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Harmful high frequency effects in low voltage electrical drives and methods for their mitigation

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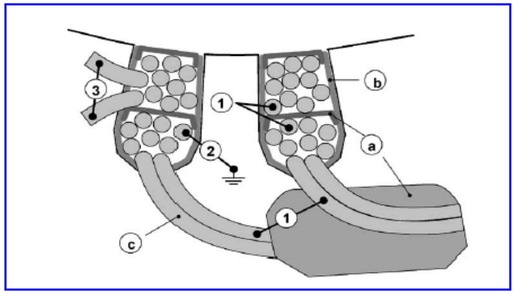
Outline

1) Presentation of two very current issues, arising from the additional stresses produced by the inverter power supply of the electrical machines:
   - i. **Short circuits in stator winding supplied at low voltage;**
   - ii. **Bearing currents in small and medium size motors.**
2) For these two types of fault, we will not discuss about the possible diagnostic techniques to detect them, since their diagnosis is very difficult with standard measurements and with the current diagnostic methods, especially due to the fact that both faults quickly progress until a failure.
3) Conversely, we will investigate the phenomena which arouse these faults and the methods to mitigate or eliminate them.

The issue of short circuits in stator windings supplied at low voltage by an inverter drive

Insulation of the winding supplied at low voltage



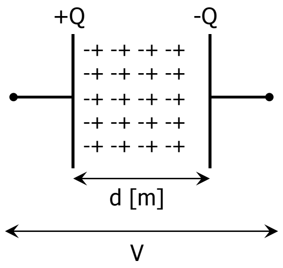
1) Phase-to-phase voltage	a) Phase insulation
2) Phase-to-ground voltage	b) Ground insulation
3) Turn-to-turn voltage	c) Turn insulation

➡ Let us to understand why a high voltage and a high dv/dt can destroy the insulation.

Characteristics of the insulating materials

The dielectric materials <u>subjected to the action of an electric field</u> are **polarized** with an intensity which is directly proportional to the value of the electric field.

Polarization means the electrical deformation of the molecules of the material, i.e. the displacement of the electric charges within each molecule in the direction of the electric field.



These displacements of electric charges are comparable to the displacements of the particles of an elastic medium under the action of deforming forces.

Characteristics of the insulating materials

For a given electric field, each insulating material polarizes with a certain degree strictly dependent on its molecular structure.

The higher the degree of polarization of the material, the higher the value of its absolute **permittivity** ε, which can be expressed as a product between the permittivity of the vacuum ε_0 and the relative permittivity ε_r (**dielectric constant**) of the material:

$$\varepsilon = \varepsilon_r \varepsilon_0 \text{ [F/m]} \qquad \varepsilon_0 = 8{,}86 \cdot 10^{-12} \text{ F/m}$$

If the insulating material is homogeneous, its permittivity is a constant value, independent on the amplitude and on the frequency of the electric field applied to the material and on the temperature.

The relative permittivity suggests the predisposition of a material to transmit (or allow) an electric field: a <u>good dielectric, used as insulator, must have low permittivity</u>.

Characteristics of the insulating materials

The <u>electrical polarization forces</u> are <u>balanced</u> by the <u>internal molecular reaction forces</u> which bond the electric charges of the individual molecules, in the same way as the deforming forces applied to an elastic medium are balanced by its internal elastic reaction forces.

If the electric polarization forces reach values which cannot balanced by the internal molecular reaction forces, the phenomenon of **disruptive discharge** happens, with <u>dielectric perforation</u>, similar to the breaking phenomenon of an elastic medium stressed by deforming forces greater than its elastic reaction forces.

Therefore, when a certain value of the electric field is reached, the dielectric material loses its insulating characteristics, as an elastic body breaks if subjected to excessive mechanical stress.

Characteristics of the insulating materials

In fact, an increase in the intensity of the electric field corresponds to an increase in the electric polarization forces that stress the peripheral electrons of the atom.

When the internal molecular reaction forces, which bond the peripheral electrons to their nucleus, are no longer able to balance the forces due to the external electric field, the electrons escape to the action of their nucleus becoming free and thus causing an <u>electrical current</u> in the material.

This current, practically instantaneous, is called **electric discharge**.

It is able to create significant thermal and luminous effects and to lead to <u>temporary or permanent loss of the insulating properties of the material</u>, depending on the type of material and on the magnitude and duration of the application of the electric field.

Dielectric strength

The value of the electric field corresponding to the discharge voltage is called **dielectric strength** and it is expressed in V/m or, in practical units, in kV/mm.

The dielectric strength of a material is a function of several factors including:

- homogeneity and purity of the material,
- humidity and temperature,
- type of stress (trend and duration of the electric field).

Therefore, the dielectric strength is not exactly a constant of the material, but an indicative parameter about its ability to withstand electric fields.

Dielectric strength

In particular:

- the dielectric strength decreases considerably with the increase of temperature and duration of the applied voltage.
- the dielectric strength of mineral oil decreases considerably even with small traces of moisture.
- the dielectric strength of the most common gases is similar to that of the air and increases proportionally to their density.

In practice, the insulation of a machine (or a system) should be sized in order to obtain that the maximum electric field, to which the insulator is subject in normal conditions, is less than half the dielectric strength of the insulator (and even lower if the desired degree of reliability is greater).

Dielectric strength and partial discharges

Some indicative values of dielectric strength E_r and dielectric constant ε_r of the most commonly used materials as insulators are:

- Air E_r = 3 kV/mm ε_r = 1.0006
- Mineral oil E_r = 20 kV/mm ε_r = 2.2
- Porcelain E_r = 30 kV/mm ε_r = 6
- Polyethylene E_r = 40 kV/mm ε_r = 2.3
- Mica E_r = 100 kV/mm ε_r = 7

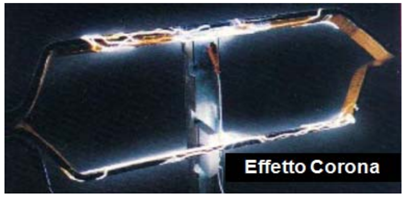
Since the dielectric strength of the air is lower than that of any non-gaseous insulator, it is clear that, in presence of voids inside (or around) the insulation, **partial discharges** may occur: these discharges are named "partial" since they involve only a part of the thickness of the insulation. They do not cause the total discharge of the insulation, but they can accelerate the deterioration of the insulating material.

Corona discharge

A particular case of partial discharge is the "**corona discharge**": this phenomenon occurs when the air surrounding a conductor loses its insulating properties close to its surface.

This occurs when the intensity of the electric field exceeds the value of the dielectric strength of the air.

During the manifestation of this phenomenon, a bright crown due to the ionization of the air is sometimes visible around the conductor.



Partial discharges

Partial discharges are defined by IEC 60270 (High-voltage test techniques - Partial discharge measurements) as:

"Localized electrical discharges that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor.

Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation.

Generally, such discharges appear as pulses having a duration of much less than 1 μs."

A partial discharge can occur in the voids of a solid insulation, in gas bubbles in insulating liquids or between dielectric layers of different characteristics.

It can also occur on acute sharp tips or edges of metal surfaces.

