High-frequency (HF) currents flowing through motor bearings cause premature bearing failure but this can be remedied with HF bonding connections, low impedance path and symmetrical multicore motor cables.

Bearing currents in modern AC drive systems

While bearing currents have been around since the advent of the electric motor, their damage has increased over the last few years. Modern variable speed drives (VSDs) have fast-rising voltage pulses and high switching frequencies and can cause current pulses through the bearings. These pulses are discharged repeatedly and erode the bearing races gradually. Proper earthing paths must be provided to avoid this damage and stray currents must be allowed to return to the inverter frame without passing through the bearings. The magnitude of the currents can be reduced by using symmetrical motor cables or inverter output filtering. Proper insulation of the motor bearing construction breaks the bearing current paths.

Generating bearing currents

HF current pulses
While motor design and manufacturing practices have nearly eliminated the low-frequency bearing currents induced by the asymmetry of the motor, the rapid switching in modern AC drive systems may generate HF current pulses through the bearings. Metal transfers from the ball and the races to the lubricant if the energy of these pulses is sufficiently high. This is known as electrical discharge machining or (EDM). The effect of a single pulse is insignificant, but a tiny EDM pit is a discontinuity which collects more pulses and expands into a typical EDM crater.

The switching frequency of modern AC drives is very high and the vast number of pulses causes erosion quickly (see Fig. 1). Faster switching Current AC drive technology incorporating insulated gate bipolar transistors (IGBTs) creates switching events 20 times faster than those considered typical ten years ago. Recent years have seen an increase in EDM-type bearing failures in AC drive systems relatively soon after startup, within one to six months. The extent to which this occurs depends on the AC drive system architecture and the installation techniques used.

Fig. 1: Bearing currents can cause bearing fluting, a rhythmic pattern on the bearing races.

Fig. 2: The phase voltages of a typical three phase PWM power supply and the average of the three, or neutral point voltage, in a modern AC drive system. The neutral voltage is clearly not zero and its presence can be defined as a common mode voltage source. The voltage is proportional to the DC bus voltage, and has a frequency equal to the inverter switching frequency.
Generating HF currents

Bearing currents are caused by the voltage induced over the bearings. In the case of HF bearing currents, this voltage can be generated in three different ways. Factors determining bearing current level include the size of the motor; grounding for the motor frame and shaft; cable type; bonding of protective conductors and electrical shield; $\frac{dI}{dt}$ of the AC drive power stage components and the DC-link voltage level affect.

Circulating current

In large motors, HF voltage is induced between the ends of the motor shaft by the HF flux circulating the stator. This flux is caused by a net asymmetry of capacitive current leaking from the winding into the stator frame along the stator circumference. This voltage between the shaft ends affects the bearings. If it is high enough to overcome the impedance of the bearings’ oil film, a current which tries to compensate the net flux in the stator starts to flow in the loop formed by the shaft, the bearings and the stator frame.

Shaft grounding current

The current leaking into the stator frame must flow back to the inverter, which is the source of this current. Any route back contains impedance and the voltage of the motor frame therefore increases in comparison to the source ground level. The increase in motor frame voltage is seen over the bearings if the motor shaft is earthed via the driven machinery. Part of the current may flow via the drive-end bearing, the shaft and the driven machine, back to the inverter, if the voltage rises high enough to overcome the impedance of the drive-end bearing oil film. This is a shaft grounding type frequency bearing current.

Capacitive discharge current

In small motors, the internal voltage division of the common mode voltage over the internal stray capacitances of the motor may cause shaft voltages high enough to create HF bearing current pulses. This can happen if the shaft is not earthed via the driven machinery while the motor frame is earthed in the standard way for protection.

Common mode circuit

HF bearing currents are a consequence of the current flow in the common mode circuit of the AC drive system. A typical 3-phase sinusoidal power supply is balanced and symmetrical under normal conditions, i.e. the vector sum of the three phases always equals zero. The neutral is therefore at zero volts. This is, however, not the case with a PWM switched 3-phase power supply, where DC voltage is converted into three-phase voltages. It is impossible to make the sum of three output voltages instantaneously equal to zero with two possible output levels available, even though the fundamental frequency components of the output voltages are symmetrical and balanced. The resulting neutral point voltage is not zero. This voltage may be defined as a common

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Fig. 3: An example of common mode current at the inverter output. The pulse is a superimposition of several frequencies due to the different natural frequencies of the parallel routes of common mode current.

