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MOTOR SHAFT VOLTAGES AND BEARING CURRENTS UNDER PWM INVERTER OPERATION

A GAMBICA / BEAMA Technical Guide
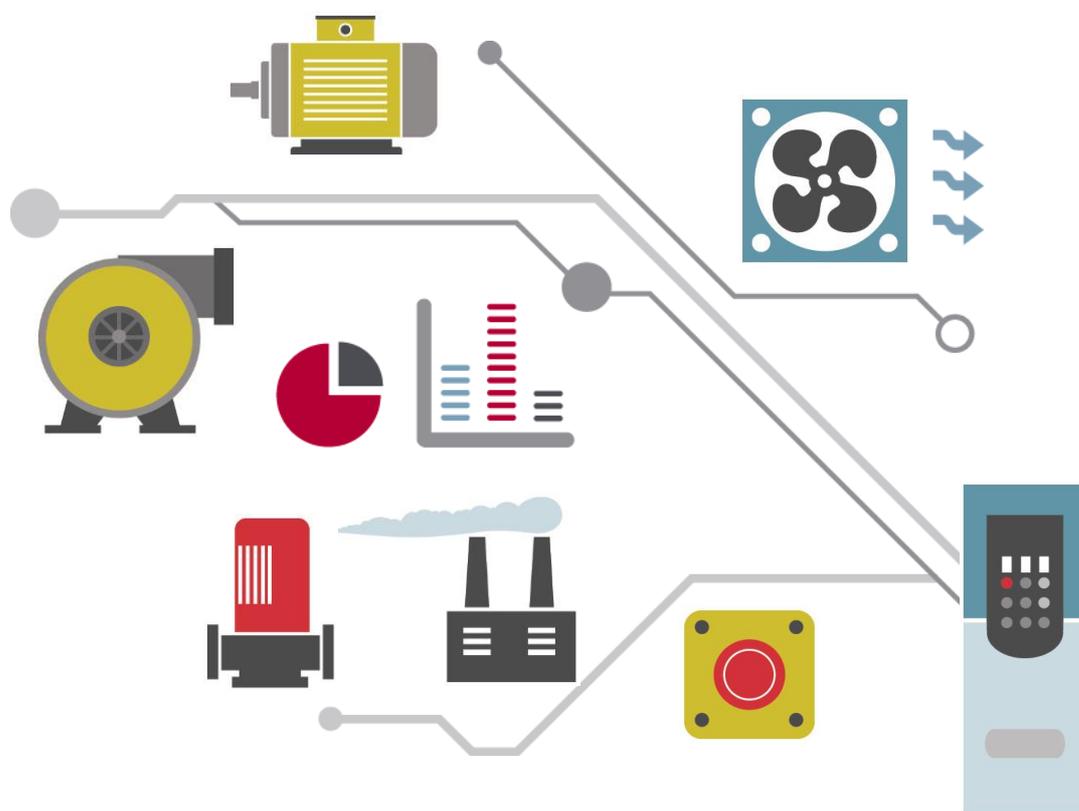
SUMMARY

- Modern motors are made to very close tolerances, and will not usually suffer from electrically induced bearing failures. Motors experience additional voltage effects when used with an inverter to those that apply when connected directly to the a.c. mains supply.

- The additional effects are dependent on the motor physical frame size, and on the supply voltage.

- For shaft heights lower than 280 mm the effects are usually minimal, and no additional provisions need to be made.

- For shaft heights greater than 280 mm the effects become more noticeable, and certain additional provisions will need to be made.

- Alternatively, additional components can be added to limit the effects to acceptable levels.

MOTOR SELECTION

Failure due to bearing currents is seldom encountered, but for security of operation the following should be observed.

Motors with shaft height 280 mm and lower

- Adhere strictly to the motor and inverter manufacturers' recommendations regarding the installation, cabling and grounding.

Motors with shaft height over 280 mm

- Adhere strictly to the motor and inverter manufacturers' recommendations regarding the installation, cabling and grounding.

- Specify a motor with an insulated non-drive-end (NDE) bearing assembly.

- Potential grounding paths through connections to the shaft system must be taken into account, and the bearing insulation must not be by-passed. This includes shaft mounted auxiliaries which may need an insulated coupling.

Supply Voltage

- For supply voltages over 500 V it may be necessary to incorporate filtering in the inverter output as well as taking into account the recommendations above.

APPLICATION SPECIFIC NOTES

Applications with 'long' cable lengths
The definition of 'long' depends on the drive rating and type, and may vary between 10m for low power drives and 500m for higher powers
Refer to specific manufacturers technical documentation. For these applications, new factors are introduced and the drive supplier should be consulted.

Drive switching strategies
Some drive types use control strategies, which could allow bipolar switching. These systems could theoretically double the motor peak voltage stress. GAMBICA inverter manufacturers implement control mechanisms to inhibit bipolar switching. If in doubt the drive supplier should be consulted.

Frequent or continuous braking duty
Where the drive spends a large part of its operating time in braking mode, the effect is similar to increasing the supply voltage by up to 20% and this should be taken into consideration - e.g. treat a 400V application as if it was supplied with 480V.

Active rectifier
For drives with PWM active rectifier (regenerative and/or unity power factor), the effective supply voltage is increased by around 15% and this should be taken into consideration e.g. treat a 480V application as if it was supplied with 550V.

Potentially Explosive Atmosphere approval (ATEX)
The application of inverters to 'Ex' motors may invalidate the certification - refer to the Gambica/BEAMA Technical Report No 4 Application of the ATEX Directives to Power Drive Systems.

ALTERNATIVE APPROACH
It may not be possible to follow the above recommendations - for example because the drive is to be retro-fitted to an existing motor, or data is not available for the motor concerned.

In these cases an additional preventative measure is recommended - options are detailed in Section 7 and the relative merits should be discussed with the drive supplier.

FOREWORD

This Technical Report has been produced to meet a demand for an authoritative guide on good practice in the application of motors on Pulse Width Modulated (PWM) inverter supplies with respect to shaft voltages. It is the result of a study carried out by GAMBICA and BEAMA taking note of well established fundamental theory, technical papers, and carrying out specific investigations. The information given, while it can be applied to motors and inverters in general, is specific to current generation products of member companies.

This report principally considers the effects of shaft voltages developed by the voltage source PWM inverter. It supplements IEC TS 60034-17: 2006 [1], which provides additional information on other important aspects including: voltage rating, torque de-rating, additional losses, noise and maximum safe operating speed.

This report covers motors and inverters installed with a separate cabling system connecting the components together; it is not wholly applicable to inverters integrated into a motor design, generally now available up to 7,5 kW.

The references together with a useful list of further reading are included in section 8 of this report.

SCOPE

This report provides information on the basic operating principles of PWM inverters, with an emphasis on those using IGBT (Insulating Gate Bipolar Transistor) switching devices, and the interface with the motor. It deals with the various mechanisms by which voltages may be induced into the shaft of the motor, and with the effects of these voltages.

Advice is given on the capability of motors to operate satisfactorily with inverter supplies and on mitigation measures to ensure satisfactory long term operation.

Supplies considered are low voltage up to 690 V a.c.

For the application of variable frequency inverters with Ex. motors, refer to the motor manufacturer for confirmation of their suitability and certification.

CONTENTS

1   INTRODUCTION

Motor bearing failures due to induced voltages were first reported nearly 100 years ago, but have become very rare indeed with mains fed motors.   In recent years the phenomenon has been reported when motors are inverter fed. The number of failures reported is small, but sufficient to cause concern in some application areas. As a result some users and consultants may be specifying counter measures which are costly and are often unnecessary. This report aims to give a clear explanation of the effects involved and straightforward advice on what precautions are required to avoid problems.

Variable speed a.c. inverters as illustrated below are used in ever-increasing numbers because of their well-known benefits for energy efficiency and flexible control of processes and machinery using low-cost maintenance-free a.c. motors. Virtually all a.c. inverters use power switching techniques and generate high rates of change of voltage.

