Partial Discharge - Part XIV: Acoustic Partial Discharge Detection -Practical Application

L.E. Lundgaard, *Norwegian Electric Power Research Institute (EFI)*

Introduction

This is the second of two articles that cover general aspects of acoustic methods for partial discharge (PD) detection. The previous article [1] presented the background in basic acoustics, including concepts and terminology, which is required to understand the finer points of acoustic PD detection systems, the subject of the present article. This article also discusses common applications of acoustic PD detection.

In some applications, electrical PD detection methods are not very effective, typically as a result of excessive interfering signals (electromagnetic interference) or excessive testpiece capacitance. As well, electrical partial discharge detection methods rarely provide a basis for location of the partial discharge. In these and many other situations, acoustic methods have advantages over electrical PD detection methods in that they are non-invasive and immune to electromagnetic noise, which can greatly reduce the sensitivity of electrical methods, especially when applied under field conditions. Perhaps most importantly, acoustic PD detection methods can be extended to facilitate PD location in many situations. In some situations, the combination of acoustic and electrical PD detection has been very effective in avoiding false alarms of on-line PD monitoring apparatus.

Acoustic partial discharge detection technology extends the range of conditions over which PD detection can be applied and the information that can be obtained. The immunity of acoustic detection to electromagnetic interference is valuable under field conditions. The ability to locate PD sources within a test object is important in large apparatus such as power transformers, and acoustic methods can be applied in situations where electrical methods are insensitive, such as for PD testing of large capacitors.

General Considerations

The PD Source

A partial discharge results in a localized, nearly instantaneous release of energy. A fraction of the released energy heats the material adjacent to the PD and can evaporate some of it, creating a small explosion. The discharge acts as a point source of acoustic waves. As the discharge duration is very short, the acoustic spectrum of the emitted wave is very broad (several MHz). The intensity of the emitted acoustic wave is proportional to the energy released in the discharge. Thus the amplitude of the wave is proportional to the square root of the energy in the discharge. As the energy released is often proportional to the charge squared, a linear relationship between the amplitude of the acoustic wave and the discharge magnitude (in Coulombs) is common. This general picture can be moderated by the location of the source. If the discharge is located within a cavity or small wedge, standing acoustic waves can be stimulated, which create a spectrum with multiple resonance peaks [2]. In addition, the local "environment" can result in directivity of the acoustic wave at higher frequencies.

The Propagation Path

The acoustic propagation path from the discharge to the sensor is specific to the apparatus under test and ranges from the simple case of discharges on overhead lines, where the sound wave propagates through only

0883-7554/92/$1.00©1992

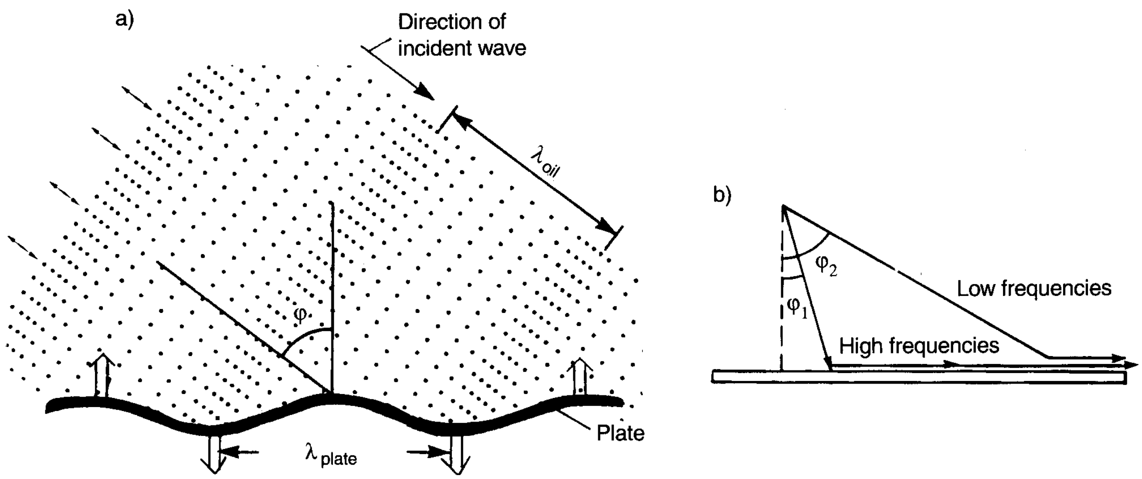

Fig. 1. Model of signal transmission from a liquid to a plate. a) Excitation. b) Possible paths for plane waves. As discussed in the previous article [1], the phase of the wave propagating in the plate must match that of the incident wave in the liquid for efficient coupling. This results in efficient coupling at only certain combinations of angle and frequency that depend on the propagation velocity of the acoustic wave in the liquid and in the plate.

