Solving Bearing Current Problems in AC Motors

Numerous bearing current technical papers have been published over the last 10 years. This report does not address the sources of bearing currents in great detail, but rather provides an overview of the problem with practical solutions.

What causes bearing currents?

There are two chief sources of shaft voltage in an induction motor: An electrostatic charge introduced from outside the motor and electromagnetic unbalance within the motor itself.

Whenever an induction motor's electromagnetic circuit becomes unbalanced, a stray flux path will link the stator and rotor across the air gap. This flux linkage will induce a stray voltage (<40 V peak) in the rotor circuit, which will build up until the insulating capability of the bearing's lubricating oil film is exceeded. At that moment the voltage collapses and a pulse of current will pass through the bearing. The extreme heat produced during this event blasts a minute pit in the bearings, and repeated discharges will permanently damage the bearings. The races and rolling elements of current-damaged bearings will have a frosted appearance as shown in **Figure 1**, below. Frosted bearings are still serviceable and may last for more than 5 years in an installation. However, if mechanical vibration is present the rolling elements will bounce during rotation and create a fluting pattern (see **Figure 2**) on the outer raceway. This greatly increases friction and vibration and such bearings may catastrophically fail in less than 6 weeks. A 9 year life test at Regal Beloit confirmed the relationship between vibration and fluting.

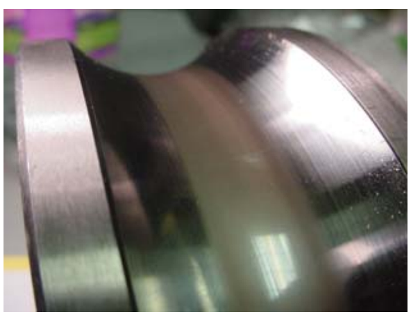


Figure 1

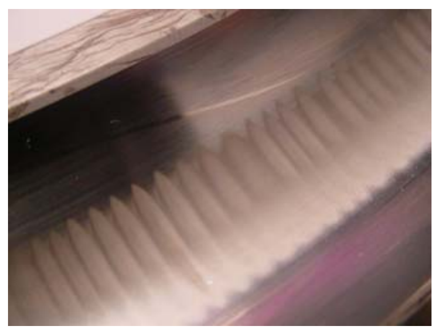


Figure 2

Common sources of electromagnetic unbalance are out-of round or off-center rotors, open rotor bars, magnetically non-symmetrical iron, or windings that are not symmetrically placed in the stator. Because the source of unbalance is internal, current will circulate in a loop and remain within the motor. Insulating one bearing will break this loop and protect both bearings from damage. If the drive end bearing is insulated instead of the opposite drive end, there's a chance that the connected load will provide a completion path for current flow, allowing it to bypass the insulated bearing. As an alternative to an insulated bearing, a shaft grounding brush may be placed at each bearing to shunt current around the bearings. The brushes may wear out prematurely if high circulating currents are present due to a severe unbalance.

Where does an electrostatic charge come from?

The second source of shaft voltage is electrostatic charge accumulation. A static charge can be transferred from the driven load to the motor shaft through belts or from a shaft-mounted fan operating in very dry air. Charge can also be introduced via unbalanced supply voltage, either from the utility or from a variable frequency drive (VFD). The actual voltage feeding the motor may be severely unbalanced (as in a 'single phase' condition) or a lesser unbalance may be introduced by a high resistance connection in the motor feeder cables or by unbalanced loads upstream from the motor.

When a motor is supplied by a balanced 3 phase sine wave supply, each phase voltage is displaced 120 ° from its companions. They sum at the neutral point of the motor winding and will add to zero. Add all 3 phases at any point in the 360° cycle and they will always sum to zero volts at the neutral. For example, in **Figure 3**, at the left-most vertical marking phase A is at zero volts, phase B is 70% negative and phase C is 70% positive, adding to zero volts at the neutral point. Select any other point in the cycle

