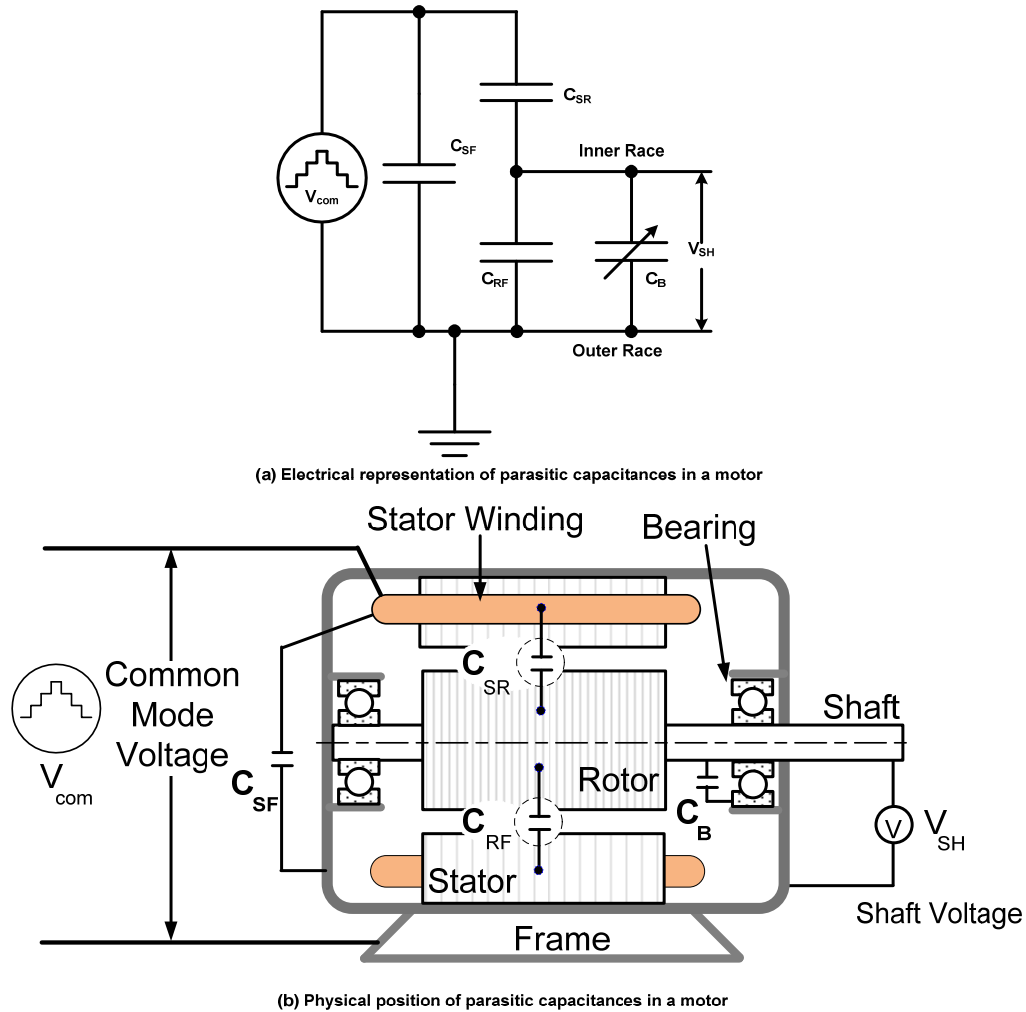


Figure 2. Electrical and physical models of parasitic capacitances in a motor

**Relationship Between Motor Shaft Voltage and Common-mode Voltage**

Figure 3 shows typical common-mode voltage and shaft voltage in a two-level inverter. As shown in Figure 3, the shaft voltage ( $V_{SH}$ ) has the same shape as the stator common-mode voltage ( $V_{com}$ ) because as mentioned earlier, the shaft voltage is formed as a result of the common mode voltage and the capacitive voltage divider circuit shown in Figure 3.  $V_{SH}$  can be obtained from the expression shown below.

$$V_{SH} = \frac{C_{SR}}{C_{SR} + C_{RF} + C_B} \cdot V_{com} \tag{3}$$

<b>Subject: Application Note</b>	Product: E7, F7, P7	Doc#: AN.AFD.17
Title: Motor Bearing Current Phenomenon		

As mentioned earlier, the ratio  $V_{SH} / V_{COM}$  is typically 1:10 because the value of  $C_{RF}$  is much larger than that of  $C_{SR}$ . The exact ratio depends on the size of the motor. From (3), it is also interesting to note that at standstill and low speeds, the inner race and outer race of the bearing are in physical contact via the balls or rollers in the bearing that results in a value of infinity for  $C_B$ , resulting in zero shaft voltage.