air, to the complicated case of sound propagating throughout the complex structure of a power transformer. The basic concept of wave propagation requires that the wavelength be short compared with the length of the propagation path. In other words, the wavelength must be short compared with the dimensions of the apparatus under test.

An assessment of probable acoustic PD signal characteristics must consider both changes in signal amplitude and signal shape as the signal propagates away from the source.

Reduced signal amplitude (attenuation) can be caused by any of:

- Geometrical spreading of the wave
- Dividing of the wave among multiple paths
- Transmission losses in propagation from one medium to another and at discontinuities in the medium or structure
- Absorption in materials

The latter three mechanisms are frequency dependent, as for cases where plates are involved as explained in Fig. 1 of the previous article [1]. In some cases, these mechanisms will reduce the sensitivity to an unacceptably low level.

Changes in signal shape as the acoustic pulse travels away from the source are dominated by:

- Frequency-dependent velocity (dispersion), which results in different frequency components arriving at the sensor at different times.
- Frequency-dependent propagation paths, which result in different wave components arriving at the sensor with relative time lags (Fig. 1).
- Absorption in materials, which preferentially removes higher frequency components.

Dispersion and frequency-dependent absorption result in transient signals being smoothed as they propagate away from the source (Fig. 2). Wavefront risetimes increase, and the duration of a pulse is lengthened. The transmission of acoustic energy in multiple wavetypes (longitudinal, transverse, torsional, etc.) with differing velocities further complicates the picture, as do reflections from discontinuities in the structure, which create "echoes".

The Sensor

A number of fundamental considerations affect the choice of an acoustic sensor from the wide range of available sensors. The tradeoff between bandwidth

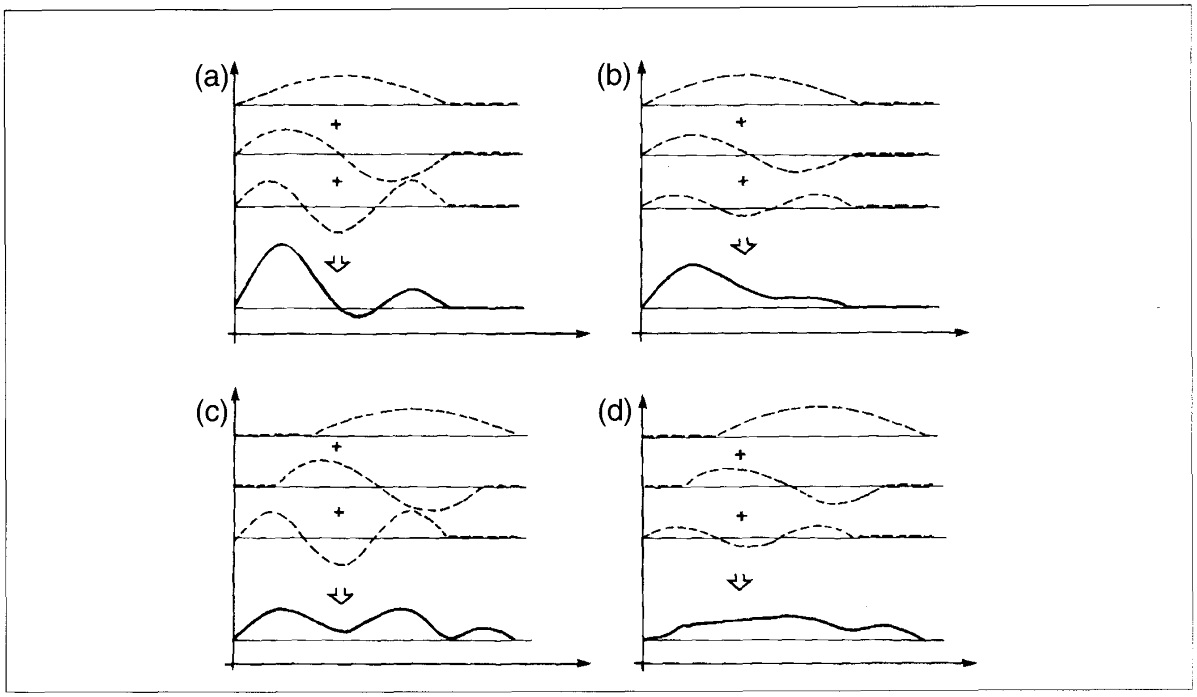

Fig. 2. Shaping of a signal consisting of three frequency components. a) Initial pulse; b) effect of absorption increasing with frequency; c) effect of dispersion with velocity increasing with frequency; d) effect of both absorption and dispersion.

