An Overview of Shaft Voltages and Bearing Currents in Rotating Machines

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***Abstract* -- Shaft voltages and associated "shaft currents" or "bearing currents" have been known since more than a century on DC and AC motors under classical line operation. More recently with the emergence of inverter drives, there has been an increase of high-frequencies bearing currents and shaft voltages creating mainly premature failure of bearings. Although those phenomena and the associated mitigation techniques are now well-known, one must be kept in mind that there are still potential issues for industrials. Lots of papers have analyzed these concerns and proposed various models and remedies. The purpose of this article is to give an overview on the subject, from causes and origins of shaft voltages, mitigation techniques for engineers new to this subject, to measurements methods, fault diagnosis and online condition monitoring. Finally it is believed that condition monitoring and fault diagnosis through shafts will expend from generators to Induction Motors and Permanent Magnet Synchronous Motors.**

***Index Terms*— Condition monitoring, fault diagnosis, variable speed drives, bearing currents, shaft currents, shaft voltages.**

I. INTRODUCTION

Studies on the presence of shaft voltages on rotating machines have been reported since last century and first summarized by Alger and Samson in 1924 [1]. Then the phenomenon has been widely reported (e.g. [2]-[11]) and thoroughly investigated. Both AC and DC machines were affected by shaft voltages, producing shaft currents and damaging component such as bearings, shaft journals, gears and seals leading to premature failures [5], [6], [12]-[14]. A large panel of mitigation techniques were found [10], [11], but at the time, shaft voltages involved were low-frequency. Then, with the rise of variable speed drives (VSD), high-frequency (HF) shaft voltages were detected, and become a new problem to deal with. Now, both low and high frequency shaft voltages have been well studied and recognized [15]-[25]. Despite all those shaft voltage issues, it has been turned into a useful purpose to improve fault diagnosis and maintenance of hydro and turbo generators. This tendency is slowly extending to all types of rotating machines, with the progressive generalization of condition monitoring in all industrial applications. In this paper, we first provide an overview of those phenomena, giving the physical explanations and mitigation solutions. Next we review the existing condition monitoring, fault diagnosis and associated measurement techniques applied to shaft voltage and bearing currents.

II. LOW FREQUENCY SHAFT VOLTAGES

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 [3], [4]. 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. References [26] and [27] distinguish clearly the "shaft end-to-end voltage" as the shaft voltage v_{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). As those voltages are linked together, the abuse of terms is recurring.

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, joints between stators segments, variation of permeability between segments, rotor eccentricities, bowed rotor can create a magnetic flux encircling the shaft [3]. 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 (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 [1]. 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.

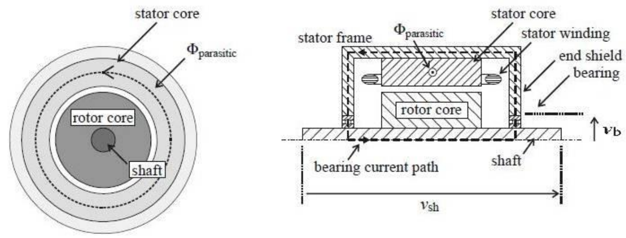

Fig. 1. Bearing currents due to magnetic asymmetries at line operation [23]

2) *Axial Rotor Flux*: A magnetic flux can be generated throw the shaft by residual magnetism (linked to magnetic particle inspection and improper demagnetization) [5] [6], 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 [1], [3].

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 [6], [8]. 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) *An 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 [2], [5].

The inspection of bearing damages was first one of the clues to highlight shaft voltage phenomena. "Low frequency" bearing currents can be classified into four types: frosting, pitting, spark tracks and welding as largely detailed in [6]. A frosted surface is generally imperceptible to the naked eye and microscopically characterized by small "craters" which are formed during electrical discharges (EDM). 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 [3], [6]. 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.

B. Measurement Methods

IEEE112, Standard Test Procedure for Polyphase Induction Motors and Generators [28] 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 [1], [28], usually with brushes and/or slip rings for practical considerations [29]. A high input impedance oscilloscope should be used since the shaft signals are rich in line frequency harmonics. The measures can also be performed with a TRMS multimeter, following the recommendations in reference [28].

NEMA MG1 Standard [30] defines a shaft voltage threshold of 300mV peak which can be applied for polyphase squirrel-cage induction motors rated 3600 kW or less at 7200V or less, whereas IEC60034-25 Standard gives a shaft voltage limit of 500mV peak with low-voltage motors [31]. For their part, manufacturers generally define a bearing voltage threshold of 2V for medium-voltage motors. If shaft voltage is above those limits, both Standards recommend a bearing insulation under sinusoidal operation, when the shaft voltage is measured according to IEEE112.

