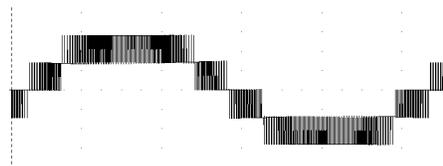


Product Application Note

Motor Bearing Current Phenomenon and 3-Level Inverter Technology

Applicable Product: G7

Rev: 05-06



G7 three-level output
waveform



Conventional two-level output
waveform

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 describes the common-mode voltage in inverter-driven AC machines and compares them in 2-level and 3-level inverters. The relationship among common-mode voltage, motor shaft voltage, and bearing currents are discussed using parasitic capacitances and its mathematical representation inside the motor. Test results of shaft voltage and bearing currents are presented to prove that 3-level technology adopted in the Yaskawa G7 has significant advantages over the 2-level inverter with regards to shaft voltage and bearing currents, which result in reduced bearing damage.

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 a three-phase AC system, the phase to ground voltage 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. 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.

$$\begin{aligned}
 V_{a,b,c-G} &= V_{a,b,c-N} + V_{N-G} \\
 \therefore V_{N-G} &= \frac{V_{a-G} + V_{b-G} + V_{c-G}}{3} \\
 \therefore \sum V_{a,b,c-N} &= 0
 \end{aligned} \tag{1}$$

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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 is also assumed to be balanced and ideal, then the sum of all three phase-to-ground voltages is zero ($\sum V_{a,b,c-G} = 0$). Under such an ideal case, for a balanced AC motor driven by a balanced three-phase AC source, from equation (1), the common mode voltage V_{N-G} , will be zero. 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.

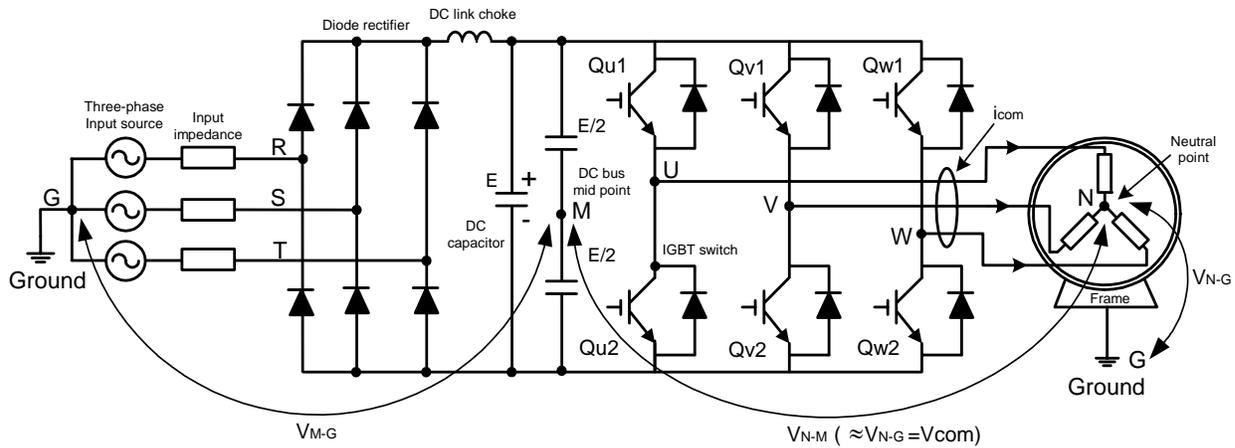


Figure 1. 2-level inverter-driven AC machine

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 done 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.

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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.

2-level Inverter

In 2-level voltage source inverters, there are eight different switching states for the six inverter-switches, and the voltages across the output terminals and the DC bus mid-point (V_{U-M} , V_{V-M} , and V_{W-M}) can be either $+E/2$ or $-E/2$ according to the inverter switching states. The three output legs could 1) be all connected to the positive or negative rail of the DC bus; 2) two legs can be connected to the positive rail and one leg to the negative rail or vice-versa. Given these constraints and from equation (2), the inverter output neutral with respect to the DC bus mid-point will have a voltage of $\pm E/2$ for condition 1) and a voltage of $\pm E/6$ for condition 2). Figure 2 shows an example of the switching states and the common-mode voltage waveform. During a PWM cycle, the change in voltage from $-E/2$ to $-E/6$ constitutes a change of $E/3$. When the level changes from $-E/6$ to $+E/6$ the change in voltage is again $E/3$. Since this change in voltage is proportional to the DC bus voltage and has a frequency equal to the inverter carrier frequency, the change in the common-mode voltage level is steep and typically occurs in hundreds of nanoseconds.

