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Study of a Low-Cost Piezoelectric Sensor for Three Phase Induction Motor Load Estimation

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Abstract: Due the high level of control and automation networks in modern industries, the sensor-based systems stand out as effective approaches for failure detection in electrical and mechanical machines. This kind of intervention has a high operational value in industrial scenario, once it can avoid corrective maintenance stops, i. e. before the failure reaches a high level of severity and compromise the machine. In consequence of that, the development of sensors applied to non-destructive techniques (NDT) for failure monitoring in electrical machines have become a recurrent theme in recent studies. In this context, this paper investigates the application of low-cost piezoelectric sensors in vibration analysis, which is an NDT that already proved to be efficient for detection of many structural anomalies in induction motors. Besides that, the proposed work presents a low-cost alternative approach for the costly commercial sensors, which can turn this NDT more likely to industrial applications. Moreover, in order to describe the piezoelectric sensor frequency response, it was performed the pencil lead break (PLB) test. After this validation, the RMS value from the voltage samples obtained in the test bench was used as a signal processing method. The comparison between the results for different levels of mechanical load attached to the machine shaft indicates not only a successful performance of the low cost sensors for load estimation purposes, but also showed that oversized motors may present higher vibration levels in some components that could cause mechanical wearing.

Keywords: piezoelectric sensors; non-destructive techniques; low-cost sensors; signal processing

1. Introduction

Nowadays, the development of several types of sensors have been increasingly the focus of several studies aiming to accomplish the correct feature extraction about the three phase induction motor (TIM) operation. Since the evolution and enhancement of variable frequency drives, allied with its efficiency and robustness, TIMs took over about 90% of industrial electrical applications [1]. Due its significance, maintenance stops in this machines has a direct link with huge financial losses and, owing to it, many techniques that allow to predict and identify faults using sensor-based systems in TIMs have been proposed [2–4]. One of the most interesting of then is the non-destructive techniques (NDT) such as the vibration analysis.

The most of the currently NDT-based systems can only be employed for failure diagnosis in TIMs by using accelerometers and devices with high financial costs. For this reason, the high cost of this type of sensors is still an obstacle for dissemination of NDT in industries. Therefore, the development of cheaper sensors shall turn this kind of approach more viable on a day-to-day maintenance routine, improving the efficiency and the safety of operations [3]. Consequently, although the vibration analysis has already present great results [3,5,6], the application of the low-cost sensors would turn the NDT more feasible and advantageous.

According to this facts, this works aims to validate the low-cost piezoelectric sensors for vibration analysis and TIM diagnosis. The piezoelectric sensor is known as a cheap and thin sensor that can be easily find on the market. The tests were accomplished in a 3 hp TIM and two of these low-cost sensors were attached in front and back side of this electric machine. Different levels of mechanical loading were applied to the TIM shaft. The RMS values of the signals produced by the piezoelectric sensors were extracted and processed, in order to estimate the corresponding load level.

The first results showed that the piezoelectric sensor was able to accurately identify the loading profile on TIM, demonstrating a great potential for vibration analysis. Furthermore, the results indicates that an incorrect sizing of a TIM can increase the vibration pattern in specific spots, which may lead to mechanical wearing in bearings, end bracket, shaft slinger, sleeves, etc. For future work, the piezoelectric sensor will be tested for mechanical and electrical failures diagnosis.

This work is divided in 6 sections. The Sections 2 and 3 present, respectively, the low cost piezoelectric sensor used in this work and the signal processing technique based on RMS analysis. The experimental setup is described in Section 4 and, then, in Section 5, the results are discussed and the article is finalized by the conclusion in Section 6.

