Artigo Técnico

Metodologia para Calibração e Verificação Operacional de um Analisador de Resposta em Frequência por Varredura

Methodology for Calibrating and Operational Check of a Sweep Frequency Response Analyzer

Fabrício Gonçalves Torres[1], Tiago Lopes Santos[1], Ryan Wictky Sallatti[1]

[1] Instituto de Pesquisas Tecnológicas do Estado de São Paulo S.A., São Paulo-SP, Brasil.

*e-mail: fabrigt@ipt.br

Palavras-chave: transformador, confiabilidade, exatidão.

Keywords: transformer; reliability; accuracy.

Resumo

Transformadores de energia são componentes essenciais para geração, transmissão e distribuição de energia, e sua manutenção e substituição devido a mau funcionamento é altamente complexa e custosa. Por isso, testes periódicos nesses componentes são eficazes em detectar possíveis falhas antecipadamente, dando tempo suficiente para mitigar o problema. O método normalmente adotado para testar transformadores é por meio do Analisador de Resposta de Frequência de Varredura, pois ele possui diversas vantagens, como permitir que o teste seja não destrutivo. Contudo, a confiabilidade metrológica deve ser garantida para que as ações tomadas pela análise dos resultados sejam as mais corretas possíveis, sem a influência da falta de exatidão das medidas do equipamento. Para isso, uma metodologia é proposta, o que envolve a calibração e checagens de operação para esses equipamentos. O método adotado foi aplicado em dois instrumentos de diferentes marcas e os resultados foram analisados.

Abstract

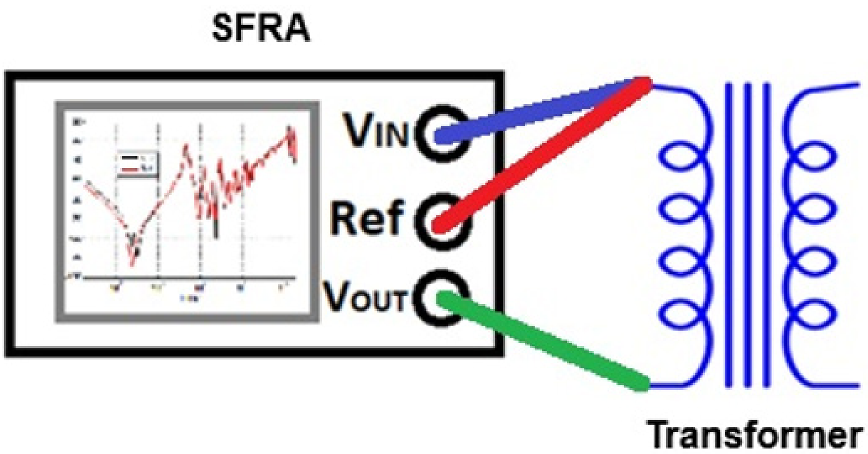
Power transformers are essential components for the generation, transmission and distribution of energy, and their maintenance or replacement due to a malfunction is highly complex and costly. Therefore, periodic tests on these components are effective in detecting possible failures in advance, allowing adequate time to mitigate the problem. The method usually adopted for testing transformers is by means of the Sweep Frequency Response Analyzer, as it has many advantages, such as allowing the test to be non-destructive. However, the metrological reliability must be guaranteed, so that the actions taken resulting from the analysis of its results are as correct as possible, without influence due to the lack of accuracy of the equipment. For this, a methodology is proposed which involves the calibration and operational checks of these equipment. The adopted method was applied in two instruments of different brands and the results were analyzed.

1 Introduction

These days, having an uninterrupted power supply is crucial and transformers are key components of the power system. However, these devices can undergo mechanical deformation due to transport, short-circuit forces or aging. Therefore, it is important to regularly monitor the integrity of transformer windings, as serious deformations that are not detected can cause prolonged damage [1].

To identify mechanical deformations in transformer windings and cores, a powerful technique is Sweep Frequency Response Analysis (SFRA). It is recommended to use the SFRA in a variety of situations, such as after short-circuit testing in the factory, during transport and installation, and after extreme events. To carry out the SFRA measurement, a signal is injected into one of the transformer terminals. The response signal is measured at another terminal and the frequency response is calculated and compared with a reference frequency response curve, and therefore, SFRA is considered to be a kind of digital signature analysis (**Figure 1**).

