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## ORIGINAL RESEARCH

# Analysis of capacitive discharges in motor bearings under different operation conditions

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## Abstract

Despite being a well-known problem, bearing faults are still one of the major challenges that the industry face. The growing use of voltage source inverters imposed the alertness of possible bearing damage due to their high-frequency signals. The aim of this paper is to investigate the effect of capacitive discharges on a rolling element bearing to obtain a series of faulty bearings with different deterioration levels. An ageing test bench is built to generate bearing roughness using Electric Discharge Machining. The purpose is to study the effect of operation conditions, such as frequency of drive, amplitude of shaft voltage, radial load level as well as rotational speed, on the capacitive discharge occurrence within the bearing. Having the desire to further understand this phenomenon, the influence of each parameter on the discharge activity and the discharge waveform is analysed. A worst-case scenario is conducted and applied to a series of bearings. Finally, the bearing damage is examined, and a quantitative fault detection method is presented based on a microscopic inspection of the bearing's surface.

## KEYWORDS

ageing, ball bearings, machine bearings, PWM invertors

## 1 | INTRODUCTION

Bearing faults are considered one of the main causes of motor outages. These faults represent 40%–50% of motor failures according to Refs [1–3] and can reach up to more than 60% in the case of medium to low-power motors [4]. Bearing failures are due to several factors such as mechanical and electrical wear, environmental pollution, misalignment during the mechanical assembly of the motor, and even poor lubrication.

However, due to the increasing use of Variable Frequency Drives (VFD) in the last decades, the electrical wear of bearings has become a major issue that is most recognisable in the case of low to medium-power motors. Indeed, the use of VFD causes high  $dV/dt$  and leads to an unbalanced three-phase system, where the sum of instantaneous voltages is no longer zero, inducing a common mode voltage  $v_{cm}$  [5]. Consequently, the bearing voltage  $v_b$ , illustrated in Figure 1, representing the potential difference between the inner and outer race of the

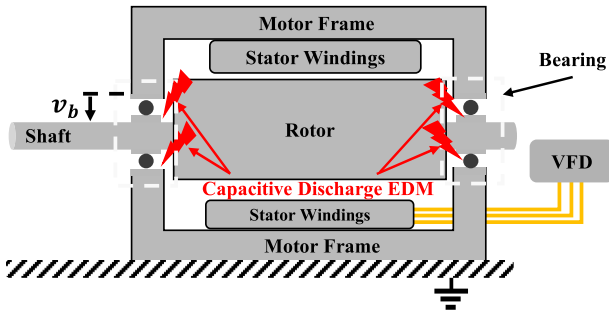
bearing, mirrors  $v_{cm}$ . This voltage prompts an accumulation of electrical energy within the lubrication film of the bearing. Consequently, when the bearing voltage  $v_b$  exceeds a critical threshold known as the lubricant breakdown voltage, capacitive discharge occurs, leading to significant damage to both the lubricant and the bearing components. This phenomenon, marked in red in Figure 1, is commonly referred to as Electrical Discharge Machining (EDM) currents.

An overview on shaft voltages and bearing currents phenomena is presented in Ref. [6], where studies, in the last two decades, linked to bearing degradation are thoroughly highlighted.

Furthermore, the damage resulting from EDM occurrence can be identified by the presence of blackened grease, surface fluting as well as small craters on the surface of the bearing [7]. Typically, randomly distributed craters, resulting from capacitive discharges within the bearing, induce either micro-pitting or pitting, based on their diameter. Though, scale consideration

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**FIGURE 1** Bearing voltage and capacitive discharges (electrical discharge machining currents) at the bearings.

may differ from one author to another (0.1–3  $\mu\text{m}$  according to Refs [8, 9] and 5–8  $\mu\text{m}$  according to Ref. [10]). Either way, based on the size of these craters, bearing faults can be classified into two main categories: generalised roughness with smaller diameters, found at an early stage of the degradation and localised faults with relatively large diameters that are observed at an advanced phase of bearing deterioration.

Naturally, several ideas were developed to overcome EDM damage. One of the most promising methods is the use of ceramic or hybrid bearings. The ceramic elements act as electrical insulation, leading to a complete suppression of EDM currents [7]. Unfortunately, ceramic and hybrid bearings reduce the mechanical performances and imply an additional production cost. These components can be 2–10 times more expensive than a standard steel bearing.

Another approach is to employ low-resistance lubricant (conductive grease). According to Ref. [11], this method was proven able to reduce EDM occurrence. Unfortunately, this result is highly dependent on the condition of the material. For instance, the effectiveness of conductive grease was tested in Ref. [12] where the lubricant being evaluated has lost its electrical conductivity after a test time of 40 h. Therefore, it is not reliable to be used in a component of a long lifespan such as bearings.

Other techniques, such as active and hybrid filters, implemented to reduce/suppress common mode voltage showed promising results, for example, in Refs [13, 14]. Yet, these techniques are not always cost-effective; hence, the need of an optimised mitigation method for EDM bearing currents remains insistent. This implies further investigation of bearing deterioration due to EDM currents, to better understand the phenomenon and the influence of operation conditions on its occurrence. In fact, this need justifies the attention of several authors that this phenomenon is holding until this day.