and sensitivity is always a consideration. A wideband or high frequency sensor must be small compared to the wavelength of the acoustic signal (Fig. 3). Reduced size of the sensor results in a smaller "detection" area and thus in a reduced sensitivity. One way of increasing sensitivity is to increase the Q factor (utilize a resonance). The drawback of doing so is the reduced bandwidth, which implies reduced temporal resolution. Limited temporal resolution can result in interference of signals separated by a small time delay. Exactly the same problem must be addressed in the design of electrical PD detection systems, where reduced bandwidth tends to reduce the effect of circuit topology on PD detection sensitivity but runs the risk of errors caused by the superposition of signals within the integration time (response time) of the detector.

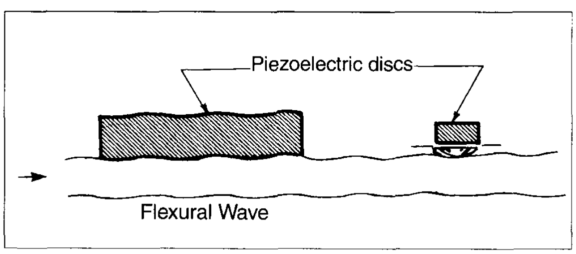

Fig. 3. Sensors for low and high frequency.

The sensitivity of the human ear as an acoustic sensor can be enhanced through the use of a stethoscope, and directional selectivity can be enhanced by listening through a long tube. The latter also has the advantage that it can be used to listen to high voltage components provided that the tube is sufficiently long and nonconducting. However, systems based on electro-acoustic sensors allow better qualitative and quantitative signal evaluation. Several sensors types are available.