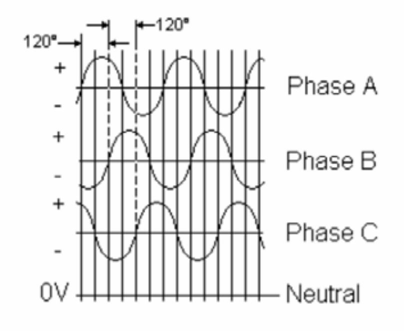


Figure 3

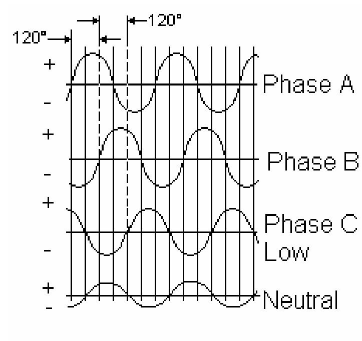


Figure 4

and the net sum will also be zero. However, if one phase is lower in magnitude (phase C in **Figure 4**), the voltage sum at the neutral point will be non-zero, and a net voltage will exist between the neutral and ground. In the example above, when phase A is zero (at the left-most vertical marking) phase C is less positive than phase B is negative, so they no longer cancel each other. The neutral point reflects this difference and a ***common mode voltage*** (CMV, the voltage common to all 3 phases) is produced. The frequency and signature of this voltage can be observed by measuring the shaft-to-frame voltage or end-to-end voltage of the shaft itself.

What happens to the common mode voltage?

The CMV will return to the source, which is the utility or the VFD. The return path will be from the motor frame back to the ground at the unbalanced source. With poor motor grounding, the motor frame may rise to the level of the CMV.

When the CMV links the rotor, a charge will accumulate on the rotor. Since the unbalance source is external to the motor, rotor current will flow through the bearings to ground and back to the source, taking the path of least resistance, which may include the connected load. To protect the bearings from an external unbalance, **both** motor bearings must be insulated **and** the load must be isolated from the motor shaft and frame. Insulated bearings may have ceramic rolling elements, an insulating coating on the inner race, or a ceramic coating on the outer race, as shown in **Figure 5**. A shaft ground brush may be installed to bleed down the rotor charge and protect both bearings.

Lab tests indicate that CMV unbalance must exceed 15-30 volts to produce enough voltage in the rotor to generate bearing currents. Most utilities provide good voltage balance and CM values normally do not reach these levels.

The voltage waveforms of transistorized VFD’s contain numerous harmonics with very high dv/dt, which can also be a source of unbalanced voltage to the motor. Fortunately, lab tests show that they do not cause noticeable bearing damage.

Figure 5

How does a VFD produce a common mode voltage?

If the motor is internally balanced and the utility voltage is symmetrical, a CMV can still be present if the motor is powered by a VFD. Unlike 3 phase utility power, the VFD output has only 2 states: The Plus and Minus values of the DC voltage stored on the DC bus capacitors. With only 2 output states it is not possible to create a completely symmetrical 3 phase waveform and thus an unbalance occurs. The result is an output voltage waveform where the neutral bounces between the plus and minus DC bus levels, creating a very large CMV (see **Figure 6**). Unlike the low magnitude CMV produced by Utility unbalance, lab tests on 460 V VFD's show that the CMV may reach 375-400 volts. CMV’s over 150 V RMS have been recorded on 230 V VFD’s powered from 115V single phase inputs. Fortunately, this voltage has very high impedance and is easily bled down to a safe level by proper grounding of the motor frame. Regal Beloit research on 13 different 115, 230, 460 & 575 V VFD’s shows that they all produce a CMV. The

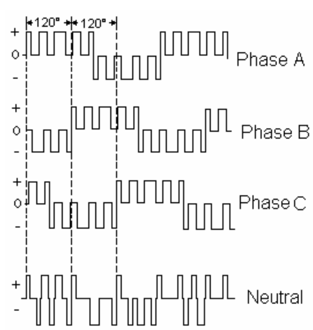


Figure 6

Grounded Transformer Neutral		
Variable torque Profile		
Fund Hz	**Ave CMV**	**Shaft V**
120	122	5.3
90	156	5.1
60	184	6.2
45	249	7.6
30	306	9.5
15	327	9.3
6	340	10.7
3	344	10.9

Table 1

values shown in **Table 1** are the average CMV from 9 different brands of 460 volt VFD's recently tested.

What factors influence the CMV?