Short circuits in stator winding supplied at LV

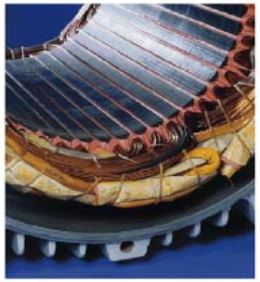
The short circuits in the stator winding can occur:

1) between turns of the same phase (**turn-to-turn**);

2) between turns of different phases (**phase-to-phase**);

3) between turns and stator core (**phase-to-ground**).

1) Short circuit between turns of the same phase:



2) Short circuit between different phases:

3.a) Short circuit between turns and stator core at the end of the slot:

Short circuits in stator winding supplied at LV

3.b) Short circuit between turns and stator core in the middle of the slot :

Short circuit on the connections:

Short circuit of the overall winding:

Short circuits in stator winding supplied at LV

Generally, a stator winding insulation failure begins with a short circuit between turns that involves few turns within the same coil.

With a **turn-to-turn** short circuit, the motor can continue to run, but for how long?

This short circuit generates a high circulation current in the short circuited turns, which causes localized heating and favors a rapid diffusion of the fault to a greater section of the winding.

If not detected, the fault between the turns can propagate and cause **phase-to-phase** or **phase-to-ground** failures.

With phase-to-phase or phase-to-ground short circuit, the motor cannot operate and the protective devices disconnect it from its power supply.

Diagnostics of the short circuits at LV

In low-voltage machines, the time between a **turn-to-turn** short circuit and a **phase-to-phase** or **phase-to-ground** short circuit can take few minutes or few hours, depending on the severity of the fault and on the motor load. So this is a quickly progressive fault.

To avoid **phase-to-phase** or **phase-to-ground** short circuits in low-voltage machines, the only solution is to detect the **turn-to-turn** short-circuits through an online diagnostic technique.

For LV machines, many manufacturers and operators argue that there is no diagnostic tool that is worth being used to detect **turn-to-turn** short circuits: their idea is that, if a motor starts to fail, it will continue to work until it will breakdown and therefore it will be substituted.

But this principle could be valid only if the failure of the motor will not damage the rest of the system and if there is a spare part of the same motor immediately ready to start to work.

Causes of the stator short circuits

In general, both in low voltage (< 700 V) and high voltage (≥ 700 V) machines, the stator short circuits can be caused by the combination of different stresses:

- ✓ **T**hermal: aging, overload, frequent start-ups, obstructed ventilation, high external temperature.
- ✓ **E**lectrical: overvoltage, rapid transient.
- ✓ **E**nvironmental: humidity, chemical products, external objects, impurity.
- ✓ **M**echanical: movement of the winding, vibrations, rotor-to-stator rubbing.

In this lecture we will focus on the electrical stresses.

A.H. Bonnett, G.C. Soukup, "Cause and analysis of stator and rotor failures in three-phase squirrel-cage induction motors", *IEEE Transactions on Industry Applications*, 1992, Vol. 28(4), pp. 921-937.

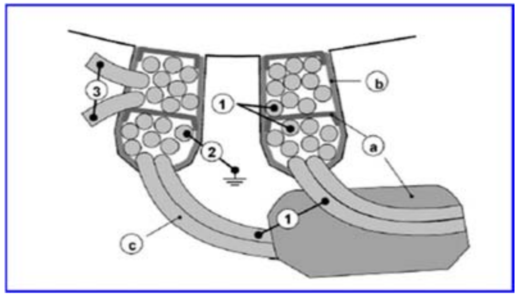
Electrical stress

The electrical stresses in low-voltage machines are mainly due to:

1) Voltage amplitudes to which the different parts of the winding are subjected:

Type of voltage	Maximum voltage at the motor input terminals (V_{peak})					
				Example for V_{line}=400 V_{rms}		
	Phase to ground (frame) (2)	(1) Phase to phase	(3) Turn to turn	(2) Phase to ground	(1) Phase to phase	(3) Turn to turn
Sinusoidal voltage, V_{line} (V_{rms})	$\sqrt{2}\,V_{line}/\sqrt{3}$	$\sqrt{2}$ Vline	($\sqrt{2}$ Vline/$\sqrt{3}$)/N	± 327	± 566	± 327/N

N = number of turns per phase.



The weaker part is the turn-to-turn insulation, whereas the phase-to-ground and the phase-to-phase insulation are generally over-sized.

Electrical stress

2) Voltage transients which can occur also as a consequence of a power converter supply.

Depending on the inverter pulse frequency, the cable length between the motor and the inverter and the stator winding structure, the voltage at the motor terminals can reach peak values even over twice the DC bus voltage.

The voltage between turns can reach the 40÷70% of the voltage at the motor terminals and can destroy the insulation.

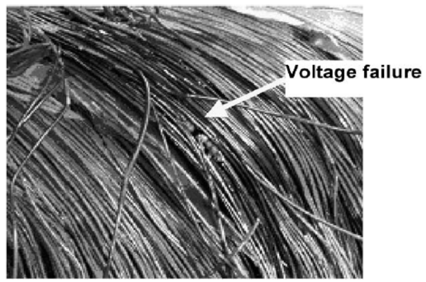
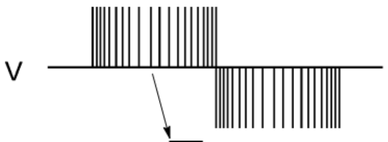


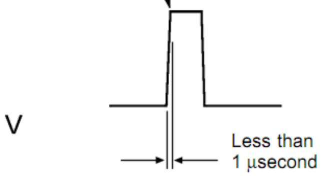
Fig. 6. Winding failure due to voltage spike.

Windings supplied by inverter

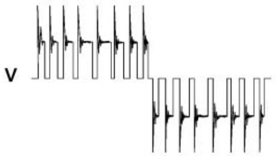
For the motors supplied by inverter, the additional problems besides those common to the motors supplied by the grid are mainly related to:



High Frequency Switching
Pulse Width Modulation attempts to simulate a sine wave by firing many full voltage pulses in rapid succession. To minimize noise, the frequency can sometimes be raised to 20,000 pulses per second.

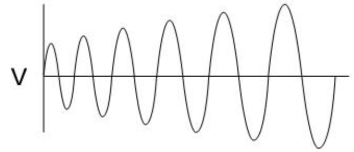


Short Rise Time
To get higher modulation frequency, each pulse must be very short and the inverter output goes from 0 volts to 650 volts DC in one–millionth of a second. This can seriously stress the motor's insulation system.

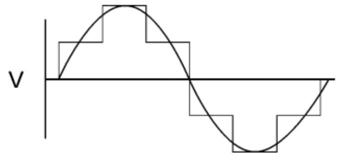


Transient Voltage Spikes
This is what the motor sees as the voltage pulse from a PWM output enters the motor windings. Each rectangular pulse begins with a spike of overvoltage nearly twice the DC bus voltage and then settles down to the bus volts. This "High Potting" can cause pin holes in the motor's insulation turn to turn or phase to phase.

Windings supplied by inverter



Reflected Wave Voltage
Also known as standing wave and voltage ring–up. Some of the inverter output is reflected from the motor, back up the line toward the inverter. If the distance and switching frequency are right, a standing wave forms. Voltage from the inverter pulse and the reflected wave add together increasing voltage to the motor. At long distances a 460V RMS output can exceed 2000 volts at the motor terminals.



