Vol.67: e24230514, 2024
https://doi.org/10.1590/1678-4324-2024230514
ISSN 1678-4324 Online Edition

BABT
Brazilian Archives of Biology and Technology

Article - Engineering, Technology and Techniques

Traveling Wave-Based Fault Location for Gas Insulated Substations

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Editor-in-Chief: Alexandre Rasi Aoki
Associate Editor: Alexandre Rasi Aoki

Received: 23-May-2023; Accepted: 31-Aug-2023

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HIGHLIGHTS

- A faulty simulation laboratory was development to simulate faults in gas insulated substations.
- A comprehensive study was carried out to select the best sensors and data analysis capabilities to treat the problem.
- The traveling waves theory is used to locate the position of a fault in the pipes.
- The results show the effectiveness of the fault location system.

Abstract: With the growing demand for solutions to prevent and resolve faults in gas-insulated substations that affect the operation of the electrical system, a fault simulation laboratory for gas-insulated substations was developed to develop solutions for monitoring and locating these faults. The laboratory is composed of instruments for a fault location system based on traveling wave theory. The laboratory also has computational programs for fault simulation control and signal acquisition, in addition to having tools to analyze the data. The results were obtained through tests carried out that confirmed the laboratory's ability to simulate the operation of faults in gas-insulated substations, which allowed demonstrating the capacity of the fault location system using the theory of traveling waves.

Keywords: Simulation laboratory; Fault location; Traveling waves; Gas insulated substations.

INTRODUCTION

Gas insulated substations (GIS) are becoming more popular for high-power transmit sion because of their advantageous features such as smaller size (compared to traditional substations), better dielectric performance, and higher reliability [1–3]. These substations use pressurized SF6 for insulation or arc extinguishing, and they also integrate various equipment like circuit breakers, current transformers, voltage transformers, and lightning rods [4].

However, GIS suffers from several faults, which are becoming more frequent due to increasing power network voltage and capacitance. the occurrence of failures in GIS can result in various issues such as gas leakage, insulation failure, and damage to equipment, leading to a reduction in the reliability of the power system [5–7]. Furthermore, transmission substation operators may face penalties directly associated with either partial or complete unavailability of equipment, caused by either maintenance or failures. The degree and duration of equipment and substation unavailability will determine the extent of the penalties [8].

Intelligent tools are necessary for detecting and locating faults in GIS, as the exact location of faults can be challenging to determine due to the enclosed design of the equipment. If a fault is incorrectly located, it can result in significant work for various professionals. Since the circuits are confined in a sealed compartment filled with SF6 gas, several steps must be taken to define the compartment to be repaired, including removing the SF6 gas, opening the compartment, repairing the fault, closing the compartment, refilling the SF6 gas, and conducting tightness tests. These procedures are time-consuming, and the tightness tests may take longer than the actual repair of the fault [9].

Traveling waves

A change of property that occurs in a particular part of the system, a disturbance for example, can propagate to other parts in the form of a progressive mechanical wave, also known as travelers. Progressive mechanical waves in an elastic medium are related to the transmission of energy and not matter from one point of the medium to other. As the wave passes, each particle undergoes a displacement perpendicular (transverse wave) or parallel (longitudinal wave) to the direction of the wave. As the wave propagates, internal tensions are created that seek to return the halfway to its original state of equilibrium.

Another important property of traveling waves is that the speed at which a wave propagates depends mainly on the material and temperature of the medium. Therefore, knowing these two properties it is possible to accurately estimate the speed of sound in the medium. Table 1 presents the speed of sound in a variety of materials. From the knowledge of the behavior of traveling waves in a medium, methods for determining the position of waves in various media and applications have emerged. Any internal event inside the GIS will propagate acoustic waves that will move in several directions, being easily captured by accelerometers attached to the outside of the compartment.

Table 1. Speed of sound in various materials.