As for the presented work, this study is essentially motivated by the need of electrically damaged bearings to be used in an upcoming research project on the diagnosis of bearing faults in permanent magnet synchronous machines. Aiming for the development of a new diagnosis method, an accelerated, yet realistic, ageing protocol was needed. A solid understanding of the bearing discharge currents phenomena and the influencing parameters is fundamental to develop this protocol. Hence, the method presented in this paper enabled us to obtain a series of electrically damaged bearings with different fault levels.

The organisation of this paper is as follows. Typical work on electrical ageing of motor bearings in the literature is listed in Section 2. Then, the capacitive discharge phenomenon is detailed in Section 3. Next, the experimental method is presented, and the results are analysed in Sections 4 and 5, respectively. Finally, Section 6 draws the conclusions.

## 2 | ELECTRICAL AGEING OF BEARINGS IN THE LITERATURE

Many studies aimed to develop an experimental method to generate realistic bearing faults [15–18]. The goal is to understand the reasons behind the shortened bearings lifetime related to the use of VFDs. The influence of different operating conditions was carefully examined during the last years. Parameters, such as bearing voltage, drive's switching frequency, bearing temperature, rotational speed, applied load and lubricant type and state, were analysed throughout the literature.

Furthermore, different forced ageing methods were developed in this context. For instance, a 120 V 60 Hz single-phase sinusoidal voltage is applied between the inner and outer races of the bearing in Ref. [17]. The bearing lubricant was removed and only 3%–5% of the lubricant quantity was re-injected. This led to a remarkable generalised roughness on the bearing surface in a relatively short period (8–36 h) while test bearings, repacked at 25%–30% of the lubricant quantity, produced failure time of 11–25 days. In this article, in a test that lasted 124 days, it has been proven that removing approximately 97% of the lubricant's original quantity does not affect the bearing lifetime unless a voltage is injected, proving that the damage was due to EDM currents, and the removal of lubricant only accelerates the process.

A more recent and detailed study was presented in Ref. [19]. The authors states that diverse parameters modify the discharge energy and the discharge activity (DA), that is, EDM current occurrence per second. Namely, voltage magnitude can alter the behaviour of the lubricant. For instance, a 5–10 V bearing voltage induced a significantly higher DA than a 40 V voltage, while the recorded dissipated energy was more significant in case of high voltage levels. In other words, according to this study, lower bearing voltage levels induce more EDM currents and therefore a more generalised roughness, while higher bearing voltage levels will most probably lead to localised bearing faults.

On the other hand, the author of this paper specified that the switching frequency of the inverter, in the range of 1–30 kHz, is not one of the influential parameters when it comes to EDM currents occurrence. This conclusion opposes to the results found in Refs [20, 21], where the authors recognised the increase of DA with the drive's switching frequency. For instance, in Ref. [21], an 8 kHz inverter frequency generates a DA approximately 17 times higher compared to 1 kHz. Correspondingly, the time to failure of a bearing was calculated, in Ref. [22], in function of the switching frequency of the inverter. The results predicted that the bearing's lifetime is

linearly proportional to the inverter switching frequency and that the longest lifetime of motor bearing should be expected when operating with a low switching frequency.

Furthermore, authors that studied the influence of load on the DA, such as Refs [19, 22–24], agreed that low and no-load conditions motivate the generation of EDM currents within the bearing. In fact, it was stated in Ref. [23] that a bearing operating in a low-load condition is more susceptible to increased peak voltage levels with at least higher bearing currents. Furthermore, bearings with lower mechanical load are subject to more corrugation. Similarly, the authors of Ref. [22] found that a full-load operation condition increases the lifetime of the bearing by a factor of 4.86 compared to no-load operated motors.

Speed is also a critical issue to be considered in any bearing ageing protocol. According to Refs [11, 19, 21, 23, 25], speed should be sufficiently high to allow the establishment of an electrically insulating lubricant film. This speed is highly dependent on the motor and bearing's type, for instance, >250 rpm is considered sufficient for discharge generation in Ref. [21], while the minimal speed for discharge occurrence in Ref. [25] is 900 rpm. It is worth mentioning that high speed and long operating time may lead to an increase in bearing's temperature, therefore affecting the thickness of lubricant film and changing its behaviour.

Other factors can influence bearing degradation, such as operating time, temperature, startup protocol and speed variation. For instance, the authors of Ref. [20] specify that bearings with cyclical use are more likely to suffer from discharge bearing currents than those of motors that are operated continuously. In addition, it was stated in Ref. [19] that a successive start/stop of the machine for 3 min (2-min acceleration followed by a 1-min deceleration) can significantly boost the observed DA. Moreover, the maximum of voltage peaks at the bearing increases with speed variation according to Ref. [26].