Figure 1. Application of the SFRA technique for transformer testing. The VIN, REF and VOUT connectors are generally of the BNC type and the connection cables to the transformer are coaxial.



Source: Prepared by the authors

The measurement by means of SFRA can be done as a voltage ratio between two terminals of a phase or as impedance or admittance of a winding, with the voltage ratio measurement being more common [2].

When measured using the voltage ratio, the frequency response is expressed in terms of Amplitude, which is the ratio of the output voltage (VOUT) to the input voltage (VIN). The frequency response analysis is graphically represented by the amplitude, in decibels (dB), as a function of frequency (1).

$$Amplitude = 20log\left(\frac{V_{OUT}}{V_{IN}}\right) \qquad (1)$$

Where:

Vout = output voltage in V

Vin = input voltage in V

The inductive (XL) and capacitive (XC) reactances of the transformer vary along the frequency, generating a series of resonances, which, added to the resistance (R), according to (2), generate a unique characteristic curve for that transformer.

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \qquad (2)$$

Where:

XL = inductve reactance in Ω

Xc = Capacitive reactance in Ω

R = Resistance in Ω

1.1 Effects on the measurement accuracy of an SFRA

The aforementioned frequency response curve analysis techniques are only effective if the accuracy of the SFRA measurements is guaranteed. Accuracy is the combination of two factors, which is precision and veracity. Precision represents the degree of dispersion between repeated measurements and veracity represents the degree of agreement between the mean of the measured values and the reference value. Accuracy is inversely proportional to measurement error and can be increased by improving precision and/or veracity.

It is important to note that precision does not indicate how close the measurement is to the reference value, but rather the dispersion between measurements. Standard deviation or variance can be used to estimate this dispersion. To assess the risks of false positives and false negatives, it is essential that the measurement uncertainty is estimated [3].

In the case of the SFRA, the absolute veracity of the amplitude measurement is less relevant, since the analysis of the frequency response curve is performed in a relative way, that is, comparing the values obtained from the measured curve with a reference curve. If there is an absolute error on both curves, it doesn't affect the comparison, as long as the errors are equal on both curves.

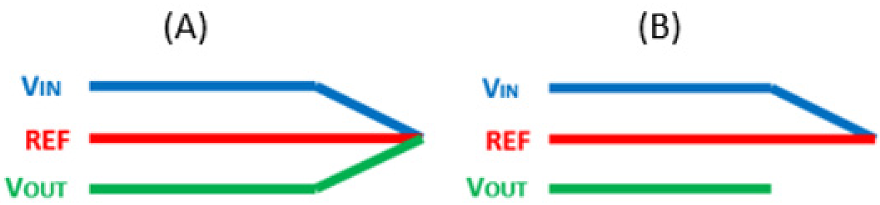
On the other hand, the analysis of measurements performed by SFRA is highly impaired if there is not enough stability (precision) in these measurements. According to [4], there are several factors that can significantly affect the accuracy of an SFRA test, such as: the presence or not of the bushing and oil, grounding, magnetization of the core, environmental conditions, mainly, temperature and humidity, applied voltage, quality of the cables and the accuracy of the measuring equipment itself.

One of the parameters related to the measurement equipment that can affect the analysis of frequency response curves is the dynamic range, which is defined by the difference between the lowest signal level that can be measured and the maximum signal level without distortion.

The lowest level is limited by the noise floor of the measurement equipment, which is the amount of noise present when no signal is applied. Depending on the equipment, the internal noise level can be between -90 dB to -130 dB. Some regulatory standards suggest that the SFRA should be able to measure a sufficient dynamic range (+20 dB to -100 dB) to test most transformers. Additionally, to achieve an accuracy of 1 dB (± 13%) down to a certain level, such as -100 dB, the internal noise level must be at least 20 dB below that level. For example, if the objective is to obtain a measurement accuracy of 1 dB to -100 dB, the internal noise level must be less than -120 dB [4].

[4] also discusses two simple checks that the SFRA user can adopt to assess the accuracy of the measuring instrument. The first one involves short-circuiting all the equipment terminals and running the test (**Figure 2A**). In this check it is possible to estimate the quality of the measurement cables and the accuracy of the measurement at the point close to 0 dB. The second check involves short-circuiting VIN and REF, keeping VOUT open (Figure 2B). In this way, it is possible to estimate the noise level of the measuring equipment.