Material	Speed of sound (m/s)
Air (20°C)	344
Helium (20°C)	999
Hydrogen (20°C)	1330
Liquid helium (4 K)	211
Mercury (20°C)	1451
Water (20°C)	1482
Water (100°C)	1543
Aluminum	6420
Lead	1960
Steel	5941

Literature review

The most captivating articles emerged in the late 1970s and early 1980s, highlighting the research of Mitsubishi Electric Corporation [10], Perry [11], and Chu and Tahiliani [12]. Notably, two publications from 1982 stand out: one by Chu and Williamson [13] on thermal sensors, and another by Boggs [14] utilizing electromagnetic techniques.

In 1984, a team of engineers from The Kansai Electric Power Co collaborated with professionals from Sumitomo Electric Industries and Furukawa Electric Co. in Japan to publish the practical findings of their fault locating techniques in a shielded installation operating at 275 kV SF6 [15]. While the article focused on line transmission, the concepts presented were also applied to armored substations.

In 1989, engineers from Chubu Electric Power Co. conducted a study on the effects of electrical arcs in shielded substations [16], which was another significant contribution to the field. The following year, Lundgaard and coauthors [17] published research on locating faults in shielded substations using acoustic methods. In the same year, a crucial study was published on the role of computers in fault location and restoration of substations [18], even though it did not specifically focus on armored substations.

A work was published in 1993 that presented an intelligent approach for analyzing events in substations that are large. Kezunovic and colleagues [19] designed an expert system to effectively handle such substations' alarms. Another work published in 1995 [20]. by Chubu Electric Power Co described a fault localization process for armored substations. This process considered the gas pressure levels in each of the compartments observed.

In 1996, a new application was introduced at the Itaipu Power Plant, which utilized neural networks of associative memory for the purpose of identifying and locating faults in the armored structure of the substation. This work was described in a publication by an author named in reference [21].

Japanese engineers remained highly engaged in this field and, in 1999, they published another study on fault localization in armored substations. This time, they used gas pressure sensors in an installation by Toshiba Corp. This work was described in a publication referred to as [22]. Additionally, in the same year, Alves da Silva and colleagues [23] also published another article on the fault location system in the Itaipu substation. The beginning of the next decade, 2001, saw the emergence of a new study by Lundgaard [24], which proposed a fault localization technique in armored substations based on acoustic signatures. Later, in 2008, Okabe and colleagues [25] published an article on the detection of the decomposition of SF6 gases, which can lead to insulation problems in armored substations. Also, in the next decade, Kezunovic published two papers [26] and [27] that presented novel ideas for operating electrical systems, including substations and their associated problems.

Justifications and Objectives

Gas detection, visual inspection, and powder coating visualization are conventional techniques for detecting faults in GIS but they are time-consuming and sometimes unsafe. Additionally, these methods may not identify all faults. Therefore, vibration analysis has been employed to address this issue. The basis of this technique is that if there is a mechanical defect in the GIS the vibration signal spectrum will change. Changes in the vibration signal spectrum can be utilized to detect the failure and its position [28,29].

In this paper, a fault diagnosis method based on vibration analysis is proposed. For this, a reduced model laboratory was developed to enable the tests of the proposed method. In the laboratory, it is possible to simulate internal failures characteristic of GIS, and through the vibration signal, it is possible to identify and locate the failure. Moreover, the method used does not depend on a baseline or something like do this.

MATERIAL AND METHODS

In this section, details on the development of the fault simulation laboratory in gas-insulated substations will be presented, as will the components used in its construction and those that make up the automated acoustic system.

Fault Simulation Laboratory

The developed laboratory is a set of armored, automated, and instrumented compartments that has as its objective the simulation of GIS faults. The laboratory can be divided into three main parts, they are the manufacture of armored pipes, the internal acoustic system, and the instrumentation.

The laboratory armored pipes, as shown in Figure 1, were built in five identical units with a thickness of 3/8" and an external diameter of 272mm. The pipes have a length of 500mm and are inserted into the gas connections for pressurization, vacuum, and installation of the SF6 gas quality analysis sensor. All pipes were painted with RAL 7035 paint. The electrostatic painting procedure was carried out to produce a consistent finish capable of resisting wear and oxidation. After painting, the piece was dried in an oven at a temperature that varies between 200ºC and 220ºC. In this way, the paint melts and penetrates the microporosities of the object, forming a uniform film that is difficult to remove. Figure 2 shows the pipes after painting.