2. Piezoelectric Sensors Review

The piezoelectricity can be defined as a bidirectional electromechanical phenomenon perceived in some specific materials known as piezoelectric crystals. If a mechanical force is applied to a capsule, containing piezoelectric crystals, an electric charge will be induced on its terminals, otherwise, if an electric charge is applied to its terminals, a mechanical deformation will be perceived on this capsule [7]. The basic constitutive relations of the direct and reverse piezoelectric effects for a piezoelectric material are given by Equation (1) and Equation (2), respectively [8]:

$$D_i = d_{ikl} T_{kl} + \varepsilon_{ik}^{T} E_k \tag{1}$$

$$S_{ij} = s_{ijkl}^{E} T_{kl} + d_{kij} E_k \tag{2}$$

where, d_{ikl} and ε_{ik}^{T} are the piezoelectric constants, is the permittivity component at constant stress, is the electric displacement component, E_k is the electric field component, S_{ijkl}^{E} is the elastic compliance constant at constant electric field, S_{ij} is the strain component, T_{kl} is the traction vector component, and i, j, k, l = 1, 2, 3.

Once proven that the mechanical stress can induce electric charges in the piezoelectric diaphragms, it is feasible to admit that the low-cost piezoelectric sensors attached to the TIM structure, as described in Section 2.3, can transduce the vibrational displacement in readable voltage signals, which will be processed using the RMS analysis, presented at Section 2.2.

The specific transducers used in this study were the piezoelectric diaphragms, which have similar characteristics to conventional PZT ceramics [9,10] . The buzzer diaphragms have a circular brass plate whose dimensions are 20 mm x 0.2 mm that houses a circular piezoelectric ceramic with dimensions of 14 mm x 0.42 mm, which is coated by a metallic film, as shown in Figure 1.

The PLB test is a well-known test in signal processing to determine the sensor frequency response, as seen in [11,12]. For the experimental setup used in this work, the cut-off frequency for the piezoelectric sensor was about 117 kHz, which is compatible with the application in vibration analysis (up to 20 kHz).

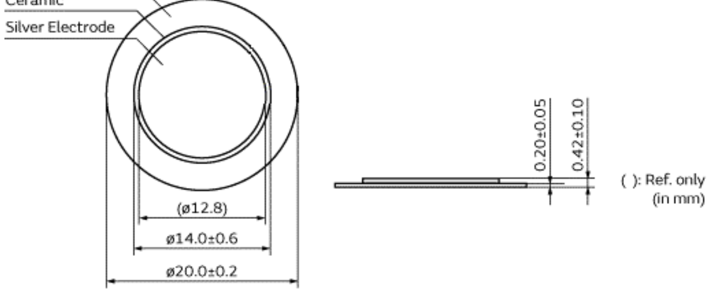


Figure 1. Buzzer representation [13]

3. RMS Signal Processing Analysis Applied to AE and Vibration signals

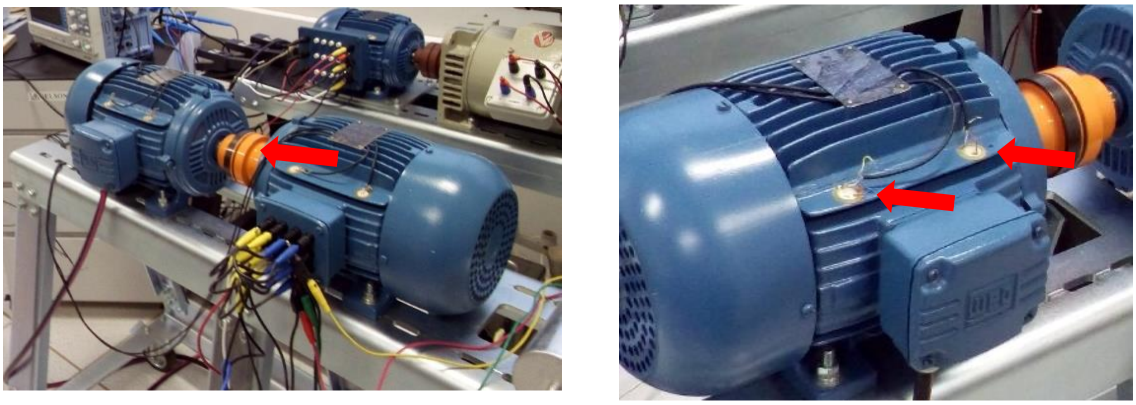
Traditionally, root mean square parameters can be an effective alternative to perform the vibration and acoustics signal characterization. This approach is directly related to the vibrational or acoustic load applied to the sensor and is an attractive attribute for any monitoring application [14]. Based on the formal definition of the RMS value, the RMS parameter for analysis of finite time AE signals is given by:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_{0}^{T}\left(V\left(t\right)\right)^{2} dt} = \sqrt{\frac{1}{n}\sum_{n=1}^{n} v_{n}^{2}} \quad (3)$$

where, in Equation (3), T is the period of the signal and $V(t)$ is the continuous time function that characterizes it, also, the equation for discrete samples is described, where n is the number of samples and v_n is the value of the n-th sample of the signal [15].

