Self-Organized Map based on Acoustic Emission Signals for Power Transformers Monitoring

Izadora Rodrigues Bittencourt, Abdo Youssif Khoury Filho, Jorge Alfredo Ardila-Rey
Member, IEEE, André Luiz Andreoli *Member, IEEE,* and Bruno Albuquerque de Castro
Senior Member, IEEE

***Abstract* -- One of the frequent issues encountered in power transformers is the discharge activities within the dielectric components, often resulting from insulation breakdown due to factors like overload, moisture, overheating, and manufacturing defects, including issues like conductor misalignment, bending, and dirt accumulation on bushings. In light of this, developing systems that can accurately classify different types of failures is crucial to improve maintenance strategies. This article introduces a novel method to categorize three operational states based on the acoustic emission technique: surface discharges on bushings, incipient short circuits (or electric arcs) within the transformer, and transformers operating without defects. An acoustic sensor was attached to the transformer wall, capturing acoustic signals produced by the faults. Subsequently, a signal processing analysis focused on spectral content was performed. The results demonstrated that skewness, the average frequency and equivalent bandwidth statistics prove effective for assessing operational conditions.**

***Index Terms*--Power Transformer Failures; Acoustic Emission; Discharges, Failures.**

I. INTRODUCTION

The diagnosis of incipient faults in power transformers is crucial for ensuring a high degree of reliability in the electrical system, as these high-voltage assets are used in energy transmission and distribution. In this context, several techniques are employed to assess the insulation condition of power transformers aiming to identify dielectric degradation due to thermal faults, discharges, inter-turn short circuits, partial discharges, etc [1,2]. These issues arise due to dielectric degradation caused by overload operation, manufacturing flaws, penetration of particles, gases, moisture, etc [3]. In addition, overload operations may cause chemical reactions in cellulose-based components, leading to the emission of gases that can initiate partial discharges (PD) [1]. Murugan and Ramasamy (2019) [3] provided a comprehensive breakdown of the various components of a power transformer and their respective failure rates. For example, windings and insulation systems have a significant percentage of transformer issues (about 56%). Bushings also exhibit a notable failure rate (15%), often due to external environmental factors and operational stress. In this context, PD activity in bushings or incipient short circuits on windings are common flaws that can lead to transformer outages. Partial discharges are characterized as low-energy discharges that partially bridge the dielectric material, while incipient short circuits are high-energy discharges that can occur, for example, between turns or between the high and low-voltage windings of the transformer [3]. There are several techniques to monitor the insulation condition of the transformer, such as Dissolved Gas Analysis (DGA) [1], Frequency Response Analysis (FRA) [4], Phase Resolved Partial Discharge (PRPD) [5], Ultra-High Frequency (UHF) signal emission analysis [6], among others. One of the most promising techniques is Acoustic Emission (AE), which uses piezoelectric transducers attached to the transformer wall to detect ultrasound signals emitted by faults. Although AE is a traditional technique, there are many technological challenges, particularly in its ability to classify different types of faults. A study proposed by Castro et al. (2023) [8] applied piezoelectric transducers with a wide response range to perform failure classification. However, many commercial ultrasonic transducers have a narrower bandwidth response, sometimes set to a specific frequency. Hence, this limitation in spectrum range may impair fault classification techniques, especially those based on the frequency response of signals emitted by faults.

In this context, this paper investigates the effectiveness of a piezoelectric ceramic with a resonance frequency of 50 kHz by characterizing and differentiating three power transformer operational conditions: healthy state, PD in bushing, and incipient short circuits in oil. The frequency spectrum of each condition was calculated, followed by the average bandwidth, the equivalent bandwidth, and the skewness of each spectrum. The goal was to assess whether the limited bandwidth affects the capability of fault classification.

The structure of the paper is as follows: Section 2 presents the signal processing tools used in this study, followed by the experimental setup described in Section 3. Section 4 presents and discusses the results, followed by the conclusions in

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Izadora Rodrigues Bittencourt, Abdo Youssif Khoury Filho, André Luiz Andreoli, and Bruno Albuquerque de Castro are with the São Paulo State University (UNESP), School of Engineering, Dept. of Electrical Engineering, 17033-360 Bauru, SP, Brazil. Jorge Alfredo Ardila-Rey is with the Universidad Tecnica Federico Santa Maria (UTFSM), Dept. of Electrical Engineering, Santiago, Chile. (e-mails: i.bittencourt@unesp.br a.khoury@unesp.br, jorge.ardila@usm.cl, andre.andreoli@unesp.br, and bruno.castro@unesp.br).