Most modern a.c. inverters use voltage-source PWM inverters with very fast-switching power semiconductor devices such as Insulated Gate Bipolar Transistors (IGBT), which have the advantage of being very robust, and having relatively low switching losses.

The nature of the voltage generated by such an inverter causes some increase in the voltages induced into the motor rotating elements - although this report will show that in most cases the additional voltages are well within their capability.


2   OVERVIEW OF MOTOR DESIGN

The development of the squirrel cage induction motor, with its associated parts such as rolling elements, bearings, grease etc., has generally been for sinusoidal supplies. Its design is well proven and inherently robust leading to long reliable service with minimum maintenance. The practical life of the rolling elements, and hence the motor life, can be many years with ultimate failure likely to be through thermal, mechanical and chemical degradation, rather than by electrical breakdown. The environment could also be a significant factor in their eventual failure.

Advances in the metallurgy for bearings and lubrication technology allied with state-of-the-art production methods employed in the manufacturing, have significantly raised the performance of the induction motor and virtually eliminated the incidences of bearing failures due to mechanical triggers when utilised within the design specification. For motors directly supplied from the network, the requirements for performance, starting characteristics, thermal classifications, mechanical protection, safety, insulation levels based on dielectric tests etc., are well established internationally in the IEC 60034 series of standards. However, the aspects of bearings and bearing life

are only covered by the British Standard, BS ISO 281: 2007 [3]. For inverter-fed machines, IEC TS 60034-17 [1], NEMA MG1-2014, Parts 30 and 31 [4], [5], and NEMA 'Application Guide for AC Adjustable Speed Drive Systems' [6] generally set the basic requirements and provide application guidance for use with inverter supplies.

As mentioned above, the bearings, in conjunction with modern greases have been developed to give long life expectancy and reduced incidence of failure. The bearing life expectancy for industrial application is typically quoted as 20 000 to 40 000 hours, with theoretical mechanical life approaching 40 000 to 60 000 hours, dependent on speed and application. However, external factors, such as abnormally applied load and speed, inappropriate maintenance regime, abnormal supply conditions – voltage imbalance, high repetitive peak voltage with short rise-time - can significantly reduce the life expectancy of bearings. Therefore, the main design effort is devoted to minimising the impact of these factors through the adoption of better practices.

Figure 1 shows a longitudinal view of an induction motor with its constituent parts.
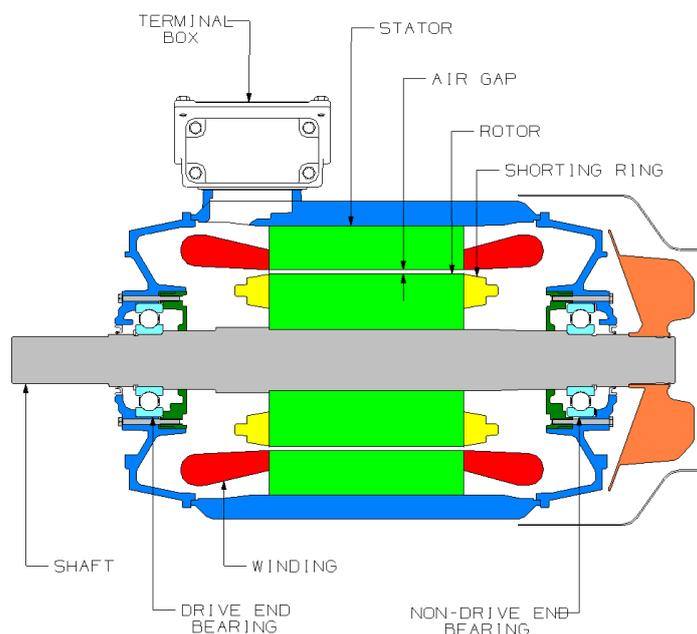
Figure 1 - Longitudinal view of an a.c. induction motor.

Shaft voltages arise from various sources in electrical machines, such as winding faults, unbalanced supplies, electrostatic effects, magnetised shaft or other machine members, and asymmetries of the magnetic field. Asymmetries in the magnetic field are caused by rotor static or dynamic eccentricity, non-complementary stator and rotor slotting or slot combinations, poor alignment, inappropriate manufacturing tolerances, uneven air-gaps, core assembly with non-annular laminations, poor slot punching, cooling ducts, keys and keyways, variations in permeability, etc.

3 SHAFT VOLTAGE AND BEARING CURRENT MECHANISMS

The two main causes that underpin the mechanism of generation of shaft voltages and bearing currents are:

- Asymmetries resulting from manufacturing tolerances
- Supply voltage effects.

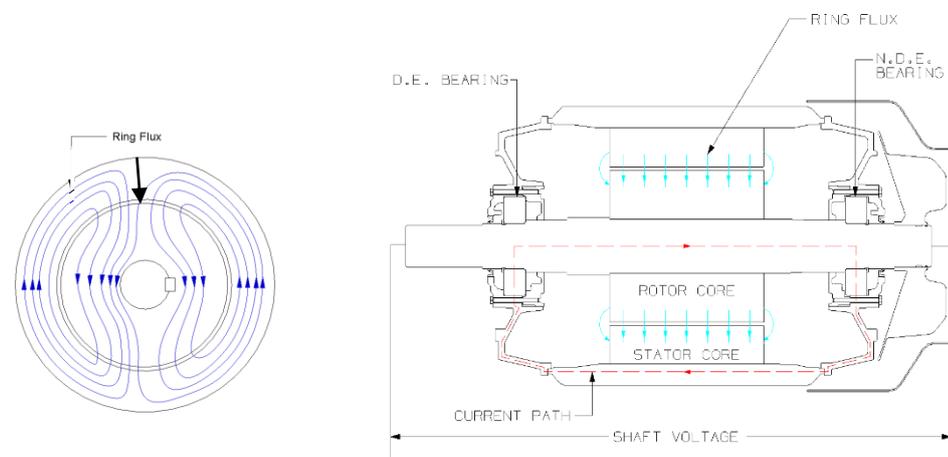### 3.1 SHAFT VOLTAGES DUE TO ASYMMETRIES

Even on pure sinusoidal supplies, asymmetries in the motor construction could cause various stray fluxes to be set up. These in turn manifest themselves in the form of shaft

voltages and if these are above the natural insulation levels of the bearings, circulating currents will exist.

3.1.1   RING FLUX LINKING SHAFT

The linkage of the alternating flux with the shaft is one of the most important causes of bearing currents. This flux flows perpendicular to the axis of the shaft and pulsates in the stator and rotor cores. It results from asymmetries in the magnetic circuit of the machine. The asymmetries arise from design and construction of the machine and from inaccurate alignment.

Normally, the flux from each pole crosses the air-gap and if the magnetic path is symmetrical, it divides equally, half clockwise and half anticlockwise. However, if there is a difference in the reluctance of the core in one direction compared with the other, there will be unequal division of the flux and a net flux linking with the circuit consisting of shaft, bearings and frame will exist (see Figure 2 (a)).


Figure 2 - (a). End view depicting asymmetric field (b). Showing shaft current and voltage due to asymmetric magnetic field

This ring flux is alternating and as such it establishes a potential difference between the ends of the shaft as shown in Figure 2 (b). If this potential difference is large enough to create an electrical breakdown in the bearing grease lubricating film, the thickness of which usually ranges from 1 μm to 20 μm, arcing occurs between the races and the rolling element. The resulting bearing current will cause bearing failure. In addition, experience has shown that dirt, microscopic metallic particles and irregular film thickness permit lubricant film to be bridged. Under this condition, the impedance of the bearing circuit is so low that small shaft voltages may cause substantial bearing currents.