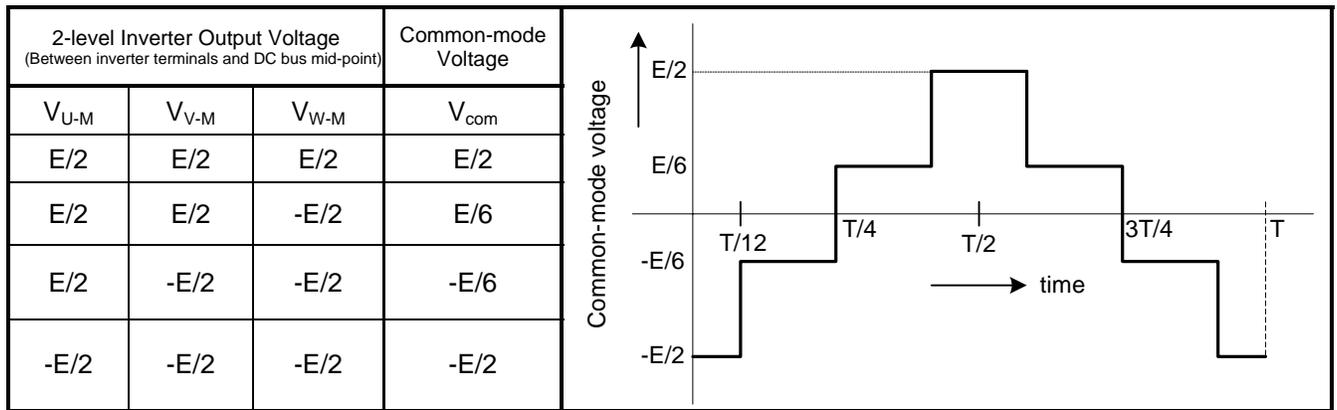


Figure 2. 2-level inverter switching states and the corresponding common-mode voltage

Since the motor windings are fed from PWM pulses having fast rising and falling common mode voltage edges, there exists a leakage current from each phase to ground due to the existence of various parasitic capacitances that include cable capacitance formed between the power leads and ground and other capacitances between the stator winding to the grounded frame. This leakage current flows only during the step change in the common mode voltage and is called common mode current.

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MOTOR SHAFT VOLTAGE AND COMMON-MODE VOLTAGE

Parasitic Capacitances Inside the Motor

Figure 3 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 3.

The parasitic capacitances shown are:

- 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.
- 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.
- 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.
- 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 3. 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 3(a) and its physical presence shown in Figure 3(b).