Figure 2. Checks to assess the accuracy of SFRA measurements. The VIN, REF and VOUT connectors are generally of the BNC type



Source: Prepared by the authors

2 Methodology

The methodology involves the proposition of operational checking by users before testing transformers and calibration with metrological traceability. The check will consist of checking the frequency response of the SFRA in a predetermined frequency range, following the tests suggested by [4]. The purpose of this check is to identify possible deviations in equipment, cable quality and noise level.

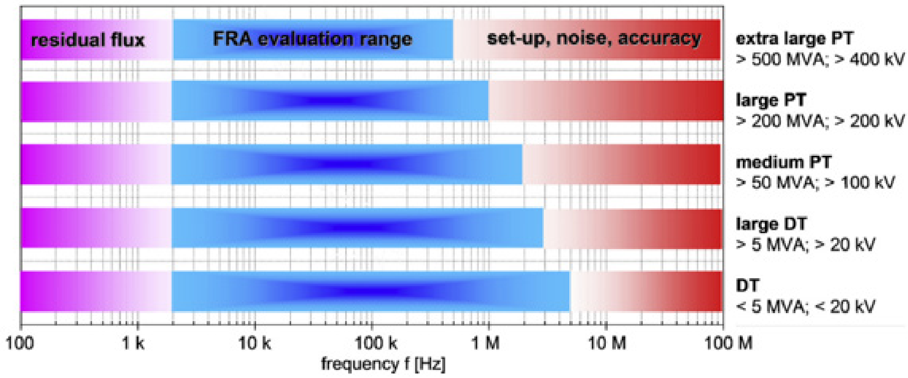
To perform the SFRA calibration, a step attenuator (**Figure 3**) with attenuation range between 0 and 70 dB will be used to create controlled attenuations, in 10 dB steps, with their respective known uncertainties, which will be measured by the SFRA. From the measurements performed by the equipment, it will be possible to calculate the measurement error at each point of the equipment's dynamic range.

Figure 3. Calibrated step attenuator used as standard to SFRA calibration.

Source: Prepared by the authors

Furthermore, it is recommended that the dynamic range (between 0 and 70 dB, in 10 dB steps) be calibrated at different frequencies, so that a significant frequency range is covered, necessary for transformer tests, i.e., 100 kHz, 1 MHz and 10 MHz. **Figure 4** presents the frequency range variation for different transformer sizes. Certainly, one should take into account how the SFRA is used by users for decision-making, thus being able to change the values of the cited frequencies. **Table 1** below summarizes the suggested points for calibrating the SFRA.

Figure 4. Frequency ranges for different transformer sizes.



Source: [2]

Table 1 – Suggested SFRA calibration points.

Frequency	Attenuation (dB)
100 kHz	0 to 70 dB (10 dB steps)
1 MHz	0 to 70 dB (10 dB steps)
10 MHz	0 to 70 dB (10 dB steps)

Source: Preoared by the authors

The suggested methodology, both for the operational check and for the calibration, was applied in two SFRA of different brands (SFRA_A and SFRA_B) and the results are discussed below.

3 Results

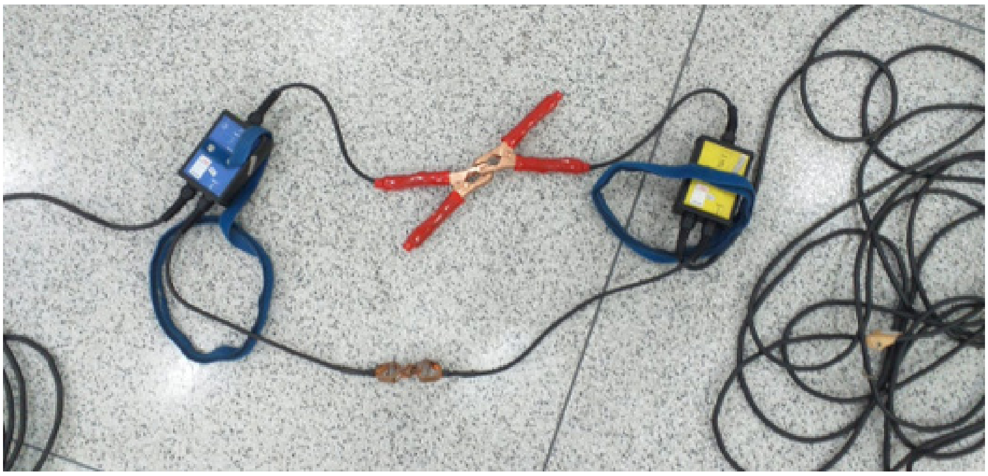
Figures 4 shows the calibration setup of one of the SFRAs. For operational checks, the cables were separated from each other to avoid any type of interference and reduce crosstalk.