Additional Heat
Basically, any portion of the waveform that is not a sine wave is converted to heat in the windings. This is more prevalent on the older 6 step inverters but still can overheat or burn out some motors even on PWM inverters.

Bearing Currents
The high frequencies in the switching and transient spikes are also induced into the rotor and build up a voltage potential between the rotor and stator. This voltage is dissipated by arcing through the ball bearings. This continuous lightning storm will ruin the finish in the bearing races and cause premature failure.

Windings supplied by inverter

First of all, we observe that, starting from the early inverters, the SCRs have been substituted by the GTOs and therefore by the IGBTs , which offer advantages from all points of view, but have a very high switching frequency (in the order of 20 kHz) and consequently a very low rise time (from 50 to 400 ns).

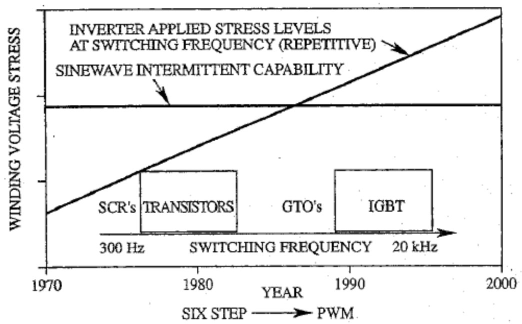


Fig. 1. Winding dielectric stress versus the development of transistors.

The electrical stress on the winding insulation increases by increasing the switching frequency.

A.H. Bonnett, Analysis of the impact pulse-width modulated inverter voltage waveform on AC induction motors, IEEE Trans. Ind. Appl., 1996.

Windings supplied by inverter

The figure shows three examples of single pulse of a typical output waveform at the PWM inverter.

At the beginning of the pulse, the voltage rises rapidly from zero to a peak (overshoot) and then returns to the normal pulse height, which is equal to the rectified voltage $E_{DC} = V_{bus}$.

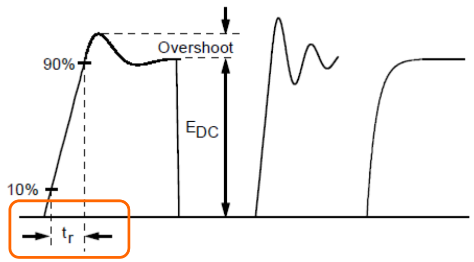


Figure 8 Typical PWM Output Pulse Shapes

Note that there may be (or not) an overshoot and that the voltage may oscillate before returning to normal pulse height.

t_r = *rise time*

Windings supplied by inverter

The rise time t_r is usually defined as the time required to the voltage to rise from 10% to 90% of the peak value V_{peak} of the output voltage from the inverter.

Beside, the *dv/dt* represents the slope of the voltage rise, usually measured in [V/μs], which can be approximated as :

$$\frac{dv}{dt} = \frac{0{,}8 \cdot V_{peak}}{t_r}$$

The following parameters affect the stress to which the insulation of a motor winding is subjected:

- rise time t_r
- *dv/dt*
- peak voltage V_{peak} (including a possible overshoot)

Windings supplied by inverter

These voltage pulses are transmitted to the motor terminals by means of the cable which connects the inverter to the motor itself.

The normal pulse height at the inverter output (excluding the overshoot) is V_{bus}, whereas the pulse height at the motor terminals is not necessarily equal to V_{bus}, but it depends on the dynamics of the circuit consisting of inverter, cable and motor, and then it depends on the following parameters:

- the rise time at the inverter output, as already defined;
- the characteristics of the transmission line consisting of the cable,
- the cable length,
- the impedance of the motor against the voltage pulse (*surge impedance*).

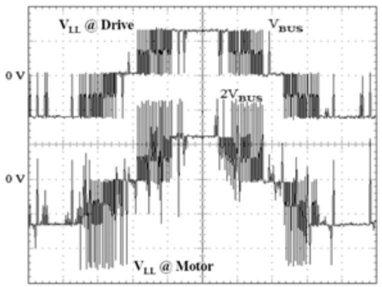
The reflected wave phenomenon

For particular combinations of these parameters, the phenomenon of the "reflected wave" may occur.

As an example, starting from a line voltage V_{line} = 400 V, the V_{bus} is given by:

$$V_{bus} = \frac{3}{\pi} \cdot \sqrt{2} \cdot V_{line} \cong 1.35 \cdot 400 = 540 \text{ V}$$

and, in the most unlucky cases, the peak voltage at the motor terminals may be equal or even higher than twice the V_{bus}:



Overshoot factor and reflection coefficient

The **overshoot factor** (not to be confused with the overshoot at the inverter output) is defined as **the ratio between the peak voltage to the motor terminals and the V_{bus}**.

This factor is used in a recent IEC Technical Specification to define the stress category under which the inverter-supplied low-voltage motor insulation system is subjected. This factor can be preliminarily estimated on the basis of some parameters.

First of all, this factor depends on the **reflection coefficient**, which in turn depends on the surge impedance of the cable Z_{cable} and on the surge impedance of the motor Z_{motor}.

The surge impedance of the cable is measurable and is in the order of magnitude between 80 and 180 Ω. The surge impedance of the motor cannot be easily measured and it can range from 2000÷5000 Ω for small motors to 400 Ω for high power motors.

Reflection coefficient

The amplitude of the voltage received at the motor terminals is given by the magnitude of the voltage sending by the inverter (V_{bus}) multiplied by $(1+\Gamma)$ where Γ is the **reflection coefficient**, defined as:

$$\Gamma = \frac{Z_{motor} - Z_{cable}}{Z_{motor} + Z_{cable}}$$

It can be verified that the multiplicative factor $(1+\Gamma)$ ranges from about 1.95 for small motors to around 1.6 for higher-power motors.

So, in general, this factor is more critical for smaller motors.

However, often for the connection between a high power motor and its inverter, parallel cables can be used, which reduce the overall impedance of the cable, thus increasing the reflection coefficient Γ and, consequently, the multiplicative factor $(1+\Gamma)$.

Critical length of the cable

Another parameter that influences the **overshoot factor** is the so-called **critical length of the cable l_c**, which in turn is mainly determined by the rise time of the output voltage pulse from the inverter.

Once this critical length has been determined, it is possible to verify that:

- If the cable length is < l_c, the overshoot factor will be lower than the multiplicative factor $(1+\Gamma)$;
- If the cable length is > l_c, the overshoot factor will be at least equal to (but also higher than) the multiplicative factor $(1+\Gamma)$.

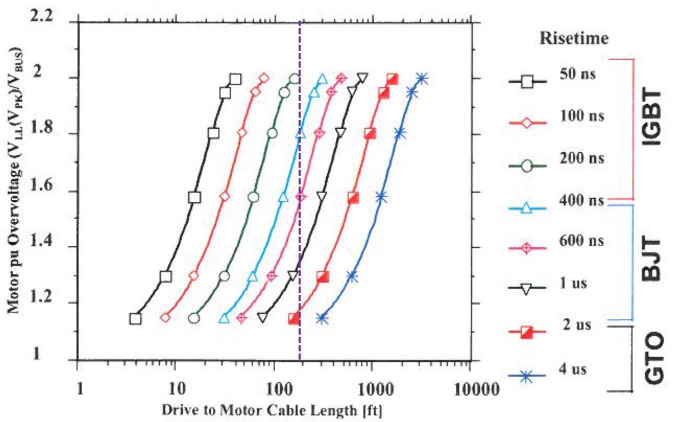
In practice, the critical length l_c decreases as the rise time decreases.

