

# Bearing Currents Induced by a Power Drive

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**Abstract:** Electric/hybrid traction will increase significantly in the next years. EMC is one of the main constraints OEM's will have to face. The most frequent cause of rotary machine failure comes from bearing problems. This paper describes a misunderstood issue due to common mode current flowing through the rolling bearings, which dramatically reduces their lifetime. Finally, the paper will present some solutions to reduce the rotor voltage or the bearing current.

**Keywords:** Bearing, EDM, EMI filter, EMC, PWM inverter, Power drive.

## 1. Introduction

This paper mainly deals with the prevention of rolling bearings damages due to capacitive currents. Three different phenomena can generate a current flow through a bearing:

- 1 - Electrostatic charge collected by an isolated mobile. This tiny current (few  $\mu\text{A}$ ) is little destructive but it generates a wide band radiofrequency noise. The "static" current can be evacuated, as one goes along, by antistatic (dissipative) waterproof gaskets.
- 2 - Magnetic imbalance that induces a shaft voltage across the shaft ground loop. This phenomenon only affects high power motors or generators ( $> 100 \text{ kW}$ ). A symmetrical wounded motor has a small radial H field, so the magnetically induced voltage is reduced.
- 3 - Capacitive common mode current injected by a PWM variable speed drive from winding to the rotor. This paper exposes the EDM (Electric Discharge Machining) phenomenon and proposes fixes.

## 2. Vocabulary and History

### 2.1 Bearing vocabulary

- The track of the inner (respectively outer) ring is called the inner (respectively outer) raceway.
- A rolling body may be a ball or a roller: a needle, a cylindrical roll, a conical roll, etc.
- The bearing cage, that keeps the rolling bodies separated, is also called the "spacer".

- The lateral waterproof gaskets can be slightly conductive to evacuate "static" electricity.

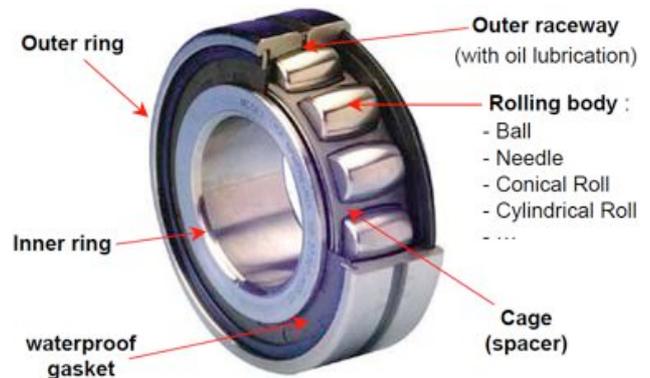


Figure 1: The parts of a rolling bearing

### 2.2 Bearing end of life

Most bearing damages are due to generalized roughness faults. Those faults mainly result from rough environment conditions (sand, dust, corrosion, over-temperature, overload...), but they can also come from EDM, which is due to a destructive electrical current flow through the bearing.

Generalized roughness faults produce unpredictable broadband changes in the machine vibration and stator current. Finally, it can lead to a shaft blocking.

### 2.3 EDM History

Shaft voltages and their resulting currents were recognized by Alger in the 1920's. The asymmetrical flux, through the arbour line loop (the shaft loop), induces common mode voltage.

In 1996, Chen and Erdman identified the capacitive common mode voltage between stator and rotor due to a switch-mode variable-speed motor drive.

Since 2000, the number of papers dealing with capacitive EDM and its consequence (the lifetime reduction of bearings) has increased. Among the 150 papers published by PCIM 2007, 6 dealt with bearings MTBF or bearings fault detection, compared to 1 in 2005, and to 3 in 2006.

### 3. Stator to rotor capacitive coupling

The common mode voltage of a 3-phase VFD output (symbolized by the letters A to C) is defined by:

$$V_{CM} = (V_A + V_B + V_C) / 3 \quad [1]$$

As we can see in figure 2, the peak-to-peak common mode voltage typically reaches the DC bus voltage.