To summarise, all the studies mentioned above suggest that the electrical wear of bearings is highly affected by the operating conditions of the motor. Therefore, a forced ageing protocol should take into consideration these effects to approach the most realistic form of bearing roughness. In our case, as mentioned earlier, faulty bearings of different deterioration severity are needed to be implemented in a future study. This study will focus on the impact of closed-loop control on the diagnosis of bearing electrical faults in PMSMs. However, the results in the literature are hardly uniform, and the limit values set for each parameter may vary with the bearing's geometry and the lubricant's type. Therefore, our ageing protocol should be thoroughly studied, which inspired the work presented in this paper.

### 3 | ORIGIN AND IDENTIFICATION OF EDM CURRENTS

Electrical discharge machining (EDM) is an event that occurs when shaft current circulates through the rotating bearing. At a low rotational speed, the lubricant is randomly distributed

between the bearing's components. Thus, contact points between the metallic elements exist as shown in Figure 2 (left), allowing the flow of current through the bearing. This state is defined in this study as 'continuous conduction' and it is observed at low speed. In this case, the boundary film thickness is in the order of a few nm permitting the passage of electrons. In these conditions, the bearing acts as an ohmic resistor  $R_b$  and there is no risk of EDM occurrence. This scenario may also be observed at high speed as a form of 'short conduction' that will be later presented in this section.

Nevertheless, beyond a certain rotational speed, the lubricant is uniformly distributed and forms a circular insulating layer, typically 0,1–2  $\mu\text{m}$  [27], along the running track of rolling elements separating them from the inner and outer races. This state is called the 'full film' state (Figure 2 [right]), where the lubricant behaves like a dielectric and is considered equivalent to a capacitor  $C_b$  when modelled in a circuit. During this state, electrical energy is accumulated in the lubricant, until it reaches its maximal charging ability, that is, the breakdown voltage.

Then, the stored energy will be discharged in the form of electrical arcs (spark discharges) over a very short period through the lubricant that acts like an ohmic resistance  $R_{EDM}$  in parallel [27], as presented in Figure 3. Hence, to detect the presence of EDM, one should be familiar with the exact form of these discharges.

Based on the description of EDM currents presented in Refs [28, 29], the capacitive discharge consists of the following phases:

- (1) Pre-breakdown: The electrical field is high and increasing.
- (2) Breakdown: Sudden discharge of the stored electrical energy during a very short time (nanoseconds). A severe

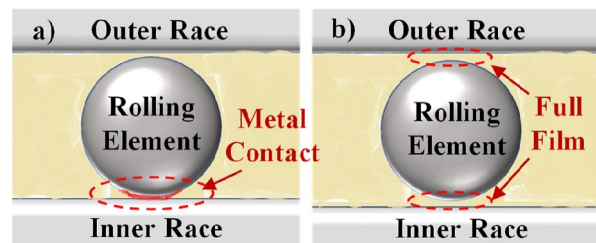


FIGURE 2 Lubrication regimes: Boundary lubrication during continuous and short conduction (a), full film lubrication during insulation (b).

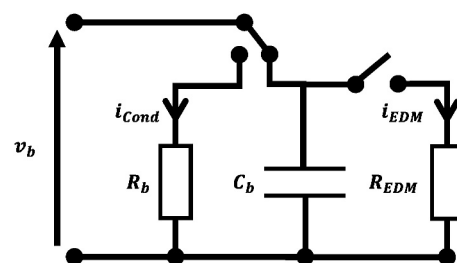


FIGURE 3 Equivalent circuit of a rolling element bearing.

voltage drop can be observed as the current increases almost instantaneously. A plasma is created leading to high temperature and therefore the melting of metal and lubricant.

- (3) End of discharge: Bearing voltage and current drop to nearly zero. The surface is damaged, and melted particles contaminated the lubricant.
- (4) Post-breakdown: The lubricant returns to its insulating behaviour after a certain recovery time.

Therefore, to detect an EDM current occurrence, one should expect a sudden voltage drop simultaneous to a current peak in the order of tens or hundreds of mA. Furthermore, signals in Figures 4 and 5 were experimentally measured using the test bench that will be presented in Section 4. Bearing voltage and bearing current behaviours during an EDM are shown in Figure 4.

As for the 'short-conduction' state occasionally observed at high speed, this event can be easily confused with an EDM current, while not having any significant effect on the bearing surface nor the lubricant. The difference between the two phenomena is illustrated in Figure 5. As it is noticeable, the main dissimilarity appears in the duration of each event, where an EDM's duration is nearly  $1 \mu\text{s}$  (phase 2) while the short conduction lasts for more than  $10 \mu\text{s}$  (phase 3).

On the other hand, the voltage collapses to zero due to the discharge occurrence, while it is proportional to the resistance  $R_b$  during a conduction phase. It is worth mentioning that the conducting behaviour dominates as the bearing's temperature

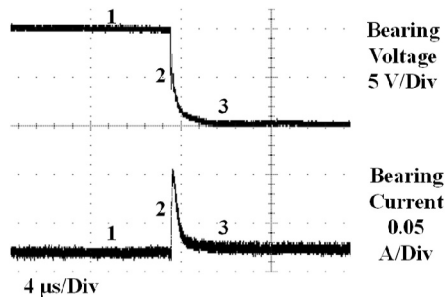


FIGURE 4 Bearing voltage and current variation during electrical discharge machining phases: (1) pre-breakdown, (2) breakdown, and (3) end of discharge.