Fig. 4: Simplified loop of the common current of a PWM inverter and induction motor. The inverter power supply acts as a common mode voltage source ($V_{cm}$). Common mode current ($CMC$) flows through the common mode cable and motor inductances, $L_c, L_m$, and through the stray capacitances between the motor windings and motor frame, combined to be $C_m$. From the motor frame, the current proceeds through the factory earth circuit which has the inductance $L_g$. $L_g$ is also fed common mode current from the stray cable capacitance $C_c$. The inverter frame is connected to the factory earth and couples the common mode current/earth currents through stray inverter to frame capacitances, combined as $C_{in}$, back to the common mode voltage source.
mode voltage source. It is measurable at the zero point of any load, e.g., the star point of the motor winding (see Fig. 2). Whenever one of the three inverter outputs is changed from one of the possible potentials to another, a current proportional to this voltage change is forced to flow to earth via the earth capacitances of all the components of the output circuit.

The current flows back to the source via the earth conductor and stray capacitances of the inverter, which are external to the 3-phase system. This type of current, which flows through the system in a loop which is closed externally to the system, is called common mode current (see Fig. 3).

Stray capacitances

A capacitance is created when two conductive components are separated by an insulator. For instance, the cable phase wire has capacitance to the PE-wire separated by e.g. PVC insulation. The motor winding turn is insulated from the frame by enamel coating and slot insulation, and so has a value of capacitance to the motor frame. The capacitances within a cable and especially inside the motor are very small which means high impedance for low frequencies and therefore the blocking of low-frequency stray currents. Fast-rising pulses produced by modern power supplies, however, contain frequencies so high that even small capacitances inside the motor provide a low impedance path for current to flow (see Fig. 4).

Current flow through the system

The return path leakage current from the motor frame back to the inverter frame consists of the motor frame, cable shielding or PE-conductors and possibly steel or aluminium parts of the factory building structure. These elements contain inductance and the flow of common mode current through this inductance causes a voltage drop which raises the motor frame potential above the source ground potential at the inverter frame. This motor frame voltage is a portion of the inverter’s common mode voltage. The common mode current will seek the path of least impedance. If high impedance is present in the intended paths (e.g. in the PE-connection of the motor frame), the motor frame voltage will cause some of the common mode current to be diverted down an unintended path, through the building. A number of parallel paths exist in actual installations. Most have a minor effect on the value of common mode current or bearing currents, but may be significant in coping with EMC-requirements.

Voltage drops

If the value of this inductance is high enough, the reactance at the upper range of typical common mode current frequencies (50 kHz to 1 MHz) can support voltage drops of over 100 V between the motor frame and the inverter frame. Where the motor shaft in these cases is connected through a metallic coupling to a gearbox or to other driven machinery...
which is solidly earthed and which is near
the same earth potential as the inverter
frame, part of the inverter common mode
current could flow via the motor bearings,
the shaft and the driven machinery, and
back to the inverter (see Fig. 5).
Current may flow via the gearbox or
machine bearings where the shaft of the
machinery has no direct contact to the
ground level. These bearings may be
damaged before the motor bearings are
(see Fig. 6).

Common mode transformer
Most of the motor’s stray capacitance
is formed between the stator windings
and the motor frame. This capacitance
is distributed around the circumference
and length of the stator. As the current
leaks into the stator along the coil, the
HF of the current entering the stator
coil is greater than that of the current
leaving.

This net current produces an HF
magnetic flux which will circulate in the
stator laminations, inducing an axial
torque in the shaft ends.
Should the voltage become large
enough, an HF circulating current could
flow internally to the motor, through the
shaft and both bearings. The motor
frame, in this case, be thought of as a
transformer where the common mode
current flowing in the stator frame
acts as a primary and induces the
circulating current into the rotor circuit
or secondary.
This bearing current is considered the
most damaging, with typical peak values
of 3 to 20 A depending on the rated
power of the motor, du/dt of the AC
drive power stage components and on
DC-link voltage level (see Fig. 7).
Another version of circulating bearing
current occurs when the current, instead
of circulating completely inside the
motor, flows via the shaft and the
bearings of the gearbox or the driven
machinery and in a structural element
which is both external and common to
the motor and the driven machine.
The origin of the current is the same as
that of the current circulating inside the
motor. An example of this “vagabond”
circulating bearing current is shown in
Fig. 8.

