PD Detection and Localization by means of Acoustic Measurements on Hydogenerator Stator Bars

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ABSTRACT

Acoustic partial discharge detection appears useful for the location of PD sources within various kinds of insulating systems. The usefulness of such a method to locate discharge sources in hydrogenerator stator bars is illustrated. The adopted measuring procedure, based on two piezo-electric transducers positioned on a bar, allows the identification of the discharge site position within an error range of ~ 2 cm. Such a measuring procedure appears useful as a diagnostic tool in quality control for bars that do not pass the specified acceptance test or in the development of new insulating systems. The measurement circuit and the relevant test procedure are presented. Further comments about the measured acoustic velocities of the acquired signals are given.

1. INTRODUCTION

USUALLY, during the manufacturing process of insulated bars for generators, a diagnostic procedure based on the measurement of the dissipation factor ($\tan\delta$) is adopted to verify the insulation system performance. In cases where anomalous $\tan\delta$ values were measured, a procedure able to locate the defects and to identify their nature would be useful for analysis and for corrective actions. Such a procedure would be useful also during the development and the processing stage of new insulating systems. It could also contribute to the analysis of service aged insulated bars. As the defects existing in such insulating systems are usually sites of partial discharge (PD) activity, the measurement and the analysis of PD can provide information about the location and the morphology of the PD source (*i.e.* of defects). Concerning defect identification, it has been shown that PD detection through phase resolved analysis techniques (PRPDA) provides extensive information on the type of defect and its characteristics [1–9]. In addition, especially for PD source localization purposes, acoustic detection techniques represent a very interesting tool. Of course these techniques are not to be used for repair purposes but they appear promising to control bars that do not pass the common tests, or in the development of new insulating systems.

The possibility of measuring the presence and level of PD by means of acoustic methods has been explored since 1940 by Kimura *et al.* [10]. Nowadays the PD acoustic measurements are widely applied in the field of electrical power equipment, such as rotating machines [11, 12], compressed gas insulated systems [13–16], capacitors and other apparatus [17, 18]. Depending on the application, different measuring techniques, related to the type of sensor and to the relevant band pass are used [19–21]. In particular, the adoption of piezoelectric sensors [22] oper-

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ating in the ultrasonic region to localize defects in solid insulation has been studied [23, 24]. Theoretically, the localization of PD sites in insulated generator bars by means of acoustic measurements is simple and could be performed by using just one sensor. The relevant procedure could be based on the search for a position where the acoustic signal is maximum, or where the delay between the acoustic signal peak and the output waveform of a conventional electric PD detector is minimum. However, the acoustic signal amplitude is strongly dependent on the conditions of the interface between sensor and surface of the insulated bar, while the complexity of the bar structure makes it impossible to know in advance the sonic propagation velocity. Therefore, in practice, the defect localization could require a large number of measurements.

For the above reasons this study has been aimed at defining a defect localization procedure based on the use of two sensors: such a procedure has been experimentally validated by locating PD sites in aged insulated bars. Also, an artificial void was installed inside the insulation of a bar, in order to better evaluate the localization error. The above procedure has been developed bearing in mind industrial needs. Therefore it can be quickly implemented and is little influenced by the operator, allowing a good repeatability of the measurements.

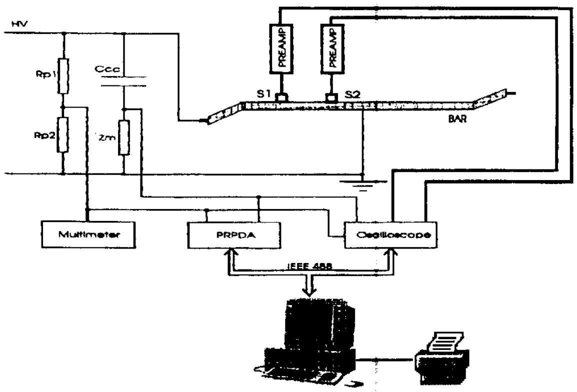

Figure 1. Measurement circuit configuration.