3.1.2   HOMOPOLAR FLUXES BETWEEN STATOR, ROTOR AND SHAFT

Homopolar flux can be significant in larger machines, frame size 400 and above. It may result from an air-gap or rotor eccentricity and consequent permeance variation, leading to unbalanced ampere-turns surrounding the shaft. The path of the homopolar flux can be seen in Figure 3. The flux crosses the air-gap in one direction and leads to local bearing currents as shown in Figure 4.
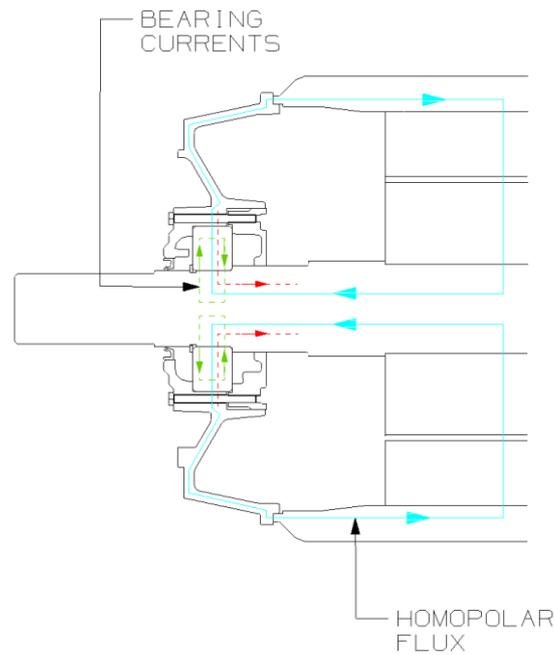
Figure 3 - Homopolar fluxes around stator, rotor and shaft
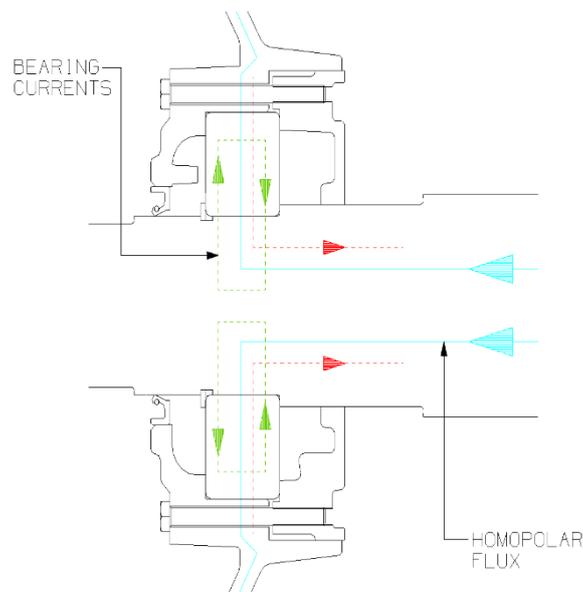
Figure 4 - Currents adding in a bearing

The homopolar flux crossing the air-gaps will generate an additional voltage as the shaft keys or keyways cut it, causing current to flow along the shaft, across the bearing and return via the bedplate and frame. At the inner region of the bearings, the circulating local bearing currents and shaft current combine. Hence, more current will flow in this region of the bearing than in the outer region. The bearing currents will have the same frequency as the homopolar flux.

There is no method of insulating bearings against homopolar voltages. It is only possible to reduce the magnetic flux by compensation in the form of counter ampere-turns (inverse magnetic circulation) or by increasing the magnetic reluctance. A reduction in the homopolar voltage can be achieved by careful adjustment of the air-gap during construction. To prevent current from flowing towards the driven equipment, a non-conducting coupling would be necessary. However, under the pure sinusoidal

supply condition the value is normally too low to warrant any remedial measure, except on large motors.

3.1.3 ELECTROSTATIC VOLTAGES

These are not due to the basic design of the machine but rather to do with special circumstances, for instance, low humidity environments, or the nature of application, e.g. belt and pulley driven loads.

The shaft voltage continues to build up until a discharge occurs through the bearings. Sometimes all that is needed is a little friction of a belt or pulley to set up electrostatic charges. Voltages originating from such sources are not usually a major problem.

3.1.4 OTHER CAUSES

Accidental, or irregular, contact of a part of the rotor winding to the rotor core can lead to stray currents through the shaft and bearings. This may result from damage to the insulation in an insulated rotor or intermittent contact of the bar in an un-insulated rotor, which is extremely rare in the die-cast rotor.

3.2 SUPPLY VOLTAGE EFFECTS

For operation on a balanced sinusoidal supply (compliant with EN 50160), there are no significant supply voltage effects. However, the use of frequency converters can introduce additional mechanisms of inducing shaft voltages, discussed in later sections.

4 BEARINGS AND BEARING LUBRICANTS

Induction motors typically have two bearings, which support and allow low-friction motion of the inner rotating shaft within the fixed outer stator housing. The normal bearing arrangement includes rolling elements, a bearing retainer to keep them in place, a bearing race that provides smooth inner and outer load surfaces over which the bearings roll, lubricant to reduce friction and aid cooling and an optional seal to keep out contaminants.

The most common types of bearings used in low voltage standard a.c. induction motor are

- Ball
- Roller

The choice of bearings depends upon the application: whether torque transmission is through direct or indirect coupling, the external loading, mounting arrangement, and environmental and electrical conditions.

The bearings need suitable lubricants for their smooth operation. The main duties of the bearing lubricants are:

- to reduce friction between the various elements of the bearing,
- to assist in dissipating heat generated within the bearings,
- to protect the highly polished working surfaces of the bearings from contaminants such as dust and moisture.

As will be discussed later, bearing lubricants can also be used to block the path of damaging high frequency currents, or, if conductive grease is used, to provide a low impedance path to the common-mode currents. Conductive greases tend to be less effective lubricants, and therefore must be used with care.

Bearings may be lubricated by grease or oil, with the choice of lubricant usually being decided upon by operating conditions and bearing design.

Grease lubricants are very widely used in low-voltage motors. It is usual to employ grease where temperatures are not excessive and the sealing arrangements do not

allow successful lubrication by oil. Whatever type of grease is used, it must not have a tendency to separate under the operating conditions.

Oil is generally considered to be a more effective lubricant and is preferred if the operating temperature or the surface speed is high. With the exception of motors for some special applications e.g. very high-speed operation, oil lubricants are very rarely used in low-voltage motors.

## 5   FREQUENCY CONVERTER DRIVES

The most common form of variable speed drive in the market place is the Voltage Source, PWM inverter drive.
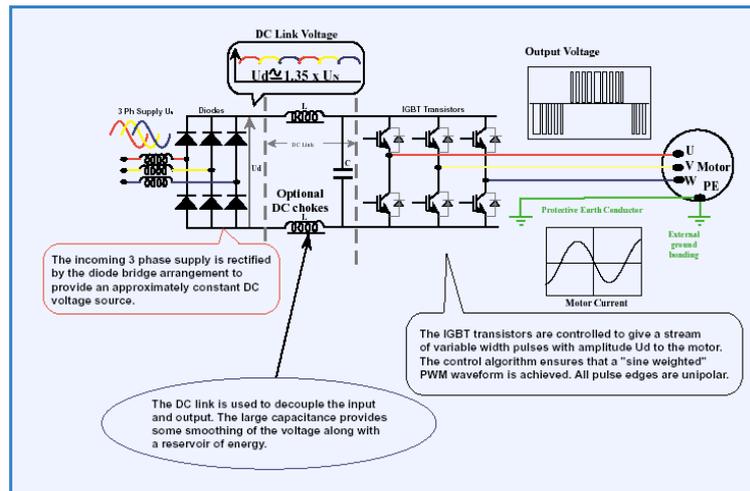
Figure 5 - Basic elements of voltage source inverter

In order to achieve the desired variable speed output from a motor the associated power electronics will include a means of rectifying the incoming mains supply to a smoothed d.c. in an intermediate link, which will incorporate some capacitive energy storage.