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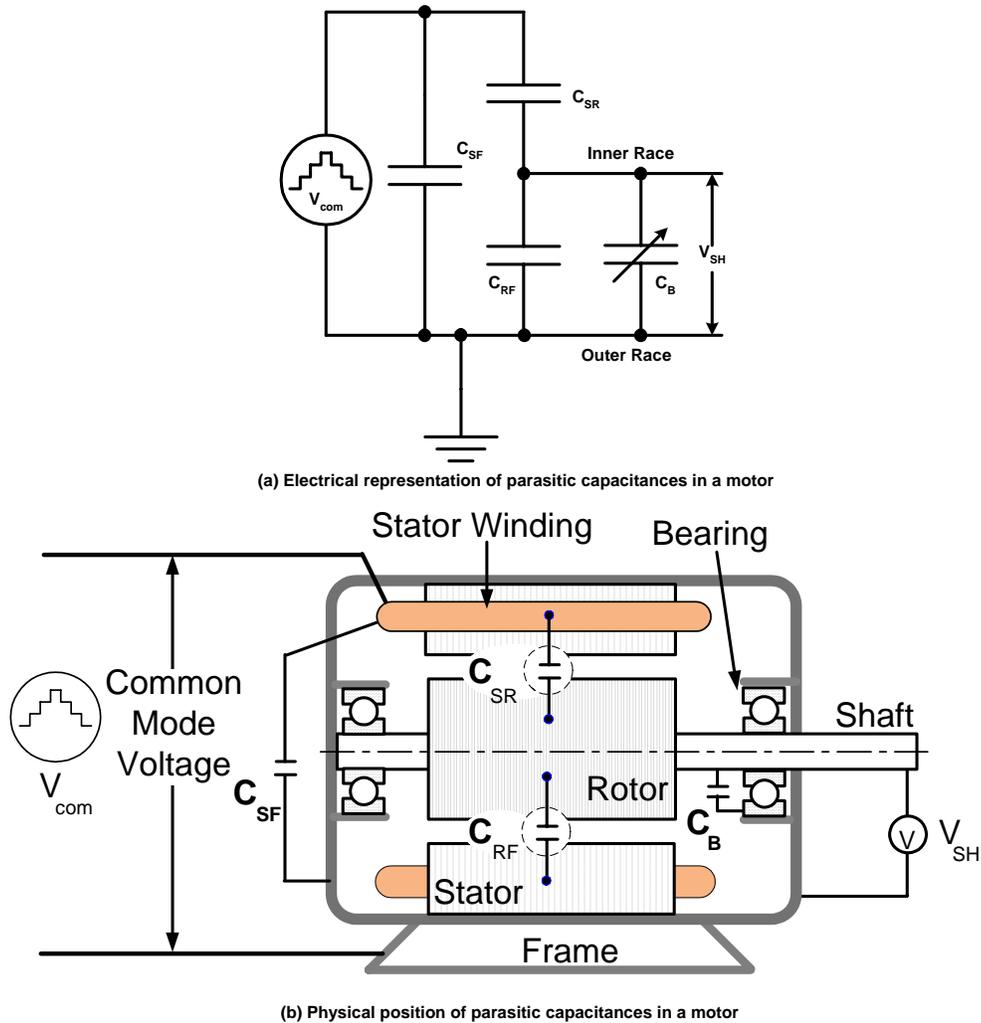


Figure 3. Electrical and physical models of parasitic capacitances in a motor

Relationship Between Motor Shaft Voltage and Common-mode Voltage

Figure 4 shows typical common-mode voltage and shaft voltage in a two-level inverter. As shown in Figure 4, 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.

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

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.

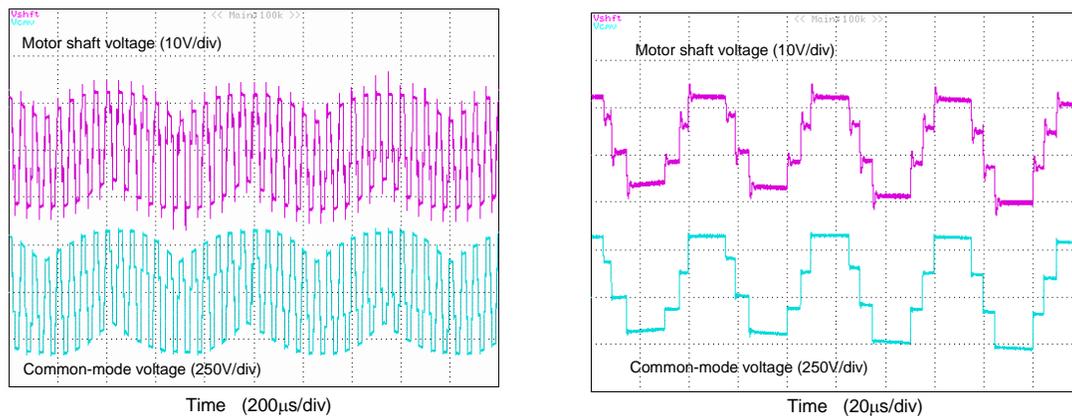


Figure 4. Common-mode voltage and shaft voltage in an inverter-driven AC machine

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 3, different mechanisms can be assigned to the generation of different types of bearing currents. As shown in Figure 5, 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 speed and mechanical load on the shaft. At low speeds, the bearing could be represented by a short

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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 3(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.