Figure 4. Calibration setup of one of the SFRA.

Source: Prepared by the authors

Figure 5 shows part of the connection made to perform the operational check with the short-circuited terminals, as shown in Figure 2A. To perform the check as shown in Figure 2B, the VOUT terminals were disconnected and removed from the circuit.

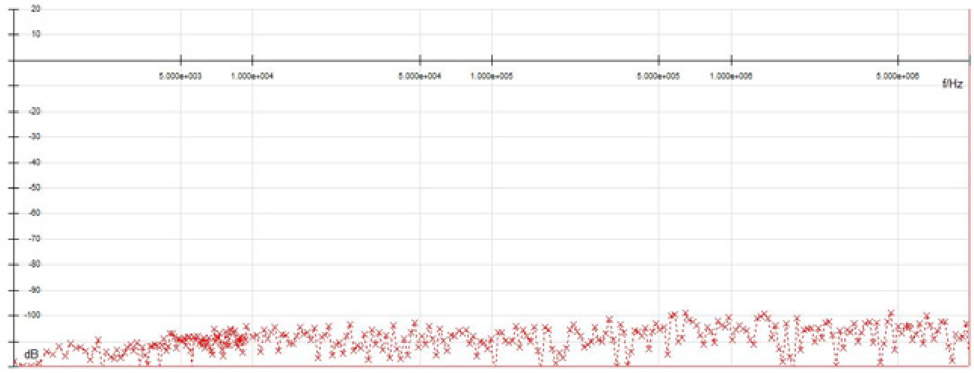
Figure 4. Figure 5. Calibration setup of one of the SFRA. setup of one of the SFRA.



Source: Prepared by the authors

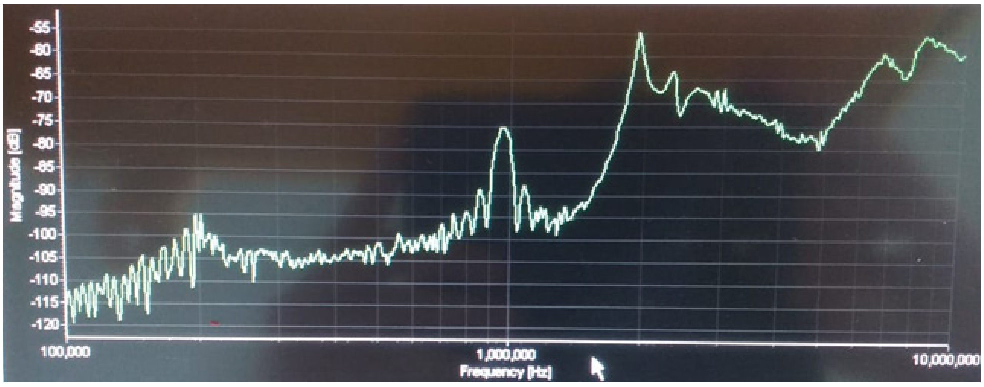
Figures 6 and 7 show the results obtained from the operational check as shown in Figure 2B, where the purpose of this check is to assess the noise level present in the SFRA tested. Both figures were obtained directly from the checked instruments.

Figure 6. Operational check of the SFRA_A in order to assess the noise level. The horizontal scale is logarithmic and is truncated to a frequency of 10 MHz.



Source: Prepared by the authors

Figure 7. Operational check of the SFRA_B in order to assess the noise level. The horizontal scale is logarithmic and is truncated to a frequency of 10 MHz.



Source: Prepared by the authors

It is essential to highlight that the calibration process and the performance test process are different and equally necessary steps. Calibration, although it is a necessary tool to ensure the metrological reliability of measurements, -has the limitation of requiring a reference standard, with metrological traceability, which allows comparison between the measurements of the item under calibration and those of the standard.