Section 5.

II. SIGNAL PROCESSING ANALYSIS

The discrete Fourier transform (DFT) is a traditional tool used to extract the spectral content of a given sequence x[n], and it is defined as:

$$X[k]=\sum_{n=0}^{N-1} x[n].e^{-j\frac{2\pi kn}{N}} \qquad (1)$$

$$f_k=\frac{2\pi k}{N}, k=0,1,2,...,N-1 \qquad (1)$$

where X[k] is the amplitude of the Fourier Transform, N is the length of the signal, and f[k] is the frequency.

As mentioned, some piezoelectric transducers have narrow bandwidths, which may reduce the content that feeds frequency-based transformer fault classification techniques. In this scenario, we applied the Fourier Transform to the acoustic emission signals to perform feature extraction of each power transformer's operational condition. Therefore, the frequency content X[k] of all signals was mathematically reduced to three statistics: Average Frequency (AF), Equivalent Bandwidth (EB), and Skewness (Sk).

The AF is defined as the central frequency of a given signal [9,10]:

$$AF=\frac{\sum_{n=0}^{N-1} f_k\left|X[k]\right|}{\sum_{n=0}^{N-1}\left|X[k]\right|} \qquad (3)$$

The Equivalent Bandwidth EB represents the effective frequency band of the total spectrum [9,10]:

$$EB=\sqrt{\frac{\sum_{n=0}^{N-1} f_k\left|X[k]\right|^2}{N\sum_{n=0}^{N-1}\left|X[k]\right|^2}} \qquad (4)$$

The Skewness (Sk) statistic can measure the degree of symmetry of the frequency content, and it is defined as [11]:

$$Sk=\frac{1}{N}\sum_{n=1}^{N}\left(\frac{\left|X[k]\right|-M}{\sigma}\right)^3 \qquad (5)$$

where M is the average amplitude of the discrete Fourier Transform and σ is the standard deviation of the spectrum. In this work, AF, EB, and Sk reduced all acoustic emission signals to a 3D coordinate point, aiming to perform a failure classification tool based on a self-organized map (SOM) combined with a narrow-band piezoelectric transducer.

III. EXPERIMENTAL SETUP

Several tests were carried out on a 30 kVA (13kV/220V/127V) distribution transformer to assess the effectiveness of the proposed SOM combined with narrow-band acoustic signals. Graphite powder was applied to the surface of the bushing in order to emulate dust contamination. After that, a high-voltage source applied 13 kV to the component, and PD activity started. Incipient short-circuits were emulated by applying 3 kV to a needle point electrode with a 2 mm gap immersed in the transformer oil. The piezoelectric ceramic with a resonance frequency of 50 kHz was attached to the center of the transformer wall, according to Figure 1.

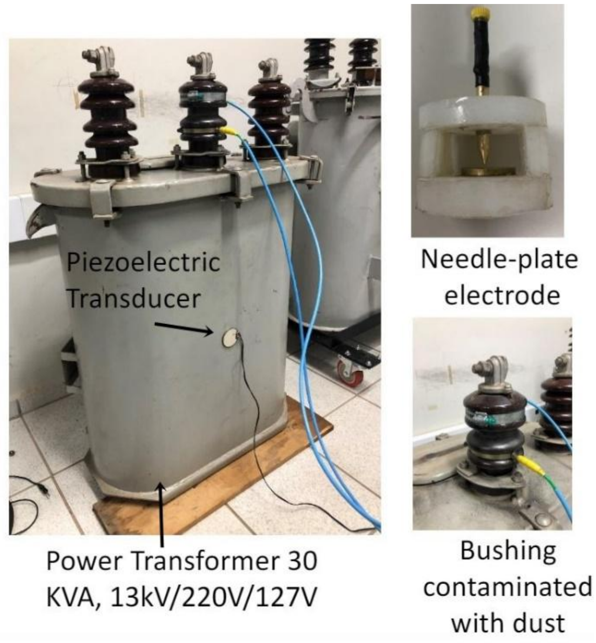


Fig. 1. Experimental Setup test bench.