FIGURE 5 Different lubricant behaviours: (1) insulating behaviour (full film), (2) electrical discharge machining, and (3) conducting behaviour during 'short conduction'.

increases. This is linked to the fact that the thickness of lubricant declines under the effect of temperature. These differences are considered in the proposed EDM detection method which will be further detailed in the following section.

## 4 | EXPERIMENTAL BEARING AGEING METHOD

The experimental method used in this study to highlight the effect of EDM on rolling element bearings is based on the test bench shown in Figure 6. This assembly consists of a 6206 SKF bearing mounted on a variable length shaft, coupled to a dc motor to ensure a reliable rotation. The bearing is mounted using an isolated support. In addition, the setup was designed in a way to enable changing the radial load level at the bearing by modifying the applied vertical force.

As for the electrical circuit, a square unipolar voltage is injected between the inner and outer races of the bearing. This voltage simulates the bearing voltage level inside an electrical machine  $v_b \cong (5 \dots 30) \text{V}$  at a bearing temperature of  $22^\circ\text{C}$  according to Ref. [30] and decreases with the increased temperature due to loaded run, which justifies the use of values from 5 to 30 V in our tests. The contact with the inner race (rotating part) is ensured using carbon fibre brushes. This assembly is sketched in Figure 7.

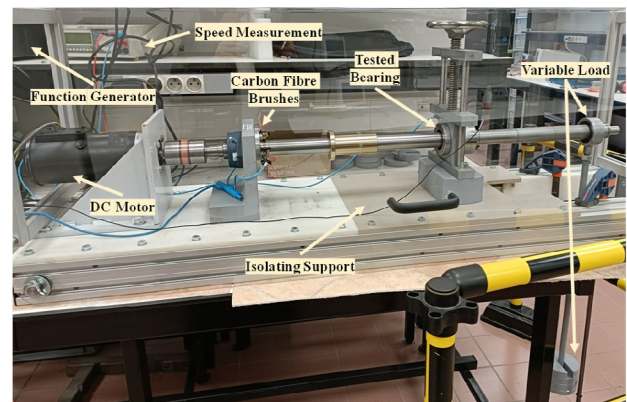


FIGURE 6 Test bench dedicated to bearing electrical ageing.

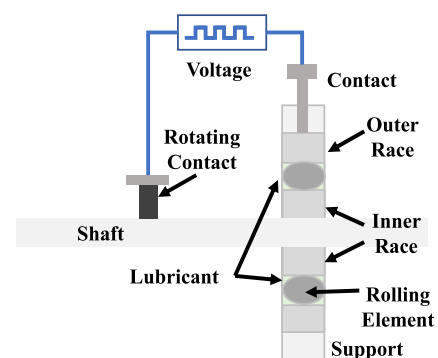


FIGURE 7 Sketch of the test bench's mechanical setup.

Thus, the square wave voltage is applied to the tested bearing while varying the operation conditions, that is, the voltage and frequency levels of the injected impulses as well as the rotational speed and the radial force. The bearing voltage and current are both measured and registered using the PXI-5105 Na high-density oscilloscope. These measurements are then analysed using a MATLAB algorithm that quantifies EDM occurrence. In addition, the amplitude and duration of each EDM are determined, and the energy dissipated in the lubricant is calculated. According to Ref. [27], this energy can be obtained using the following equation:

$$E_{b,EDM} = V_{b,EDM} \cdot i_{b,max} \cdot \tau_{EDM} \quad (1)$$

where  $E_{b,EDM}$  is the dissipated energy during an EDM,  $V_{b,EDM}$  the breakdown voltage,  $i_{b,max}$  the amplitude of the current peak, and  $\tau_{EDM}$  the duration of the discharge. Using Equation (1), a detection current threshold is set to exclusively detect EDM currents with sufficient energy to induce damage. Based on Ref. [23], one can estimate the dissipated energy  $E_{melting}$  (in  $\mu$ J) necessary to melt a hemisphere of radius  $r$  (in  $\mu$ m) using the following Equation (2):

$$E_{melting} = 2,2 \cdot 10^{-2} \cdot r^3 \quad (2)$$

Therefore, the minimal dissipated energy, capable of inducing real damage to the bearing's surface ( $r = 1 \mu$ m), is approximately 22 nJ. Considering the risk of possible measurement inaccuracies, a threshold discharge energy was set to 50 nJ. Hence, to highlight the effect of operation conditions on the discharge occurrence, several measurement series were held. For each series, only one parameter is varying among the following: voltage level, frequency level, rotational speed, and radial force level.