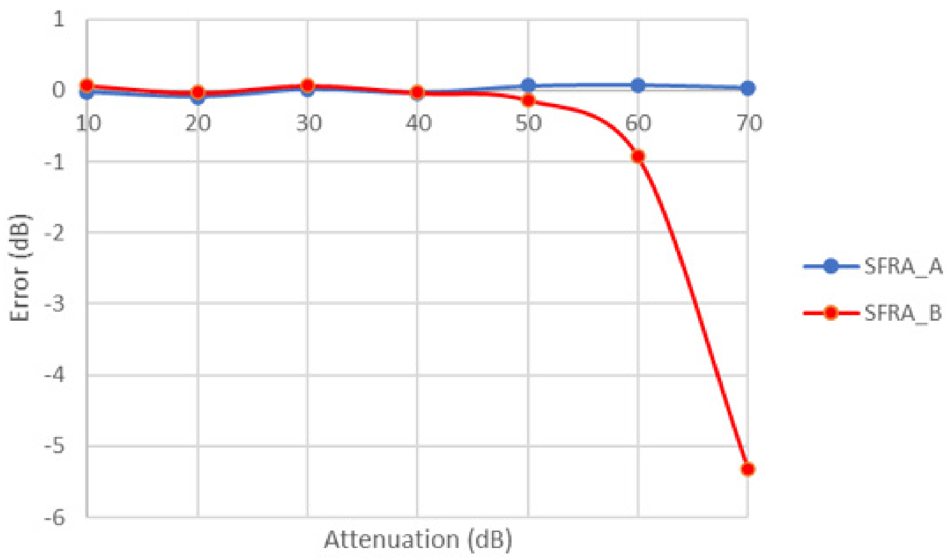
In the case of SFRA, it would be necessary to have a standard, with adequate accuracy, that could offer metrological traceability for attenuation values above 100 dB, in the range between 100 Hz and 100 MHz, something quite difficult to find in calibration laboratories accredited by the Coordenação Geral de Acreditação (CGCRE) [5].

Additionally, the complete calibration, considering the entire range of level, frequency and settings of an SFRA, may be impracticable to be carried out due to the huge number of possible points and, therefore, it is recommended that the calibrated points be sampled, and that these points can adequately represent a significant portion of the SFRA measurements.

The operational check was tested in both SFRA and it was found that the noise level presented by SFRA_A was below 100 dB in practically the entire frequency range (**Figure 6**). On the other hand, SFRA_B presented very high noise levels, mainly at higher frequencies (**Figure 7**), reaching values close to 55 dB of attenuation.

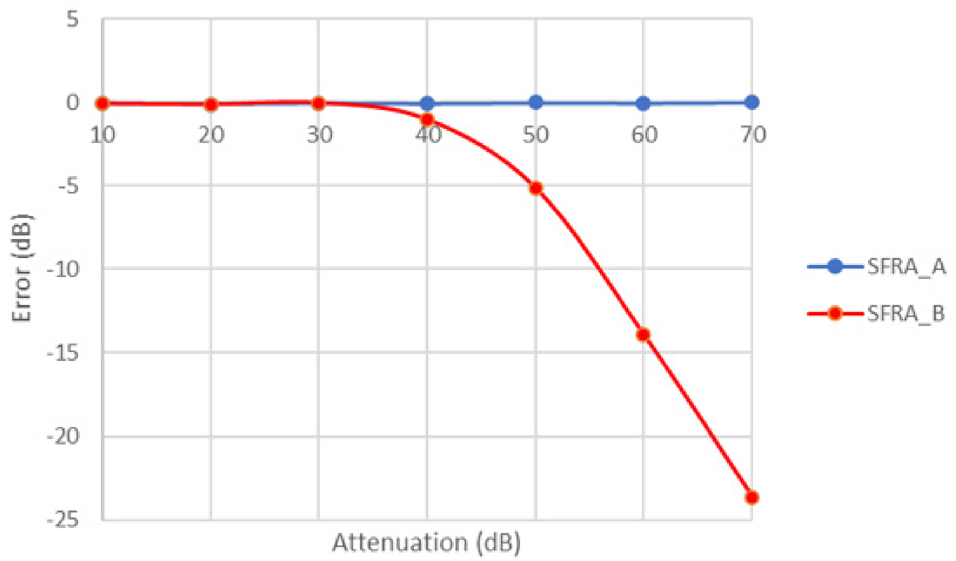
From **Figures 8, 9 and 10**, it was possible to see how much the noise floor influences the calibration results. While SFRA_A has low measurement errors over the entire frequency range, SFRA_B, due to the high noise, resulted in very high measurement errors at the highest attenuation values and at the highest frequencies. These measurement errors can significantly influence the ranges in which the SFRA is used for testing transformers whose anomalies are presented in the higher frequency bands.