The VFD's CMV magnitude is determined primarily by the level of the DC bus voltage and the amount of time each motor phase is turned off (via connection to the same bus polarity as an adjacent phase). The longer this period is, the higher the CMV will be. The highest CMV's occur at low fundamental frequencies when the carrier frequency is high and the volts/hertz profile is set for a variable torque (fan or pump) load. This is evident in the center column of **Table 1**, where the voltage is much higher at 3 or 15 Hz than at 60 Hz.

Just as on line power, a portion of the CMV will be transferred to the rotor ('Shaft V' column in **Table 1**) and will return to the source of unbalance (the DC bus in this case) through the motor bearings and ground. As shown in **Figure 7**, if the motor coupling is conductive, some current may also flow along the motor shaft and through the load's bearings to ground. Damaged load bearings have been reported on gearboxes and applications where the motor is face or flange-mounted directly to the load. **Figure 7** traces several paths for the common mode current to return from the motor windings to the DC bus. The best internal path is between the motor winding and the stator frame, and ~97% of the CMV transfers by capacitor action here, with ~3% coupling to the rotor.

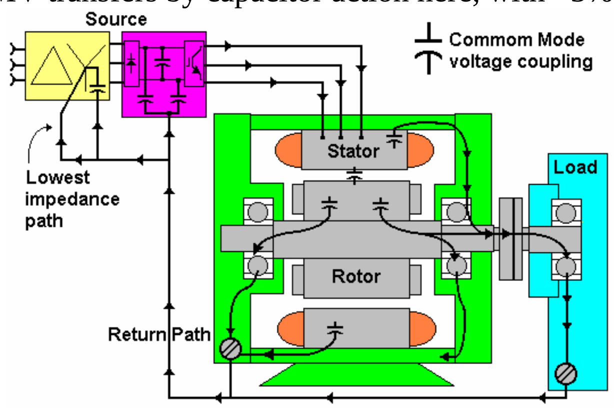


Figure 7

The lowest impedance external path is from stator frame to the grounded neutral of a wye-connected transformer at the VFD input. From there it couples around the input bridge diodes (when they are reverse-biased) and back to the DC bus. A small portion of the CM return current will reach the DC bus directly via the bus bar-to-ground capacitance, but the transformer neutral lead is by far the lowest impedance path.

Since the CMV is coupled capacitively to the rotor, its reduction may be addressed from a capacitive electrostatic model. **Figure 8** illustrates such a model, with 375 VRMS dropped across the stator winding-to-frame capacitance and 12 volts coupled to the rotor via the air gap capacitance. The oil film between the bearing rolling elements and races creates additional capacitors, allowing the rotor to store a charge until this insulating oil

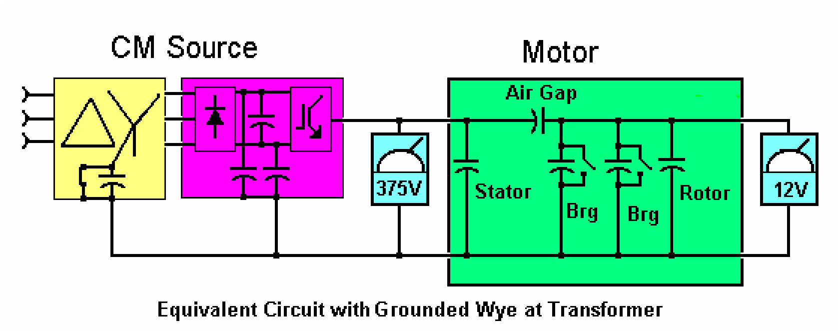
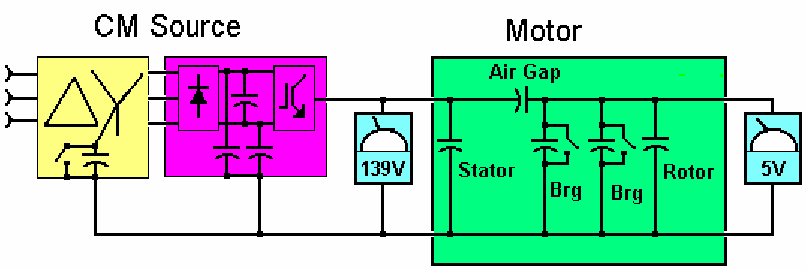


Figure 8

film breaks down (illustrated in **Figure 8** as a switch closing) and the voltage collapses, pitting the bearings in the process. As bearing rotation continues, the oil film is re-established and the rotor circuit is recharged to 12 volts (open circuit).