The inverter will then synthesise the d.c. back to an alternating voltage and fundamental frequency. Figure 5 shows the basic principles of the main circuitry.
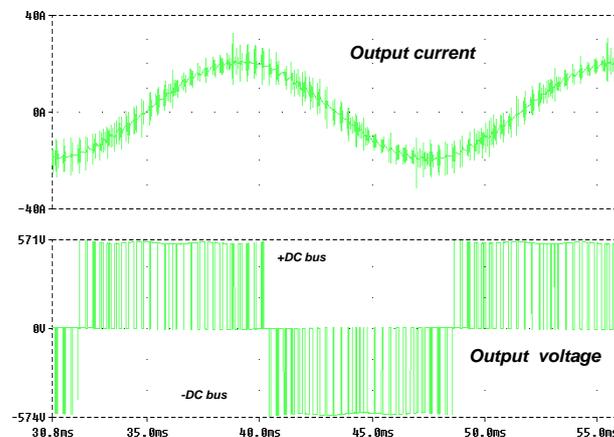
Figure 6 – Typical PWM voltage and current motor waveforms

The output voltage is generated as a pulse string, typically as shown in Figure 6. The resultant current is modified substantially by the motor inductance and consists basically of a sinewave at the fundamental frequency.

The magnitude of the d.c. link voltage Ud will normally lie between 135 % and 140 % of the incoming a.c. r.m.s. voltage, and this value is applied constantly, irrespective of the output r.m.s voltage.

This in turn implies that the peak to peak voltage applied to the motor is around 270 % of the a.c. r.m.s. value. The impedances of the system may allow some oscillation of the output waveform. The level of this oscillation will vary principally with the length and structure of the inverter-motor cable.
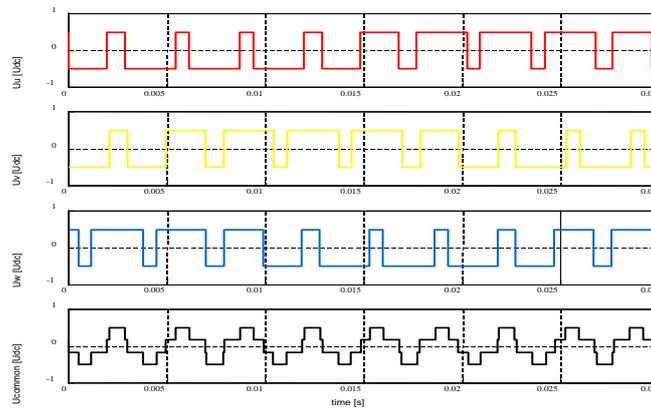
Figure 7 - Typical line voltages for the three phases, and common-mode voltage

In a sinusoidal network supply the vector sum of the three phases is normally zero. When a voltage is synthesised by an inverter there are a limited number of potential switch positions, and the switching pattern of the semiconductors is governed by a need to maintain acceptable switch positions. This leads to a non-zero neutral at the inverter output, which can be considered as a common-mode voltage source.

Figure 7 shows the inputs at the windings of a three phase motor relative to earth (Uu, Uv, Uw). The common-mode voltage is equal to 1/3(Uu + Uv + Uw), assuming no coupling capacitances.

The common-mode voltage is proportional in magnitude to the d.c. link voltage, and has a frequency equal to the inverter carrier frequency.

When designing an inverter, the aim is generally to use the highest practical switching rate, which will have the benefits of lower additional losses of the motor and lower audible noise.

Faster power devices will in turn give rise to shorter rise times, and therefore steeper wave fronts. This gives rise to higher rates of voltage change, with consequent overshoots and oscillations due to the impedances of the connecting cables and motor (see Figure 8). Table 1 lists typical relative values of pulse rise times compared to the power frequency and switching frequency periods.
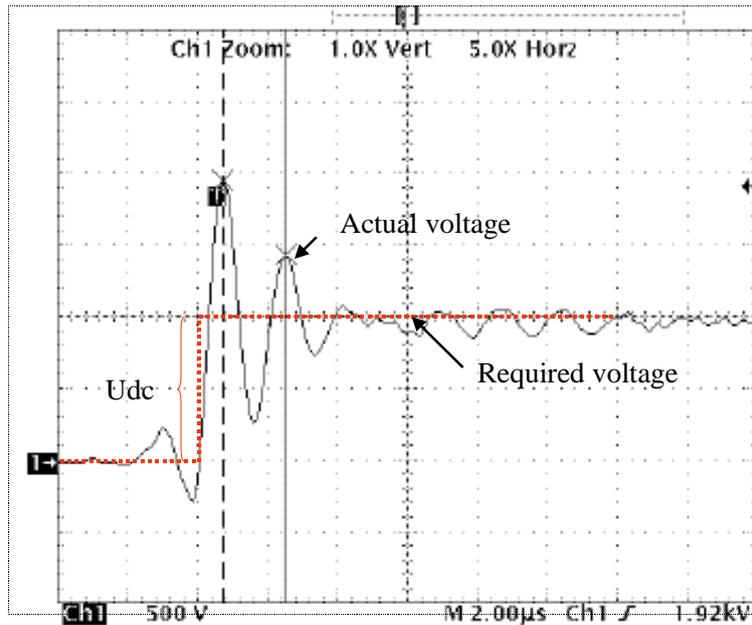
Figure 8 - Unfiltered output pulse edge from an IGBT inverter

Table 1 - Typical frequencies and times

|	Frequency (Hz)	Period/Time
Power frequency	50	20 ms
PWM switching frequency	3 000	333 μs
Pulse rise time	-	100 ns

6   DRIVE SYSTEM EFFECTS AND INTEGRATION

6.1   Sources and routes of bearing current caused by inverter operation

The previous section explains the typical output voltage waveform for a PWM inverter drive. When this is connected to a motor through a cable, the fast-changing voltage waveform causes pulses of current to flow in all of the stray capacitances at every voltage transition. The capacitance of the motor cable phase conductors to the earth conductor is often the highest in the circuit, but the most important capacitances in terms of bearing current are those within the motor:

- C_{sf} From stator winding to stator core and hence to motor frame
- C_{sr} From stator winding to rotor (i.e. through the stator slots, and from the end-winding)
- C_{rf} From rotor to stator core and frame

The stator windings are embedded in the laminated steel core, and separated from it by thin slot liners which have a relative permittivity of (typically) 3 to 4. The slots are quite narrow, the air-gap is larger than the slot-liner thickness, and the air has a permittivity of only 1. Therefore C_{sf} is much higher than C_{sr} – typically 50-100 times [7]. This is illustrated in Figure 9.

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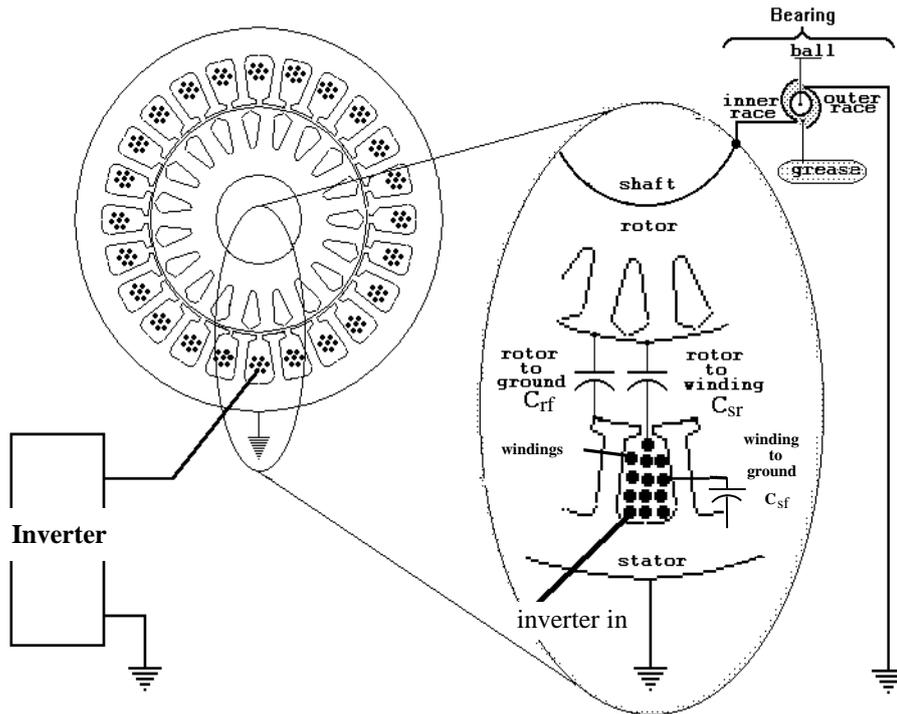
Figure 9 - Capacitances of motor winding