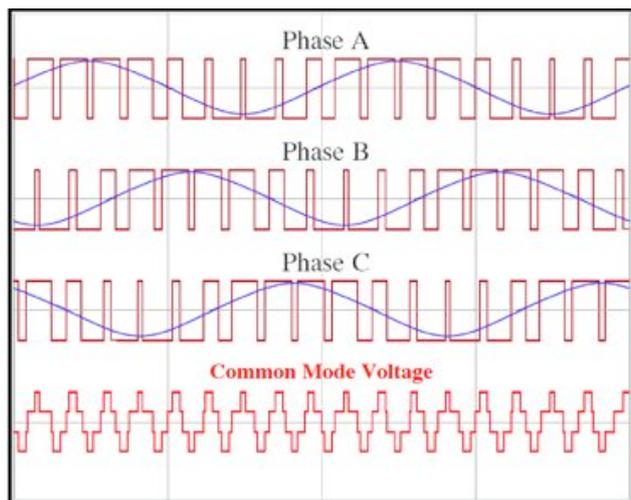


Figure 2: PWM two-level voltages principle

Fortunately, this common mode voltage is not directly applied to the rotor. The stray capacitance of a motor depends on its power, but not on its type: asynchronous, synchronous or permanent magnet rotors have the same capacitances.

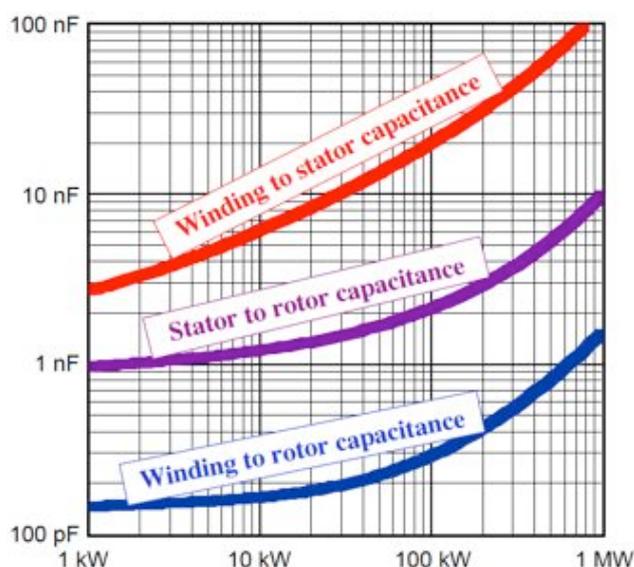


Figure 3: Motor capacitances vs. power

For EDM purpose, the winding to stator capacitance,  $C_{WS}$ , provides no direct effect. The winding to rotor capacitance,  $C_{WR}$ , is approximately 6 to 7 times smaller than rotor to stator capacitance,  $C_{RS}$ .

The voltage response of this capacitive coupling is not frequency dependent. Indeed, as in the low-frequency equivalent circuit (figure 4), while the bearing is isolating, the rotor voltage  $V_R$  is just a part of the common mode voltage  $V_{CM}$ :

$$V_R = V_{CM} \cdot C_{WR} / (C_{WR} + C_{RS}) \quad [2]$$

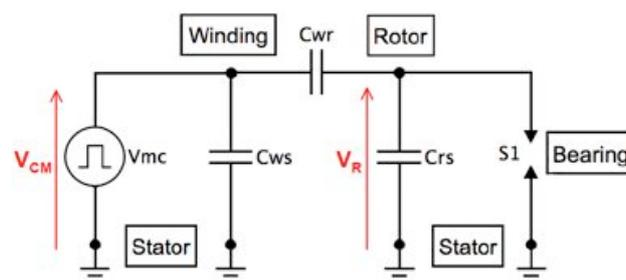


Figure 4: Equivalent low-frequency CM circuit

In high frequency, let's say above 1 MHz, the common mode equivalent circuit becomes more complicated. This complication is due to numerous effects as:

- Winding resonances
- Line effect (phase rotations and delays)
- Dissymmetry by geometrical differences
- Magnetic couplings
- And so on!

Just remember that in low frequency (let's say from DC to 1 MHz), the rotor to stator voltage is about 7 to 8 times smaller than the output common mode voltage generated by the speed drive.

Over 1 MHz, all the coupling troubles can be efficiently solved by a passive EMI filter installed at the inverter output. Such a HF filter is small and may be needed to meet EMC radiated emission specs, even if the inverter to motor cable is shielded.