4. Methods

In order to verify the effectiveness of the piezoelectric diaphragm for IM load estimation, two electrical machines were used to perform the tests: a TIM and an Induction Generator (IG). Both machines were fixed firmly on a bench and their shafts were coupled using a metal joint. (Figure 2 (a)). The piezoelectric were attached in TIM as shown in Figure 2(b). To simplify, this section is divided in two parts. The first is presents the TIM setup and, finally, the second one, discuss the data acquisition systems and sensors validation setup.



(a) **(b)**

Figure 2. Joint between two electric machines (a) and sensors location at TIM (b)

4.1 TIM setup

Once the machines were coupled, the TIM was powered at its nominal voltage by the three phase source supply. The IG was used as a mechanical load and, for the first measure, its output terminals were set as an open circuit, i. e. the initial loading corresponds only to the IG inertia. After this, a three phase load bank was connected to IG and set to increase the current value in steps of 0.5 A, starting in 0 A until it reaches 12 A.

Each current value on IG terminals represents a different loading demand on the TIM shaft, which means that the current flowing through the TIM also varies. The software that controls the three phase source also has a graphic interface, where the motor current can be read. The loading value can be achieved comparing this information with the "current vs loading" curve presented in the datasheet provided by the TIM manufacturer. Later, the TIM loading will be linked with the signals acquired by the low-cost sensors.

4.2. Sensor and Data Acquisition

Two piezoelectric diaphragms were attached to the front and back sides of the TIM using cyanoacrylate-based glue, as shown in Figure 2(b). Before the signals from the sensor could be acquired by the oscilloscope, they were amplified by an instrumentation amplifier (INA 128P – Texas®) whose frequency response is up to 400kHz and amplitude gain set to 25. The oscilloscope sample rate was set to 1MS/s, which satisfies the Nyquist theorem, since the cutoff frequency for this sensors is about 117 kHz according to PLB test. Avoiding high-frequency interferences, the resulting signals from the piezoelectric sensors were subjected to a 20 kHz low-pass filter and processed using MATLAB® software. The results were showed and discussed in Section 3.

The connection cables between the sensors and the amplifier board were shielded using a grounded mesh to avoid electromagnetic interference, the bench and the symmetrical D.C source used to power the instrumentation board also needed to be grounded. In addition, to avoid temperature fluctuations, the TIM was taken to steady state before any measurement and, for loads greater than 100%, the tests were performed quickly.

5. Results and Discussion

In order to evaluate the effectiveness of piezoelectric for TIM load estimation, the RMS values were calculated for different types of TIM loading. The Figure 3 shown the RMS curves for front and back piezoelectric coupling.