Figure 1. Laboratory Pipe after electrostatic painting.

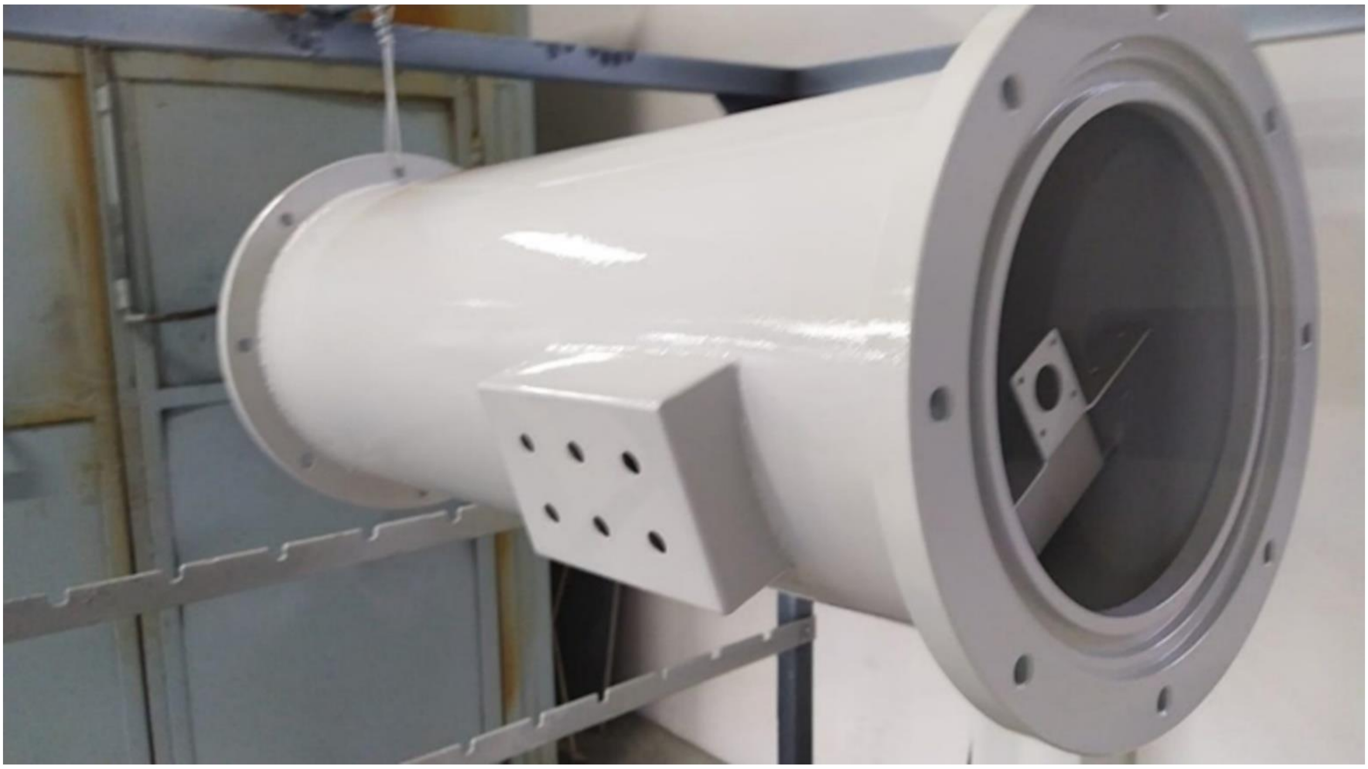

Figure 2. Laboratory Pipe after electrostatic painting.

From the study of the system and behavior of the signals, the necessary characteristics were selected so that the acquisition hardware could correctly capture the signal. Initially, it was identified the need to have isolated channels for the acquisition of signals from vibration sensors simultaneously, since, in this way, it is possible to guarantee a low level of noise in the fluctuating signals.