The common-mode voltage generated by the inverter causes pulses of current to flow in these capacitances, from the motor winding to the frame and rotor, which do not sum to zero as would three-phase current. The current pulses are very short, of the order of 1 µs, but the peak magnitude of the current in Csf may be up to 2 A peak, and their rise-time is also very short. This means that they can cause considerable voltage drops in the inductances of the power cable and the earth return arrangements. Figure 10 shows a typical current waveform.
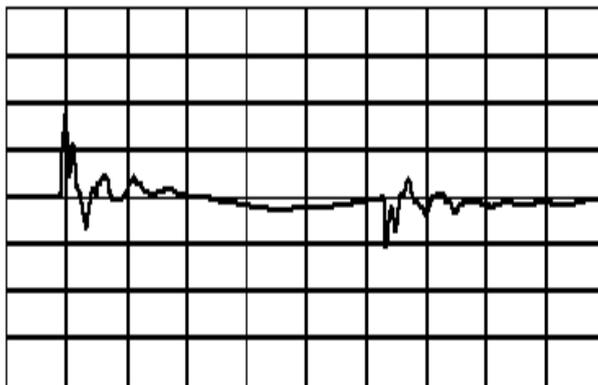
Scales:	
Vertical	500 mA/div.
Horizontal	5 µs/div.

Figure 10 - Typical waveform of motor frame earth current

The capacitive coupling can give rise to bearing current through two different mechanisms, which are generally referred to as capacitive discharge current and shaft grounding current. These are illustrated by the equivalent circuits in Figure 11 and Figure 14 respectively. Some published papers use different terminology, which can be confusing.

6.1.1 Capacitive discharge current

Current transferred to the rotor by capacitance Csr tends to return to the earthed stator through the bearings. This is illustrated in the equivalent circuit in Figure 11.
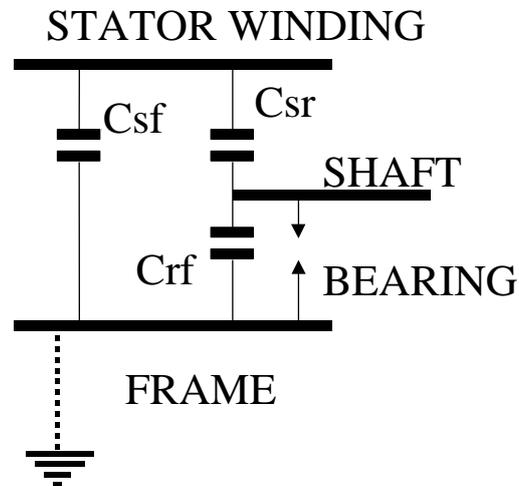

Figure 11 - Capacitive discharge current equivalent circuit

As explained above, Csr has a small value, and Crf is relatively large because of the rotor size and its proximity to the stator over its entire surface area. Therefore the voltage developed on the shaft is not normally sufficient to break down the bearing oil film, and the available charge is very limited. In some literature this particular mechanism of bearing current production is referred to as Electro-Discharge Machining (EDM). Although this form of bearing current has been discussed in the literature, and remedies such as conductive slot wedges have been proposed, it is generally recognised that shaft grounding current is a far more important source of bearing current. [8]

6.1.2 Common-mode current paths – earth current – shaft grounding current

The current in the capacitances returns to its source at the inverter drive through the earth paths. Where there are several possible routes, it divides between them in a proportion depending on their high-frequency impedance, which is mainly a function of their inductance. This is where the possibility of earthing-related bearing current arises. If there are earth paths present which pass through the bearings, and if the inductances are such that a significant part of the earth current flows through this route, then bearing damage may arise. Figure 12 illustrates the essential features of this effect.
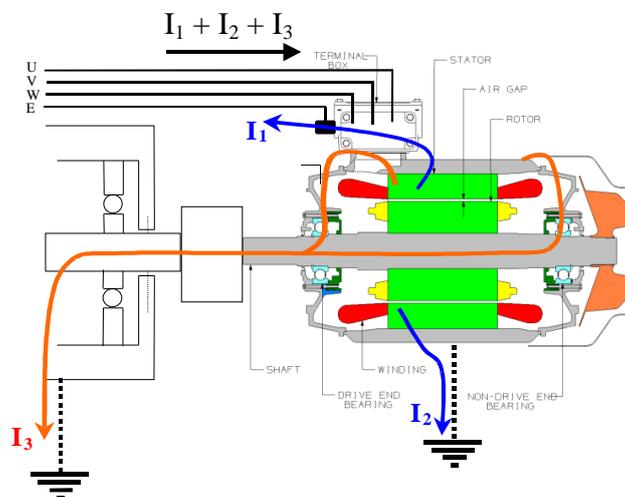
Figure 12 - Earth paths for high-frequency current

- I_1 is the current flowing into the designated earth return path to the inverter.

- I_2 returns to the inverter through an alternative path, such as the motor mountings. It does not pass through the bearings, and therefore is harmless to them - it may cause EMC (Electro-Magnetic Compatibility) problems.

- I_3 passes through the motor bearings to the shaft and hence to earth via the driven machine. I_3 may be harmful, as well as being a possible cause of EMC problems.

Figure 13 shows an overview of the complete system and earth paths.
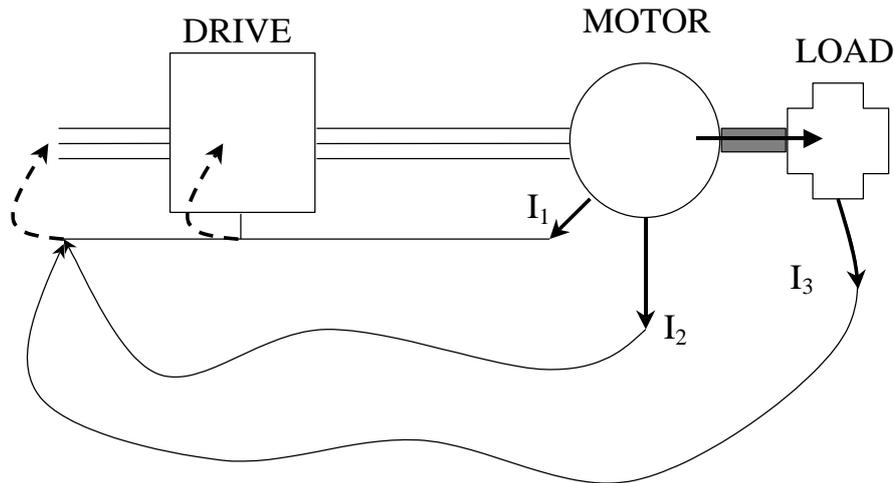
Figure 13 - Overview of potential earth current paths

The current paths shown dashed in Figure 13 are the return routes for high-frequency earth current to return to the supply. The flow of common-mode current in the supply may be responsible for electrical interference problems, and measures such as filters are used to ensure that the return route is restricted to within the drive system.

Figure 14 shows an equivalent circuit. The inductance Lfe represents the inductance of the two parallel earthing paths which carry I_1 and I_2. The circuit shows how the earth currents $I_1 + I_2$ result in a voltage on the motor frame relative to earth, which can cause a current I_3 to return to earth through the bearing and shaft. Part of I_3 flows in Crf and is harmless, but if the voltage across the bearing is sufficient then it may suffer dielectric breakdown and carry current, with resulting damage. Note that in this case the source of the current is coupling through Csf, which has a much higher value than Crf and therefore passes a higher current for a given rate of change of stator winding voltage. This is why shaft grounding current, if it occurs, is more serious than capacitive discharge current.