C. Failures on account of Shaft Voltages / Mitigation Technique

Counter-measures to protect the bearings are mainly bearing insulation and shaft grounding brushes [1]-[2]-[5]. The performances of the latter systems should not be neglected, as shown in a study [32] carried out, amongst others, on a 2.8MW generator. The use of different ground resistances shows the importance of a high performance grounding system. A ground resistance of 90.9 ohms had allowed electrostatic charges accumulation with a shaft voltage increasing up to 170V 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.

Some case study showed the apparition of fluted bearings (term explained in section III-C) on DC motors related to shaft voltages. An experiment has been conducted in [13]: 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 (EDM) based on voltage level and waveform (dV/dt).

In addition, traditional carbon brushes are not suitable for shaft voltage measurements or shaft grounding according to some papers [5], [6], [11]. It is explained that on 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 [5], [6], [11]. However in industry, quantities of trouble-free AC and DC motor applications are protected against shaft voltages by means of specially designed carbon brushes.

III. Shaft Voltage Under Inverter Operation

A. Review on the Phenomena

The phenomenon of bearing currents when the motor is operated by a Pulse Width Modulation (PWM) Voltage Source Inverter (VSI) has been widely reported in the last decades (see, e.g., [15]-[25]). A large quantity of papers has considered the common mode (CM) voltage of a PWM inverter to be linked to bearing currents appearance.

The generation of high frequency 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 high-frequency (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 kilohertz to several megahertz according to multiple authors (e.g. [23], [33]).

The literature distinguishes "circulating" and "non-circulating" bearings currents with four main types of inverter-induced bearing currents classified as follow:

- Small capacitive HF bearing currents (≈ 5-200mA), "non-circulating" type, which appear at low speed. Its effects are neglected compared to other bearing currents [25].
- EDM bearing currents, "non-circulating" type. The bearing voltage v_b mirrors the common mode voltage through a capacitive voltage divider also called "bearing voltage ratio" (BVR) [18], [19]. The bearing voltage increases, charges the lubricant until its threshold voltage (5-30V) is surpassed and causes a breakdown with the apparition of the EDM current pulse (≈ 0.5-3A) [21].
- 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. If the lubricating film breaks down, HF current (≈ 0.5-20A) circulates in the loop "stator frame – drive end bearing – rotor shaft – non drive-end bearing" [18], [25].
- 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 towards the shaft [18], [25]. These currents can reach high levels (≈ 1-35A) and prematurely damaging the bearings.

In particular configurations, a "combined" bearing current can be present which has both inductive and capacitive origins [34]. Equivalent circuit models of bearing currents have been proposed [19], [35]-[37] for an in-depth understanding of the phenomena, for instance the calculation of the BVR (i.e the ratio between the bearing voltage and the CM voltage) which is a function of the HF parasitic capacitances of the machine (Fig. 2): C_{wr} stator winding-to-rotor, C_{rf} rotor to frame, and bearing $C_{b,DE} \approx \mathrm{C_{b,NDE}}$.

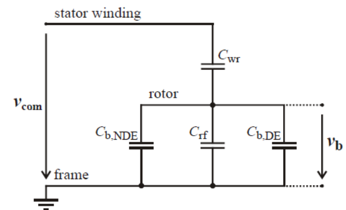

Fig. 2. Equivalent circuit model to estimate the BVR of a machine under inverter operation [36]

Finally, some references have reported the differential-mode voltage as being the source of a shaft end-to-end voltage [26], [27].

B. Measurement Methods

At this time, no thresholds are defined for shaft or bearing voltages of machines under inverter operation [30]-[31], but manufacturers usually suggest a bearing voltage limit of 5V for medium-voltage motors. Moreover there are no standard equipment, and method for measuring this voltage [28]. Reference [38] compares 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 HF circulating current [38]-[39]. 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 [40].

Measurements of HF bearing currents are mostly intrusive methods which need a thorough motor preparation [23], [38]. 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 [39]. In addition, estimating the values of potentially harmful bearing currents is complicated as the bearings depends on the size of the machine and field of application. Thus, authors usually define the "apparent bearing current density" J_b [19], [25] and agree that bearing current densities $J_b \leq 0.1\text{A/mm}^2$ 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 [41], in the vicinity of the bearing (Fig. 3).