Therefore, if for a GTO inverter this critical length is so high that normally it will not be reached in real cases, on the contrary this critical length can actually be reached in the installations with IGBT inverters.

Overshoot factor

The following graph shows that, with the same cable length (e.g. 200 ft ≅ 70 m), a GTO inverter produces a very low overshoot factor, which is lower than the overshoot factor given by a BJT inverter, which in turn determines an overshoot factor significantly lower than an IGBT inverter.

The IGBT can reach even an overshoot factor equal to 2.



Windings supplied by inverter

Therefore, for inverter-fed motors, the additional stresses which may increase the failure rate of their winding insulation are mainly related to the high slope of the rising waveform sending by the inverter (*dv/dt*).

In fact, for particular lengths of the cable between inverter and motor (> l_c), the rising edge of the voltage causes the "reflected wave" phenomenon.

This phenomenon consists of an overvoltage that develops along the line to the motor terminals, causing a constant over-stress on its insulation.

Recent experiences also suggest that these steep slopes of the voltage waveform could arouse the so-called "shaft voltage" on the motor and lead to the phenomenon of the bearing currents recognized as a cause of "fluting" or electro-erosion of the bearings.

Windings supplied by inverter

Therefore, the connection cable between the inverter and the motor takes a fundamental importance, as these phenomena are excited (or damped) by its configuration.

The phenomenon starts from the fact that a PWM inverter does not generate a sinusoidal output wave, but a continuous pulse train whose maximum voltage value is equal to the DC bus value (V_{bus}) .

The corresponding sequence of pulses received at the motor terminals has an amplitude not equal to V_{bus} , but it shows peak values at each switching operation, which can reach (or even exceed) twice V_{bus} .

This overvoltage phenomenon, known as "reflected wave" or "transmission line effect", could particularly stress the insulation of the motor, arising its failure.

Windings supplied by inverter

This phenomenon is related to the general dynamics of the inverter-cable-motor system, depending on: the inverter output waveform amplitude; the pulse rising edge generated by the inverter and its frequency; the characteristics impedances of the cable and of the motor; the length of the connection between the inverter and the motor.

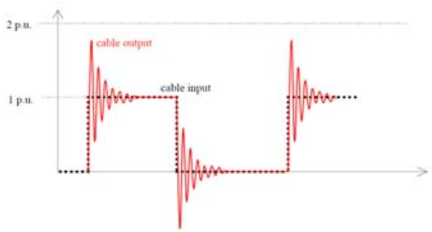
A voltage wave traveling along a line is mainly reflected due to the decoupling between the characteristic impedances of the cable and the motor.

If the motor impedance is equivalent to the cable impedance, there is no reflected wave and there is no overvoltage problem.

However, if there is a significant difference between the cable and motor impedance values, the reflected wave amplitude will be equal to that of the incident wave, as the reflection coefficient Γ approaches the unit.

Windings supplied by inverter

The figure shows how the reflection phenomenon occurs at the motor terminals. There are more frequent overvoltages as the driving frequency, with which the pulses are generated, increases.



The initial overvoltage due to the wave reflection does not compromise the motor operation and its performance, but it has a harmful effect on its insulation.

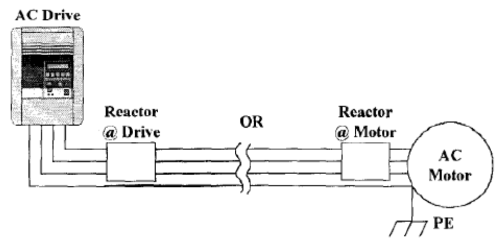
In fact, both the amplitude of the overvoltage and the high dv/dt affect the life and the performance of insulation.

The main effects which can appear are the partial discharges and the corona discharge.

Solutions to reduce the reflected wave

The techniques to reduce these overvoltage on the motor are:

1) Choose a lower voltage power supply, whenever possible;
2) Require proper motor insulation for IGBT power supply;
3) Limit, if possible, the cable length between the inverter and the motor;
4) Introduce additional devices as:
   - Output reactor at the drive,
   - Reactor at the motor,
   - Output dv/dt and sinewave filters at the drive,
   - Line termination network, which performs the impedance adaptation.



First solution to reduce the reflected wave

The first solution, if technically acceptable, requires a voltage supply system at 230 V.

In this way, the V_{bus} will be about 300 V and, even with an overshoot factor equal to 2, the motor will be subjected to an overvoltage of 600 V, which is normally tolerated by the actual insulation systems.

Nevertheless, the sending wave from an IGBT inverter has a rise time in the order of 100 ns and therefore it stresses the insulation more than a sinusoidal wave of equal rms value.

In general, for rated voltages ≤ 400 V, it is believed that most standard motors are able to withstand the additional stresses due to the inverter supply, however in some cases the voltage peaks may exceed twice the V_{bus} and therefore 1000 V, which often represents the voltage limit above which partial discharges may occur.

Second solution to reduce the reflected wave

The second solution requires an insulation system specially designed and realised to withstand the higher stresses arising from the inverter supply.

This type of insulation has to satisfy the qualification tests and the quality control tests provided by the Standard IEC 60034-18-41 "*Partial discharge free electrical insulation systems (Type I) used in rotating electrical machines fed from voltage converters – Qualification and quality control tests*" (2014).

The Type I insulation systems are related to rated voltage <700 V and, under sinusoidal power conditions, are not subject to partial discharges.

It worth to remember that there is also the Technical Specification IEC/TS 60034-18-42 "*Qualification and acceptance tests for partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters*" (2008) for Type II insulations systems (rated voltage ≥ 700 V).

Other solutions to reduce the reflected wave

The third solution, if feasible, minimizes the cable length between the inverter and the motor.

Whenever the first three solutions are not feasible, or in case of existing installations, it is possible to mitigate the problem by adding appropriate devices.

An output reactor at the drive improves the shape of the reflected wave, by slowing its rise time and decreasing its amplitude, thus reducing the dielectric stress on the winding insulation of the motor.

The disadvantage of this solution is that it can introduce a voltage drop at the fundamental frequency, which reduces the ability of the motor to produce its rated torque.

Solutions to reduce the reflected wave

A reactor at the motor improves the shape of the reflected wave, reducing its amplitude, but only slightly slowing the drive rise time. In any case, the dielectric stress on the winding of the motor is reduced.

The disadvantages of this solution are similar to those of the previous one.

Another solution is the installation of dv/dt filters or sinewave filters at the drive output:

- ✓ the dv/dt filters consist of appropriate combinations of R-L-C components to form dampened low pass filters;
- ✓ the sinewave filters convert the PWM voltage into a sinewave from, virtually eliminating the carrier frequency pulses.

Solutions to reduce the reflected wave

However, although the waveform of the line-to-line voltage is sinusoidal, it can be found that the neutral-to-ground stator voltage overshoots V_{bus}, because the high inductance used for the filter resonates with the line-to-ground cable capacitance.