Another need was to choose a suitable analog-to-digital converter (ADC). The ADC is a circuit used to convert an analog signal into a digital signal. This conversion is necessary to be able to process the signal digitally. There are four steps in the analog-to-digital conversion process. The first step is to apply a pre-filter to avoid aliasing, which is an error that causes some frequencies to be displayed incorrectly. The next step is the sample-and-hold stage, where the input signal is held long enough for it to be properly digitized through a sample-and-hold circuit. The ADC uses a clock to determine when it will take the next sample of the input signal, known as the sampling clock, which is generally faster than the input signal. Then, the third step performs the conversion by dividing the reference voltage into ranges of values, called quantization. Typically, there are 2N lanes, where N is the number of digital output bits. In this step, you discover how far each input voltage value is from the nearest lower range. Finally, the last step uses the range of values found so that the processor can digitize the information and find the related digital output. Thus, within a time interval, a sampled analog input signal is converted into a corresponding digital output value. It is worth remembering that the ADC must have a sampling frequency at least twice the maximum frequency of the converted signal so that there is no loss of signal information [30,31].

Finally, it is necessary to choose a suitable vibration sensor for the application. Vibration sensors are chosen based on the type of vibration they detect, the frequency range, and the sensitivity. There are three main types of vibration: linear, rotational, and pendular. There are three primary frequency ranges: low, medium, and high. Low-frequency sensors detect vibrations in the range of 0 to 20 Hz, medium-frequency sensors detect vibrations in the range of 20 to 200 Hz, and high-frequency sensors detect vibrations in the range of 200 Hz and higher [32, 33]. The sensitivity of a vibration sensor is the sensor's ability to convert the mechanical energy of vibration into a proportional electrical signal. In other words, it is a measure of the sensor's response to vibration, indicating how easily it detects the vibration and how well it converts that vibration into a usable electrical signal. The sensor used to acquire the vibration signal is the industrial accelerometer with axial output, shown in Figure 3, which is used to acquire the vibration signal. This accelerometer offers dynamics of 100 mV/g and 80g with a temperature range of -40 to 130°C and is capable of operating in the frequency range of 0.6 Hz to 15 kHz. To connect the accelerometer to the acquisition hardware, it is necessary to perform signal conditioning previously. This operation is necessary because the signal that is acquired by the sensor is not within a voltage range that can be directly managed by the acquisition hardware. As a result, the signal must be conditioned so that it is placed in a voltage range compatible with the acquisition hardware. The conditioning of the accelerometer signal will be carried out through the Terminal Block for Accelerometers (Figure 4), in which any type of industrial accelerometer of the type IEPE (Integrated Electronics Piezo-Electric) can have its signal conditioned.

Figure 3. Accelerometer.

Figure 4. Terminal block for accelerometers [34].

RESULTS AND DISCUSSION

In this section, the tests carried out in the laboratory will be presented. Several features and validated concepts important for the fault simulation of a gas-powered substation were tested in a reduced-model laboratory.

Mechanical disturbance

The mechanical disturbance test aims to simulate a substation equipment failure that may be caused by a fault, commissioning, or maintenance problem. The objective of the test is to prove that the sensors have their signals captured synchronously and to verify if there is a relationship between the lag of the captured signals and the distance between the sensors. To carry out the tests, three accelerometers were installed along the pipeline so that it was possible to carry out the triangulation of the signals in order to discover the position of the disturbance in the pipeline.

Mechanical disturbance 1: The disturbance site occurred at the left end of the test laboratory, as identified in Figure 5. A solid iron bar was used to cause the disturbance.