Due to the CMV's fast rise time and high magnitude, the very small VFD chassis-to-DC bus capacitance and transformer core-to-winding capacitance become significant pathways for return current flow. When the transformer's wye connection is bonded to a good ground, its winding-to-core capacitance is bypassed and as a result almost all of the CMV is dropped across the motor circuit.

If the transformer wye is ungrounded (transformer switch opened in **Figure 9**), its core-to-winding capacitance is added back into the circuit, creating a voltage divider with the stator-to-ground capacitance. The same effect is produced if the transformer secondary is delta connected. Instead of all the CMV being dropped across the stator-to-ground capacitance, a portion now appears across the transformer-to-ground capacitance. This effectively reduces the CMV on both the stator and the rotor. Rotor-to-ground voltage



Equivalent Circuit with Ungrounded Wye at Transformer

Figure 9

drops from 12 V to 5 V (open circuit) and the energy available to damage the bearings is greatly diminished.

What determines the amount of bearing damage?

If other factors remain constant, the arc energy released during a bearing discharge will vary by the square of the voltage applied. In the **Figure 9** example, shaft voltage has decreased by 58% and arc energy has dropped by 82%. This helps explain why one motor experiences bearing current failure when another does not: The failed motor may be on a grounded wye system and the VFD of the surviving motor may be on a delta-connected power system. Its bearings might last for 3 years while the grounded wye bearings fail in just 6 months.

Can the CMV be reduced more?

To further reduce the CMV, another voltage divider can be created by adding loading capacitors between each output phase of the VFD and the earth ground (**Figure 10**). These caps load down the high impedance CMV source, effectively bleeding it off before it ever reaches the motor terminals. In a working circuit, a series resistor and common mode choke are added to limit high frequency current spikes. Such spikes may cause nuisance tripping and instability, especially on vector drives, which utilize fast-response current regulators. Values in **Figure 10** were obtained during lab testing. Note that the loading circuit drops the stator CMV to 20 volts and the rotor voltage to 0.6 volts (open circuit). At speeds above ~500 RPM the bearing oil film will be thick enough to withstand this voltage and if a discharge does occur the arc energy is so low that little or no bearing damage would result.

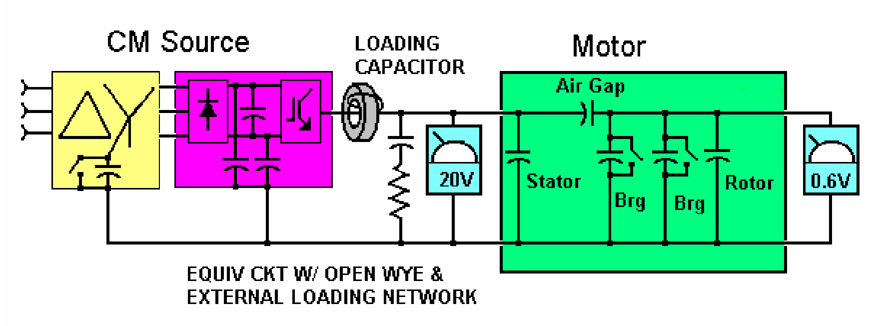


Figure 10

To test the impact of these 3 grounding schemes, Regal Beloit conducted a life test, using the layout shown in **Figure 11**. After 12 months the results were as expected: Unprotected bearings with the highest CMV suffered the most, motors powered from inverters with delta secondary transformers suffered less, and motors powered from the loading filter inverter showed essentially no damage at all. By ungrounding the transformer neutral and adding a CM loading filter, bearing current damage can be completely eliminated without any modification to the motor.