### 4. The EDM phenomenon

#### 4.1 EDM orders of magnitude

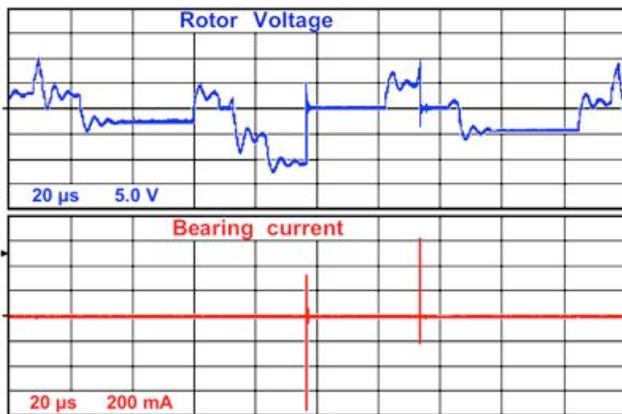
At rest, the electrical contact between the inner and outer raceways is guaranteed. But during operation, even at a low speed, a thin layer of lubricant over the rolling bodies isolates the bearing. Grease is oil dissolved in soap. Lubricant is a really critical part of a bearing. Even carbonized grease of an old or overheated bearing remains insulating.

The thickness of the lubricant film, typically from 0.2  $\mu\text{m}$  to 2  $\mu\text{m}$ , decreases when oil temperature increases, and decreases with time. The electric field in oil (or grease) before a breakdown occurs is close to 15 kV/mm. So, the breakdown voltage of the shaft is about 10 V (typically from 3 to 30 volts).

After a breakdown, the arcing creates a very small metal displacement; this phenomenon is close to electro-erosion. After an arcing, the quantity of displaced metal is very small, but it creates tiny asperities that are cumulative.

The current rise time is in 1 ns range and the peak current is in the Amp range (from 300 mA to 3 amps). Its duration is short, in the range of tens of nanoseconds.

The mechanical damages on the raceways and on the rolling body increase with the transferred electric charge. In figure 5, the peak current is a little bit underestimated due to the set-up limited bandwidth.



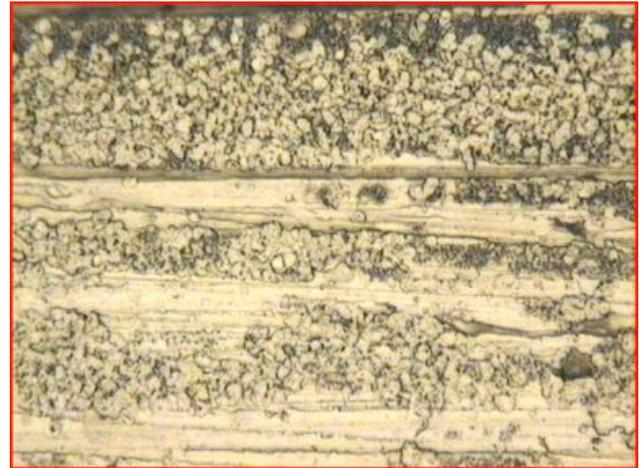
**Figure 5: Typical shaft voltage and EDM current**

Due to capacitive divider effect ( $\approx 8 \times$ ) with a DC bus voltage smaller than 24 V, the shaft voltage remains lower than 3 V; then EDM is impossible or negligible. Conversely, EDMs fatally appear in standard bearings with a standard motor, driven by a standard speed drive, with a DC bus voltage larger than 25 V.

## 2.2 Effects of EDM

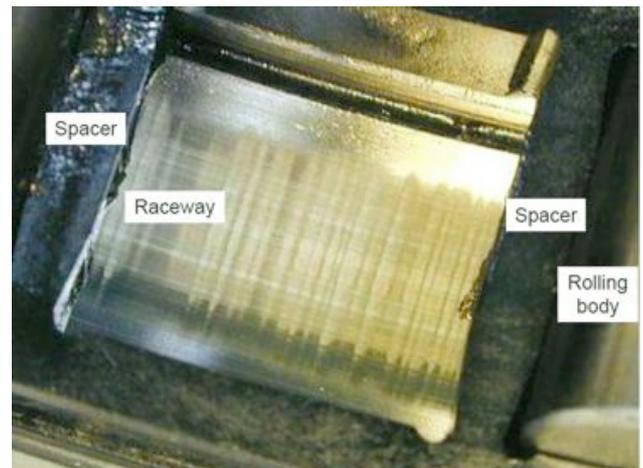
Usually, the cold working of the under-layer of the raceway of a loaded bearing precedes its scaling, which lead to the bearing destruction at last. The EDMs accelerate this event.

The effects of EDMs are destructive on the long term because they provoke local fusion of the raceway surface. The material is heated to temperatures ranging from tempering to melting levels. This creates re-hardening of metal, and small craters and pits appear on the rolling bodies (figure 6).