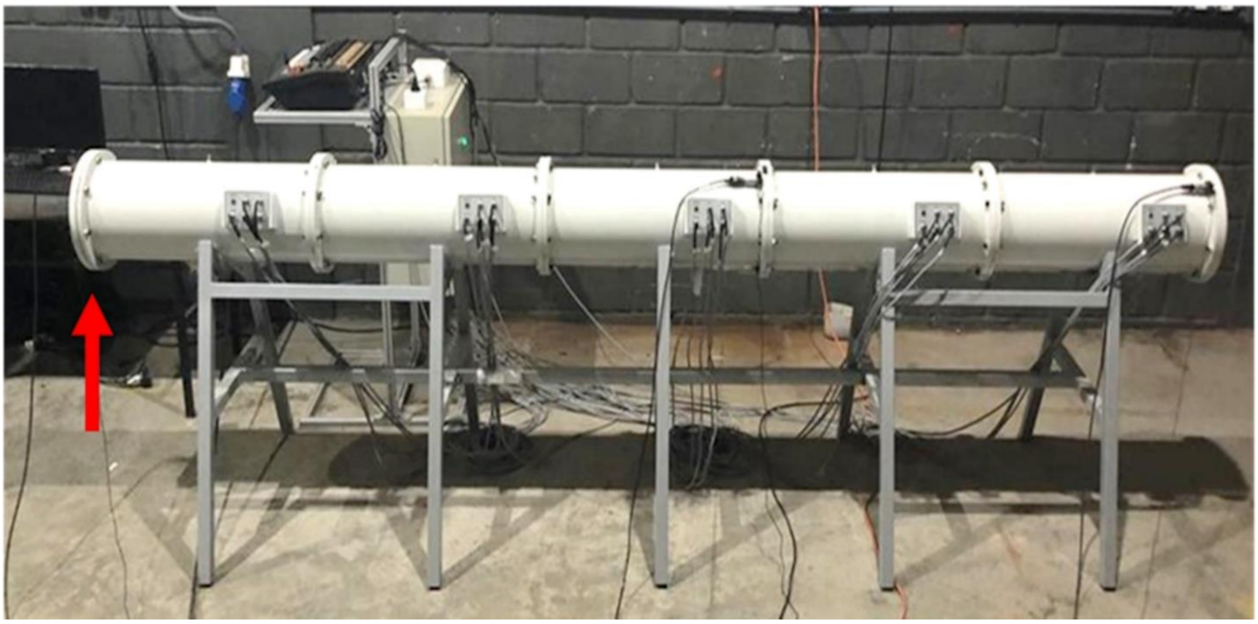

Figure 5. Indication of the location of the mechanical disturbance 1.