Furthermore, each test is held for 1 h, followed by at least 1 h of rest time. This rest time is essential to prevent the domination of conductive behaviour due to the increase of temperature as previously mentioned. During each test, sub-measurements of 100 milliseconds, separated by 5 min, are registered using a 20 MHz sampling frequency giving a total of 12 sub-measurements per test. Therefore, the frequency of discharges obtained during these 12 sub-measurements is considered as an image of the actual number of discharges that are capable of inducing bearing defects during the total test period (1 h).

Moreover, since this ageing method is based on capacitive discharges, it was important to evaluate the effect of the 'conduction' phases on the degradation. Firstly, it is crucial to distinguish the conduction phase discussed in this paper from the phenomenon of circulating bearing currents, known in the literature to be a significant cause of bearing failure, particularly in larger motors. Despite sharing the same path, circulating bearing currents and the conduction current mentioned in our paper originate from different sources and have distinct characteristics. Thus, the interaction between the high  $dV/dt$  and the winding-to-frame capacitance of the motor creates

circulating bearing currents with a frequency ranging from 100 kHz to several MHz and a peak amplitude ranging from 0.5 to 20 A, depending on the motor size [27]. On the other hand, the conduction phase described in our paper refers to the moment when the lubricant no longer forms a full film, as presented in Figure 2a, that is, when the bearing behaviour is purely resistive. In this case, this injected current presents a peak amplitude that is lower than the case of circulating bearing currents,  $< 0.3$  A in our case, at the same frequency of the applied square voltage, chosen to be  $< 30$  kHz in this paper. These differences suggest that the effect of the circulating bearing currents within a real motor is different than the influence of the conduction phase.

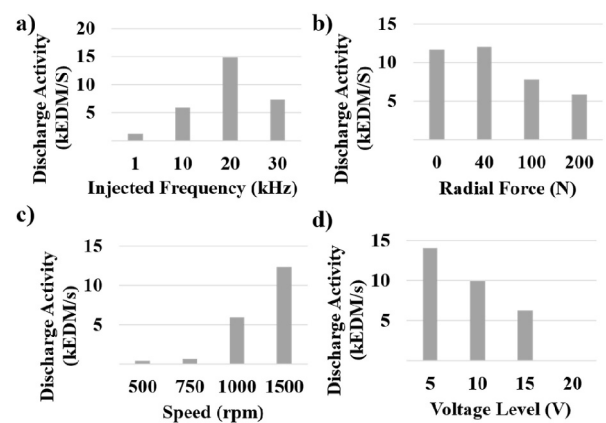
Thus, to evaluate the influence of the conduction phase on the bearing state, a 10 V square voltage was applied to a healthy bearing at rest for 72 h. Consequently, the bearing was only subject to the conductive current, and no EDM occurrence was observed. The bearing was then cut in half and its surface was examined using an optical microscope and  $\times 10$  magnification. It was found that the surface of the bearing was intact. This would suggest that, with this setup, the current conduction due to a metal-metal contact has no effect on the bearing neither on the lubricant. Therefore, any future electrical degradation can be directly linked to the presence of EDM currents.

## 5 | EXPERIMENTAL RESULTS

### 5.1 | Operation conditions effect on discharge activity

The effect of operating conditions on the occurrence of EDM currents was thoroughly analysed in two phases: DA analysis and discharge characteristics analysis.

First, the DA evolution for each series of measurements was evaluated. Obtained results are detailed in Figure 8, where the variation of DA (expressed in number of EDM detected per second) with different operation conditions is highlighted.



**FIGURE 8** Discharge activity in different operation conditions. (a) Frequency, (b) radial force, (c) speed, and (d) voltage level.

It is worth mentioning that the variation of DA throughout the test duration was not considered in this test; therefore, the discharge occurrence frequency expressed in Figure 8 is the average frequency. The chosen test intervals and limit values for each parameter were set based on the literature [19, 20, 28–30], as well as the test bench limitations. For example, the voltage test values were initially set to (5...30) V. Then, the results showed rare occurrence of discharge for voltage levels above 20 V; this justifies not taking these values into consideration in the following results. Another encountered limitation was the high vibration level at speed points >1500 rpm. This is due to the ageing test bench design.

It was found that the variation of each parameter has a distinct outcome on the number of detected discharges. Some of these results were expected based on our understanding of the phenomenon and the results of previous studies. For instance, it is only logical for EDM currents to increasingly appear with higher speed, given that the full film lubricant is only achieved above a certain rotational speed. Also, when the bearing is radially loaded, the thickness of the lubrication layer at the stress point decreases. This would suggest that high load levels promote conductive behaviour and therefore reduce the DA. These theories were confirmed as shown in Figure 8b,c. It is shown that the DA declines under high-load levels and significantly increases with high rotational speed. These results line up with the conclusions of Refs [19, 22–24] previously listed. However, the effect of frequency was not equally obvious. On one hand, test results under dc excitation showed no evidence of EDM occurrence, which aligns with the literature.