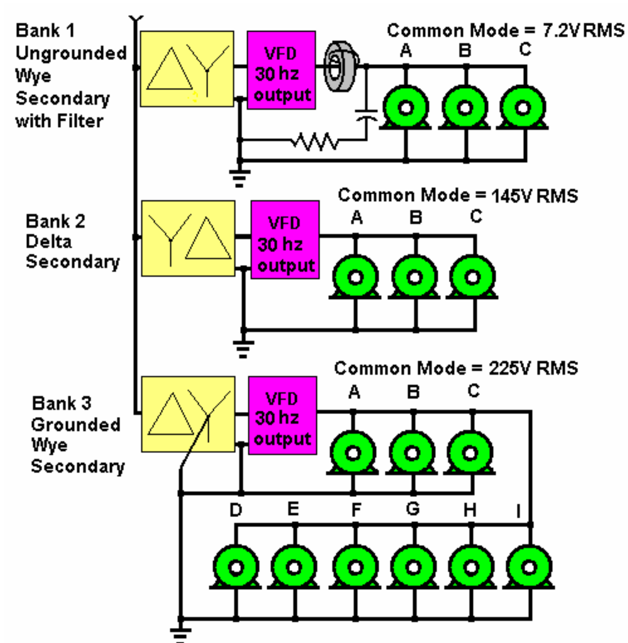


Figure 11

Can the transformer neutral be safely ungrounded?

The National Electric Code (NEC section 250-21) does permit a transformer's secondary neutral to be ungrounded if the VFD is the only load attached. The transformer case must remain grounded for safety, and the motor-to-VFD-to-transformer ground conductors may still be shielded and configured to provide a high frequency low impedance ground path. It is important for the motor installer to differentiate between the transformer's neutral lead and the motor's neutral lead. Our lab experience shows that if the motor neutral is grounded, the VFD's ground fault circuit will detect a severe unbalance and trip off.

What if the neutral can't be ungrounded?

If there is more than just the VFD load on the transformer secondary, the NEC requires the secondary neutral to be grounded. Either the extra loads must be removed from the transformer or another means of bearing protection must be employed. Also, VFD vendors prefer (and may specify) a grounded wye secondary to reduce potential VFD damage from large voltage transients at the VFD input. Fortunately, other measures can be taken to reduce bearing damage, such as adding insulated bearings (**Figure 5**) or adding a ground brush (**Figure 12**). A good brush bleeds off the rotor CMV, reduces arc energy 95-99%, and will effectively protect both the motor and driven load bearings. Field experience shows that solid composition brushes are subject to failure by contamination, but bristle brushes survive well in greasy and dirty environments. Since brush current is very low in the CMV circuit, ground brush life becomes dependent on shaft surface speed. Riding on a 6" shaft @ 3600 RPM the brush might last only 1 year, but riding on a 5/8" shaft it could last 10 years. Longest brush life is obtained when the brush sits axially on the end of the shaft, as shown in **Figure 12**. Lab tests indicate that one ground brush is effective in motors as large as 449T frames. Above 449T, the rotor end-to-end impedance may be large enough to

Figure 12

permit some voltage to still remain on the ungrounded end of the motor. In these cases it is advisable to insulate the opposite-brush-end bearing. Insulating one bearing also protects the motor from the effects of an unbalanced magnetic circuit. Larger motors are more prone to this than small motors, so it makes sense to take precautionary measures. Keep in mind that the bearing currents in a given motor may be caused by more than one source. For example, a motor may have an inherent unbalanced magnetic circuit and also be operated from a VFD. The proper remedy must therefore address both sources of trouble.

What protection is available for Explosion Proof motors?

Due to the risk of sparking, UL & CSA prohibit ground brushes on the outside of any motor installed in a Division 1 or Division 2 location. They may accept brushes inside the motor, where sparks are contained within the motor’s explosion proof enclosure, but such an arrangement must be approved and added to the motor OEM's agency file first. Insulated bearings are also prohibited, so the only protection currently available is the loading filter described in **Figure 10**.

Summary

To completely protect a motor from internal electromagnetic unbalance one motor bearing must be insulated or grounding brushes must shunt both bearings. To protect from an external unbalance (common mode voltages) both bearings must be insulated or a ground brush must be installed, or the source of unbalance must be diverted from the motor via filters. If the bearings of a VFD-powered motor are not protected, they will not obtain their expected B-10 life.

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