**Figure 6: Craters on a roller surface (x930)**

It is easy to identify an EDM problem: the abrasion of the raceway is quite characteristic. The outer raceway shows a “washboard pattern”, in X-Y grid (figure 7). This “bearing fluting” generates vibrations, acoustic noise, and finally the bearing destruction.



**Figure 7: “Washboard” pattern of a raceway**

The peak current is about 0.1 Amp per shaft Volt before an EDM occurs. Not to significantly reduce the lifetime of a bearing, the peak EDM current density has to remain lower than  $0.5 A_{\text{peak}}/\text{mm}^2$ . Unfortunately, the area of an arcing is so small that even with current arcing of only 0.3 amp, the current density may frequently exceed  $10 A_{\text{peak}}/\text{mm}^2$ .

In summary, the lifetime of a bearing may be strongly affected by EDMs. According to experiment, the MTBF reduction can be larger than a factor 10. For instance typical EDMs can reduce the 30 000 hours MTBF of a properly chosen bearing to barely 1000 hours. Such a reduction is dramatic for most of applications.

## 5. How to avoid EDMs?

Numerous suggestions have been proposed to avoid EDM occurrence and bleakness. Unfortunately, some usual proposals are inadequate or deficient. First of all, let's survey the inappropriate fixes.

### 5.1 Output passive EMI filter

Numerous papers propose to filter the inverter output by a passive low-pass EMI filter; against EDMs, this proposal is not rational. At the opposite of what is usually claimed, an EDM is not due to a high  $\Delta V/\Delta t$ , but to a common mode voltage - no matter its shape. Just remember that a 3 volts CM voltage may create an EDM. The voltage frequency doesn't matter because the winding to rotor and shaft capacitive coupling is frequency independent (equation [2]).

So, to reduce the output common mode voltage to a low enough level, the insertion loss of the passive filter should reach at least 20 dB at 20 kHz (order of magnitude of an inverter switching frequency). This M-C filter (M is the mutual inductance of a common mode choke and C is the sum of 3 caps connected between the 3 phases and the frame ground) should have its resonating frequency lower than 6 kHz.

$$F_r = \frac{1}{2 \cdot \sqrt{MC}} \quad [3]$$

Such a filter has a huge size because the CM choke must not saturate when a large common mode voltage is generated at the switching frequency.

Moreover, large capacitors values increase losses in the inverter switches. To limit this stress, differential mode inductances may be necessary, but such windings would be big, costly and create losses.

Capacitors submitted to a rather large voltage over 10 kHz must have an excellent quality factor. For instance most Y caps (commonly used for common mode filters) have a typical  $\tan(\delta) > 1\%$ . With such a poor quality factor ( $Q < 100$ ), to avoid burnout, those caps cannot withstand more than a peak repetitive voltage larger than 10 V at 20 kHz.

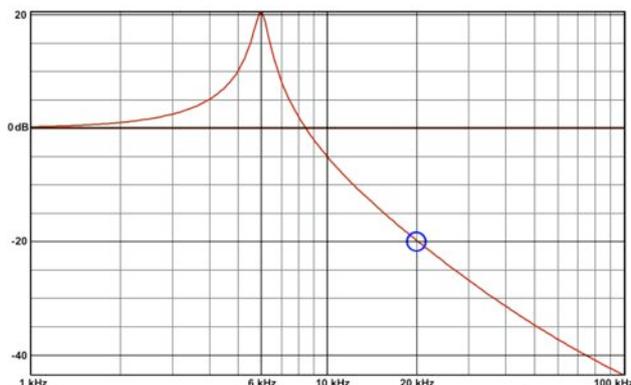


Figure 8: Insertion loss of an effective M-C filter

In the example of figure 8, the mutual inductance is as large as  $3 \times 10$  mH and the CM capacitors values are  $3 \times 27$  nF. Finally, let's suppose we could design such an enormous and ruinous EMI filter. Its adverse effect on the inverter efficiency would be obvious. Output passive EMI filters for motor drives may be useful for EMC purpose, but over 1 MHz only. Besides, changing the switching frequency is not an effective solution.

For any switched-mode inverter, an input EMI filter is mandatory to meet EMC conducted emission limits. An output EMI filter is possibly useful to meet HF radiated emission limits (not to shield the output cable). An HF filter is rather small, without severe adverse effects. Such a filter slows-down the commutation transitions (it reduces  $\Delta V/\Delta t$ ) but it does not reduce the EDM severity that are linked to the common mode output voltage generated by the inverter at its fundamental frequency.