Figure 8. Calibration at 100 kHz.



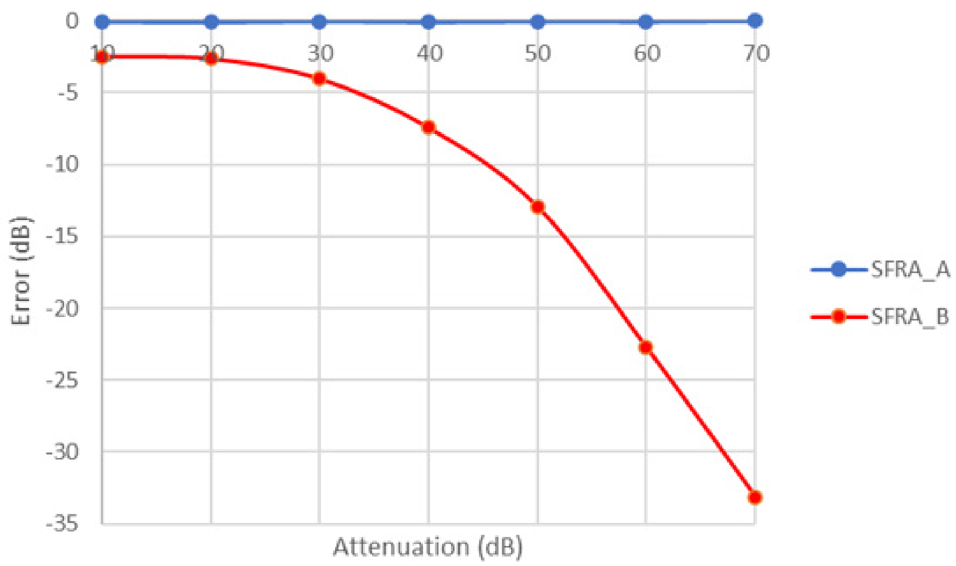
Source: Prepared by the authors

Figure 9. Calibration at 1 MHz.



Source: Prepared by the authors

Figure 10. Calibration at 10 MHz.



Source: Prepared by the authors

4 Conclusions

The proposed methodology involving calibration and operational checks is critical in guaranteeing the metrological reliability of SFRA measurements, allowing correct and accurate actions to be taken based on the analysis of results. By addressing noise-related challenges and ensuring accurate calibration, the SFRA remains a valuable tool for detecting transformer faults in a timely and efficient manner, thus contributing to the overall stability and reliability of power systems.

Operational checks were conducted on two SFRA instruments of different brands, SFRA_A and SFRA_B. SFRA_A demonstrated low noise levels across the frequency range, while SFRA_B exhibited high noise levels, particularly at higher frequencies. This noise floor greatly influenced the calibration results, resulting in high measurement errors for SFRA_B at higher attenuation values and frequencies. The presence of high noise levels in SFRA_B can significantly impact the accurate testing of transformers with anomalies in higher frequency bands.

5 References

[1] AJUDIYA, Y. V. **Classical Review of Frequency Response Analysis of Transformer. International Conference on Trends in Electronics and Informatics**. Tirunelveli: 2017, p. 459-464.

[2] SENOBARI, R. K.; SADEH, J.; BORSI, H. **Frequency response analysis (FRA) of transformers as a tool for fault detection and location: A review. Electric Power Systems Research.** v. 155, p. 172-183, 2018.

[3] KAWAKITA, K. **Zé Pacel segue apresentando sua série sobre a ciência das medições.** Revista O Papel, São Paulo, v. 7, p. 38-39, July, 2021b.

[4] JAHORMI, A. N.; BOCHENSKI, B. M.; FUJIMOTO, N. **Effect of Dynamic Range in SFRA Measurement. Electrical Insulation Conference**, Pennsylvania: 2014, p. 189-192.

[5] INSTITUTO NACIONAL DE METROLOGIA, NORMALIZAÇÃO E QUALIDADE INDUSTRIAL. **Rede Brasileira de Calibração -** RBC. Available in: < http://www.inmetro.gov.br/laboratorios/rbc/>. Access on: July 18, 2024.

10.29327/2152495.9.28-2