# A Comprehensive Study on Shaft Voltages and Bearing Currents in Rotating Machines

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***Abstract*—This paper puts into perspective the state-of-the art knowledge on bearing currents and diagnosis tools, which rely on shaft voltages and bearing currents phenomena. Today, shaft signals measurements are progressively included in predictive health monitoring of large turbo and hydro generators. In addition, bearing fault diagnosis through shaft signals have recently gained some attention to improve reliability and estimation of the remaining useful life in electrical drives. The main objective of this paper is to provide diagnosticians with a broad overview of the current trends in fault diagnosis through shaft signals. Therefore, the study presents a critical review of the measurements methods, advantages, and disadvantages of fault diagnosis methods, and suggests future possible enhancements for bearing health monitoring through shaft signals.**

***Index Terms*—Bearing currents, bearing fault, bearing voltage, condition monitoring, fault detection, fault diagnosis, inverter, shaft currents, shaft voltages.**

## I. Introduction

In THE context of electrical drives, more than 50% of motor failures are due to rolling element bearing failures, which are the primary cause of downtime [1], [2]. Among the causes of the bearing faults, shaft voltages and associated bearing currents are well known to accelerate the bearing degradation. Although mitigation solutions are increasingly employed to deal with bearing currents, they could create reliability issues and additional maintenance. For these reasons, diagnosis and prognosis of bearing faults have attracted attention in recent years [3], [4]. To determine the health state of the bearings and to predict the time to failure, all causes and failures modes must be addressed, including bearing currents. In the field of condition monitoring of large turbo and hydro generators, shaft signals are exploited to provide redundant fault indicators to strengthen the machine's diagnosis and avoid catastrophic failures.

The fact that fault diagnosis through shaft signals is not widespread, had encouraged the authors of this paper to develop a state-of-the-art presentation of this scattered works, which can be used by diagnosticians as a basis for future contributions. Therefore, the purpose of this paper is to review the entire shaft voltages and bearing currents phenomena and discuss the measurement methods, detection, diagnosis applications along with condition monitoring processes that have been made available in the literature. The study begins with a presentation of the shaft voltages and bearing currents under traditional operation and in the case of inverter-based drives. The measurement techniques are also discussed along with an overview of mitigation solutions employed by industrials. Then, diagnosis and monitoring techniques and emerging trends in prognosis are reviewed. Later, some research direction are outlined and a few improvements are proposed based on the current work.

## II. Shaft Voltages Under Traditional Operation

### A. Review on the Phenomena

Within a drive system, it is now well know that four potential types of shaft voltages may exist, which can arise from multiple sources, resulting in the apparition of shaft currents [5], [6]. One or more sources can be present on a machine, so the diagnosis should be done carefully. One should also remind that the common use of the technical term "shaft voltage" in papers and articles can be sometimes confusing. Shami and Akagi [7], [8] distinguish clearly the "shaft end-to-end voltage" as the shaft voltage $v_{\mathrm{sh}}$ (i.e., the voltage between the two bearings along the motor shaft) and the "shaft-to-frame voltage" as the bearing voltage $v_b$ (i.e., the difference of potential between the inner and outer race of a bearing, or between the journal and the bearing shell). As those voltages are linked together, the abuse of terms is recurring. In this section we review only the low-frequency (LF) phenomena and we will deal with high-frequency (HF) phenomena in the next section.

*1) Alternating Voltages Induced in the Shaft:* Unbalanced magnetic fields caused by design, manufacturing details such as axial cooling holes in the stator or/and rotor laminations,

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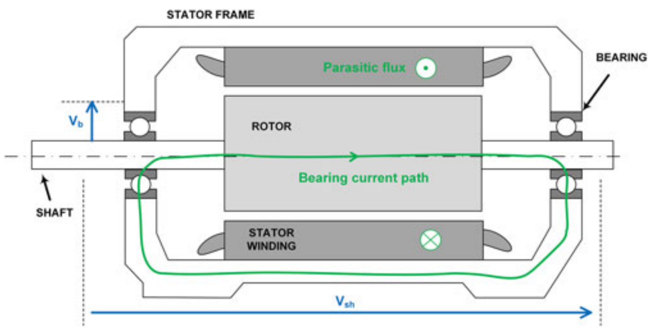


Fig. 1. Bearing currents due to magnetic asymmetries at line operation.

joints between stator segments, variation of permeability between segments, rotor eccentricities, bowed rotor can create a magnetic flux encircling the shaft [5]. Thus, alternating voltages are induced in the shaft and may cause a circulating current in the loop "stator frame–drive-end bearing–rotor shaft–non-drive-end bearing" if the bearing voltage increases above a threshold to broke the insulating lubricant film of the bearing (see Fig. 1). One example is the study conducted by Alger and Samson on the particular case of sectionalized laminated stators causing flux asymmetries, resulting in production of shaft current [9]. As a result, it has been established design rules to avoid this trouble and manufacturer's engineering offices need to keep in mind those rules during the sizing phase.

*2) Axial Rotor Flux:* A magnetic flux can be generated throw the shaft by residual magnetism (linked to magnetic particle inspection and improper demagnetization) [10], [11], local saturation, asymmetries in the rotor field winding, rotor eccentricities. The homopolar flux will circulate from the shaft, in the loop "stator frame–drive end bearing–rotor shaft–non-drive-end bearing." A voltage will be induced along the length of the journal bearing, creating a local current loop within the bearing [5], [9].