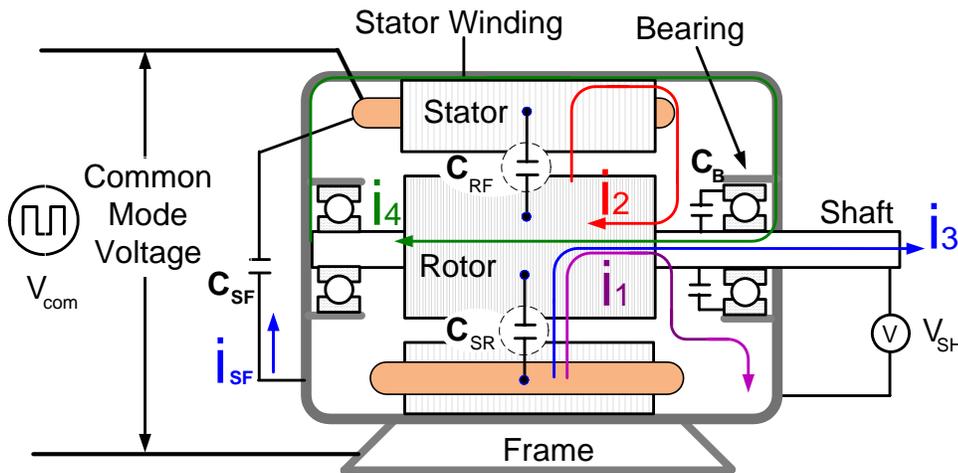


Figure 5. Bearing current paths in an inverter-driven AC machine

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 C_{SR} and charges up the rotor structure now finds a way to flow through the

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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 discussed thus far. This phenomenon is observed only in long axial machines that are used for large horsepower applications typically greater than 110-kW [2]. 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 [3].

BEARING CURRENT REDUCTION

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

- 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.

- 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 required the replacement of the existing bearings in the motor.

- 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

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technology has made it possible to introduce a 3-level inverter (i.e. the G7 Drive) to the general purpose-inverter market [1]. The advantages of a 3-level inverter are discussed in the next section.

FEATURES AND ADVANTAGES OF THE G7 3-LEVEL INVERTER

General Features of the 3-Level Inverter

Figure 6 shows a typical neutral-point clamped 3-level inverter. In order to determine the common-mode voltage in a three-level inverter, it is important to understand the various switching combinations in a 3-level inverter. In contrast to a 2-level inverter, a 3-level inverter has four switches (IGBTs) per phase, totaling twelve switches (IGBTs) for all three phases. According to the switching signals, each output phase voltage with respect to the DC bus mid-point can have three distinct levels, i.e. $E/2$, 0, and $-E/2$. Consequently, this arrangement is called a 3-level inverter.