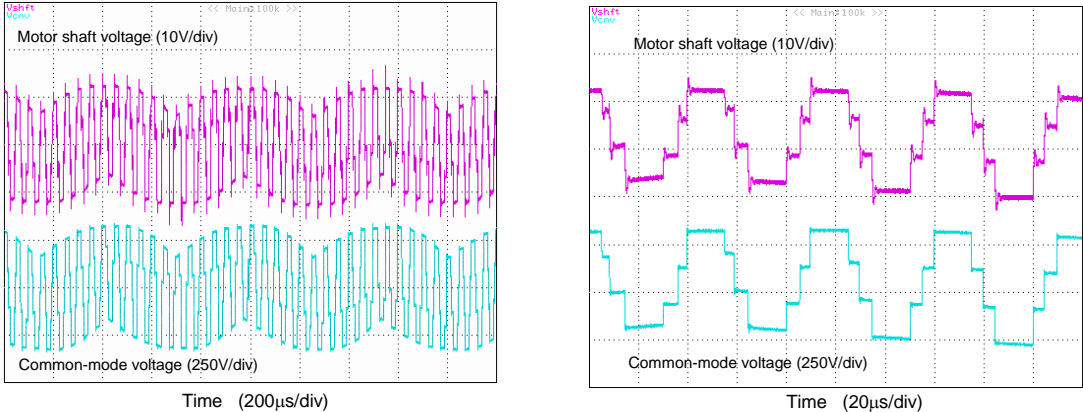


Figure 3. Common-mode voltage and shaft voltage in an inverter-driven AC machine

**BEARING CURRENTS AND ITS GENERATION MECHANISMS**

The common-mode voltage and its associated  $dv/dt$ , generate bearing currents. Due to the various physical paths that exist as shown in Figure 2, different mechanisms can be assigned to the generation of different types of bearing currents. As shown in Figure 4, bearing currents can be summarized into four different currents according to their generation mechanism.

1) Capacitive bearing currents ( $i_1$ )

High common-mode voltage  $dv/dt$  in the stator windings causes pulse currents to flow to the rotor through the stray capacitance between the stator winding and the rotor surface ( $C_{SR}$ ). These currents get distributed to two different paths. The first path is the return path formed by the capacitance between the rotor and the frame  $C_{RF}$  and the second path is that formed by the capacitance in between the inner race of the bearing and the outer race of the bearing,  $C_B$ . Since  $C_{SR}$  is much smaller than the parallel combination of  $C_{RF}$  and  $C_B$ , the amplitude of  $i_1$  is small compared to the total common-mode current ( $i_{SF}$ ). However, the consistent flow of this current through the bearing capacitance causes heat in the lubricating medium and its exact influence on bearing failure is still being investigated by researchers in this field. It should be pointed out that the portion of the current that flows through the bearing is dependent on the

<b>Subject: Application Note</b>	Product: E7, F7, P7	Doc#: AN.AFD.17
Title: Motor Bearing Current Phenomenon		

speed and mechanical load on the shaft. At low speeds, the bearing could be represented by a short circuit resulting in relatively higher value of  $i_1$  to flow through it. Since this current flows through the metallic parts in the bearing, its influence on the insulating film is thought to be negligible.

2) Electric Discharge Machining (EDM) bearing currents ( $i_2$ )

Due to the common-mode voltage, an electric charge is stored in the capacitance ( $C_{RF}$ ) that is formed across the rotor body and the grounded stator frame. The voltage across  $C_{RF}$  is practically the voltage across the shaft as seen from Figures 2(a) and (b). The voltage across this capacitor can keep building up and eventually reach such a level so as to cause the insulation of the lubricating film to breakdown. This dielectric breakdown results in the charge stored across  $C_{RF}$  to discharge through the insulating film of the bearing thereby creating what is known as EDM bearing current. Since the capacitance of  $C_{RF}$  is relatively higher than  $C_{SR}$ , the energy stored in  $C_{RF}$  can be sufficiently large to cause bearing damage. EDM currents are not generated if the motor shaft is grounded or the rotating speed is low enough for the ball bearing assembly to contact the stator frame. EDM current does not flow at every edge of the common mode voltage. The instant at which it flows depends on when the insulation film undergoes a dielectric breakdown and this could be arbitrary.