*3) Electrostatic Effect:* This phenomenon is external to the machine, often due to the load. It can occur with friction of belts, pulleys, or the friction between blades and wet steam in low-pressure turbines [10], [12]. This is a capacitive effect, the bearing voltage increases, charges the lubricant until its threshold voltage is surpassed and causes a breakdown. The latter creates the so-called "electric discharge machining" (EDM) current pulse within the bearing.

*4) External Potential Applied on the Shaft:* The excitation system in synchronous machines, often thyristor controlled rectifiers, introduces relatively high transient voltage pulses in the rotor winding and create a potential on the shaft by capacitive coupling between the rotor winding and the shaft [11], [13].

### *B. Bearing Failure Modes*

The visual inspection of bearing damages was first one of the clues to highlight shaft voltage phenomena. Bearing failure modes can be classified into five types: fluting, frosting, pitting, spark tracks, and welding as largely detailed in [10]. Fluting is characterized by transverse evenly distributed flutes burnt into the bearing race, having the appearance of washboarding [14]. A frosted raceway surface has the appearance of a "sand blasted" surface. This damage is generally imperceptible to the naked eye and is microscopically characterized by small "craters," which are formed during electrical discharges. Pitting, which consists in much larger "craters," is a more serious form of frosting. Spark tracks are irregulars and often askew to the direction of the rotation. Welding is linked to a large amount of current passing through a journal bearing and can easily be seen to the naked eye. Physical explanations of those phenomena can be found in [5], [10]. The inspection is generally carried out under a microscope to confirm the origin of the damage, as it can also simply be mechanical or chemical.

### *C. Measurement Methods*

IEEE112 "Standard test procedure for polyphase induction motors and generators" [15] establishes guidelines to perform shaft voltage and current measurements while the machine is operating under rated speed and voltage. The bearing voltage has to be measured on all bearings, insulated or not, which gives information on the oil-film health. Another method implies measuring the potential across opposite ends of the shaft [9], [15], usually with brushes and/or slip rings for practical considerations [16]. A high input impedance oscilloscope or a TRMS multimeter should be used since the shaft signals are rich in line frequency harmonics. Shaft voltage measurement following the recommendations in [15] is the first step for LF shaft monitoring as explained in Sections IV-A and IV-B.

### *D. Failures on Account of Shaft Voltages and Mitigation Techniques*

Under traditional operation, counter-measures to protect the bearings against shaft voltages are mainly bearing insulation and shaft grounding brushes [9], [11], [13], [17]. Bearing insulation can be accomplished on the machine by either insulating the bearing housing, or the shaft journal. Coated bearing or hybrid ceramic bearing are also often used. Traditional carbon brushes are not suitable for shaft grounding according to some papers [10], [11], [18]. With classical carbon brushes, the typical current density is never reach in shaft grounding applications, thus, creating a possible build-up of high contact impedance between the shaft and the brush, leading to contact sparking. Besides theses brushes are oil and dust sensitive. Some publications claim that most reliable brushes are metallic brushes, braid or bristle type [10], [11], [18]. However, in industry, quantities of trouble-free ac and dc motor applications are protected against shaft voltages by means of specially designed brushes. The performances of the grounding system are essentials and should not be neglected, as shown in a study [19] carried out, amongst others, on a 2.8 MW generator. The use of different ground resistances shows the importance of a high-performance grounding system. A ground resistance of 90.9 Ω had allowed electrostatic charges accumulation with a shaft voltage increasing up to 170 V on turbine shaft. As a bearing lubricant acts as a capacitor, if the bearing voltage becomes higher than the oil film break-down voltage, a damaging current will circulate through the bearing to the bearing pedestal.

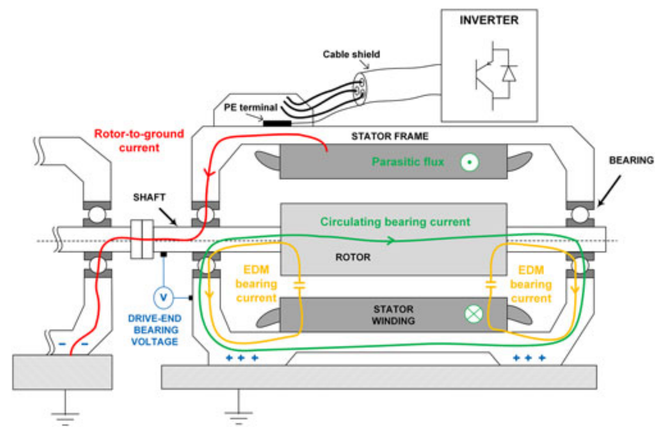


Fig. 2. Possible bearing current paths.

Some case study showed the apparition of fluted bearings on dc motors related to shaft voltages in paper mills. An experiment has been conducted in [14]: the dc motors were powered by rectifier systems, which are known to produce harmonics. The establishment of field pole transient voltages creates air gap flux imbalances, producing shaft voltages because of the field poles transient reactance, which are not perfectly identical due to the manufacturing process. The bearing dielectric oil film disrupted, creating an electrical discharge based on voltage level and waveform ($dV/dt$). Fluted bearings were also found on dc motors due to capacitive coupling between the armature winding and the shaft, because of the rectifiers [20].