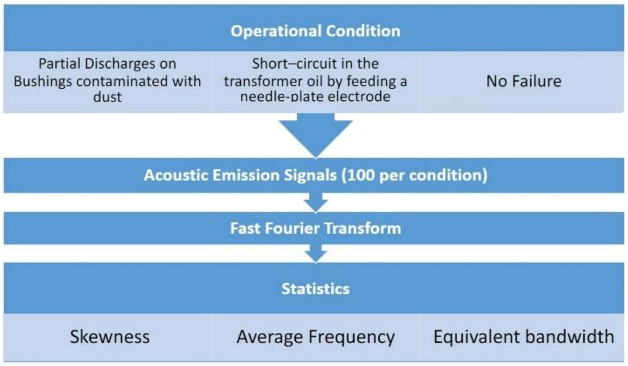
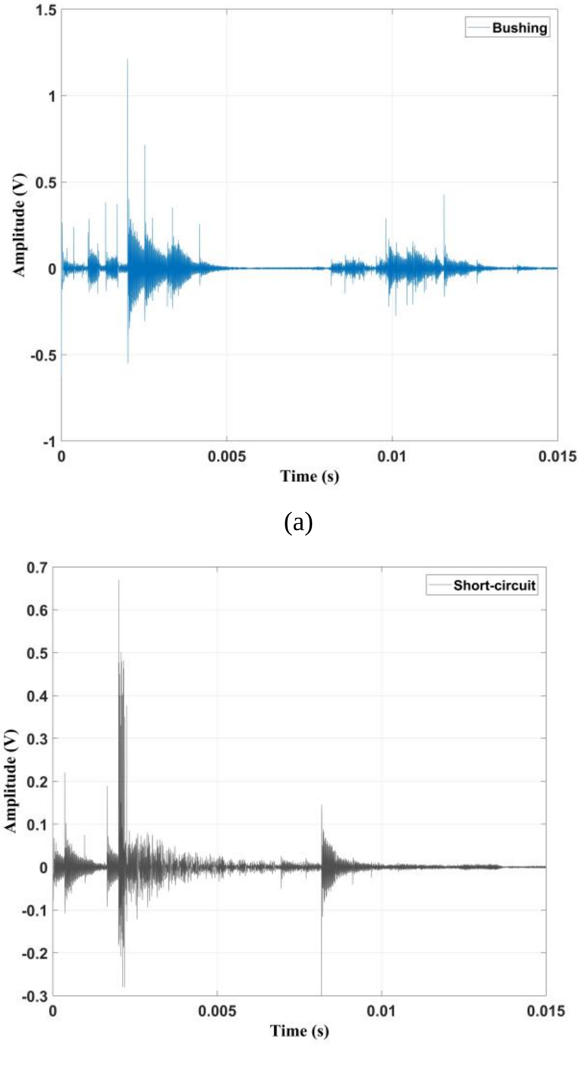


Fig. 2. Flowchart of method.

After that, one hundred acoustic emission signals per condition (no failure, incipient short-circuit, and partial discharges on bushings) were acquired with an oscilloscope at a frequency rate set at 1 MHz. The discrete Fourier transform was calculated by using Matlab software with the Fast Fourier Transform (FFT) algorithm. For each spectrum, Skewness, Average Frequency, and Equivalent Bandwidth were extracted aiming to perform a data reduction and to create a new SOM. All statistical values were normalized. Figure 2 shows a flowchart of the signal processing methodology. In this scenario, each signal was summarized as a three-dimensional coordinate point.

IV. RESULT AND DISCUSSIONS

Figure 3 shows the time domain signals for each failure condition.