On the other hand, our measurements illustrate an obvious evolution of the DA with different frequencies. The results show that the frequency level enhances the DA until a certain maximal point at a 20 kHz switching frequency. Beyond this point, the number of discharges declines. One way to explain this attenuation might be that faster unipolar impulses do not allow sufficient energy storage in the lubricant. However, this statement is to be further investigated. Moreover, the DA seemed to be highly influenced by the excitation voltage level. In fact, the number of detected discharges significantly drops with higher voltages. Based on our observation, this drop could be related to the domination of conductive behaviour when the lubricant is subject to relatively high voltage levels. High voltage levels induce more powerful discharges [19], consequently, the lubricant's temperature rises faster, and it loses its insulating behaviour for few hours. During these tests, it was possible to note this phenomenon after realising that resting the bearing for several hours enabled the lubricant to regain its insulating characteristics.

It is important to highlight that the DA observed in the 1 kHz test (Figure 8a), in the 500 and 750 rpm tests (Figure 8c), and in the 20 V test (Figure 8d) is notably lower compared to the corresponding values observed in other tests. Consequently, it would be unfitting to include the results of these measurements in the subsequent analysis.

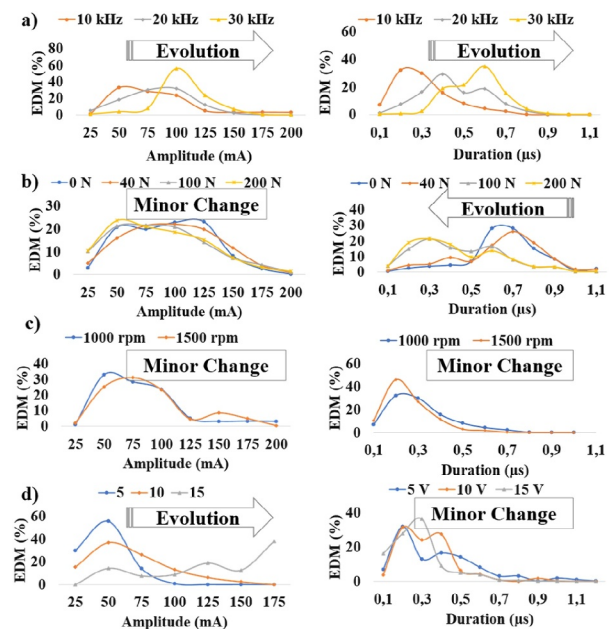
Admittedly, these results present major information regarding the preferred environment for EDM occurrence.

Though, analysing the DA alone cannot guarantee full knowledge of the discharges form and characteristics, namely the energy dissipated due to these sparks. For this reason, the influence of operation conditions on the amplitude and the duration of the detected capacitive discharges were further examined. This is presented in Figure 9 where the influence of each parameter on the form of EDM currents is highlighted. The applied voltage in Figures 9a–c is fixed to 10 V, while the switching frequency in Figures 9b–d is set to 10 kHz.

Hence, the variations of the amplitude distribution (left column) and duration distribution (right column) with different operating conditions are approximated. For instance, Figure 9a (left) presents the influence of different frequency levels on the amplitude of detected EDM currents. Each plot is attributed to a frequency value and obtained by the interpolation of the marked points. Let  $A_k$  be a marked point on a plot attributed to a frequency  $f$ , where  $k$  is an integer in  $\{1, \dots, 8\}$ . In that case,  $\gamma_{A_k}$  presents the percentage of EDM currents with an amplitude value in  $]x_{A_{k-1}}; x_{A_k}]$ .

The results show a noticeable impact on the characteristics of EDM currents, especially in the case of frequency variation Figure 9a. As the frequency level increases, the discharges tend to present both higher amplitude and duration. This results in higher energy dissipated through the bearing according to the expression in Equation (1). Indeed, this result is in accordance with Ref. [31], where it was stated that the breakdown strength increases dramatically with high-frequency impulse shaft voltage.

On the other hand, Figure 9b shows shorter EDM currents when the bearing is heavily loaded. This is possibly related to the thinner lubrication layer in the loaded bearing leading to smaller capacitance  $C_b$ . However, no apparent influence of the



**FIGURE 9** Influence of operation conditions on the electrical discharge machining currents amplitude (left) and duration (right). (a) Frequency, (b) radial force, (c) speed, and (d) voltage level.

vertical force variation on the amplitude distribution is recorded. Similarly, despite having a remarkable effect on the DA, the rotational speed variation has a minor effect on the EDM characteristics according to Figure 9c.

As for the injected voltage, Figure 9d shows that higher voltage levels induce EDM currents with higher amplitude. According to (1), this is equivalent to higher energy dissipation. On the other hand, the voltage level has a minor effect on the EDM duration.

Table 1 summarises the interpretation of our results. It also identifies the ‘worst-case scenario’ that was then used in our accelerated ageing strategy. Indeed, the highest speed and lowest load levels (radial force) producing the maximal bearing damage while guaranteeing the stability of the ageing test bench are used. In addition, a 10 V voltage level and 20 kHz frequency levels are chosen as a compromise between high DA and powerful EDM currents.

## 5.2 | Damage analysis and quantification

The test bearings were further evaluated by visual inspection. For instance, Figure 10 shows the difference between the lubricant of an electrically damaged bearing (right), which was subject to the ‘worst-case scenario’ defined in the previous section, for 60 h, and a test bearing that was subject to the same mechanical constraints without any electrical excitation (left).