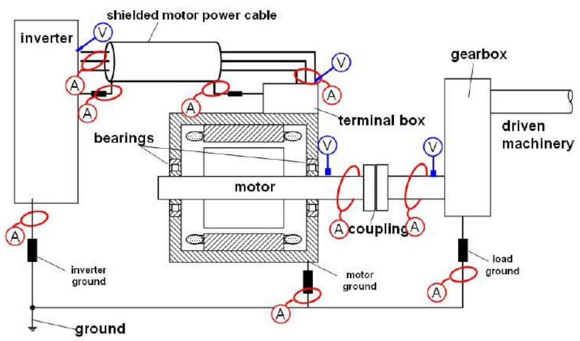

Fig. 3. Most important measurement points used for condition monitoring and fault diagnosis [42]

The current trend is toward non intrusive radio-frequency (RF) measurements to detect high-frequency discharge bearing currents (EDM) [23], [33], [43]-[45]. The method presumes that the high frequency 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 [45] as an assessment of the bearing's health towards HF discharge currents. If high-frequency discharge voltages on one of the bearings or more are suspected, the EDD pen from SKF [46] can be used to count the number of discharges and thus estimate the extent and severity of the bearing defect.

C. 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 [25]: solutions applied on inverter side, or techniques to mitigate bearing currents within the motor. The purpose is to reduce or eliminate the common mode voltage of the inverter, as it is the source of HF bearing currents. The first group comprises inverter output filters (dV/dt-reactors, dV/dt-filters), sinusoidal filters, common mode chokes [47] and shielded cables. Common-mode filters can also be used to reduce or eliminate the CM voltage [48]. The second group includes HF bonding straps [22], rings [41], insulated bearings, ceramic or hybrid bearings, insulated couplings, or electrostatically shielded rotor [20]. Ceramic bearings break the current paths, while the insulating layers of insulated bearings reduce circulating bearing currents and bearing currents due to rotor ground currents, but are ineffective against EDM bearing currents [49].

The classical solution to break the HF circulating currents in the machine is to set up one ceramic or hybrid bearing. Generally, induction machines above 1MW have at least one or two insulated bearings. Other solutions imply the use of a ceramic bearing on the non-drive end and a shaft grounding mechanism on the drive end. In all cases, the phenomena have to be thoroughly investigated before applying any mitigation technique. 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 [50]-[52]. 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 high-frequency 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 120A continuously up to 13,5MHz with voltage discharges up to 3kV peak [41]. Critical operating machines in the industry are often equipped with such bearing protections which require very little maintenance compared to conventional grounding brushes.

It should be noticed that the bearing damages by cause of low-frequency and high-frequency currents are quiet similar except for the well-known fluting phenomenon commonly related to rectifier and inverter-fed machines. Fluting is characterized by transverse evenly distributed flutes burnt into the bearing race, having the appearance of washboarding [13]. In paper mills, DC motors were suffering from fluted bearings due to capacitive coupling between the armature winding and the shaft, because of the rectifiers [14]. Reference [12] highlights the possible causes of bearing damages on DC machines. In the previous case, a shaft grounding mechanism was developed by connecting the shaft and the frame with the lowest impedance path. However they had problems with a carbon layer build-up on the shaft which increased the impedance path [14]. After this event, fluting was largely reported (see e.g., [18]-[21], [25]). Therefore, practical rules of application are given in [49] before the installation of an inverter-fed machine, to prevent bearing damages. An evaluation of bearing currents type is prescribed to choose the most appropriate mitigation technique.

IV. Fault Diagnosis And Condition Monitoring

Condition monitoring and fault diagnosis are functional layers of a more global architecture [53] named OSA/CBM (open system architecture for condition based-maintenance). These layers can be distributed sequentially (Fig. 4) [54].

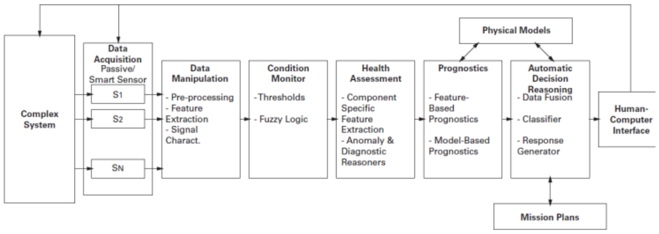

Fig. 4. OSA/CBM sequential architecture according to [54]

A. *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 [55].

Nippes, one of the pioneers in shaft voltage monitoring, successfully developed and spread out an online condition monitoring system called Shaft Condition Monitoring (SCM) with Magnetic Product and Services Company (MPS). 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 [5], [56]. Iris Power society developed similar shaft voltages and currents monitoring tools applied on turbo generators [55].