According to multiple authors, the involved bearing current frequencies are rarely more than a few kilohertz contrary to the phenomena detailed in the next section.

## III. Shaft Voltages Under Inverter Operation

### A. Review on the Phenomena

The phenomenon of bearing currents when the motor is operated by a pulse-width modulation (PWM) insulated-gate bipolar transistor (IGBT) voltage source inverter has been widely reported in the last decades (see, e.g., [21]–[31]). A large quantity of papers has considered the common mode (CM) voltage $v_{\mathrm{com}}$ of a PWM inverter to be linked to bearing currents appearance. In [32]–[34], global reviews on the subject are also proposed.

The generation of HF bearing currents involves capacitive and inductive coupling inside the machine. All drive systems have parasitic capacitances and inductances, always neglected under sinewave operation. Under inverter operation, it has been found that the HF components of the CM voltage excite the parasitic capacitances and inductances of the motor, producing the so-called "inverter-induced bearing currents."

These phenomena are in the range of 100 kHz to several megahertzs according to multiple authors (e.g., [30], [35]). The literature distinguishes "circulating" and "noncirculating" bearings currents with four main types of inverter-induced bearing currents classified as follow (see Fig. 2).

1) Small capacitive HF bearing currents (≈5–200 mA), "noncirculating" type, which appear at low speed. Its effects are neglected compared to other bearing currents [31].
2) EDM bearing currents, "noncirculating" type. The bearing voltage $v_b$ mirrors the CM voltage through a capacitive voltage divider also called "bearing voltage ratio" (BVR) [25], [26]. The bearing voltage increases, charges the lubricant until its breakdown field strength is surpassed and causes a breakdown with the apparition of the EDM current pulse (≈0.5–3 A), which is oscillating at frequencies in the megahertz range [28].
3) HF "circulating" type bearing current. The parasitic capacitances between the stator winding and the frame are excited by the high $dV/dt$ at the motor terminals, which creates an HF ground current. The latter produces a circular flux around the motor shaft, inducing bearing voltages [25], [36], [37]. If the lubricating film breaks down, HF current (≈0.5–20 A) circulates in the loop "stator frame–drive end bearing–rotor shaft–non-drive-end bearing" with a frequency of several 100 kHz. This type of bearing current is due to inductive coupling, it mirrors the CM current. One should be noticed that the circulating bearing currents are of opposite direction in the bearings.
4) Bearing currents, "circulating" type due to rotor ground currents. It occurs if the rotor-to-ground impedance is lower than the stator-to-ground impedance. In this case, a portion of the ground current crosses the bearings toward the shaft [25], [31]. These currents can reach high levels (≈1–35 A) and prematurely damage the bearings.

According to the study in [38], small motors up to 20 kW are more sensitive to EDM bearing currents, whereas larger motors are likely to be subjected to circulating bearing currents. The bearing has two electrical modes: capacitive mode for the noncirculating bearing currents and resistive mode for the circulating bearing currents. Depending on operating parameters such as bearing temperature and rotational speed, the bearing changes from pure resistive to pure capacitive mode [39].

EDM currents arise at an established film of lubricant in the bearing and a high bearing voltage. These currents are a function of the bearing capacitance, the lubricant thickness and the bearing voltage prior to a breakdown. Furthermore, these parameters are interrelated to the bearing temperature, the motor speed and the bearing load [40], [41]. Circulating currents appear mainly at low speed and high bearing temperature, a configuration in which the oil film is thin enough to enable an ohmic contact between the raceways and the rolling elements [39]. For some operating conditions, the bearings randomly alternate between capacitive and ohmic mode as discussed in [42].

In addition to that, a "combined" bearing current, which has both inductive and capacitive origins can occur in steady state on journal oil-lubricated bearing [43]. Finally, some references have also reported the differential-mode voltage as being the source of a shaft end-to-end voltage [7], [8]. By way of comparison, it has been established in [44] that HF bearing currents due to IGBT inverters, accelerate bearing failures at a rate seven times higher than bearing currents due to systems without IGBT inverter supply (see Section II). The HF bearing currents generate high peak energy on a small surface of the bearing at a high

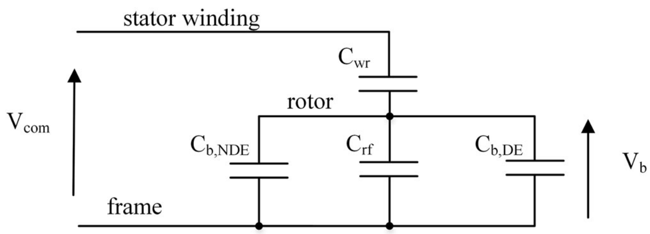


Fig. 3. Equivalent circuit model to estimate the BVR of a machine under inverter operation [46].

rate contrary to LF bearing currents energy, which is believed to be more evenly distributed across the surface of the bearing [45]. As already observed in [44], experiments conducted in [45] demonstrate that HF electric regime within the bearing generate fluting patterns in shorter times than LF electric regime, while the total accumulated energy in the bearing in LF regime is three times higher than in HF regime.

### B. Bearing Currents Models

Equivalent circuit models of bearing currents have been proposed (see, e.g., [26], [37], [46], [47]) for an in-depth understanding of the phenomena. Generally a system approach is required, reducing the model to the inverter, the cabling with the grounding configuration and the machine. It has been well established that the machine behave mainly capacitively at high frequencies.