Capacitive voltage divider
Other stray capacitances are also
present in the motor, such as the
capacitance between the stator windings
and the rotor or the capacitance in the
motor’s air gap, between the stator iron
and the rotor. The bearings themselves
may even have stray capacitance.
The existence of capacitance between the
stator windings and the rotor effectively
couples the stator windings to the rotor
iron, which is also connected to the shaft

![Common mode loop of variable speed drive, showing stator, rotor and bearing stray capacitances.](image1)

![Recommended motor cable with symmetrical core configuration.](image2)

![Proper 360° termination with European cabling practice.](image3)

![Proper 360° termination with American cabling practice.](image4)
and the bearing’s inner races. Rapid changes in the common mode current from the inverter can not only result in currents in the capacitance around the circumference and length of the motor, but also between the stator windings and the rotor into the bearings (see Fig. 9).

The current flow into the bearings can change rapidly as it depends on the physical state of the bearing at any particular time. For instance, the presence of stray capacitance in the bearings is only sustained as long as the balls of the bearings are covered in oil or grease and are non-conducting.

This capacitance, where the induced shaft voltage builds up, can be short-circuited if the bearing voltage exceeds the threshold of its breakover value or if a “high spot” on a ball breaks through the oil film and makes contact with both bearing races. At very low speed, the bearings have metallic contact as the balls have not risen on an oil film.

Generally, bearing impedance governs the voltage level at which the bearings start to conduct. This impedance is a nonlinear function of bearing load, temperature, speed of rotation and lubricant used, and the impedance varies from case to case.

Preventing HF bearing current damage

Three approaches

The three approaches to affect HF bearing currents are a proper cabling and earthing system breaking the bearing current loops and damping the HF common mode current.

All these aim to decrease the bearing voltage to values which do not induce HF bearing current pulses at all, or damp the value of the pulses to levels which have no effect on bearing life. Different measures must be taken for different types of HF bearing currents.

A proper earthing system forms the basis of all HF current mastering. Standard equipment earthing practices are mainly designed to provide a sufficiently low impedance connection to protect people and equipment from system frequency faults.

A variable speed drive can be earthed effectively at the high common mode current frequencies if the installation follows these three practices:

1. Multicore motor cables
   Use only symmetrical multicore motor cables. The earth (protective earth, PE) connector arrangement in the motor cable must be symmetrical to avoid bearing currents at fundamental frequency. The symmetry of the PE conductor is achieved by a conductor surrounding all the phase leads or by a cable which contains a symmetrical arrangement of three phase leads and three earth conductors (see Fig. 10).

2. Short impedance path
   Define a short, low impedance path for common mode current to return to the inverter. The best and easiest way is to use shielded motor cables.
The shield must be continuous and of good conducting material, i.e. copper or aluminium, and the connections at both ends must be made with 360° termination (see Figs. 11a and 11b).

**HF bonding connections**

Add HF bonding connections between the installation and known earth reference points to equalise the potential of the affected items. Use barded straps of copper 50 – 100 mm wide; flat conductors will provide a lower inductance path than round wires (see Fig. 12).

These connections must be made at the points where discontinuity between the earth level of the inverter and that of the motor is suspected. It may also be necessary to equalise the potential between the frames of the motor and the driven machinery to short the current path through the motor and the driven machine bearings.

**Follow product-specific instructions**

Installation practices may differ for different products even though the basic principles of installations are the same. It is therefore essential to follow the installation instructions in product manuals carefully.

**Measuring HF bearing currents**

Monitoring the bearing condition must be conducted with established vibration measurements. It is impossible to measure bearing currents directly from a standard motor but field measurements can be taken to verify the existence of suspected current loops where HF bearing currents are suspected. Measuring equipment must have wide bandwidth (10 kHz – 2 MHz minimum) able to detect peak values of at least 150 to 200 A and RMS values of at least down to 10 mA. The crest factor of measured signals is seldom under 20. The current may flow in unusual places such as in rotating shafts. The most important measurement points are found within the motor. The motor speed must be at least 10% of the nominal for the bearings to rise on the oil film during measurements. Basic measurements are shown in Fig. 13 as an example. Fig. 14 shows examples of measured current waveforms. Gate turn-off (GTO) thyristor inverters were used mainly in the 1980s while IGBT inverters are used today. Note the different scale in the various graphs.

**Measurement**

It is recommended that bearing current measurements be made by dedicated personnel only. Suitable measurement equipment is not available on the market commercially and specialised experience is needed to make the measurements and interpret the results.

**References**


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