2. EXPERIMENTAL

A schematic diagram of the measuring circuits and of the data acquisition systems is shown in Figure 1. As concerns the circuit for PD electrical measurement, the coupling capacitor is $C_{cc} = 1500$ pF. The Z_m measurement impedance is an RLC circuit whose resonant frequency is 300 kHz and the attenuation factor is 0.75. Such choices provide, at each PD pulse, a damped oscillatory signal with a time duration < 4 μs. To avoid the presence of high frequency noise, a low pass filter, cutoff frequency 5 MHz, has been introduced. The high value of such a frequency allows avoidance of strong sensitivity reduction. The signal is sent to the system for amplification and phase resolved analysis (PRPDA). To the latter system is sent also the applied voltage, scaled by a resistive voltage divider, for phase reference. The digitally converted signals are stored in a buffer memory and then transferred to a PC, through an IEEE 488 interface.

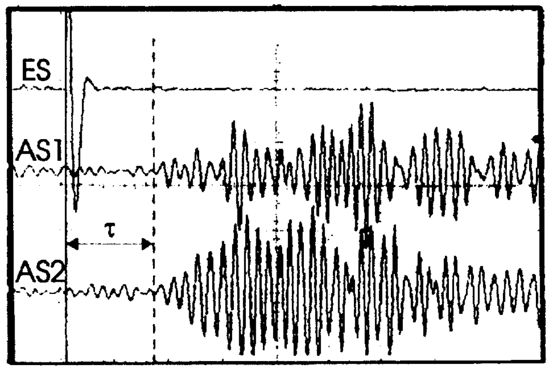

Figure 2.

Example of PD measurement. (ES) PD pulse detected by means of the electrical measurement circuit. (AS1, AS2) acoustic signals relevant to the PD pulse. (τ) time delay of the acoustic signals AS1, AS2 with respect to electrical signal ES.

The acoustic detection system consists of two ultrasonic piezoelectric sensors having a resonance frequency of 150 kHz and a bandwidth within 80 to 600 kHz. This choice is in agreement with Harrold [20] and it also virtually eliminates noise problems [18]. The sensors have a diameter of 17.5 mm; such a value, as experimentally verified, is also the localization error, in agreement with [23]. Each sensor is connected to a preamplifier and the relevant signal is sent, through a high pass filter (cutoff frequency 100 kHz), to a digital oscilloscope, together with the applied voltage wave (used as triggering signal) and with PD signals, detected by the electric method. The signals acquired by the oscilloscope are sent to a computer via the IEEE 488 interface and then processed (filtering, harmonic analysis, *etc.*) by software. An example of signal acquisition is shown in Figure 2, where the delay time between the acoustic signal and the electric signal is evident. The acoustical coupling between the surface of the insulated bar and the sensors has been improved by introducing silicon gel as an intermediate medium and providing a contact pressure of roughly 60 kPa, obtained by means of clamps or weights positioned on the sensor. Different coupling gels and pressures were tested to obtain reproducible measurements and to maximize the acoustic signal. The data reported in Figure 3

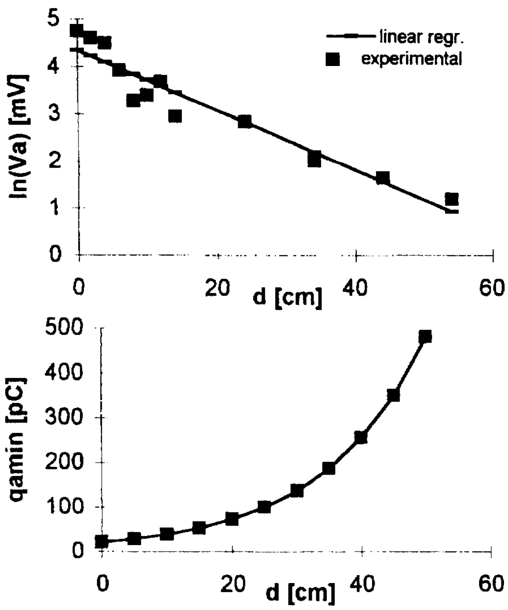

Figure 3.

Acoustic measurement circuit sensitivity. (a) Amplitude of the acoustic signal *vs.* distance from PD site. (b) Minimum PD apparent charge necessary to recognize an acoustic signal *vs.* distance from PD site.

a have been obtained under the latter conditions. They concern the maximum amplitudes of the acoustic signal *vs.* the distance from the PD site. The relevant signals have been acquired by applying to an insulated bar an ac voltage slightly higher than the PD inception voltage. At the inception voltage, data were acquired by means of the electrical measurement circuit, with an apparent charge of ~ 160 pC.