When no EDM discharge events occur, the bearing voltage is the image of the CM voltage mirrored over the HF parasitic capacitances of the machine (see Fig. 3): $C_{\text{wr}}$ stator winding-to-rotor, $C_{\text{rf}}$ rotor to frame, and bearing $C_{b,\text{DE}} \approx C_{b,\text{NDE}}$. The BVR (i.e., the ratio between the bearing voltage and the CM voltage) can be determined through the measure or the calculation of the HF parasitic capacitances as detailed in [26] and [46]. Thus, the bearing voltage can be determined with the BVR and the CM voltage. The BVR magnitude, typically 3%–10% given by [46], is a first indicator of the probability of HF discharge bearing currents and is calculated as [26]

$$\text{BVR} = \frac{v_b}{v_{\text{com}}} = \frac{C_{\text{wr}}}{C_{\text{wr}} + C_{\text{rf}} + C_{b,\text{DE}} + C_{b,\text{NDE}}}.$$

The EDM current can be derived from the estimation of the threshold voltage prior to a breakdown [48] and the estimation of the bearing resistance [49]. On simulation, lubricant breakdown is modeled by a controlled switch, which is closed when the bearing voltage surpasses the estimated threshold voltage (1.5–30 V).

Modeling of the HF circulating bearing currents involves the calculation or the measurement of the CM current. Physical explanation and equivalent models can be found in [36], [37], [50], and [51]. To summarize, it is admitted that the CM current enters via the stator winding, leaks through the distributed capacitance $C_{\text{wr}}$ between the winding and the frame and leaves the machine through the grounding connection(s). Due to the skin depth effect, the CM current flows on the surface of the stator stack laminations, which generates a CM flux inducing a voltage $v_{\text{sh}}$ along the motor shaft. If this voltage is high enough to puncture the lubricant film, bearing current circulates in the loop "stator frame–drive end bearing–rotor shaft–non-drive-end bearing" including both the stator and rotor lamination stacks [52]. It has been found that the induced shaft voltage increases with the cube of the motor frame size, thus, explaining the increase of circulating bearing currents amplitudes in large machines [38]. A bearing current ratio BCR (i.e., the ratio between the bearing current peak and the CM current peak) can be defined to evaluate the amplitude of the circulating bearing currents. The BCR values are in the range of 20%–30% as reported in [37] and [38].

### C. Bearing Failure Modes

According to experiments, run to failure tests and industrial feedbacks under inverter operation, the most common pattern seen on visual inspection of the bearings is the fluting pattern (see [45], [53]–[55]). The frosting patterns and grey traces can remain unnoticed and can be confounded with other bearing failure modes on visual inspection, while the pitting patterns are the result of more severe electrical discharges in the bearing, which lead to failures in months. All these patterns are the result of the accumulation of localized pits associated to discharge bearing currents. The resultant pattern depend mainly on the HF energy released in the bearing. In addition, a part of the energy dissipated in the bearing is dissipated into the grease increasing its degradation [56], [57] and leading to a blackened grease [45]. It has been stated in [40] that frosted grey traces composed of small flattened craters, resulting from melting, do not reduce the bearing lifetime, whereas larger craters (2–5 $\mu$m), resulting from vaporization of the raceways, lead to corrugated patterns, degraded grease and, thus, reduce the bearing lifetime.

Moreover, vibration levels and frequencies can increase discharge events [58], since they modify the lubricant film thickness, and thus, the electrical field strength, increasing the amount of voltage breakdowns in a defined time frame. Besides, an increasing of bearing currents events leads to corrugated patterns, which increase in turn the vibration levels. Therefore, the formation of corrugated patterns is a self-amplified process [59]. With existing vibration monitoring systems, these advanced corrugation on bearings can be detected (see Section IV-C).

### D. Measurements Methods

At this time, no thresholds are defined for shaft or bearing voltages of machines under inverter operation, but manufacturers usually suggest a bearing voltage limit of 5 V for medium-voltage motors. Moreover there are no standard equipment, and method for measuring this voltage [15]. Ong *et al.* [60] compare different techniques for measurement of shaft currents. It has been pointed out that the shunt current method described in IEEE112 is not suitable. This method creates a low-impedance path between the shaft ends and does not reflect the real shaft current. If no measurement devices are already installed *in situ*, it is generally impossible to measure the bearing currents.

Mounting a Rogowski coil around the shaft inside the machine is a mean to measure the true shaft current including the

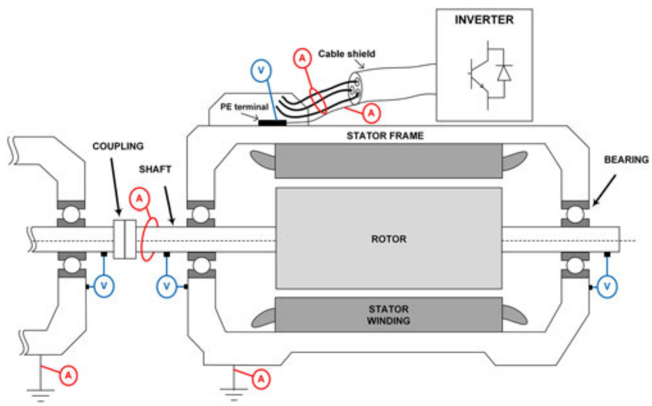


Fig. 4. Most important measurement points used for condition monitoring and fault diagnosis [40].