Consequently, the motor phase-to-ground insulation may be subjected to dielectric stress; besides, the harmful effects due to motor bearing currents and electromagnetic interference noise may be present.

A sinewave filter specially designed for an existing installation can be very expensive and physically bulky: it is the most expensive solution to solve this problem.

The commercially available R-L-C filters are less costly and physically smaller, but they allows to obtain a voltage at the motor terminals similar to that obtained with an output reactor at the drive (rise time about 2 μs and V_{peak} around 1000 V).

Solutions to reduce the reflected wave

A cost effective method for controlling voltage reflection is a termination network installed at the motor terminals.

These devices are small, dissipate minimal power, cost less than the previous filtering solutions (except for small motors) and can be easily configured for both single and multiple motor installations.

A termination network is installed in parallel with the motor and therefore does not cause a voltage drop in the circuit.

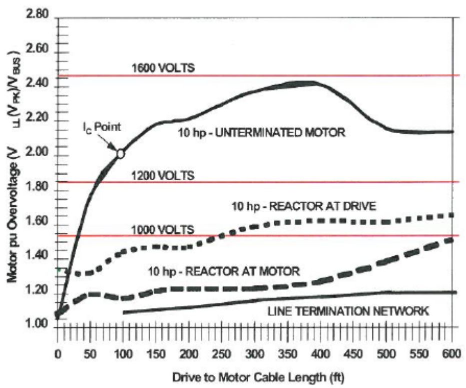
Its operation is based on the concept that if a line terminates on a load with the same impedance of the cable, the reflection coefficient is nullified.

So, if this device inserts an impedance equal to that of the cable, it eliminates the reflected wave phenomenon.

Solutions to reduce the reflected wave

With this solution, the voltage at the motor terminals typically reaches the V_{bus}, but never exceeds 1.2 times the V_{bus}.

The following figure shows that this solution allows to obtain a greater voltage reduction at the terminals of the motor, with the same length of cable.



L.A. Saunders et al., Riding the reflected wave – IGBT drive technology demands new motor and cable considerations, IEEE IAS Petroleum & Chemical Industry Conference, 1996.

Solutions to reduce the reflected wave

The following table reports the indicative costs (as a percentage of the motor cost) of the above described solutions:

Typical relative costs – Drives and preventative measures (Motor = 100%)

Rating	Drive	Preventative Measure			
		Output inductor	Output du/dt filter	Sinusoidal filter	Motor termination unit
2.2kW 400V	125%	50%	100%	150%	150%
75kW 400V	100%	30%	40%	45%	10%
250kW 400V	90%	10%	15%	30%	3%
160kW 690V	100%	10%	20%	35%	4%
250kW 690V	70%	10%	15%	25%	2%
500kW 690V	60%	10%	15%	20%	1%

It should be noted that the cost variability of the different solutions, as a percentage of the motor cost, is closely related to its power.

"Motor insulation voltage stresses under PWM inverter operation", Gambica/Rema Technical Guide, 2008.

Other references

Other interesting references on this topic can be found in:

- ✓ E. Persson, "Transient effects in application of PWM inverters to induction motors," *IEEE Trans. Ind. Appl.*, vol. 28, Sep./Oct. 1992, pp. 1095-1101.
- ✓ A. Binder, "High frequency effects in inverter-fed AC electric machinery," presented as tutorial handouts at ICEM 2016, http://www.icem.cc/2016/index.php/tutorials.
- ✓ M. Tozzi, A. Cavallini, G.C. Montanari, "Monitoring off-line and on-line PD under impulsive voltage on induction motors - part 1: standard procedure," *IEEE Elect. Insul. Mag*, vol. 26, pp. 16-26, 2010.
- ✓ ABB Industrial System Inc., Technical guide No. 102, "Effects of AC drives on Motor insulation," 1997.

The issue of bearing currents in small and medium size motors supplied at low voltage by an inverter drive

Common mode voltage

In a three-phase sinusoidal system, the instantaneous sum of the three phase voltage vectors is always zero.

The same condition is not verified in case of a <u>three-phase PWM supply</u>, where a DC voltage is converted into a series of pulses, in order to obtain a waveform having a sinusoidal alternate component.

Although the components at the fundamental frequency of the line-to-line output voltages are symmetrical and balanced, it is impossible that the sum of the instantaneous voltage pulses is always equal to zero.

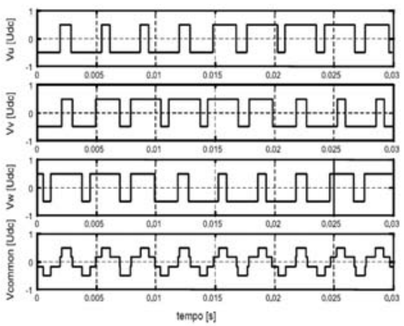
As a consequence, the star point (or the neutral point) of the motor moves to a potential always different, depending on the commutations during the pulse modulation.

Common mode voltage

These continuous "movements" of the star point generate a particular voltage waveform, known as <u>common mode voltage</u>, which represents the trend of the voltage assumed by the star point with respect to the ground.

The figure shows the three phase voltages of a three-phase PWM supply and their average, i.e. the common mode voltage.

This voltage waveform has a frequency equal to three times the switching frequency of the inverter.



Inverter-induced bearing currents

In motors driven by inverters, in addition to the "classical" shaft currents which can occur with a supply from the mains, other bearing currents may appear.

The main cause of these bearing currents is the presence of the common mode voltage at the inverter output.

Moreover, all the capacitances within an electric machine, which with a supply from the mains prevent the current passage, are transformed into impedances of relatively low value against the common mode voltage, which is at high frequency (> tens of kHz).

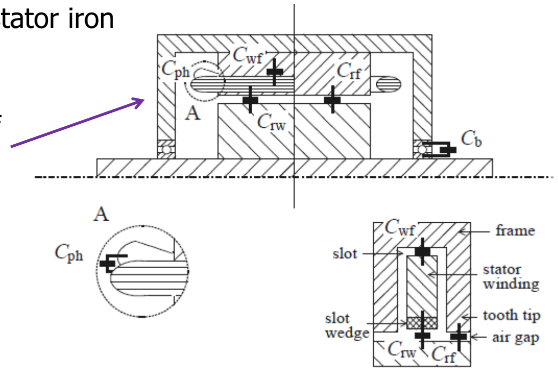
Consequently, a current flow may occur through these capacitances, which may arouse an early damage to the bearings.

Inverter-induced bearing currents

The capacitances inside an electric motor can be divided into:

- C_{wf} between the stator winding and the stator iron (at grounded potential)
- C_{ph} between two phases of the stator winding
- C_{rw} between the rotor and the stator winding
- C_{rf} between the rotor and the stator iron
- C_b inside the bearing

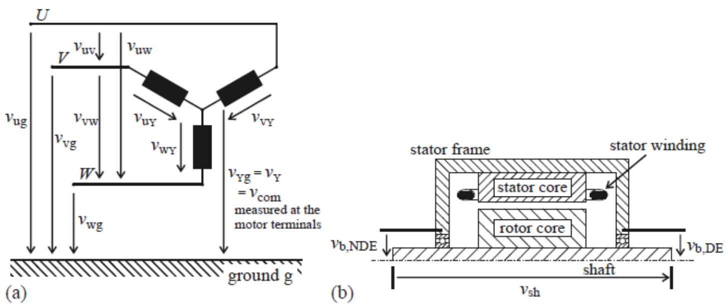
The following figure shows half of the lateral section of a motor, symmetric with respect to its shaft axis.