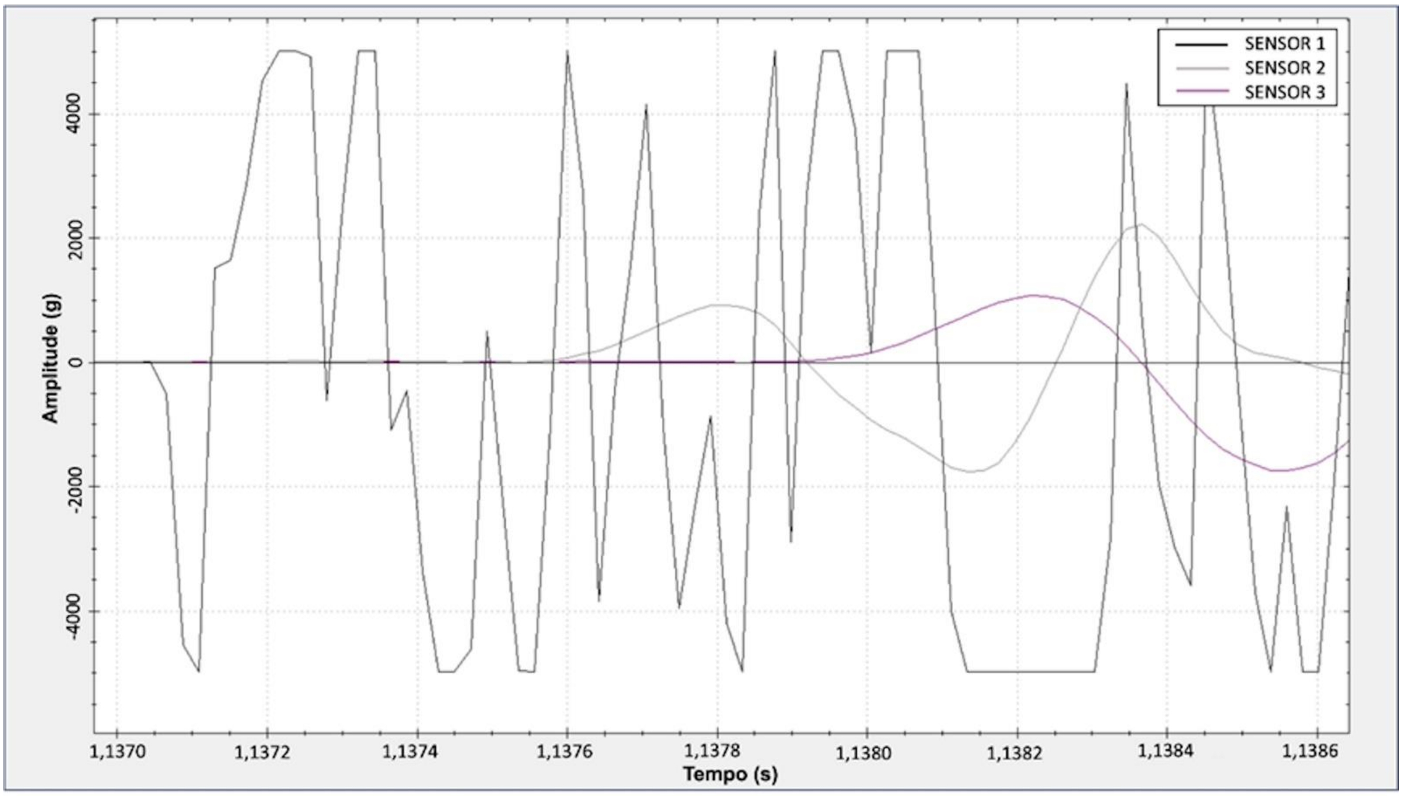

Figure 6. Accelerometer acquisition signal for the mechanical disturbance 1.

Figure 6 shows the signals from the three accelerometers simultaneously. To prove the relationship between the distance between the sensors and the delay of the signals, the calculation of the speed of sound propagation in the metal was performed, using sensors 2 and 3 and the distance between the sensors. Then, with these data, the time of the beginning of the signal in sensor 1 can be calculated.

Using data from the initial time of sensors 2 and 3, the speed of sound propagation in the metal is obtained.

$$Speed = \frac{Distance\ [m]}{Time\ [s]}$$

$$\Delta t = sensor\ 3\ time - sensor\ 2\ time$$
$$\Delta t = 1.13822 - 1.13781$$
$$\Delta t = 0.00041\ \mathrm{s}$$

$$Speed = \frac{Distance\ [m]}{\Delta t\ [s]}$$

$$Speed = \frac{1.4450}{0.00041}$$

$$Speed = 3524.39\ [m/s]$$

Because the distance between sensor 1 and sensor 2 is known, it is possible to calculate the beginning of the signal time from the first sensor, where the disturbance started.

$$Sensor\ 1\ time = \ sensor\ 2\ time - \frac{Distance\ [m]}{Speed\ [m/s]}$$

$$Sensor\ 1\ time = 1.13781 - \frac{2.1750}{3.524{,}39}$$

$$Sensor\ 1\ time = 1.13719\ [s]$$

By enlarging the image of the sensor 1 signal, Figure 7, it is possible to confirm that the time of the first pulse captured by sensor 1 is correct. Thus, it appears that the time and signals captured by the sensors are current in relation to speed and distance.