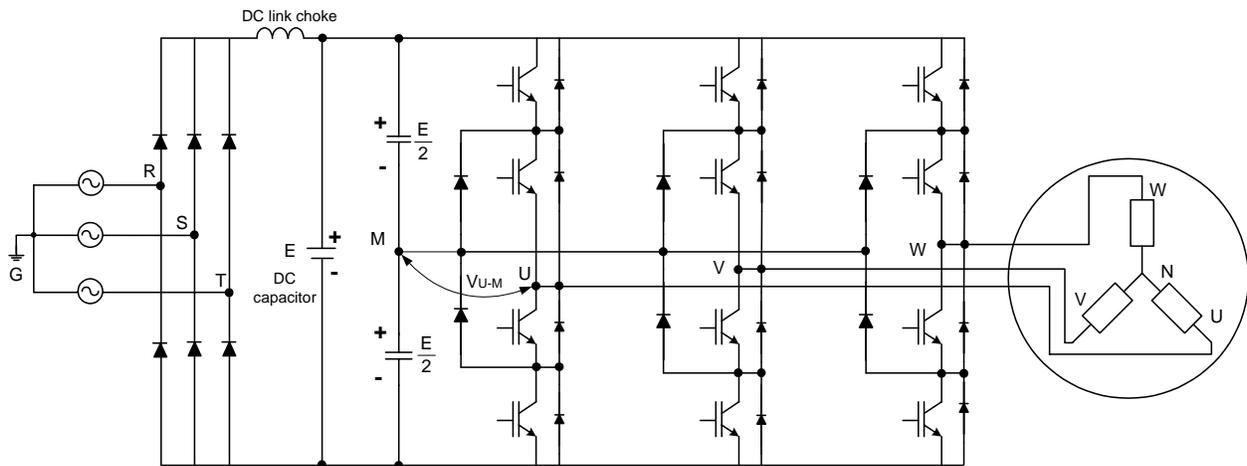


Figure 6. A typical neutral-point clamped 3-level inverter

Figure 7 shows various switching states and common-mode voltage waveforms among 27 different switching states of the 3-level inverter. By comparing the common-mode voltage of a 3-level inverter to that of a 2-level inverter as shown in figure 2, it is clear that in a 2-level inverter the difference in voltage level from one state to the other is always $\pm E/3$. In the case of a 3-level inverter, the voltage level is generally $\pm E/6$. This means that the transition level of the common-mode voltage in a 3-level inverter is typically one-half of that in the 2-level inverter. In a 3-level inverter, the amplitude of the common-mode voltage can be lower than a 2-level inverter in the high voltage region. In fact, the maximum and minimum values of the common-mode voltage in a 3-level inverter at higher voltage (i.e. at higher speed) reaches only $\pm E/3$ as shown in Figure 7(b), while the common-mode voltage

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reaches $\pm E/2$ in the case of a traditional 2-level inverter as shown in Figure 2. The lower transition level of the 3-level inverter also results in a lower common-mode current compared to the 2-level inverter. This is an important advantage of the 3-level inverter over the traditional 2-level inverter.

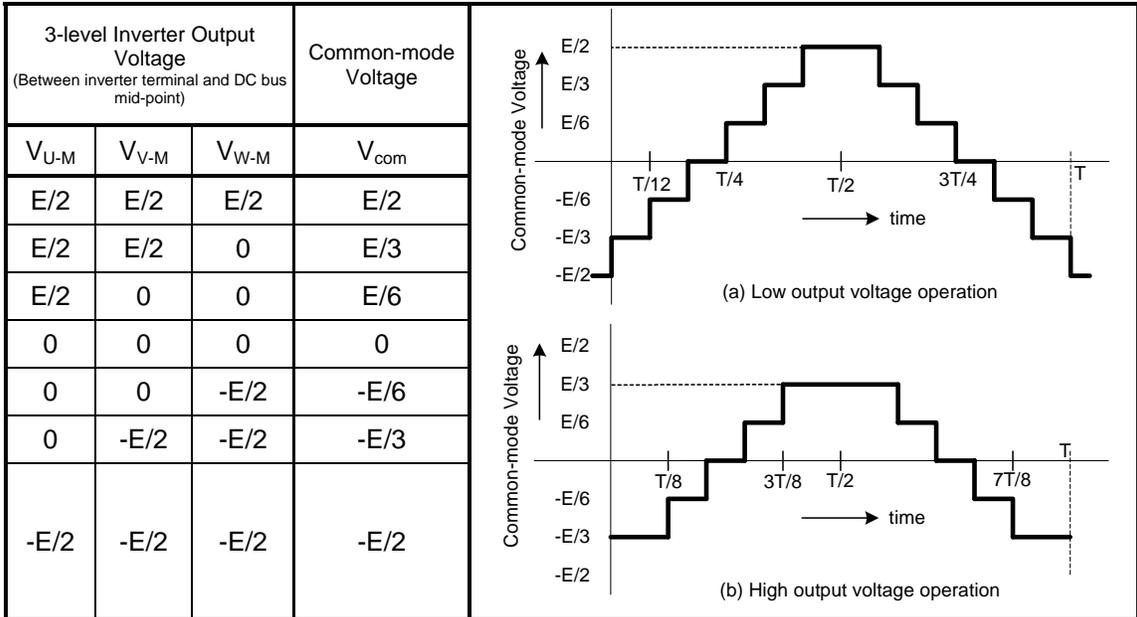


Figure 7. Various 3-level inverter switching-states and the corresponding common-mode voltage

Reduced Bearing Current and Increased Bearing Life with the G7 3-Level Inverter

The steep voltage transient in the shaft voltage causes current to flow through the bearing insulation. This leads to the breakdown of the bearing grease insulation and discharge of the shaft voltage. Since the change of the common-mode voltage is smaller in the 3-level inverter, this provides a significant advantage over the 2-level inverter with regards to shaft voltage and bearing currents. Figure 8 shows the comparative test results of the shaft voltage and bearing current for the 2-level and 3-level inverters. In these tests, insulation material was inserted in between the bearing and the housing so that the current through the bearing could be observed. Figure 8 shows that the bearing current of the 3-level inverter in Figure 8(b) is significantly smaller than a 2-level inverter in Figure 8(a).