STATOR WINDING
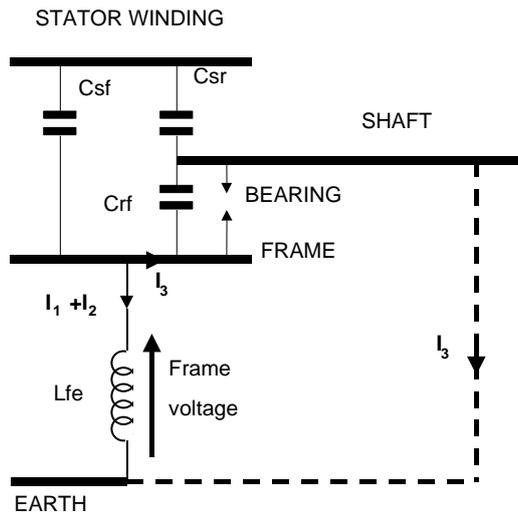
Figure 14 - Shaft grounding current equivalent circuit

The relative values of I_1, I_2 and I_3 depend on the relative impedances of their paths. To minimise I_3, it is necessary to ensure that the paths for I_1, and to some extent I_2, have much lower impedance than the paths for I_3. At the high frequencies associated with modern inverters, the impedances are predominantly inductive.

The problem of earthing for high frequencies is well understood from EMC considerations, and to a considerable degree the solutions are the same – ensuring a low-inductance earth path returning from the motor frame to the inverter drive, and using screened cable whose mutual inductance effect minimises the earth difference potential. In addition, provided the potential of the driven machinery is the same as that of the motor frame, there will be no tendency for earth current to flow through the bearings. Therefore the provision of low-inductance connections between the motor frame and the driven machine is the single most effective precaution required. This is illustrated in Figure 15, where it can be seen that the direct earth connection between the motor frame and the driven machine prevents a potential from appearing across the bearing. The current I_3 still flows into the driven machine, but does not pass through the shaft and bearings.
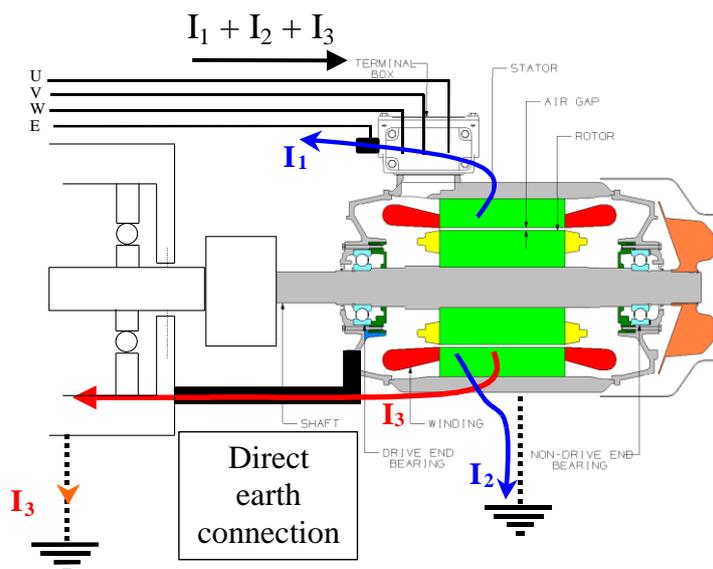
Figure 15 - Addition of direct earth connection between motor and driven machine, to prevent shaft grounding current

Inductance of cables

The inductance of a conductor depends on its dimensions and also on the geometry of the complete current circuit.

For a complete circuit, the inductance is a function of the area enclosed by the circuit. This can be reduced by running the conductors together in the same cable – e.g. with unscreened cable the earth conductor should be in the same cable as the phase conductors. However a screened construction is superior to any other, the external inductance of the total cable being very close to zero.

For an individual conductor, its inductance is minimised for a given cross-sectional area by using a wide, flat shape. In some cases it is more practical to use two or more round conductors of smaller cross-section, rather than a single larger one. The objective is to provide current paths which are not magnetically coupled, so that changing current in one path does not contribute an e.m.f. in the others.

Note that the use of a flat conductor alone does not automatically give low inductance unless the area of the complete circuit is kept to a minimum.

6.1.3   Circulating current

In the explanation given above, it has been assumed that the current flows uniformly from the three phases to the motor body through the motor stray capacitance. In fact the precise path of the current flow within the motor is complex, because the capacitance is distributed along the winding, and the shape of the pulse edges changes as they propagate along the winding. The propagation is not normally geometrically symmetrical since the winding terminations are naturally at one end of the stator. Consequently there is a component of high-frequency current, which is not symmetrical with respect to the rotor, i.e. the currents in opposite arms of the coils are not the same. This causes voltage to be induced in the rotor-bearing-frame-bearing loop by transformer action, which can result in a circulating current [8]. Figure 16 shows a simplified illustration of the effect in the motor, and Figure 17 shows an equivalent circuit.
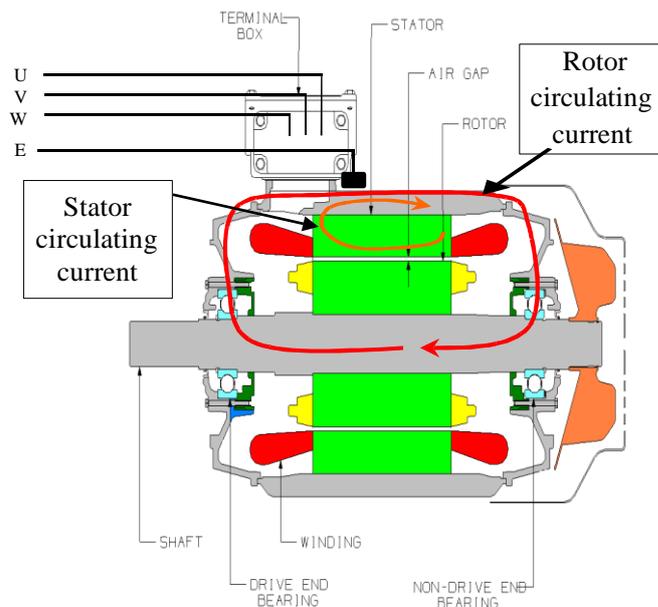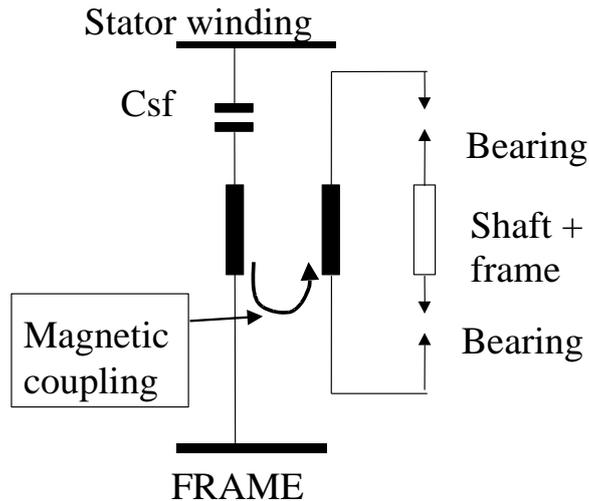

Figure 16 - Induction of rotor circulating current

Figure 17 - Equivalent circuit for circulating current

Unlike the earth current, this circulating current is a function of the geometry of the motor and is not affected by earthing arrangements. The magnitude of the current depends on the dimensions of the coils relative to the velocity of propagation of the pulses, and their rise-times. In practice the effect is significant only for motors of frame size 280 and above.