A. Muetze, "Bearing currents in inverter-fed AC-motors", PhD dissertation, 2003.

Inverter-induced bearing currents

The voltages inside the motor are:



Y represents the star point (or the neutral point)

DE = Drive End (side connected to the load)

NDE = Non-Drive End

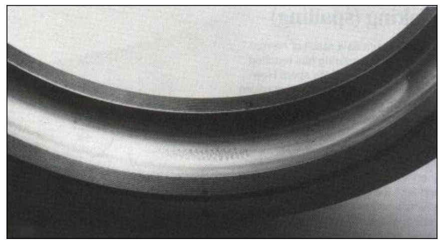
The common mode voltage is given by the arithmetic mean of the three phase-to-ground voltages:

$$v_{com} = \frac{v_{ug} + v_{vg} + v_{wg}}{3}$$

Inverter-induced bearing currents

The three types of inverter-induced bearing currents can be distinguished as:

1) Electrostatic discharge currents;
2) Circulating bearing currents;
3) Rotor ground currents.



1) Electrostatic discharge currents

The difference of potential between inner and outer race of each bearing v_b derives from the common mode voltage v_{com} through a capacitive voltage divider and is proportional to it.

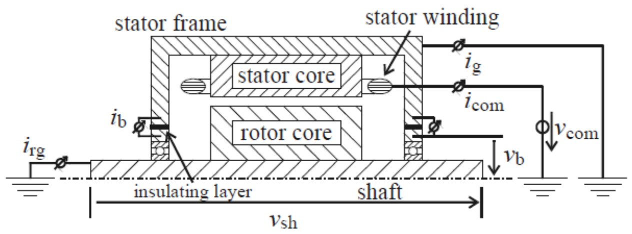
So, the first type of current arises directly from the common mode voltage v_{com} , which is reflected on the voltage v_b inside the bearing and can exceed the lubricant film discharge threshold voltage between the bearing metal elements (balls and running surface).

This effect is particularly evident in small size motors, due to the small contact area inside the bearings.

The peak amplitude of these currents may be in the order of 0,5÷3 A and their frequency in the order of MHz.

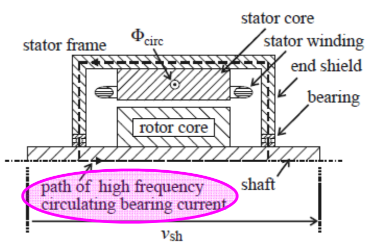
2) Circulating bearing currents

The second type of current derives from the presence of the common mode voltage v_{com} and from the fact that it is at high frequency: for these two reasons, the insulation between stator winding and stator iron (represented by the C_{wf} capacitance) becomes an impedance of relatively low value, which allows the flow of current i_g to the ground.



2) Circulating bearing currents

This current gives rise to a circular magnetic flux around the motor shaft, which in turn induces a voltage v_{sh} along the motor shaft.



If this voltage v_{sh} is sufficiently high to produce a discharge inside the lubricating film of the bearing, it will cause an i_b current to flow throughout the closed path formed by the stator frame, the bearings and the motor shaft .

Note that this current has opposite sign in the two bearings.

2) Circulating bearing currents

This circulating current has peak values in the order of 0.5÷20 A, which increase with the rated power of the motor.

The frequency of this current is in the order of hundreds of kHz.

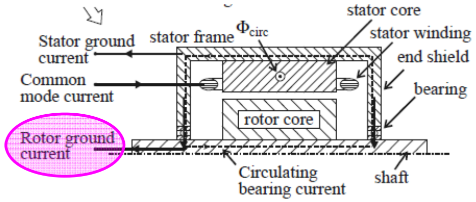
Note that the currents of type 1) are produced by a potential difference inside the bearing, similarly to the case where the shaft assumes a constant potential difference from the ground.

Instead, the currents of type 2) are produced by a potential difference between the two ends of the shaft.

3) Rotor ground currents

Also the third type of current derives from the presence of the common mode voltage v_{com} and from the fact that it is at high frequency, but it can occur only if the rotor is grounded through a path with a significantly lower impedance compared to that of the grounding of the stator frame (e.g. by means of its load).

In these cases, a rotor ground current i_{rg} can flow both through the motor bearings and the load bearings.



Note that this current has the same sign in both the motor bearings.

The total common mode current is given by: $i_{com} = i_u + i_v + i_w = i_g + i_{rg}$

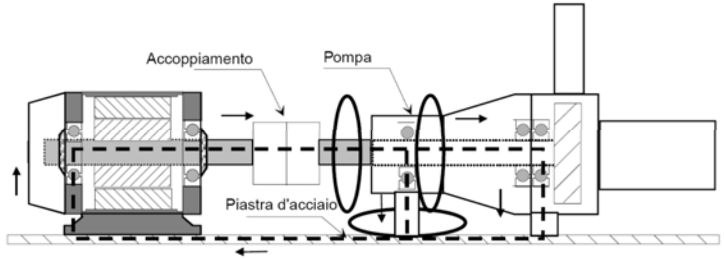
where: i_g = stator ground current.

3) Rotor ground currents

This is the rotor ground current, which can reach considerable amplitudes, especially for large size motors, and can destroy the bearings within few months.

Therefore, it is worth to try to remove this current with a low impedance grounding of the stator frame.

The frequency of these current is in the order of hundreds of kHz.

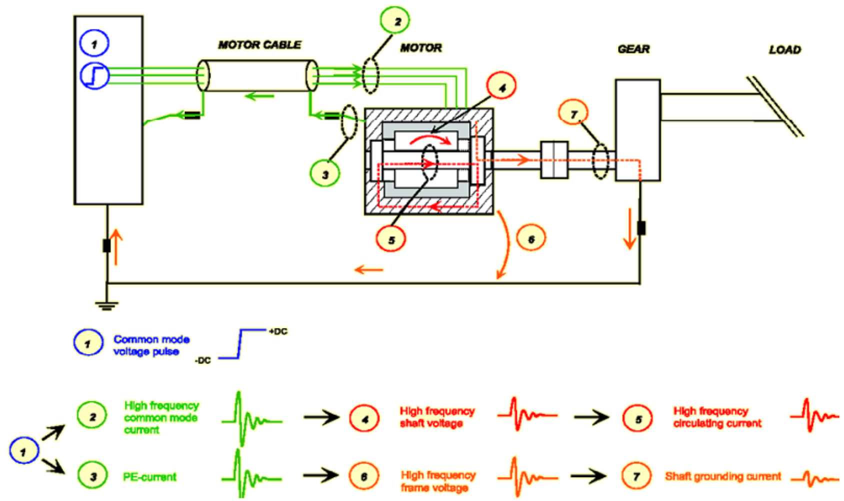


Inverter-induced bearing currents

By summarizing …

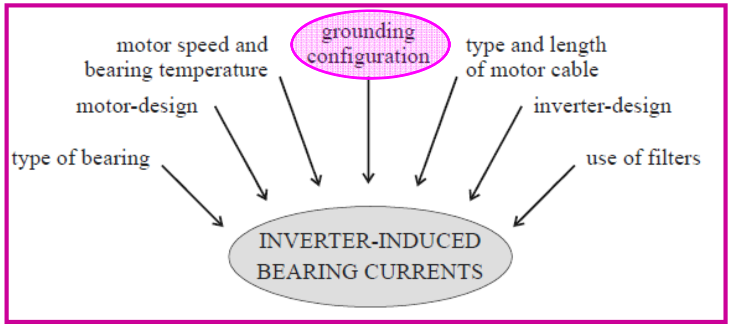
- The PWM inverter-induced bearing currents arise from the common mode voltage and the coupling through high frequency parasitic capacitances.
- There is a capacitance where two conductive components are separated by means of an insulator.
- The internal capacitances inside a motor are very weak.
- A weak capacitance represents a high impedance at low frequency (50÷60 Hz), with consequent absence of parasitic currents.
- The fast rise pulses generated by modern drives contain high frequencies: as a consequence, even the weak internal capacitances of the motor may configure a low impedance path for the current flow.