HF circulating current [60], [61]. Such a method needs a complex motor preparation and is not easily applicable in the field. However, Rogowski coils are widely used by ABB especially to monitor ground currents associated to high $dV/dt$ on machines fed by inverters [62].

Measurements of HF bearing currents are mostly intrusive methods, which need a thorough motor preparation [30], [60]. Generally an electrical insulation is introduced between the bearing and the frame. Then, a low-impedance wire is set up to shorten the insulation, and the current through this wire is measured. It should be noticed that this technique only provides a bearing current estimation [61]. In addition, estimating the values of potentially harmful bearing currents is complicated as the bearings depend on the size of the machine and field of application. Thus, authors usually define the "apparent bearing current density" $J_b$ [24], [25], [53] and agree that bearing current densities $J_b \leq 0.8$ A/mm$^2$ are safe for the bearing life. A simple but intrusive way to measure the bearing voltage with a high bandwidth, is the usage of shaft brushes, such as the AEGIS Shaft Voltage Probe [63], in the vicinity of the bearing (see Fig. 4).

The current trend is toward nonintrusive radio-frequency (RF) measurements to detect HF discharge bearing currents [30], [35], [64]–[66]. The method presumes that the HF discharge current pulse emit a fraction of its energy in the vicinity of the machine. The objective is to count the number of radiated pulses above a certain threshold and received within a defined time frame. This is defined as the "discharge activity" (DA) in [66] as an assessment of the bearing's health toward HF discharge currents. If HF discharge voltages on one of the bearings or more are suspected, the EDD pen from SKF [67] can be used to count the number of discharges and, thus, estimate the extent and severity of the bearing defect. Depending on the application, one or several measurement techniques can be applied to detect and monitor electrical events within the bearing as explained below in Section IV-C. Table I summarizes the available industrial measurement techniques for HF bearing currents. Note that one measurement technique will provide only a partial picture of the phenomena.

### *E. Mitigation Techniques for Bearings Protection*

The main purpose of studying bearing currents is obviously to propose practical rules and solutions to preserve the machines in various operating conditions. Many solutions that have been analyzed both on test bench and in industry can be classified in two groups [31]: solutions applied on inverter side and techniques to mitigate or modify bearing currents loops within the motor. For the first group, the purpose is to reduce or eliminate the CM voltage of the inverter, as it is the source of HF bearing currents. It comprises inverter output filters ($dV/dt$-reactors, $dV/dt$-filters), sinusoidal filters, CM chokes [68], and shielded cables. CM filters can also be used to reduce or eliminate the CM voltage [69]. The second group includes HF bonding straps [29], shaft grounding brushes, shaft grounding rings [63], insulated bearings, ceramic or hybrid ceramic bearings, electrostatically shielded rotor [27], and insulated coupling for load protection. Ceramic bearings break the current paths, while the insulating layers of insulated or "coated" bearings reduce circulating bearing currents, bearing currents due to rotor ground currents and are ineffective against EDM bearing currents [70]. Mitigation systems of the second group are discussed in detail in [71]. Other mitigation techniques can be found in IEC60034-25 [72].

Generally, induction machines above 1 MW have an insulated or ceramic bearing on the nondrive end and a shaft grounding mechanism on the drive end. The bearing breaks the HF circulating bearing current loops while the shaft grounding insure a low potential on the shaft. In all cases, the phenomena have to be thoroughly investigated before applying any mitigation technique. Traditional grounding mechanisms are generally not efficient against HF bearing currents. A patented solution for bearing currents protection, which is now well spread in the industry, provides a low impedance path to ground for bearing currents. The technique is detailed in [73]–[75]. It consists in a conductive ring mounted on the shaft, which contains millions of conductive microfibers. It has been experimentally proven that the system is well designed for the mitigation of HF currents and voltages in the megahertz range such as EDM-bearing currents and HF circulating bearing currents. For example, a high current bearing protection range, specially designed for large motors and generators, can withstand 120 A continuously up to 13.5 MHz with voltage discharges up to 3 kV peak [63]. Critical operating machines in the industry are often equipped with such bearing protections, which require very little maintenance compared to conventional grounding brushes. Finally, proper grounding of the motor frame using HF grounding straps is generally used to provide a low impedance path from motor shaft to earth ground. If no insulated coupling is available, HF grounding straps should be used between motor frame and the driven load to reduce rotor ground currents. Practical rules of application are given in [70] before the installation of an inverter-fed machine, to prevent bearing damages. An evaluation of bearing currents type is also prescribed to choose the most appropriate mitigation technique. Even with mitigation devices installed, critical applications could also request a bearing monitoring system to detect machine faults and also to insure the effectiveness of the protections: this is discussed in the next section. Table II

TABLE I
INDUSTRIAL MEASUREMENT TECHNIQUES FOR HF BEARING CURRENT DETECTION

| | **EDM currents** | **Circulating currents** | **Rotor ground currents** | **Specification** |
|---|---|---|---|---|
| Specific RF antenna | Events detection with suitable threshold | - No detection at industrial stage<br>- Recently : beginning of detection at research stage | | - Non-intrusive<br>- Sensitive to EMI |
| HF voltage probe | | | | - Moderately intrusive<br>- Sensitive to shaft pollution |
| Rogowski coil | No detection | Detection if placed on the inside of the machine | Detection if placed on the outside of the machine | Highly intrusive |