6.2 Mounting

The method of mounting the motor on the driven machinery affects the possibility of bearing current. Shaft grounding current will not occur if there is direct metallic contact between the motor and the load over a large area. If the motor and driven machinery are in direct contact then their frames are at the same potential, so there is no potential available to drive the undesirable current I_3 through the bearing.

The worst mounting arrangement would be where the motor frame makes no contact with the driven machine. This is relatively unusual, but cases may arise where gaskets or other insulating material prevent a good connection. In this case a potential equalising connection must be made between the motor and the load, as illustrated in Figure 15.

Circulating current could flow in the bearings of the driven machine as well as the motor drive-end bearing. This is minimised by the use of an insulated non-drive-end bearing.

6.3 Motor cable

The motor cable has a considerable capacitance between its power cores and earth, so high-frequency current flows to earth in the cable. This current should return to the drive earth directly, and not contribute significantly to motor bearing current. However if earthing practice is poor, so that the motor cable earth connection at the inverter has a high inductance, the cable current will increase the motor earthing current. A long motor cable with poor earth connection at the drive end could cause a major increase in bearing current.

A screened motor cable is very desirable for EMC reasons, and it also minimises motor frame potential because the magnetic coupling between its inner and outer conductors encourages most of the motor frame current to return to the inverter rather than take other paths. This is only effective if the cable is connected in the correct manner for EMC, i.e. the screen must be connected by the shortest practicable link to the motor frame and to the earthed metal parts of the inverter. Ideally, these connections should be made by EMC glands, giving a 360° contact.

6.4 Effect of rate of change of voltage (dv/dt)

It is possible to control the inverter output dv/dt, usually by some form of output filter. Reducing the dv/dt reduces the bearing currents related to inductive effects, i.e. the shaft grounding current and circulating current. It is the rate of change of the common-mode voltage, which needs to be reduced, so the filter needs to be effective in the common-mode. Reducing the dv/dt does not affect the capacitive discharge current because this is purely determined by the division of charge between the stator and rotor and is independent of inductance.

6.5 Bearings and the effect of bearing voltage and current

Bearings operate with thin films of lubricant (typically 1 µm – 20 µm) between the moving surfaces. The lubricant is generally an electrical insulator and the breakdown voltage is typically of the order of 30 V- 50 V. In addition, experience has shown that dirt, microscopic metallic particles and irregular film thickness permit the lubricant film to be bridged occasionally.

If current flows in the bearing either because the lubricant is momentarily bridged or because electrical breakdown occurs, its magnitude depends on the source impedance of the voltage source. With low-frequency magnetically induced sources such as the homopolar effect, the impedance is very low and the current may be enough to cause rapid destruction of the bearing. With capacitive effects the impedance is much higher so that deterioration is by a progressive erosion of the bearing surface.

The principal effect of bearing current is the damage caused by arcing across the bearing surface. As electric current passes through the surfaces in contact, the flow is concentrated through the contacting points, and the local current density can be extremely high (a tolerable level is considered to be 1 A/mm^2). The main consequence of arcing is the wear of the bearings and journal due to the removal of fused metals in the arc, resulting in closely pitched marks and burned craters. By this roughening of the surface the mechanical wear is considerably accelerated. The arcing causes the lubricating grease to lose its purity by oxidation, the mechanical roughening of the bearing surface and the liberated metallic particles all result in its rapid ageing and premature breakdown.

Inverter-induced discharge often results in a characteristic "fluted" appearance, as shown in Figure 18. With the capacitive discharge and bearing earthing current mechanisms the impedance is capacitive so that when the bearing film breaks down there is a short pulse of current which rapidly discharges the capacitance. The energy released is proportional to the capacitance, and is much higher for the bearing earthing current (Csf) than for capacitive discharge (Crf in parallel with Csr).

Figure 18 – 'Characteristic 'fluting' wear of inner race

7 MITIGATION MEASURES

The selection of the most appropriate measures will depend to a large extent on the installation, the supply voltage and power. It is also possible to transfer potential problems from one area of a machine to another, and extreme care must be taken in the selection of the appropriate techniques.

A comprehensive range of possible solutions is detailed as follows:-

- Apply rigorous installation procedures
- Modify the switching frequency
- Use an insulated bearing
- Modify the inverter waveform
- Install a shaft grounding system
- Apply conductive lubrication grease
- Install a Faraday shield in the motor

Some details of these are given in the following paragraphs, which are followed by a summary of the techniques and practical measures to minimise problems.

7.1   Electrical installation

This is perhaps the most important element of achieving good bearing life. As with mechanical issues (mis-alignment etc) correct electrical installation is very important although these aspects can be somewhat easier to overlook. Good practice installation techniques are essential in any case to avoid potential problems with EMC. The same principles conveniently reduce the bearing current.

The principle is to ensure the lowest possible impedance path on the shield connection to avoid stray currents travelling through the bearings back to ground. Ground potential equalisation techniques (i.e. high frequency bonding) should be applied between the VSD, the motor and the load. This technique dramatically reduces the chance of shaft grounding currents.

This essential measure is practical and cost effective. Manufacturers offer detailed guidance on correct installation techniques.

7.2   Modify the switching frequency

Modern inverters use switching frequencies of around 2 kHz – 20 kHz. Most inverters allow the switching frequency to be modified. For increased switching frequencies, the frequency of any damaging events is also increased. In many cases, the switching frequency may be reduced without compromising the overall application (performance, motor heating, audible noise etc). This has an additional benefit of reducing EMC emissions.

7.3   Use of insulated bearings

This traditional technique of insulating one bearing (normally NDE) is used to reduce the problems associated with mains frequency generated bearing currents associated with magnetic asymmetries.   Typically, a thin coating (50 μm - 300 μm) of high performance insulation medium is plasma sprayed onto the outer surface of the bearings as can be seen in Figure 19.
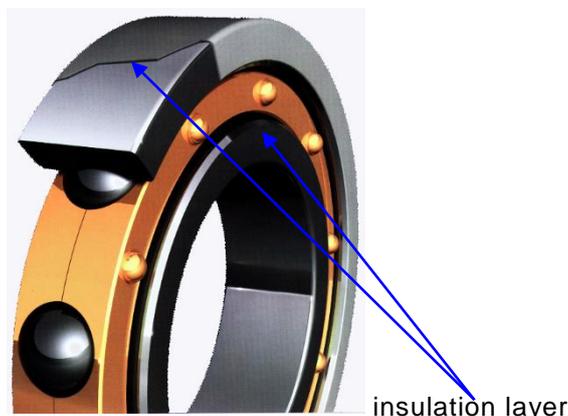
insulation layer

Figure 19 - Insulated bearing showing the insulation layer

This may not eliminate the issues of higher frequency currents as capacitive displacement currents could still potentially pass through the thin insulation layer. The capacitance of the bearing insulation must be low enough to minimise the value of any stray current. More exotic insulated bearing solutions such as composite or ceramic bearings may offer a more effective technique for highly specialist applications. Due to cost and standardisation issues, these solutions are unlikely to be offered by motor manufacturers as standard fittings.

Alternative approaches are to use insulated bearings in conjunction with reduced switching frequency and dv/dt filters, or to use standard bearings within an insulated bearing housing. The thickness of the insulation is normally sufficient to prevent the bearing currents. As well as being supplied as a factory fitted option on larger motors, this solution can sometimes be retrofitted to existing motors.

If the rotor can be adequately isolated from the stator by two insulated motor bearings, the high frequency capacitive discharge currents will seek to find the lowest impedance ground. In this case, shaft currents could possibly flow through to the load and compromise the life expectancy of other bearings - unless insulated couplings are also used.

One must also be particularly careful with accessories such as tachogenerators etc. Reports have been made that these devices may unwittingly be used as sacrificial protective elements offering a path to the shaft currents (reducing the main bearing currents). This very expensive "solution" should be avoided! (use an insulated coupling for the accessory).