The typical shaft monitoring installation consists in two voltage brushes for voltage measurements and two grounding brushes to protect bearings from shaft currents (Fig. 5), the latter being often monitored with a high bandwidth Hall Effect probe.

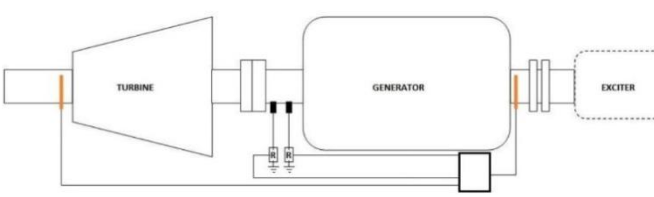

Fig. 5. Typical shaft monitoring installation, two voltage measurement and two grounding brushes [55]

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 [57]. The device measures continuously fundamental and third harmonic components of the shaft current, the latter being generally associated to eccentricities and magnetic saturation of laminated cores [58].

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. For example, 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 420Hz, frequencies which do not change with the machine pole-pair number [58], [59]. 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 [5], [55].

B. *Fault Diagnosis and Health Assessment*

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 shaft voltage to identify faults such as eccentricities, field winding interturn short circuit (e.g. [7], [11], [29], [60]-[61] and [62]-[64],) in synchronous machines. Their studies are validated by stator current analysis (MCSA) or by the use of Finite Element Analysis. Rotor broken bars, a subject extensively addressed by MCSA which is one of the preferred methods, can also be detected by shaft voltage analysis [65]. A rectifier fault of a synchronous machine has been detected by shaft voltage [64] on simulation, with a diode open-circuited which shows significant changes in the amplitudes of 200 and 250Hz harmonics, at both no load and full load.

Journal bearings and their insulation system can be monitored as presented in [66]-[67] 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 [18] could be innovative combined with the use of a Rogowski coil without an integrator detailed in [68]. 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 high frequency discharges on bearings, or early signs of failure of grounding brushes.

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 detecting bearing currents is not feasible unless the machine is suitably equipped [39]. Moreover, multiple parameters influence the apparition of bearing currents type and levels. 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 film or 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 [42]. 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 [69].

Radio-frequencies measurement devices commercially available can be useful when the presence of HF discharge currents is suspected [46]. 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 discharge activity) is not necessary synonymous of bearing endangerment if the energy involved is unknown [70]. In laboratory, thanks to recent work [33], [71]-[72], 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 [44]-[71], 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 [71]-[72]. 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 [33]. Such tools will require special attention for the maintenance personnel.

Over the past few years, Prognostics and Health Management (PHM) techniques have become more and more implemented to improve global maintenance (Fig. 4). Bearing condition monitoring and fault detection is one of the top trends in the diagnosis of electrical machines fed by inverters [73]. The PHM methods on this subject were recently summarized in [74] to estimate the time to failure of bearings (Remaining Useful Life, RUL). Some diagnosis techniques, among other papers, can be found in [75], [76]. Measurements used to assess the bearing's mechanical health are mainly vibration signals, stator currents, or common-mode currents through their different features, such as time domain, frequency domain and/or time-frequency domain [75]-[77]. A probabilistic method, based on a Bayesian estimation algorithm provides an effective solution to monitor bearing degradations by analyzing vibration signals from the machine [78]. More recently a machine learning method similar to [78] has been developed for shaft voltage monitoring which implies a naive Bayes classifier [79]. 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 [80].

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 [42] which consist in a detailed analysis of the bearing voltage. The latter method simultaneously coupled to an FFT with envelope analysis of the vibration signals [81], 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 [69]. Reference [42] gives the most important measurement points (Fig. 2) to perform data acquisition for condition monitoring and fault diagnosis. Both intrusive and non-intrusive methods which classify and detect the HF bearing currents events need to be improved and validated on much longer periods 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.

V. Summary

In this paper, an overview on the shaft voltage 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 to get an overall perspective on the phenomena in the hope for improvements of rotating machines installation, condition monitoring, diagnosis and prognosis toward bearing currents. 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 multi-faceted 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. Improvements have to be made on the detection and monitoring of HF bearing currents with intrusive and non-intrusive methods as both present interests. Finally it seems that there is a lack of knowledge in the shaft voltage as a tool for improving diagnosis and prognosis as explained in section IV.

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