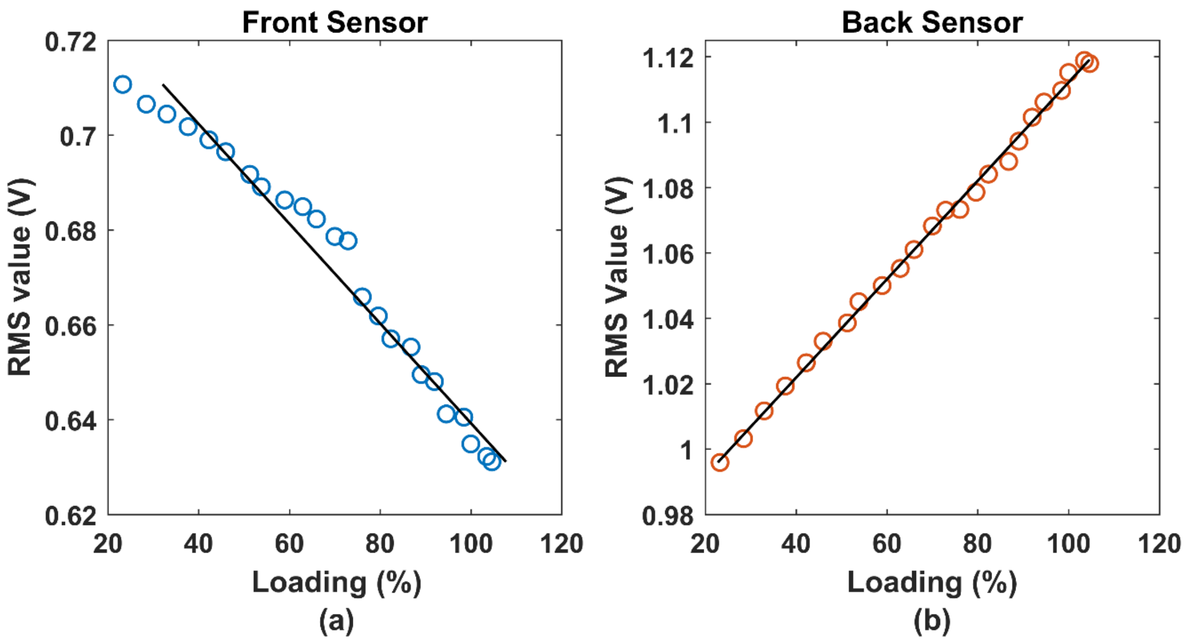


Figure 3. RMS values for the: (a) front piezoelectric sensor; (b) back piezoelectric sensor.

As seen in Figure 3 (a), in the front side sensor, the RMS values decreased in a close to linear trend. This behavior shows that the coupling between the TIM and the load (IG) becomes tighter for higher loads, leading to lower levels of vibratory displacements for areas closer to the metal joint.

Consequently, as the loading decreased, the coupling became freer, increasing the vibratory displacements.

Instead of the front coupling, the RMS values for the back-side sensor, presented in Figure 3 (b), followed a directly proportional linear trend to the TIM loading. This behavior shows that places further from the coupling between the machines are less affected by the phenomenon seen in the front side of TIM and tend to suffer with higher vibratory displacements for higher loads.

Owing to the linear behaviors present by both curves (Table 1), the loading estimation using the RMS values and the low-cost piezoelectric sensors can be achieved using a simple linear regression.

Regarding the results obtained, it can be concluded that the piezoelectric sensor was able to diagnose the load pattern in the TIM.

Table 1. Linear regression equations

Sensor	Slope	y-intercept
Front side	-0.0010161	0.74196
Back side	0.0015009	0.9619

6. Conclusions

This work evaluated the low-cost piezoelectric sensor as a transductor in vibrational analysis approaches to diagnose and prevent failures in TIMs. For this purpose, it was proposed an experimental setup where two sensors were attached to a TIM and the resulting signals for different loading levels were processed using MATLAB® software.

The growing demand for cheaper and reliable sensor-based systems, mainly in TIM fault detection and maintenance, endorses the study of applications based on piezoelectric sensors. Due the high commercial prices of prevailing devices, low-cost approaches establish a safer and profitable industrial environment by promoting affordable solutions using NDT.

Based on the results presented by this work, the RMS curves, attest that the piezoelectric sensors are capable to estimate the TIM loading through a linear regression of these curves. Additionally, they indicated that oversized motors may present mechanical wear in their front side components due to the higher vibratory oscillations, caused by the freedom observed in the coupling between the TIM and the load for lower loading values.

The first experimental results demonstrated that low-cost sensors have the potential to act as transducers in vibration analysis, therefore, for future studies, it is feasible that these sensors could be able to identify electrical and mechanical failures in TIM. This is an initial experiment and more tests must be applied to the sensors for future validation.

Author Contributions: all authors contributed in writing, proofreading, and providing suggestions for the improvement of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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