Indeed, the chemical change in the lubricant of the electrically aged bearing was remarkable. The grease is turning black, and the texture is drier, and it also contains clumps and dark particles. It was noticed as well, during the runtime, that the lubricant becomes more and more conductive as the bearing ages. This is due to the grease being contaminated with metallic particles snatched from the bearing's surface on one hand and to this surface's roughness presenting pits and peaks, enhancing the metal–metal contact, on the other hand. In fact, beyond a certain stage of electrical damage, the lubricant was unable to regain its dielectric characteristics even after three consecutive days of rest time.

Additionally, the inner and outer race of the electrically aged bearing presented a grey running track. This can be concluded from Figure 11 which shows the inner races of the above-mentioned bearings. We can notice the shining surface of the indicator bearing while a grey line is observed on the

surface of the aged bearing. This grey line can be linked to the degraded state of the lubricant. The author of Ref. [19] supports this possibility by linking this kind of fault (grey line on the race) to insufficient lubrication leading to a higher friction force.

Besides these consequences that are visible to the unaided eye, a closer visual inspection with the help of an optical



FIGURE 10 Lubricant chemical change due to electrical wear.

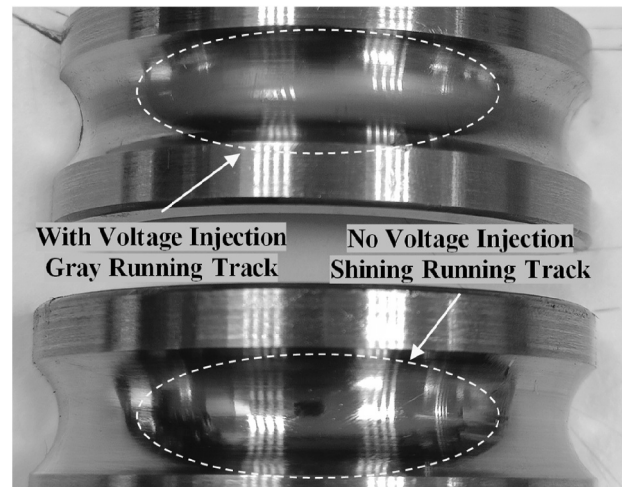


FIGURE 11 Inner race running track of the electrically aged test bearing (top) and the indicator test bearing (bottom).

TABLE 1 Influence of operation conditions on EDM occurrence and characteristics.

Parameter increase	DA	$i_{EDM}$	$\tau_{EDM}$	Comments	Worst-case scenario {tested values}
Frequency	↑↑	↑↑	↑↑	Compromise needed	20 kHz {1, 10, 20, 30} kHz
Load	↓↓	None	↓↓	Lower load induces higher damage	No load {0, 40, 100, 200} N
Speed	↑↑	None	None	Higher speed induces higher damage	1500 rpm {500, 750, 1000, 1500} rpm
Voltage	↓↓	↑↑	None	Compromise needed	10 V {5, 10, 15, 20} V

Note: ↑↑: Increase with parameter increase. ↓↓: Decrease with parameter increase. None: No or minor effect.

Abbreviations: DA, discharge activity; EDM, electrical discharge machining.

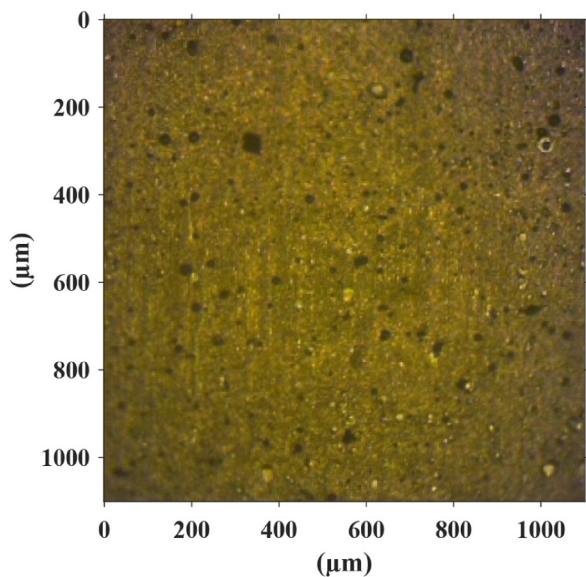


microscope highlights the direct outcome of EDM currents. A group of four bearings was damaged using the proposed ageing method and the operation conditions of the 'worst-case scenario'. The ageing lasted for 1, 6, 18, and 60 h, respectively. Consequently, different fault levels were obtained and photographed. To illustrate, Figure 12 presents the original image showing surface roughness of different diameters on the outer race of a bearing aged for 18 h. It should be noted that all the images used in the visual inspection test were taken at the same location of the outer race for each test bearing with  $\times 10$  magnification zoom. The photos were then analysed using a MATLAB image processing algorithm that can detect the presence of micro-pits and micro-peaks using colour identification and then calculate their percentages in each image. In fact, the micro-pits are the result of discharges that melt the metal particles of the bearing.