Actual longevity tests were conducted to verify the superiority of the 3-level inverter. The tests simulated extreme conditions including temperature, types of grease, and motor speed. The results of the bearing life test are shown in Figure 9. A key point to note during normal operation is that the normal bearing life would be longer than that

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shown here. Figure 9 clearly proves that the use of a G7 Drive with a 3-level inverter topology can result in a significantly longer bearing life.

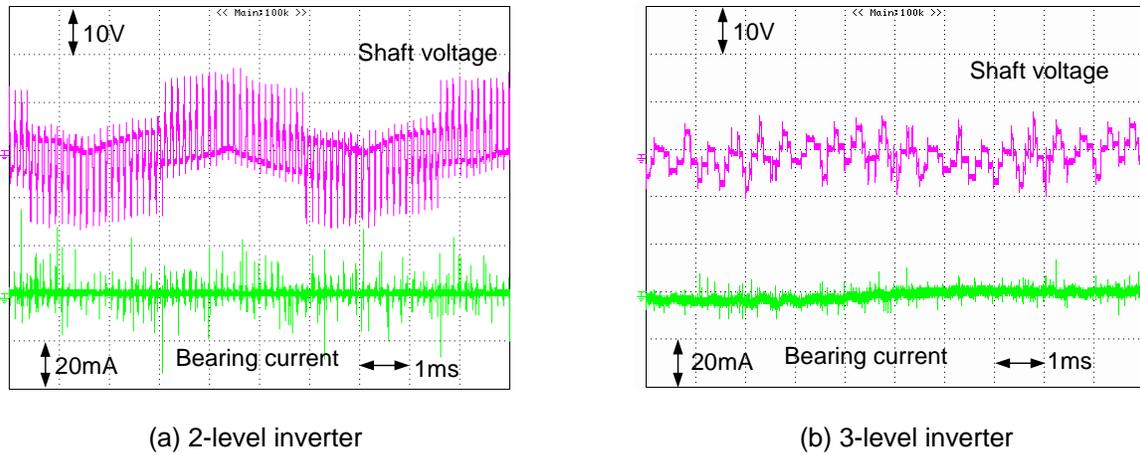


Figure 8. Shaft voltage and bearing current of the 2-level and 3-level inverters

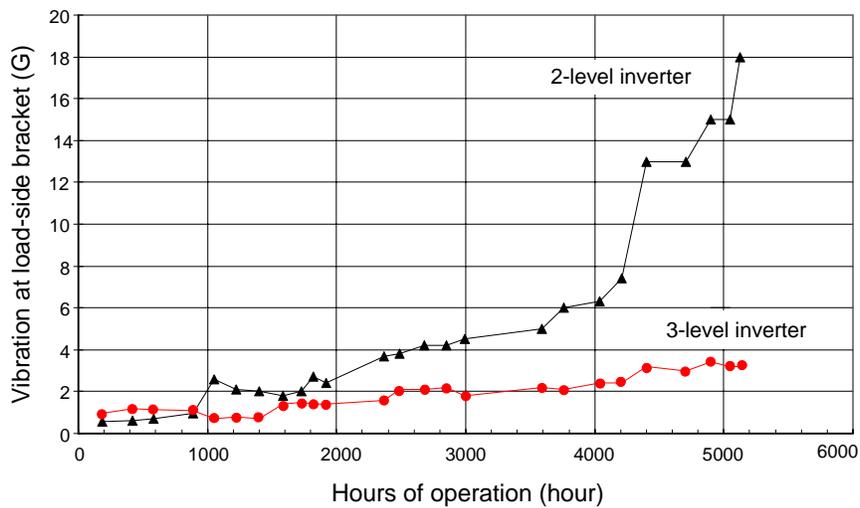


Figure 9. Bearing life test results (1HP, 2100rpm)

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CONCLUSION

In an inverter-driven AC machine, the common-mode voltage and dv/dt may cause premature motor bearing failure. This paper compared the common-mode voltage of the 2-level and 3-level inverter. The common-mode voltage and shaft voltage relationships were also described along with the bearing current mechanisms due to common-mode voltages. Features and benefits of the G7 Drive 3-level inverter topology that reduce the shaft voltage and bearing current generation have been presented. Analytical and experimental results show that the G7 Drive has lower common-mode mode voltage that results in lower bearing currents. Long-term operation tests also prove that the 3-level technology is effective to prevent bearing damage of motors.

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