TABLE II
MOST USED INDUSTRIAL MITIGATION TECHNIQUES FOR HF BEARING CURRENTS

| | **EDM currents** | **Circulating currents** | **Rotor ground currents** |
|---|---|---|---|
| Passive filters | No influence | Reduction depending on the type of filter | |
| HF shaft grounding brush across one motor bearing | Complete suppression | Effective with opposite bearing insulated | Possible increase without using HF bonding strap between motor and load or insulated coupling |
| Insulated coupling | Possible increase without using HF shaft grounding brush, insulated or hybrid bearings | No influence | Complete suppression |
| One or two insulated bearings | Partial reduction | High reduction | |
| Ceramic hybrid bearings | Complete suppression | | |

summarizes the most used industrial mitigation techniques for HF bearing currents under inverter operation. Note that techniques applied on the motor can also be used under classical operation.

## IV. FAULT DIAGNOSIS AND CONDITION MONITORING

### A. *Machine Typical Faults Diagnosis*

On one side it is clear that shaft voltages and grounding currents must be reduced and on the other side, shaft signals contain large quantity of unexploited data related to the machine's health. Numerous authors studied the harmonic content of the shaft voltage to identify machine faults (see, e.g., [11]). Concerning synchronous machines, studies [76]–[80] reported significant changes in shaft voltage harmonics below 300 Hz in the presence of field coil interturn short circuit. Static eccentricity, a common and inevitable fault in generators can be detected by shaft voltage whose signature is often linked with odd harmonics such as 60, 180, 300, and 420 Hz, frequencies that do not change with the machine pole-pair number [77], [79]–[82]. Variations of rotational frequency component of the shaft voltage spectrum (see Fig. 5) has been evaluated in [16] in the case of a 15 MW synchronous machine, demonstrating a favorable sensibility of shaft voltage as fault detecting medium.

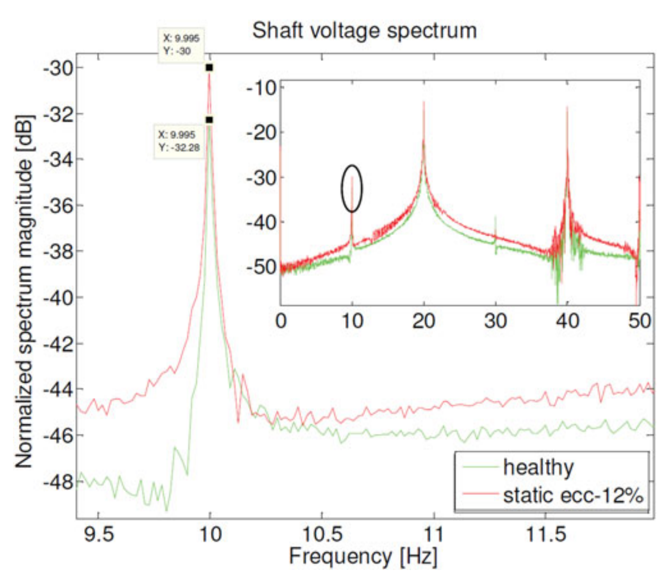


Fig. 5. Shaft voltage spectrum for healthy and 12% static eccentricity, zoomed at rotational frequency component (10 Hz), for 20 Hz stator supply frequency [16].

Additionally, a rectifier fault of a synchronous machine has been detected by shaft voltage [82] on simulation, with a diode open-circuited that shows significant changes in the amplitudes of 200 and 250 Hz harmonics, at both no load and full load. Stator interturn short circuit has been discussed in [83] on a finite element method model. It highlights the presence of side lobes on all odd harmonics of the shaft voltage spectrum. Finally, rotor broken bars, a subject extensively addressed by MCSA, which is one of the preferred methods, can also be detected by shaft voltage analysis [84]. In the presence of multiple unrelated faults, e.g., multiple bearings degradation, eccentricity, stator winding shorts, similar features are often witnessed. Including shaft voltages measurements in an existing multidimensionnal database could help to isolate one fault among the others by employing categorization techniques. Today, these techniques have mainly been employed to detect stator winding faults [85]. In addition to that, all these fault-related spectral variations in the shaft voltage could refined categorization of the state of one specific fault relying on methods successfully applied in the literature, e.g., linear discriminant analysis, clustering methods, support vector techniques. Such measurements could also be utilized to enrich data-based models with additionnal features in order to improved prognosis methods such as extended Kalman filtering [86], particle filtering [87], or the hidden Markov model [88].

### *B. Review on the Existing Condition Monitoring*

Shaft voltages and currents monitoring cannot be neglected in condition monitoring of large turbo generators, as it is one origin of forced outages, which often lead to massive operating losses. The most common way to insure a minimal shaft voltage is to use insulated bearings combined to shaft grounding by means of one or more grounding brushes depending on the application. The location of the shaft grounding is to be chosen carefully to avoid grounding loops. One grounding brush is often set up between turbine and generator to avoid electrostatic charges build-up on the shaft. Besides the shaft grounding system must have high performances to be immune from oil, dust and to insure a continuous grounding and monitoring [89].