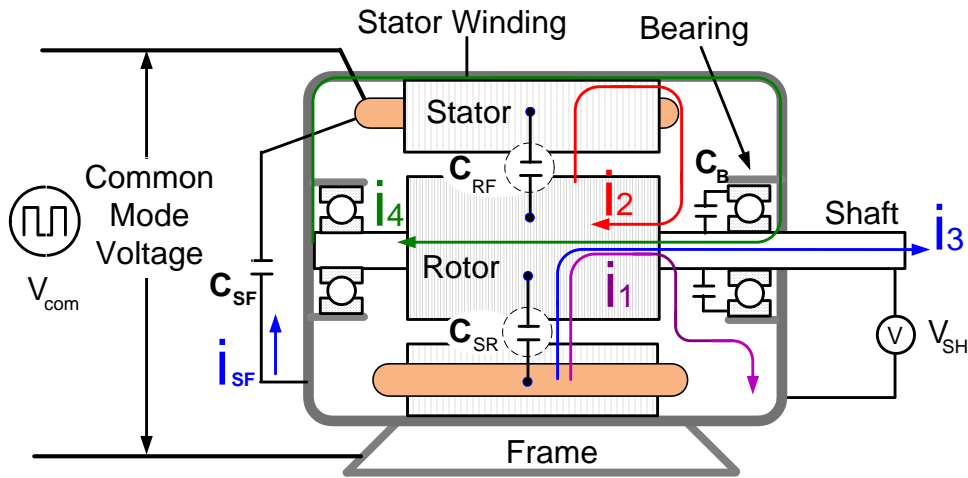


Figure 4. Bearing current paths in an inverter-driven AC machine

<b>Subject: Application Note</b>	Product: E7, F7, P7	Doc#: AN.AFD.17
Title: Motor Bearing Current Phenomenon		

3) Common mode current flow through shaft due to poor grounding ( $i_3$ )

If the motor frame is poorly grounded and the motor shaft is connected to a mechanical load that has much lower ground impedance, the common mode current that flows at every edge of the common mode voltage through the capacitor CSR and charges up the rotor structure now finds a way to flow through the shaft into an external ground that has a lower impedance. This is exactly what happens when an external grounding brush kit is used to ground the rotating shaft. The current bypasses the bearing and makes its way safely into a lower impedance ground through the shaft or the load structure connected to the shaft.

4) Circulating bearing currents ( $i_4$ )

The shaft voltage is due to asymmetry in the magnetic field from one end of the rotor to the other end of the rotor and is prevalent in long axial machines. This asymmetry induces a shaft voltage across the length of the rotor and is basically an electromagnetic induction phenomenon opposed to the capacitive coupled phenomenon. Yet another distinction that should be pointed out here is that the induced voltage is of very low frequency and depends on the fundamental excitation of the motor. The circulating current flows along the axis of the rotor, through the bearings and circulates through the stator frame and returns back from the other bearing end. This current is generally not significant in small power AC machines less than 110kW [2].

## BEARING CURRENT REDUCTION

There are some approaches that prevent bearing current damage of AC machines. They are as follows:

- Motor shaft ground brushes or insulated bearings

The grounding of the motor shaft by connecting a brush between the motor shaft and the motor frame is an effective way to shunt the current path that normally would flow through the motor bearing. However, regular maintenance is required due to limited lifetime of the brush. Insulated bearings such as ceramic bearings can also prevent bearing current problems but require the replacement of the existing bearings in the motor.

- External passive / active common-mode filters

Common-mode noise filters are a good solution to cancel common-mode noise of the system, but typical common-mode noise filters consist of magnetically coupled three-phase inductor and capacitor components. These filters are bulky and expensive; in addition, filters reduce efficiency, and can cause voltage oscillation if parameters of the passive components are not tuned properly.



<b>Subject: Application Note</b>	Product: E7, F7, P7	Doc#: AN.AFD.17
Title: Motor Bearing Current Phenomenon		

- Multi-level inverter technologies

Reducing the amplitude and voltage transition step of the common-mode voltage can reduce bearing currents. One way of achieving this is to use a multi-level inverter topology. Progress in inverter technology has made it possible to introduce a 3-level inverter (i.e. the Yaskawa G7 Drive) to the general purpose-inverter market [1]. The advantages of a 3-level inverter are found at [yaskawa.com](http://yaskawa.com).

## CONCLUSION

The common-mode voltage and shaft voltage relationships were described along with the bearing current mechanisms due to common-mode voltages in an inverter-driven AC machine.

## REFERENCES

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