Inverter-induced bearing currents



Inverter-induced bearing currents

The parameters that most influence the inverter-induced bearing currents are:



A. Muetze, "Bearing currents in inverter-fed AC-motors", PhD dissertation, 2003.

Inverter-induced bearing currents

The first parameter to consider is the rotor grounding configuration, as it determines whether or not rotor ground currents can circulate. If the rotor grounding cannot be eliminated or modified, these currents can be significantly reduced by using shielded cables between inverter and motor.

Regarding the other two types of bearing current:

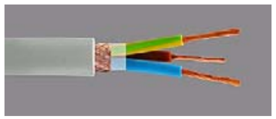
- For small size motors (shaft length < 10 cm), only electrostatic discharge currents can occur;
- For large size motors (shaft length > 28 cm), only circulating bearing currents can occur and their amplitude increase with the size of the motor;
- For intermediate size motors, both types of current can occur.

Inverter-induced bearing currents

Other parameters which can influence the bearing currents are:

- inverter switching frequency: it affects the likelihood of appearance of bearing currents, but not their amplitude;
- cable length: if the rotor is grounded with a low impedance and if the cables between inverter and motor are not shielded, longer cables will increase rotor ground currents. On the contrary, circulating bearing currents are not significantly influenced by this parameter and the electrostatic discharge currents are unaffected.

Examples of shielded cables:
(the shield may be composed of braided strands of copper or aluminum, which are grounded to carry to earth possible leakage currents)



Mitigation techniques for bearing currents

To eliminate or reduce inverter-induced bearing currents, different techniques can be applied, essentially divided into two groups:

a) Mitigation techniques on inverter side, including: filters at the drive, special modulation techniques to reduce or eliminate the common mode voltage, special shielded cables.

b) counter-measures within the motor, including: insulated bearings, hybrid bearings, rotor grounding brushes, electrostatically shielded rotor (rotor in Faraday cage).

The choice of one or more among these different techniques depends mainly on the type of bearing current that one chooses to reduce or suppress.

Mitigation techniques for bearing currents

Note that filters or modulation techniques, able to eliminate the common mode voltage, suppress any type of bearing current, as they remove the primary source of the same currents.

Even the use of both hybrid bearings, although not removing the source of the problem, eliminates all three types of current in the bearings.

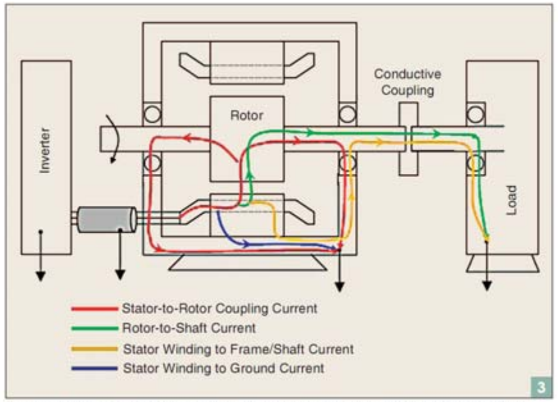
The whole diameter of the ceramic balls of the bearings represents the length of the insulating gap. The bearing voltage is not large enough to generate sufficient electric field strength across this length to discharge the lubricating film: therefore, <u>the ceramic balls act as an electrical insulation and interrupt the circulating bearing currents</u>.

Inverter-induced bearing currents

The figure shows a drive with the inverter connected to the motor through a shielded cable and the load connected to the motor shaft with a non-insulated metal coupling.

The motor, the shielded cable, the inverter and the load have a grounding connection, indicated with the black arrow pointing down.

In the same figure, the possible circuits in which the leakage current can flow are also reported.



Capacitively coupled current paths in an inverter driven induction motor system.

Inverter-induced bearing currents

The **red** circuit is related to a <u>capacitive coupling current between stator winding and rotor</u> that affects <u>both the bearings of the motor</u>.

This particular path is very dangerous as it remains inside the motor and is hardly measurable.

Also the **green** circuit is related to a <u>capacitive coupling current between stator winding and rotor</u>, which <u>passes through the shaft and the non-insulated mechanical joint</u> and closes to ground via the <u>bearings of the load</u> .

In this case, the risk of failure is not for the motor, but for the load.

Inverter-induced bearing currents

The **yellow** path involves the <u>capacitances between the stator winding and the stator frame, in case of a poor grounding of the stator frame</u>.

As shown, the current flows through the parasitic capacitance of the stator winding, stator frame, DE bearing of the motor, metal joint and finally close to ground through the load bearing.

This path is quite dangerous because it affects <u>both the motor bearings and the load bearings</u>.

The best path, where all the currents should flow to reduce the risk of damage for the bearings, is indicated in **blue**.

Inverter-induced bearing currents

Improving the grounding of the motor is one of the key solution for reducing bearing currents.

It is therefore important to provide low impedance paths among the ground connection points, so that the inverter-induced bearing currents are kept away from the motor or the load and then from the bearings.

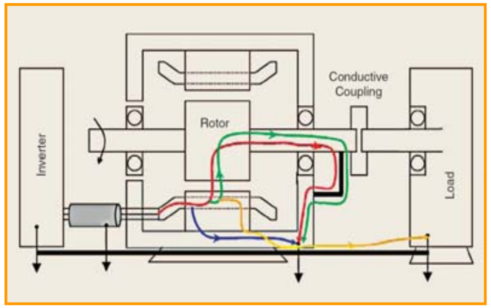
In existing installations, to avoid possible bearing damages, the solution to choose depends on the type of current to eliminate, since no single solution can completely eliminate all components.

Moreover, in some cases, one solution may reduce the current in one part of the system, while increasing damaging current flow in other parts.

Inverter-induced bearing currents

An optimal configuration, which reduces or eliminates the inverter-induced bearing currents, is shown in the following figure: both an **insulated bearing** and an a **shaft grounding brush** are correctly installed in this system (on opposite sides).

In addition, a proper grounding of inverter, motor and load increases the performance and effectiveness of this solution.



Inverter-induced bearing currents

Each remedy acts to either interrupt a potential damaging current path (insulated bearing) or redirect the current away from the bearings, by providing a lower impedance path (shaft grounding brush and improved ground connection).