Nippes, one of the pioneers in shaft voltage monitoring, successfully developed and spread out an online condition monitoring system called shaft condition monitoring with Magnetic Product and Services Company. The technology is effective in detecting the followings faults: static charges build-up, residual magnetism, electromagnetic asymmetries such as rotor winding shorted turns, core lamination shorted out, among other faults [11], [90]. Iris Power society developed similar shaft voltages and currents monitoring tools applied on turbo generators [89].

The typical shaft monitoring installation consists in two voltage brushes for voltage measurements and two grounding brushes to protect bearings from shaft currents (see Fig. 6), the latter being often monitored with a high-bandwidth Hall effect probe.

In addition to shaft grounding, ABB developed a shaft current protection relay (RARIC) used for turbo and hydro generators bearing protection. It consists of a ring shaped current transformer to be mounted around the shaft, generally on turbine side [91]. The device measures continuously fundamental and third harmonic components of the shaft current, the latter being

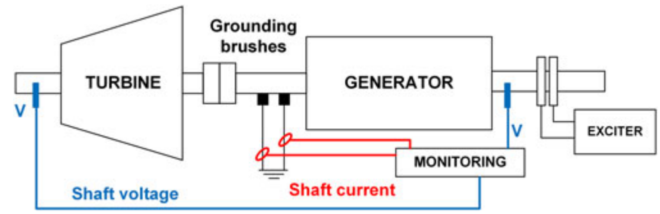


Fig. 6. Typical shaft monitoring installation, two voltage measurements and two grounding brushes [89].

generally associated to eccentricities and magnetic saturation of laminated cores [76].

Journal bearings and their insulation system can be monitored as presented in [92] and [93] by means of a Rogowski transducer. Oil supply and bearing insulation are assessed by a shaft current spectral analysis focused on the oil film breakage. However, the mounting of the Rogowski coil around the shaft is rather complex even though the idea presented in [25] could be innovative combined with the use of a Rogowski coil without an integrator detailed in [94]. The latter paper shows that the removal of the integrator increases harmonics amplitudes, which were difficult to dissociate from noise with a traditional Rogowski sensor. Thus, incipient faults could be detected on the shaft currents, such as HF discharges on bearings, or early signs of failure of grounding brushes.

In shaft condition monitoring, all collected raw signals are sent to a monitor for data processing, and logging. An online diagnostic is performed through fast Fourier transform (FFT) analysis based on specific frequencies tracking and associated amplitudes. However, all authors highly recommend the use of other monitoring techniques to cross results for diagnostic improvement, such as partial discharge level, stator current analysis (MCSA), vibration analysis [11], [89]. A machine learning method based on a Bayesian estimation algorithm has been developed for shaft voltage monitoring [95]. This method is very robust in detecting rotor eccentricity faults and provides good performance if the training of the classifier bases itself on accurate training data which could be difficult to obtain in practice [96].

### *C. Diagnosis of Bearing Damages Due to Bearing Currents*

Over the past few years, Prognostics and Health Management (PHM) techniques have become more and more implemented to improve global maintenance. Bearing condition monitoring and fault detection are one of the top trends in the diagnosis of electrical machines fed by inverters [97]. The PHM and diagnosis methods applied on inverted induced bearing faults were recently summarized in [3] giving the remaining steps to estimate the time to failure of bearings [remaining useful life (RUL)]. This section reviews the current diagnosis methods used to evaluate the bearing damages due to bearing currents. One should be noticed that electrical stress patterns can be considered as generalized roughness faults [98]. A generalized roughness fault is a degradation of a large area of the bearing raceways typically caused by bearing currents, a shaft misalignment or a contamination or lack of lubricant. For diagnosis purposes, generalized roughness faults have been produced via shaft current injection in [99]. The generalized roughness fault is known to be difficult to detect. As stated in [98] and [99], this type of fault produce on vibration and stator current spectra, an increase of the noise floor and broadband changes with the absence of characteristic fault frequencies. A condition monitoring technique based on stator current filtering is proposed in [100]. The idea is to remove the predictable known frequencies of the stator current while keeping the frequency contents related to the bearing fault to train an autoregressive signal model. A reference spectrum is computed for the healthy state, and as the bearing degrade, the modeled spectrum deviate from the reference spectrum model, which is used as a fault index.

Similar methods were described in [101] and [102], with the usage of a noise cancelation method based on a Wiener filter to suppress all frequency components unrelated to bearing fault. The idea was to model the healthy state by a wiener filter, then evaluate the modeling error while the bearing degrade. From a certain electrical bearing degradation stage, the bearing corrugated patterns can be detected by means of vibration signals enhanced through envelope analysis [59]. The spectral kurtosis (SK) method was used in [103] on both vibration and stator currents to detect a generalized roughness fault. The SK identifies the optimal bandwidth in which the fault is more likely to appear, the energy of this bandwidth been utilized as a diagnosis index.

However, to reliably incriminate bearing damages only due to bearing currents, electrical measurements are preferred. When an inverter-fed unit is operating, diagnosis of potential HF bearing currents are conducted by measuring bearing voltages for practical reasons. Indeed, the measurement of a bearing voltage involves only a physical contact with the shaft nearby the bearing and the frame, while measuring bearing currents is not feasible unless the machine is suitably equipped [61]. Nevertheless, as investigated in [104], the discharges bearing currents are reflecting in the CM current and can be detected on both temporal and frequency analysis.