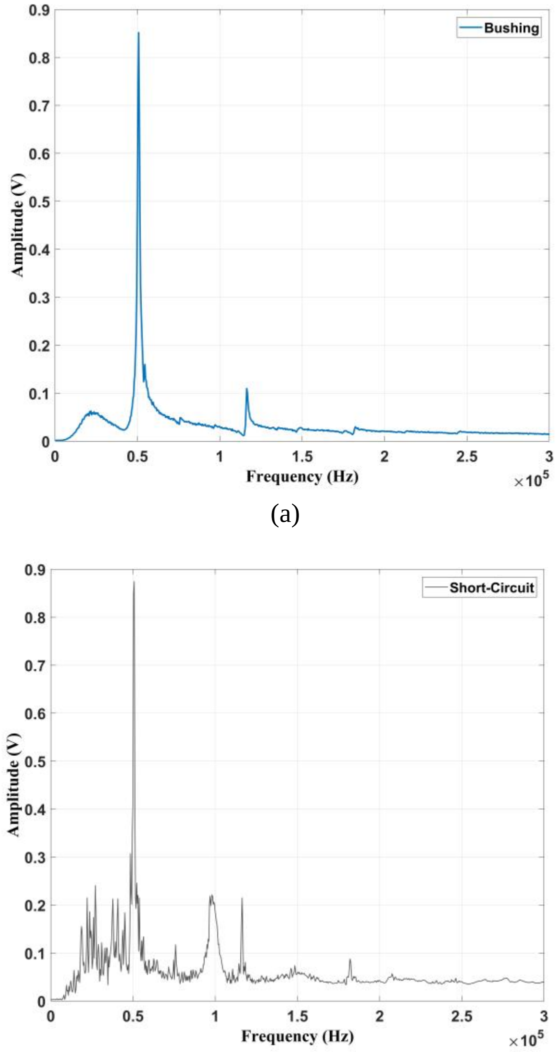


(a)

(b)

Fig. 3. Time domain signals for (a) bushing discharge, and (b) incipient short circuit.

Based on Figure 3, it can be observed that the acoustic signals of both faults indicate similarities, as the signals for both failures are impulsive and have a decay. However, for a in-depth analysis, the average frequency response of the 100 faults is shown in Figure 4.



(a)

(b)

Fig. 4. Average spectrum content for 100 failures for (a) bushing discharges and (b) incipient short circuit.

According to Figure 4, it can be noted that the maximum value for both faults is observed at 50 kHz, which is the resonance frequency of the piezoelectric transducer. However, for the bushing fault, peaks can be seen at 25 kHz and 125 kHz. For the short circuits, the spectrum also presented a peak at 100 kHz. Based on this observation, since the transducer has a frequency response tuned to 50 kHz, it is necessary to evaluate how self-organizing maps based on frequency response work with the bandwidth limitation caused by the transducer's resonance. In this context, Figure 5 presents the SOM developed in this article.

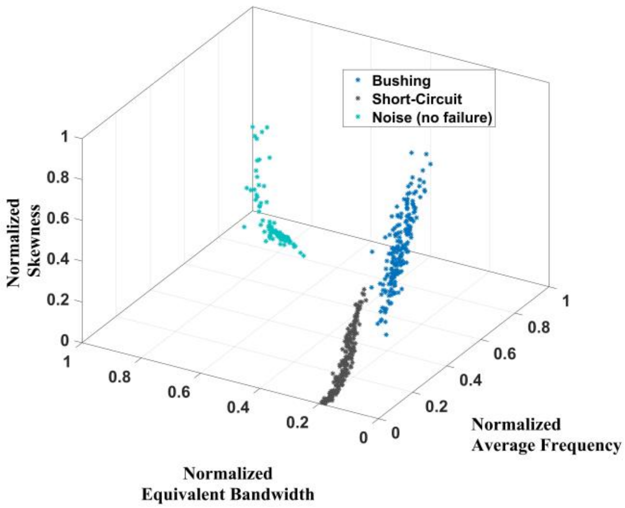


Fig. 5. Failure classification SOM.

It can be observed that despite the bandwidth limitation, the proposed method is effective in classifying the operating condition of the power transformer, as three well-defined regions are presented in Figure 4. In this context, the skewness varied from 0 to 0.6 for short circuits, and from 0.3 to 1 for bushing discharges. When the transformer did not present faults, meaning only the background noise of the acoustic signal was measured, this statistic varied between 0 and 0.4. The average frequency ranged between 0 and 0.15 for short circuits and from 0.05 to 0.06 for bushing discharges. And finally, for no failure condition, this statistic exhibited values between 0.8 and 1. The highest values of average frequency and equivalent bandwidth are observed for the acoustic signals without faults, as these cases involve spectra of background acoustic noise signals. In this scenario, the frequency range has the same amplitude across the entire spectrum, leading these statistics to have higher values, since the faults are concentrated close to the transducer's resonance frequency.