### 5.2 Output active filter

Some years ago, an interesting paper proposed an active cancellation of an inverter common mode output current by an active injection of CM voltage thanks to a double-winding output CM choke.

But there is no concern with CM current at low frequency: the only cause of an EDM is the shaft voltage. So, the correct data to cancel should not be the output CM current but the output CM voltage.

A serious drawback of this solution would be the size of the CM choke: It would be as large as for a passive filter because it must not saturate by the fundamental output CM voltage.

Moreover, it is difficult to effectively cancel the common mode voltage from 10 kHz to at 1 MHz by an active filter because the impedance of the load greatly varies with frequency. Compared to a passive filter, the only benefit of an active filter is not to increase the switching losses.

As far as we know, an active filtering of an inverter output has never been implemented on any commercial equipment. It will probably remain a theoretical dream for years.

### 5.3 Preventive maintenance

A worn bearing becomes acoustically noisy; then it is recommended to replace it quickly. Nowadays, most of the motor bearings are equipped with prepacked, lifetime lubricated bearings.

The MTBF of a bearing is longer than 10,000 hours. The best ceramic bearings can reach more than 100,000 hours. The question is: who can think it is rational to control a bearing every 1000 hours, just because no care has been taken to avoid EDM?

For automotive applications, only trucks or trams, with their very long life expectancy (more than 10 years and 1 million kilometres) may justify a planned preventive maintenance.

#### 5.4 Shaft grounding

A brush is a piece of carbon or metal serving as an electrical contact between the stator and a collector slip ring mounted on the shaft. The brush may short-circuit the capacitive current coupled from the winding to the rotor.

For “static” currents or capacitive EDMs, this solution is effective, but there is no evidence that this can solve an asymmetrical flux EDM because the circuit impedance is very low. An isolating part added along the shaft (to open the loop) would be a safer fix.

Moreover, any brush is a wear piece that needs some maintenance. That is one of the reasons why brushless permanent magnet rotors are preferred.

Nevertheless a shaft grounding brush may be used to limit HF radiation by the shaft of a DC motor, due to broadband interference generated by the switching commutations of the brush: the outer part of the shaft is acting as an antenna. But for a brushless motor, a HF passive low-pass filter is preferable to limit radiation.

Now, let’s consider the really effective fixes.

#### 5.5 Electric isolation

A semi-conductive gasket is effective enough to evacuate static currents, but not capacitive coupled currents: the gasket resistance (hundreds of k $\Omega$ ) is too high to ground the shaft.

An isolating sleeve or a ceramic coating, for instance in aluminium oxide (50  $\mu\text{m}$  of alumina) around the outer ring of both bearings can effectively isolate the rotor from the stator ground. So, both capacitive EDM and asymmetrical flux EDM are cured.

Such a solution is efficient, sufficient, and is the less expensive of all fixes. It can be used both for sleeve or roller bearings. So, why to look for another solution since this one has no drawback?

#### 5.6 Ceramic bearings

Ceramic balls or full ceramic bearings are perfectly isolating, so they solve all EDM issue (both the capacitive and the asymmetrical flux EDM).

Their benefit, compared to the electrical isolation, is to guarantee a longer MTBF (about twice longer), to accept higher speeds and not to need any lubricant. So there are less temperature issues and no more ageing at all.

The two drawbacks of a ceramic balls bearing are a slightly higher cost and a higher acoustical noise compared to a lubricated bearing.

#### 5.7 ESIM

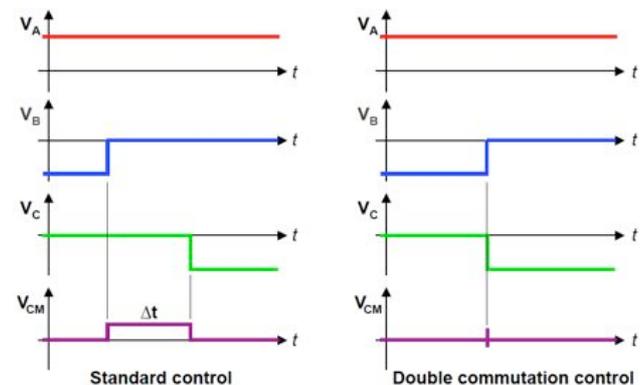
ESIM is the acronym for “Electrostatically Shielded Induction Motor”. Such a specially designed motor uses conductive but non-magnetic flaps (instead of isolating ones) to mask the apertures of the stator. So, the magnetic field and performance are practically unchanged (the air gap may be slightly increased), but the stator efficiency reduces by more than 90% the electric field of its winding.