It can be noted that the measurements performed near the PD site involve a high percentage variation of the maximum amplitudes, even by moving the sensor by as little as 1 cm. The maximum acoustic signal sensitivity was found to be ~ 0.7 mV/pC, by placing the sensor on the discharge site, while an apparent sensitivity of ~ 50 μV/pC at 40 cm from the PD site has been calculated. As shown in Figure 3(a), the acoustic signal amplitude A seems to depend on the distance x from the PD site as follows

$$A(x) = A_o \exp(-kx) \quad (1)$$

where A_o is the signal amplitude measured by the sensor located on the PD site. Relation (1) is in agreement with the law of absorption of an acoustic signal in a homogeneous medium [21]. As the noise of the measuring system is of the order of 2 to 5 mV, it can be inferred that only acoustic signals having a minimum amplitude of ~ 10 mV can be detected. Therefore, using Equation (1), the curve reported in Figure 3(b) was calculated. This indicates the sensor distance from the PD site as a function of the minimum PD apparent charge necessary to measure an acoustic signal $\geqslant$ 10 mV. It can be noted that, at distances from the PD site > 30 cm, levels of apparent charge of the order of ~ 150 pC are necessary to measure an acoustic signal. Therefore, it has been assumed that the acoustic measuring system has a sensitivity suitable to detect PD sites at distances from the sensor < 30 cm.

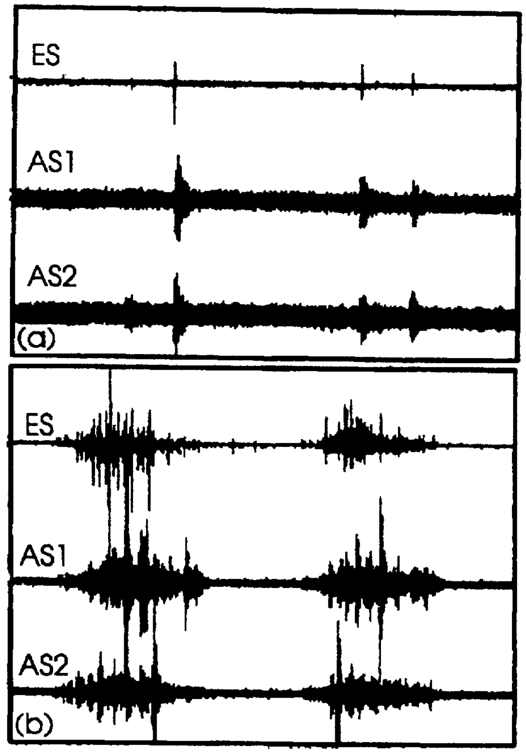

Figure 4.

Example of signal acquisition. (a) The acoustic signals can be referred with certainty to the corresponding electrical PD pulse. (b) The PD repetition rate is too high and a superimposition of acoustic signals is present.

3. LOCALIZATION PROCEDURE

The two ultrasonic transducers are placed on the insulated bar in arbitrary positions. The applied voltage should be sufficiently high so as to induce a stable onset of PD at the PD site of interest and, at same time, it should be sufficiently low so as to give rise to a rather low PD pulse repetition rate. This way it becomes possible to assign with certainty the acoustic signal to the corresponding electrical PD pulse as shown in Figure 4(a) and to allow a safe measurement of the delay time between the electrical and the acoustical signals, as shown in Figure 2, avoiding a superimposition of acoustic signals relevant to different discharges, as shown in Figure 4(b). The above condition is generally satisfied by applying a voltage level $\sim$ 10% higher than the PD inception voltage V_i detected by means of the electrical systems. Then, if the acoustic signal propagation velocity v was known, it would be possible to estimate the position of the PD site from the relation $\Delta x = v\Delta t$, where Δx is the distance between PD site and sensor. However, the tests have shown that the sonic propagation velocity in the bar can vary, due to several factors such as materials, interfaces, type of defect, from $\sim$ 2000 to 4000 m/s.

Thus, to identify the defect position, it would be necessary to repeat this detection procedure several times, moving one of the sensors on the expected position and keeping the other one fixed to provide a reference waveform and time delay between acoustic and electric signals: the PD signals, acquired after the movement of the sensor, still refers to the same discharge site. The measurements and the evaluation of the new Δt, necessary to compute the new expected position, are repeated until the measured delay time is roughly zero.