V. CONCLUSION

The development of systems enabling the classification of faults in transformers is crucial to ensure better maintenance planning for these high-cost assets, as different faults require distinct maintenance actions. Therefore, this article evaluated the application of narrow-band piezoelectric transducers in classifying three operational conditions such as partial discharges in transformers bushings, short-circuits in the windings, as well the fault-free condition. The article also presented a new self-organizing map based on the average frequency, skewness, and equivalent bandwidth statistics. In this context, although fault spectra closely approached the resonance frequency of the piezoelectric transducer, it can be concluded that the techniques presented in this study effectively classified all operational conditions assessed despite the bandwidth limitation imposed by the transducer. Future works may incorporate other types of faults such as corona discharges in oil, partial discharges in paper, partial discharges in bushings caused by mechanical structural damage, and also the possibility of evaluating the fault levels under others temperature variations.

VI. ACKNOWLEDGMENT

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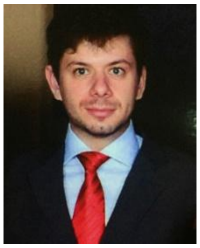
VIII. BIOGRAPHIES

Izadora Rodrigues Bittencourt was born in Porto Alegre, RS, Brazil, in 1995. She holds a bachelor's degree in Electrical Engineering from UNISAGRADO - Centro Universitário Sagrado Coração, completed in 2019. She is currently pursuing a master's degree at UNESP - Universidade Estadual Paulista, Bauru campus, Brazil. Her research focuses on sensors and fault diagnosis in transformers. She is a member of the Laboratory of Sensors and Signal Processing Applied to Medium Voltage Devices (LSPDM).

Abdo Youssif Khoury Filho was born in Alto Alegre, SP, Brazil, in 1996. He holds a bachelor's degree in Computer Engineering and Electrical Engineering from UNILINS - Centro Universitário de Lins, completed in 2019 and 2021, respectively. He is currently pursuing a master's degree at UNESP - Universidade Estadual Paulista, Bauru campus, Brazil. His research focuses on sensors and fault diagnosis in transformers. He is a member of the Laboratory of Sensors and Signal Processing Applied to Medium Voltage Devices (LSPDM).

Jorge Alfredo Ardila-Rey (Member, IEEE) received the B.Sc. degree in mechatronic engineering from Universidad de Pamplona, Pamplona, Colombia, in 2007. He received the M.Sc. and Ph.D. degrees in electrical engineering from Universidad Carlos III de Madrid, Madrid, Spain, in 2012 and 2014, respectively. He is a Professor with the Department of Electrical Engineering, Universidad Técnica Federico Santa María, Santiago, Chile. His research interests include data clustering, partial discharges, and insulation systems diagnosis for high voltage.

André Luiz Andreoli André Luiz Andreoli (Member, IEEE) received the B.Sc. degree from São Paulo State University (UNESP), Bauru, Brazil, in 1997, the master’s and Ph.D. degrees from São Paulo State University, São Paulo, Brazil, in 2005, and 2011, respectively, all in electrical engineering. He is currently a Professor with the Department of Electrical Engineering, Faculty of Engineering, UNESP, Bauru. His field of research focuses in signal processing, industrial electronics, power quality, and electrical machines and drives.



Bruno Albuquerque de Castro (M’08, SM’21) Bruno Albuquerque de Castro (Senior Member, IEEE) received the B.S. and M.Sc. degrees in electrical engineering from São Paulo State University, in 2012 and 2016, respectively, and the Ph.D. degree in electrical engineering from São Paulo State University, São Paulo, Brazil, in 2019 with a period of a sandwich doctorate at the Aerospace Center of University of Surrey, U.K. His research field focuses on nondestructive inspection, electronic instrumentation, sensors, digital signal processing, acoustic emission, data acquisition, and intelligent systems. He is an Associate Editor in Chief of the IEEE Transactions on Instrumentation and Measurement Journal. He has published more than 60 technical journals, (including IEEE) and conference papers.