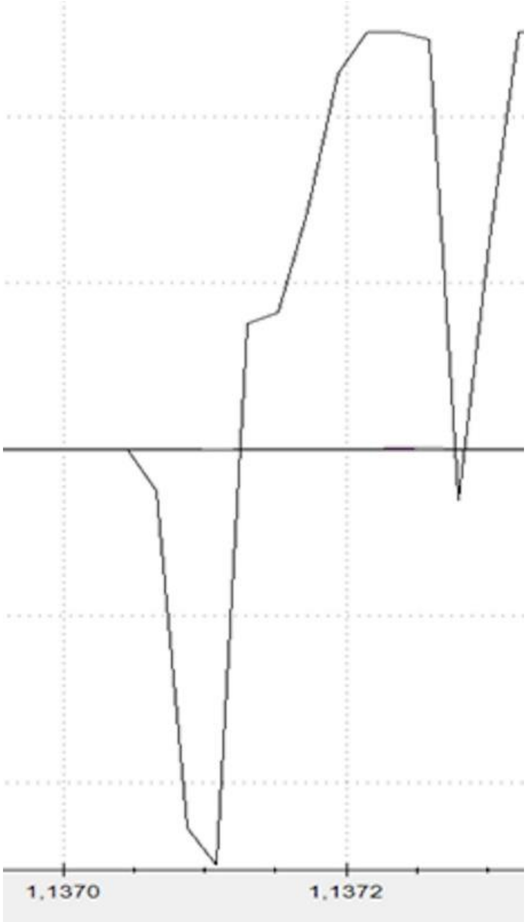

Figure 7. Accelerometer-acquired perturbation start signal 1.

Mechanical disturbance 2: The disturbance was in the center of the test ducts, identified in Figure 8. A solid iron bar was used to cause the disturbance.

Figure 8. Indication of the location of the mechanical disturbance 2.

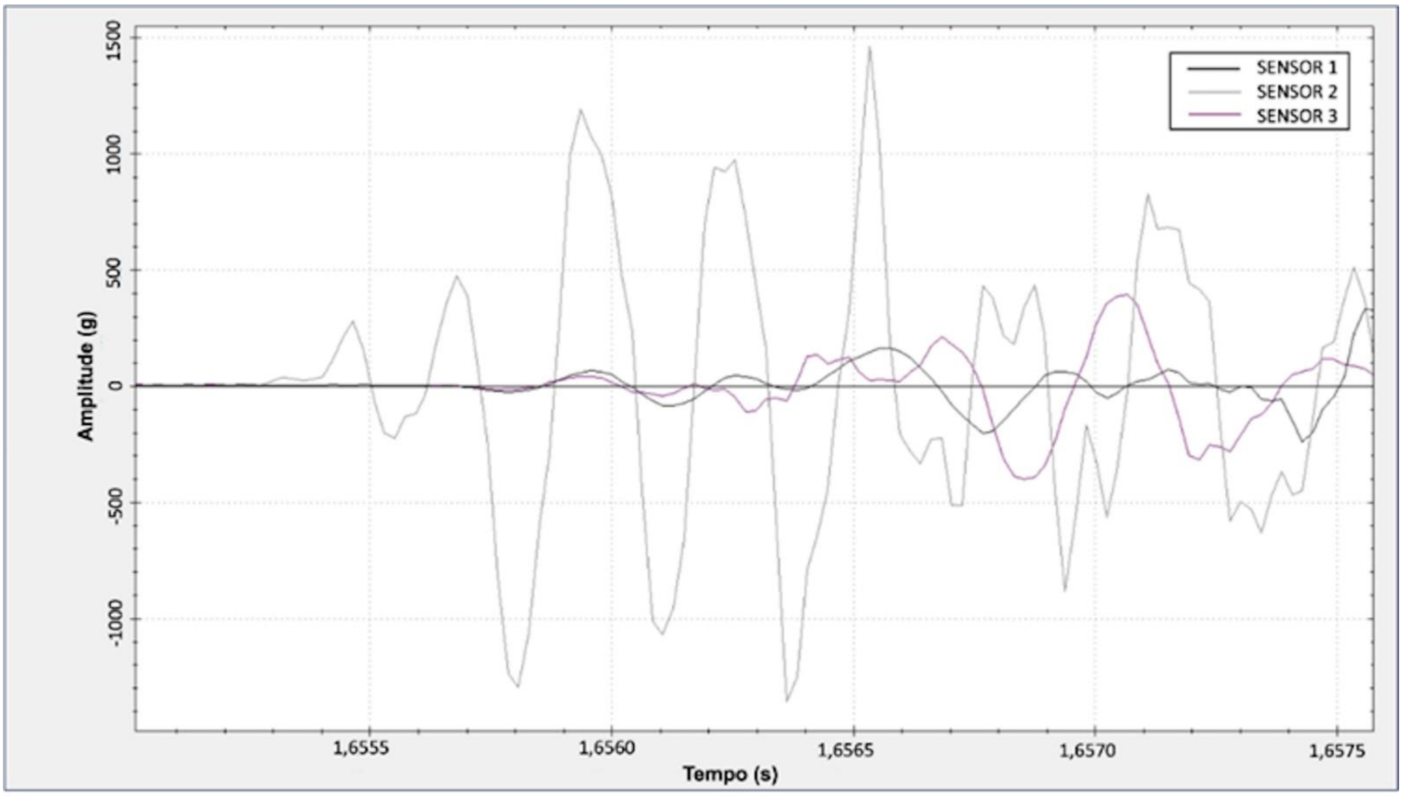

Figure 9. Accelerometer acquisition signal for the mechanical disturbance 2.