Moreover, an ESIM - and especially large power ones - has to be precisely wound (symmetrically wound) so that its asymmetrical flux remains low enough to avoid magnetic EDMs.

The main drawbacks of an ESIM are a higher cost, the little number of double-source manufacturers and the trained specialist needed to renew its winding.

#### 5.8 “Double commutation” strategy

The “double commutation” method is also known as “simultaneous opposite switching” (versus classical “isolated” single commutations). It uses one of the well-known degrees of freedom of a three-level neutral-point-clamp inverter to nearly cancel the output common mode voltage.



**Figure 9: Double commutation principle**

The double commutation method may not perfectly cancel all EDMs, but they are lowered so that they can practically be neglected. The CM voltage is reduced by more than 10 dB up to several MHz.

Moreover, the primary EMC filtering of the speed drive is simplified because the needed insertion loss is reduced. The conducted emission margin is significantly increased, especially if the stray capacitances between the 3 outputs and the chassis ground (stator ground) are well balanced.

Unfortunately, the radiated emission over 30 MHz (which can exceed EMC limits up to 150 MHz) cannot be significantly reduced by a double commutation control. This regrettable restriction is linked to numerous causes:

- Ripple voltage of the DC bus
- Dispersion of the driver delays
- Switches voltage drop dissymmetry
- Turn-on versus turn-off delays offsets
- Edges dissymmetry:  $\Delta V/\Delta t$ , shape, ringing...
- Cabling and load HF impedance dissymmetry

About this last point, it is critical to limit the HF dissymmetry of the stator winding. The first turn of the wire (on the "hot" side) is one of the most critical points to control. Its position related to the stator slot and gap should be exactly the same for the three phases. The distance between the bobbin heads and the stator ground (and cover) is another point to take care of.

Otherwise, the HF impedance difference between the three phases would convert the differential mode voltage into common mode current.

A drawback of the double commutation strategy is the DC output current which is rather difficult to cancel because there is no flywheel cancellation period. So, a DC current measurement is needed on 2 of the 3 output phases not to saturate the stator.

A precise current measurement is quite difficult on a "hot" (noisy) line. A shunt resistor needs a very high CMRR amplifier and some precision components. A DC hall-effect probe has a significant offset (typically at least 1 % of its full scale). Using a DCCT would be an expensive misfit for such a basic DC current cancellation.

The neutral point balancing of the DC bus (the "0 V") is an additional element to control.

## 6. Conclusion

The serious lifetime reduction of bearings due to EDMs remains frequently misunderstood and generally underestimated. A fault detection of bearings is certainly possible without a vibration sensor. Nevertheless it is preferable to improve the bearings lifetime by avoiding EDMs than to replace faulty bearings in time.

Except for very low DC bus voltage ( $V \leq 24$  Volts), any standard PWM inverter generates a large enough common mode output voltage to create EDMs through conventional bearings. For industrial applications as for high-power automotive motors, a MTBF of only 1000 hours is clearly unacceptable.

Some usually proposed fixes are inadequate:

- Passive output filtering is inappropriate.

- Active output filtering is utopian.

- Preventive maintenance should only be used for very long life applications (trucks and trams).

- Shaft grounding is only appropriate to limit HF radiation of a DC (collector) motor, when an isolating part cannot be added along the shaft.

Four fixes are rational and cost effective:

- To electrically isolate the bearings is efficient and sufficient. This is obviously the simplest solution.

- Ceramic balls bearings constitute an alternative solution, especially for long life bearings.

- An ESIM is a possible but rather costly alternative.

- A double commutation control is an effective and low cost strategy. Moreover, this control significantly reduces the size of the input EMI filter without any functional drawback. This strategy may be coupled with one of the previous solutions.

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## 8. Glossary

<i>CM:</i>	Common Mode
<i>CMRR:</i>	Common Mode Rejection Ratio
<i>DC:</i>	Direct Current
<i>DCCT:</i>	Direct-Current Current Transformer
<i>EDM:</i>	Electric Discharge Machining
<i>EMC:</i>	Electromagnetic Compatibility
<i>EMI:</i>	Electromagnetic Interference
<i>ESIM:</i>	Electrostatically Shielded Induction Motor
<i>HF:</i>	High Frequency (over 1 MHz for EMC purpose)
<i>MTBF:</i>	Mean Time Between Failures
<i>PWM:</i>	Pulse Width Modulation
<i>VFD:</i>	Variable Frequency Drive