In existing installations, it is important to consider the overall system and the possible paths for the current, before proceeding with a specific solution.

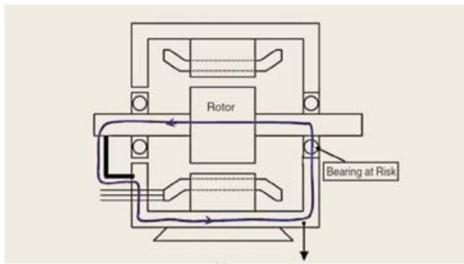
For example, it is common to add a shaft grounding brush when a bearing damage occurred and bearing currents are suspected.

But it should be noted that the addition of this brush could increase the current flowing in another section of the system, due to its lower impedance path.

Inverter-induced bearing currents

The addition of a shaft grounding brush without insulated bearings greatly reduces the impedance seen from the current.

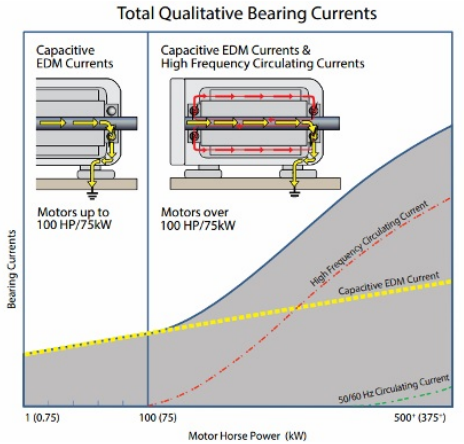
The result could be an increase of the current in the bearing opposite the brush, with a consequent damage of the same bearing.

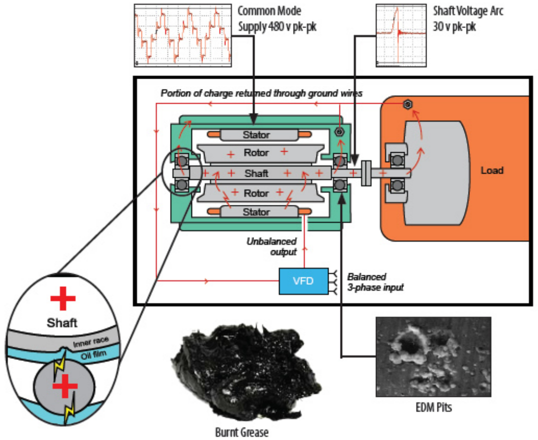


Besides, if an insulated bearing is present and if the grounding brush is installed on the same side of the insulated bearing (as shown in the figure), the current may increase, by damaging the opposite bearing.

R.F. Schiferl, M.J. Melfi, J.S. Wang, "Inverter Driven Induction Motor Bearing Current Solutions", in *Proc. of IAS Petroleum and Chemical Industry Conference*, 2002.

Inverter-induced bearing currents



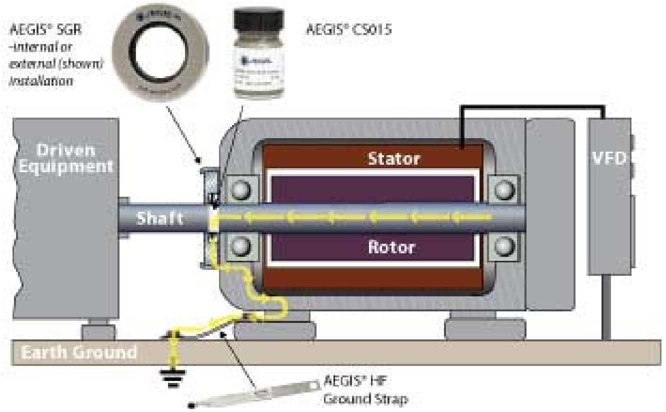


http://www.est-aegis.com/bearing-protection-bearing-currents.php

Shaft grounding brushes

A special type of patented shaft grounding brush is the ring AEGIS:

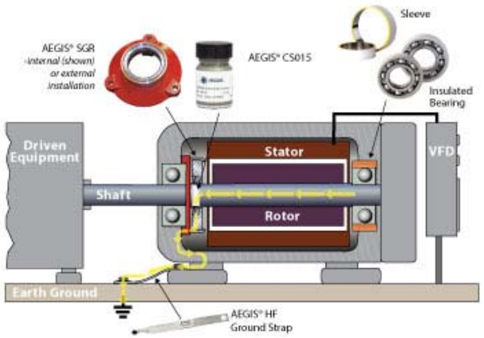
For motor size < 75 kW, the shaft grounding ring on the drive end may be sufficient to eliminate the bearing currents problem, although not all the manufacturers agree on this procedure (many manufacturers recommend an insulated or hybrid bearing instead of the shaft grounding brush).

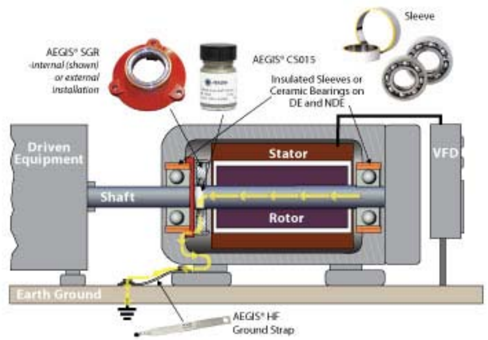


http://www.est-aegis.com/best-practices.php

Shaft grounding brushes and insulated bearings

For motors > 75 kW, in addition to the shaft grounding ring on the drive end, at least one insulated or hybrid bearing on the other side (non-drive end) is recommended.



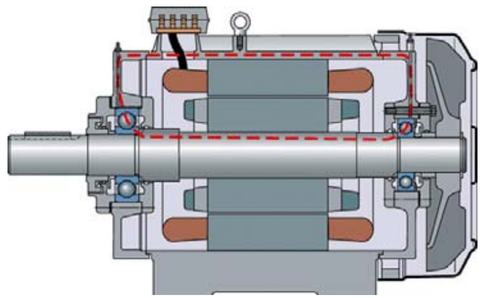


In general, two insulated (or hybrid) bearings on the motor provide a greater safety to avoid bearing currents.

Insulated bearings

The impedance given by the bearing insulation must be as high as possible.

To achieve a high impedance, the resistance of the insulating layer must be large and its capacitance must be low.



This can be achieved by using an insulation layer as thick as possible, minimizing its surface.

For a bearing, the ideal application of the insulating layer is on the inner race.

Nevertheless, due to its lower cost and more simple manufacturing process, the insulation on the outer race is more common, as in most cases it provides a sufficient protection against the bearing currents.

Insulated bearings

The race can be insulated with ceramic oxides, aluminium oxide or resins.

The inner race insulation is preferred for large size bearings or in case of external rotor.

Hybrid bearings

Hybrid bearings are an alternative to insulated rolling bearings: their races are made of steel, whereas their rolling elements (balls or rollers) are made of ceramic, which is more wear resistant and acts as an electrical insulation.

Advantages of the hybrid bearings:

- Maximum impedance to the current circulation;
- Higher rotation speed with lower friction and lower temperature;
- Improved operating characteristics under critical working conditions;
- For small sizes, hybrid bearings are economically more advantageous than insulated ones (for large sizes, hybrids are much more expensive than insulated ones).