7.4   Modify the inverter waveform

It is possible to modify the inverter output waveform electronically or by using a variety of inverter output inductors or filters, which are specially designed to minimise the high frequency common-mode disturbance voltages. Without the excitation of the high frequency parasitic elements, bearing currents are dramatically reduced. The disadvantages of such filters are the costs and practicalities involved in installing such devices in the inverter output circuit.

A range of standard chokes and filters (ranging from simple dv/dt filters through to sinusoidal output voltage filters) are often applied for other reasons - for example:-

- To mitigate capacitive cable charging currents due to long motor cables

- To reduce motor peak voltages

- To minimise motor audible noise etc

- To reduce EMC emissions

Although it is not their primary design purpose, these measures will also have a beneficial effect in reducing bearing currents.

Common-mode output filters (for example ferrite rings around the motor cables) have also been shown to offer a beneficial effect by reducing the magnitude and frequency of the high frequency current.

The application of filters to drives will result in a volt drop, and the drive output may be limited. Typically a Sinusoidal output filter can have a volt drop between 30 and 60 Volts on a low voltage system.

Output filters may also be necessary with long motor cables to limit earth leakage currents and prevent overloading the input RFI filters.

7.5   Install a shaft grounding system

This technique has been applied for a number of years to reduce the low frequency currents associated with the homopolar effects of stator/rotor magnetic asymmetry. The application of such devices has typically been limited to multi - megawatt high voltage

machines and is very infrequently applied in Europe to standard low voltage motors, although it is reportedly more widely used in the USA. Drawbacks include an extra piece of equipment to install with additional maintenance, additional cost and the possibility of contamination, in addition there is no provision made in the standard motor dimensions, therefore a special construction may be required. This method requires verification in cases of motors already having one insulated bearing as eddy current effects could cause currents to flow through the uninsulated bearing. In some applications, such as motors for potentially explosive atmospheres, it is not feasible to add such devices without certification.

7.6 Apply conductive lubrication grease

Conductive greases can provide a low impedance path thereby preventing the potential across the bearing from rising. Due to the very thin grease films involved, and the issue of bearing asperity contact, this is unlikely to offer a practical solution. In any event, the particulates added to make the grease conductive, create additional abrasion and may well yield impaired bearing lifetime. Potentially, IF these limitations could be overcome, a high conductivity grease could offer a good solution.

7.7 Install a Faraday shield in the motor

Evaluations have been made with motors having a Faraday shield in the stator/rotor air-gap to minimise the high frequency parasitic coupling between the stator and the rotor. Typically this is achieved by introducing grounded (high frequency) copper foil shields between the rotor and stator - carefully installed to avoid shorting the stator laminations. This technique does not prevent circulating current effects or shaft grounding currents. There are considerable additional costs and manufacturing problems associated with this technique - which would be unjustifiable for the majority of applications or for mains supplied motors. These factors probably preclude its use as a standard solution in the foreseeable future.

7.8 Summary of mitigation measures

Table 2 - Summary of the potential mitigation measures

	Counter-measure	Current type			Additional comments
		Circulating currents	Shaft grounding currents	Capacitive discharge currents	
1.	Installation procedure	Correct installation and grounding procedures are essential to limit the problem			
2.	Frame to driven load connection	Not effective	Effective	Not effective	Also prevents possible damage to driven load.
3.	Modify switching frequency	Limits effects	Limits effects	Limits effects	Lowest practical switching frequency reduces numbers of damaging events. Generally used in conjunction with other measures.
4.	NDE insulated, or ceramic rolling elements	Effective	Not effective: Only protects one bearing.	Not effective: Only protects one bearing.	NDE insulated to avoid need for an insulated coupling.
5.	a. Modify inverter waveform, or b. output inductors, or c. output dv/dt filter	Limits dv/dt effects	Limits dv/dt effects	Limits dv/dt effects	Reducing rate of rising edge of switching pulses reduces magnitude of damaging events. Generally used in conjunction with other measures.

	Counter-measure	Current type			Additional comments
		Circulating currents	Shaft grounding currents	Capacitive discharge currents	
6.	a. Common-mode voltage filter, or b. sinusoidal filter	Effective: Reduced HF voltage also decreases LF currents.	Effective	Effective	Greatest reduction of common-mode voltage if filter fitted at converter output.
7.	NDE and DE insulated, or ceramic rolling elements	Effective: One insulated bearing is adequate for this current type.	Effective	Effective	Most effective for small frame sizes. Less practical for large frame sizes. Does not protect bearings in driven load. May require additional countermeasures
8.	NDE and DE insulated, or ceramic rolling elements + Insulated coupling	Effective	Effective	Effective	Most effective for Low Voltage motors up to 500 kW. Less practical for large frame sizes. May require additional grounding brush.
9.	Insulated coupling	Not effective	Effective	Not effective	Also prevents possible damage to driven load.
10.	NDE insulated + One DE grounding brush contact	Effective: Brush unnecessary for this current type. NDE tachometer bearing, if fitted, needs protection.	Effective: Care needed to ensure low brush contact impedance Does not protect bearings in driven load.	Effective: Care needed to ensure low brush contact impedance.	Servicing necessary. Not practical for the majority of standard motors. DE brush used to avoid insulated coupling.
11.	One grounding brush contact No bearing insulation	Not effective: Only protects one bearing.	Effective: Care needed to ensure low brush contact impedance Does not protect bearings in driven load.	Effective: Care needed to ensure low brush contact impedance.	Servicing necessary. Not practical for the majority of standard motors.
12.	Two grounding brush contacts, DE and NDE No bearing insulation	Effective: Care needed to ensure low brush contact impedance.	Effective: Care needed to ensure low brush contact impedance Does not protect bearings in driven load.	Effective: Care needed to ensure low brush contact impedance.	Servicing necessary. Not practical for the majority of standard motors.
13.	Low resistance lubrication and carbon-filled bearing seals	Poor	Poor	Effective: Depends on condition of materials.	No long term experience. Lubrication effectiveness reduced.
14.	Rotor in Faraday cage	Not effective	Not effective	Effective	Problems from converter generated circulating currents that normally only occur in larger motors.

Counter-measure	Current type			Additional comments
	Circulating currents	**Shaft grounding currents**	**Capacitive discharge currents**	
NOTE - DE = Drive End; NDE = Non Drive End				

7.9 Costs of mitigation measures

An indicative summary of the relative cost of mitigation measures is shown in Table 3.

Table 3 – Relative cost of mitigation measures

Motor rating (kW)	Mitigation measure	Relative cost (Motor = 100%)
2.2 to 75	• Installation strictly in accordance with manufacturers instructions (mitigation measure 1) • Lowest practical switching frequency (mitigation measure 3)	No additional cost
All higher ratings	• Installation strictly in accordance with manufacturers instructions (mitigation measure 1) • Lowest practical switching frequency (mitigation measure 3)	No additional cost
90 (or > 280 frame)	Preferred additional measure • NDE insulated bearing (mitigation measure 4)	15%
	Option 1 • Output inductors (mitigation measure 5b.)	30%
	Option 2 • Output dv/dt filter (mitigation measure 5c.)	35%
	Option 3 • Output sinusoidal filter (mitigation measure 6b.)	65%
250	Preferred additional measure(s) • NDE insulated bearing (mitigation measure 4) • If > 500 V supply add Common-mode filter (mitigation measure 6a.)	10%
	Option 1 • Output dv/dt filter (mitigation measure 5c.)	20%
	Option 2 • Output sinusoidal filter (mitigation measure 6b.)	35%
400	Preferred additional measure • NDE insulated bearing (mitigation measure 4), and Common-mode filter (mitigation measure 6a.)	5%
	Option 1 • Output sinusoidal filter (mitigation measure 6b.)	25%

IMPORTANT NOTES:-

• Before fitting any mitigation measure consult the equipment manufacturer.

• Insulated bearings may be retro-fitted to replace standard ball bearings, before proceeding consult motor manufacturer.

• Output inductors may be incorporated into larger drives as standard option. Check with the supplier.

• Filters will affect system performance, Check with the supplier.

• Percentage costs are indicative values only.

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