Parts of this melted metal contaminate the lubricant as previously highlighted. Other melted particles solidify and adhere to the surface once again, creating the above-mentioned micro-peaks. Thus, by calculating the percentage of micro-pits and micro-peaks, we can evaluate the surface damage generated in each bearing. The detection of micro-pits and micro-peaks is illustrated in Figure 13. The total damaged surface detected in Figure 12 is then 2.48% of the total analysed surface.

The evolution of surface damage with ageing duration is plotted below (Figure 14). Indeed, after 18 h of electrical excitation, the surface damage rapidly rises representing an exponential increase tendency. Thus, the fourth test bearing that was aged for 60 h presented 16 times the damage of the bearing aged for 6 h.

It is worth mentioning that these results are based on a relatively small sample and should be further completed using a larger sequence of aged bearings photographed at several



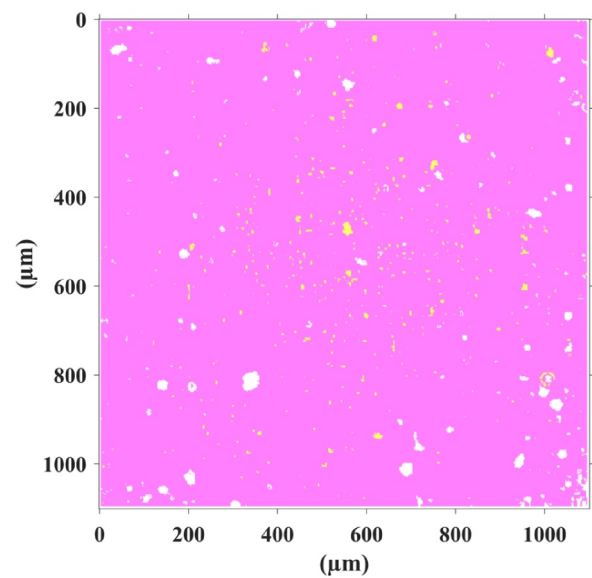
**FIGURE 12** Microscopic damage on a bearing surface due to electrical discharge machining currents: Total calculated damage 2.48%.

spots. Indeed, this method can replace traditional visual inspection, often used to evaluate a bearing's status based on the experience of the researcher, which risks leading to a subjective judgement.

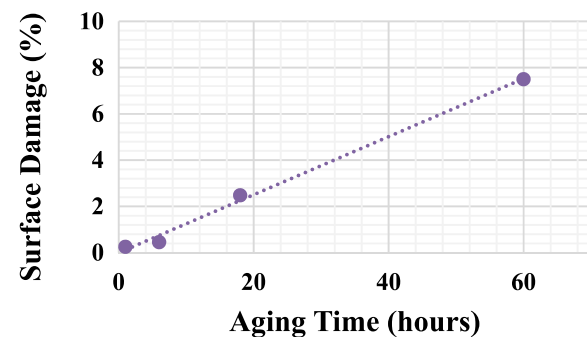
## 6 | CONCLUSION

This paper presents the influence of several factors in the evolution of capacitive discharges which appear in the bearing of electrical motors fed by inverters. Considering other studies and methods presented in the literature, the roughness of the bearing was generated experimentally in situ by electrical discharges. The influence of the EDM currents and the operation conditions in the occurrence of DA and discharge energy was identified and quantified.

Thus, the method presented in this paper allowed us to obtain a series of electrically damaged bearings with different fault levels. Bearing roughness and lubricant failure were detected by visual inspection. Additionally, microscope images of the surface roughness were analysed and micro-pitting at different damage stages was quantified using image analysis.



**FIGURE 13** Roughness inspection using image processing: Micro-pits in white (1.6%) and micro-peaks in yellow (0.88%).



**FIGURE 14** Evolution of surface damage percentage with time.

So, it was proven that the destructive scenario occurs when the bearing is unloaded, at high speed, under relatively high inverter switching frequency and medium shaft voltage. Finally, a forced ageing protocol was proposed where the roughness evolution showed accelerated surface degradation over time after less than 60 h of ageing.

## AUTHOR CONTRIBUTIONS

**Sara Jammoul:** Conceptualisation; data curation; formal analysis; investigation; methodology; software; visualisation; writing – original draft; writing – review & editing. **Remus Pusca:** Conceptualisation; investigation; methodology; project administration; supervision; validation; writing – original draft; writing – review & editing. **Raphael Romary:** Conceptualisation; investigation; methodology; project administration; supervision; validation; writing – original draft; writing – review & editing. **Guillaume Lefevre:** Conceptualisation; methodology; project administration; supervision; writing – review & editing. **Nicolas Voyer:** Conceptualisation; methodology; project administration; supervision; validation; writing – review & editing. **Guilherme Bueno Mariani:** Conceptualisation; methodology; writing – review & editing.

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## CONFLICT OF INTEREST STATEMENT

No conflict of interest.

## DATA AVAILABILITY STATEMENT

Research data are not shared.

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