Radio-frequencies measurement devices commercially available can be useful when the presence of HF discharge currents is suspected [67]. However, the energy accumulated in the bearing capacitances and dissipated during a bearing voltage breakdown cannot be measured. Thus, a large quantity of EDM current spikes (i.e., a high DA) is not necessary synonymous of bearing endangerment if the energy involved is unknown [55]. In laboratory, thanks to recent work [35], [105], [106], EDM bearing currents, HF circulating bearing currents, and HF rotor ground currents can be measured with RF methods. It is possible to detect and locate EDM discharges in the bearing [65], [105], while circulating bearing currents and rotor ground currents can be detected when the bearing becomes conductive as a small fraction of energy is emitted outside the machine. This phenomenon is similar to an EDM current event, although this time, the energy radiated has a much smaller level [105], [106]. Nevertheless, RF detection methods are sensitive to interferences such as the radio transmission bandwidth or the inverter itself. Thus, it implies an appropriate filtering, directive, and multiple antennas to locate the discharges before any measurements or interpretations [35]. Such tools will require special attention for the maintenance personnel as it is highly sensitive to EMI.

In this context, evaluating the bearing health toward current flow is still challenging. Bearing voltages are usually valuable mirrors of damaging bearing currents: A method to evaluate the bearing current is defined in [40], which consist in a detailed analysis of the bearing voltage leading to a classification of bearing currents types. The latter method simultaneously coupled to an FFT with envelope analysis of the vibration signals [59], can be very useful to detect incipient bearings faults such as early signs of fluting patterns. The bearing currents can also be calculated with HF prediction models, knowing some parameters of the drive system and, thus, estimate a potential bearing fault [39]. A probability model for discharge events in bearings has been proposed in [107], based on bearing geometry and motor operating conditions. Tischmacher and Gattermann [40] provide the most important measurement points (see Fig. 4) to perform data acquisition for condition monitoring and fault diagnosis. Recently, on test-bench, incipient bearing current damage has been monitored [108] on a dedicated inverter-fed induction motor. The damage was artificially generated via HF bearing current injection during 940 h. The pitting damages on outer and inner rings were found to be unrelated to the increase of the bearing fault frequencies as stated in [98]. As a first step, it is suggested to monitor multiple HF components of vibration by performing time-frequency analysis on specific HF bands. Similar bearing degradation on test-bed has been proposed in [4]. The study shows that tracking the number of bearing discharge events can be used both as an early warning of a bearing degradation and as a starting point to estimate the RUL of a bearing. However, this methods implies intrusive bearing current measurement. Both intrusive and nonintrusive methods, which classify and detect the HF bearing currents events need to be improved and validated on much longer periods in the field by performing statistical and probabilistic methods. This will contribute to determine the aging impacts of these currents on the bearings and to assess the potential mitigation devices already *in situ*. The usage of multiple measurements methods can facilitate faults discrimination, giving compound fault features. This also provides more sensitive and accurate indicators. The combination of data- and model-based techniques seems be the direction being taken for monitoring bearing fault evolution [3].

## V. Conclusion and Future Approaches

In this paper, an overview on the shaft voltages and bearing currents phenomena has been presented. This article has not the vocation of being exhaustive; the main purpose is to regroup different research topics putting in perspective the bearing currents phenomena and fault detection through shaft signals in the hope for improvements of rotating machines condition monitoring, diagnosis, and prognosis toward bearing currents and other motor faults. This paper is intended to be a guide for potential future works in this field. A summary of “classical” bearing currents is given in Section I with a review on the exiting mitigation techniques. Then, a grouping of the recent researches on HF bearing currents is exposed. The phenomena are broadly understood, however, since the matter is multifaceted and complex, it is far from being closed. Shaft voltage condition monitoring reviewed in Section IV has proven efficiency when associated with other condition monitoring methods to detect incipient faults on large synchronous machines. Sustained efforts have been made on mitigation techniques, although more work is needed to improve the actual condition based maintenance. Based on this study, several future research directions are described in the following paragraph.

More work is needed to classify and quantify the "LF" content of bearing voltage related to faults such as eccentricities, broken bars and rotor or stator interturn short circuit. Concerning electrical bearing degradation due to inverter-induced bearing current, forced aging has been performed by several means, but the damage mechanisms inside the bearing are not precisely known and currently no database on the fault development has been disclosed. First, the detection, classification and quantification of HF bearing current events either with intrusive or nonintrusive methods have to be improved. Moreover, correlation with *in situ* bearing aging is still lacking and can be of great interest to predict bearing time to failure with accuracy and confidence in prognosis. Electrical models have analyzed the different bearing electrical modes but no model related to the development of the bearing fault has been proposed. However, predictive models would also require systems parameters, which depend on environment and operating conditions. The bearing voltage could be utilized to monitor the fault evolution and predict failure as also outlined in [3], [58]. Then, together with bearing voltage monitoring, data-based models focused on bearing vibrations and stator currents measurements to detect the consequences of bearing currents degradation could be utilized. Indeed, promising results have been found in studying the generalized roughness fault which is considered as an incipient electrical bearing fault. In this regard, there is a growing need of signal processing methods tracking the changing degradation mechanisms in the bearings.

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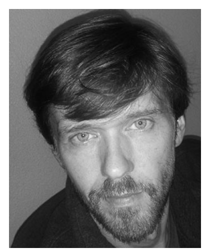

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