According to the distances of the accelerometers and contact microphones, it is expected that the signals from sensors 1 and 3 are in phase or very close. On the other hand, sensor 2 must be ahead of the signals from sensors 1 and 3 because it is closer to the place where the disturbance occurred.

With the amplification of the signal, Figure 9, it is possible to verify that, after the beginning of the disturbance, close to the time of 1.6552 seconds, the first peak of the signal from sensors 1 and 3 are very close. This occurs because the sensors are at the same distances from the point where the disturbance occurred. On the other hand, sensor 2 is at a closer distance.

The location of the point where the disturbance occurred can be calculated through the speed that is found by the difference between sensor 2 and sensor 3, also considering the distances between them. In this way, one has:

$$Speed = \frac{Distance\ [m]}{Time\ [s]}$$

$$\Delta t = sensor\ 2\ time - sensor\ 3\ time$$

$$\Delta t = 1.655950 - 1.655467$$

$$\Delta t = 0.000483$$

$$Speed = \frac{Distance\ [m]}{\Delta t\ [s]}$$

$$Speed = \frac{1.4450}{0.000483}$$

$$Speed = 2991.72\ [m/s]$$

When the signal from sensors 1 and 3 are in phase, it means that the disturbance occurred at the same distance between them. Since the distance between them is known, it is possible to find the distance from the sensor to the disturbance. For this, calculate:

$$D_t = Distance\ 1 + Distance\ 2$$

$$D_t = (Speed\ 1 * Sensor\ 1\ time) + (Speed\ 2 * Sensor\ 2\ time)$$

If the signal in time of sensors 1 and 2 are the same, we have:

$$Sensor\ 1\ time = Sensor\ 2\ time$$

Therefore, they have the same distance to the origin point:

$$D_1 = D_3$$

Hence,

$$D_t = 2 * D$$

$$D = \frac{D_t}{2}$$

$$Disturbance\ distance = \frac{0.362}{2} = 0.181[m]$$

The distance from the beginning, sensor 1, to the place where the disturbance occurred is 0.181 meters.

CONCLUSION

This paper presented the development of the reduced model laboratory. The laboratory achieved its main objective by proving to be capable of simulating failures in SF6 gas-insulated substations. The development of this laboratory and the computer programs made it possible to simulate faults with characteristics like in a real GIS. In addition, this work contributes to the field of condition monitoring based on the theory of traveling waves by showing the potential of using vibration as a tool for locating the fault location. Based on this theory, it was possible to understand the wave propagation characteristics of the material, and the wave propagation time relationship between the sensors made it possible to identify the location of origin of the disturbance in the monitored compartments. In the mechanical disturbance test, a comparison was made between three points in the test laboratory for comparison purposes, where the greater efficiency of the accelerometer-type vibration sensor in capturing the less intense disturbance signal was verified. When comparing the two types of sensors, contact microphone and accelerometer, a difference in the response capacity between them was verified, in which the accelerometer presented a precise and faithful response in relation to the position of the disturbance. In addition, the tests carried out confirmed the laboratory's ability to simulate the operation of faults in gas-insulated substations, in addition to demonstrating the capacity of the fault location system using the traveling wave theory.

Funding: The projects presented in this paper are part of the R&D project PD-06491-0513-2018, executed by Gnarus Institute for COPEL Generation and Transmission, under the Brazilian Electric Sector Research and Development Program, regulated by the National Electric Energy Agency (ANEEL).
Acknowledgments: The authors would like to express their thanks to CNPq, and CAPES**.**
Conflicts of Interest: The authors declare no conflict of interest**.**

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