An alternative approach requires the evaluation of the actual propagation velocity. The necessary information derives from two measurements: the first is carried out with the sensors in arbitrary positions, the second after having moved one of the sensors a known distance Δx. The ratio of such Δx distance to the difference in delay time between the two readings of the same sensor provides the actual velocity. Once this velocity is known, the above described approach can be applied and a smaller number of steps is needed to localize the PD source.

An example of PD site localization is shown in Figure 5. At first the sensors were set on the insulated bar at 30 and 90 cm from the origin (*i.e.* the beginning of the bar flat part from one of the extremities). By means of sensor 1 an acoustic signal was found to have a time delay of 27 μs with respect to the electrical signal (Figure 5(a)). No signal was found with sensor 2 (Figure 5(b)), so this sensor was moved to $\sim$ 40 cm from the origin of the bar. A 59 μs time delay was so measured (Figure 5(c)). Then sensor 2 was moved to acquire the time delay in a new position in order to calculate the actual propagation velocity of 2500 m/s. Once such a velocity is known, the estimation of the PD site distance from sensors (7 cm from sensor 1) is possible. To obtain a more precise PD site location, a further measurement was performed with the PD site situated between the sensors. In the present

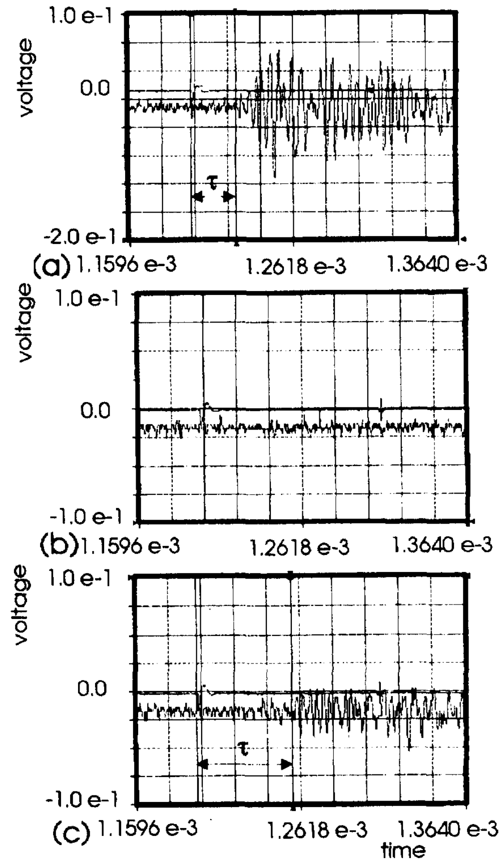

Figure 5.

Example of time delay measurements.
(a) Sensor 1 positioned at 5 cm from PD source.
(b) Sensor 2 positioned at 55 cm from PD source.
(c) Sensor 2 positioned at 15 cm from PD source.

case, the distance from the insulated bar origin was calculated to be 23.6 cm. The position found was further verified by placing one of the transducers on the calculated co-ordinate, where a delay time equal to 0 should be detected. Nevertheless the measurements revealed a delay time of 7 μs. This means that the PD source was probably located on one of the short sides of the insulated bar; the sensor 2 was placed directly on the short side of the bar and the measurement effectively revealed a delay time equal to 0.

The above described procedures have as main assumption that the propagation velocity of the acoustic signals is constant. But the experimental results show that it is possible to identify two different velocities, one longitudinal (V_x) and one transversal (V_y) to the bar. The transversal velocity was found to be fairly constant for all detected defects and equal to 2800 m/s; only in the case of a large void, artificially made in the bar, was it 2000 m/s.

On the contrary, the longitudinal velocity was found to differ depending on the source detected, and ranged from 2500 to 4000 m/s. Thus, if the PD source is on one of the short sides of the insulated stator bar and one of the sensors is placed close to the source, the above relationships used in the location procedure are not effective any more. To minimize the latter effect, the sensors should be placed so as to detect a delay time > 30 μs. This implies a distance between the sensors and the source larger than the transversal dimension of the bar. In such a case the influence of the transversal velocity on the propagation velocity is reduced and the same propagation velocity for both sensors can be assumed.

4. FURTHER MEASUREMENTS AND DISCUSSION

Measurements have been carried out on three artificially damaged insulated bars to provide suitable PD sources. The bars were insulated with resin impregnated mica tape and had the dimensions $54\times18\times2400$ mm^3. Using the above described procedures, several PD sources were localized in the bars. In one of these bars an artificial void has been incorporated in order to better verify the locating procedure and to obtain acoustic signals linkable to a known defect geometry, in view of a possible extension of the method to the identification of the PD site morphology. To improve the identification of the void signals, the void dimensions have been chosen so that the relevant PD inception voltage and apparent charge are higher than the ones associated with other PD sites.

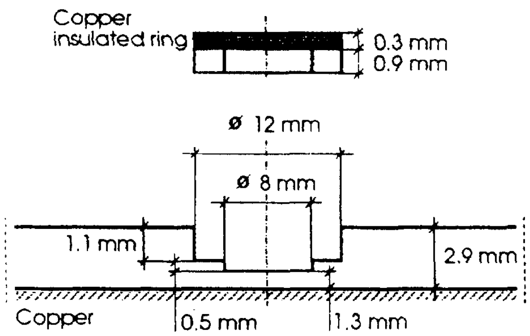

Figure 6.
Schematic view of the artificial void geometry.

The void PD inception voltage V_i, calculated according to [25], was defined as being ~ 3× that of the PD inception voltage of other sites. Thus an artificial void with a height of 1.4 mm has been realized, as shown in Figure 6, by drilling two concentric holes of different diameter and depth, using a numerically controlled specially arranged cutter machine. The void was topped by a copper disc, whose ability to inject free charge carriers into the void, had been shown to improve the PD stability, in terms of PD apparent charge and PD repetition rate, in comparison with other topping solutions. With the above void geometry, at a PD inception voltage of ~ 6 kV, an apparent charge of ~ 500 pC has been measured.

By means of the artificial void, the location procedure has been verified and the error in the void location was found to be in the range of 1 to 2 cm. with respect to its real physical location.

As previously mentioned, two different velocities were found, a longitudinal velocity V_x, and a transversal velocity V_y. In Table 1 a summary of the localized PD sites together with the relevant velocities is reported. The localized PD sites were not so numerous as to allow the finding of sure correlations between sites (position and type) and acoustic signal characteristics. Nevertheless it was possible to verify two considerations. No correlation seems to exist between variations of the longitudinal velocity and position of the PD site on the short or long side of the insulated bar.

Table 1.
Example of characteristic frequency velocities calculated by means of the FFT on an acquired signal

Bar number	Site number	V_x m/s	V_y m/s
1	1	2500	2800
1	2	2500	2800
1	3	4000	2800
2	1	4000	2800
2	2	4000	2800
2	artif. void	2800	2000
3	1	2500	2600
3	2	2600	2600

In the same insulated bar PD sites showing different propagation velocities can be present. Varying the position of sensors along the bar, the transversal and the longitudinal velocities are kept, and it can be assumed that the differences in velocity are associated with the variation in depth of the PD site. It could be inferred that the highest measured longitudinal velocities (4000 m/s) correspond to PD sites near the copper conductor, which has a theoretical velocity (of the so called 'pressure waves') ≈ 4700 m/s [21].

This assumption is consistent with the data of a PD site, showing a 4000 m/s velocity, which is considered to be located near the conductor, because the time delay between electric and acoustic signals could not be rendered zero by moving the acoustic sensor. Besides, the artificial void, situated at 0.5 mm distance from the conductor, shows a longitudinal velocity of 2800 m/s.

5. CONCLUSIONS

THIS work has shown the possibility of using acoustical and electrical measurements in order to correctly locate PD sources in insulating systems. The association between electrical and acoustical signals allows the location of those sites which can be more dangerous from the point of view of aging and of insulation failure. These are the sites which present a higher PD pulse repetition rate, due to the low inception voltage, or to the high relevant apparent charge.

This measuring method could lead to a deeper study on identification techniques of insulation system defects. The identification of damage in a complex insulation system, as in hydrogenerator bars, by means of acoustic signal harmonic content analysis, can start from simple and compact geometry models but these models are to be upgraded in order to represent such a complex system correctly. This method can be used successfully in identification of recursive defects in insulating systems during production, in order to start prompt corrective action in the production cycle and could be adopted in the development and setting of new production technologies.

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