Fig.4. Parabolic reflector

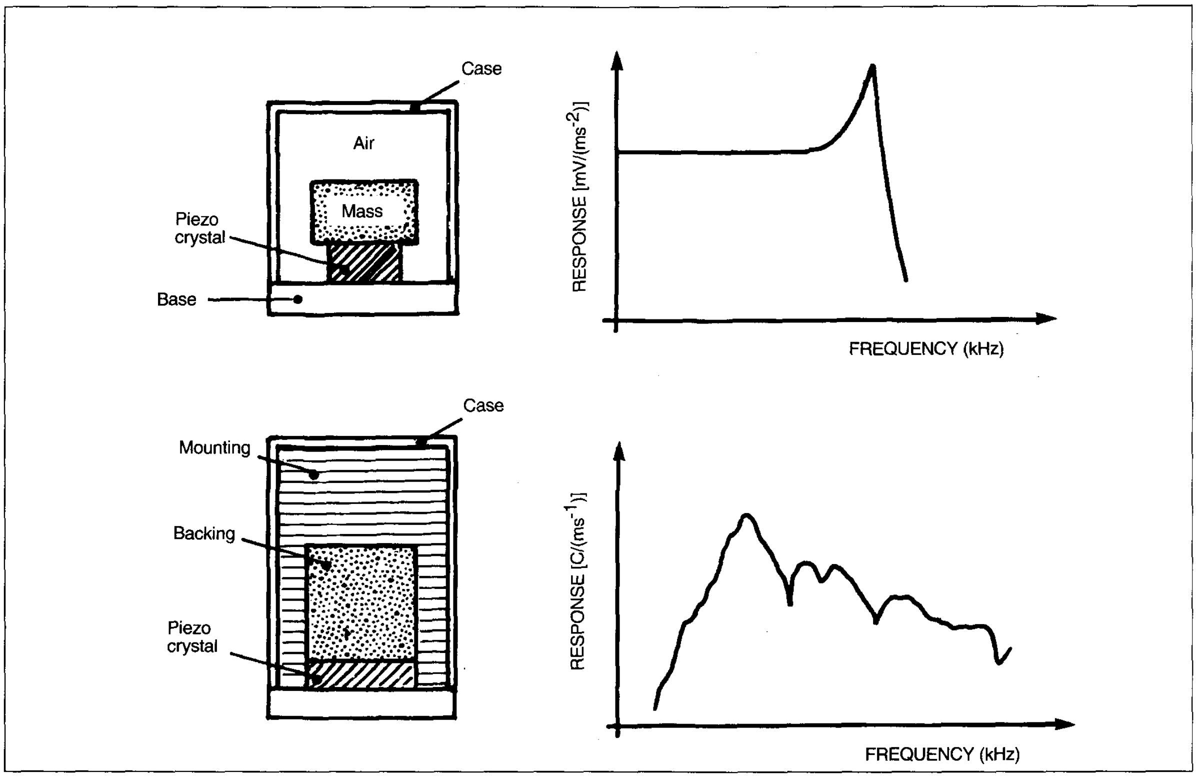

Fig. 5. Accelerometer (a) and acoustic emission transducer (b) with typical frequency response.

In air and gases, microphones are usually employed as sensors. Microphones produce a voltage proportional to the pressure of the sonic wave. The condenser microphone, which is based on the capacitance of a membrane to a fixed plate, features wide bandwidth, high accuracy, and wide dynamic range. Such microphones require a separate polarizing power supply and are expensive, although a 3 mm condenser microphone can be used to 150 kHz. Electret microphones are based on the same principle; however, the capacitor charge is provided by a polarized electret membrane. Such microphones are much less expensive. The primary disadvantage is the possibility of a slow depolarization of the electret, which would result in a slowly decreasing sensitivity. For the lower frequency regime, dynamic microphones are used. These are based on conventional loudspeaker topology optimized for use as microphones (sound detectors) rather than speakers (sound emitters). The sensitivity of all microphones is a function of direction, and directivity becomes more pronounced with increasing frequency. Parabolic reflectors can be used to increase directivity at high frequencies (Fig. 4).

Hydrophones, constructed from piezoelectric materials such as PZT, are designed for use in liquids. Various shapes of crystals (flat, ring-shaped, spherical, etc.) can provide desired directional characteristics. Hydrophones can be very wideband (>150 kHz).

Primarily two sensor types are used for detecting acoustics waves in solids (Fig. 5). Accelerometers, designed to achieve flat frequency response, can be used up to about 50 kHz. Most accelerometers are based on a piezoelectric crystal and produce a charge proportional to the acceleration of the surface to which they are fixed ($pC/m\text{-}s^{-2}$). The voltage across the sensor depends on the cable capacitance. Accelerometers can be fixed to a surface using a pin screw, magnet, glue, etc.

Acoustic emission sensors have been developed for a variety of frequency ranges (30 kHz to 1 MHz). They are resonant sensors also made from piezoelectric crystals, often using a special "lossy" backing, which reduces the Q and assures a reasonable pulse response. The backing can be dropped in order to increase sensitivity. Such sensors produce an electric signal proportional to the velocity of the surface to which they are attached ($V/m\text{-}s^{-2}$). Usually acoustic emission (AE) sensors have an insulating base, and they are available in differential (electrical) configurations, that provide immunity to electromagnetic interference (EMI). Sensors are usually mounted with a thin layer of acoustic couplant (e.g., grease) to assure good sensitivity and are fixed by magnetic hold-downs, tape, elastic bands, etc.

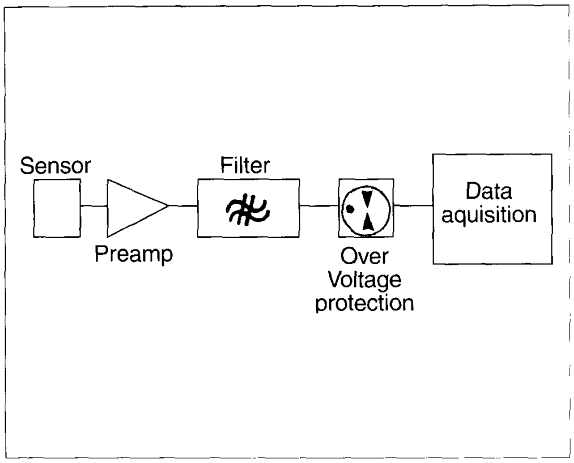

Fig. 6. Acoustic PD detection circuit.

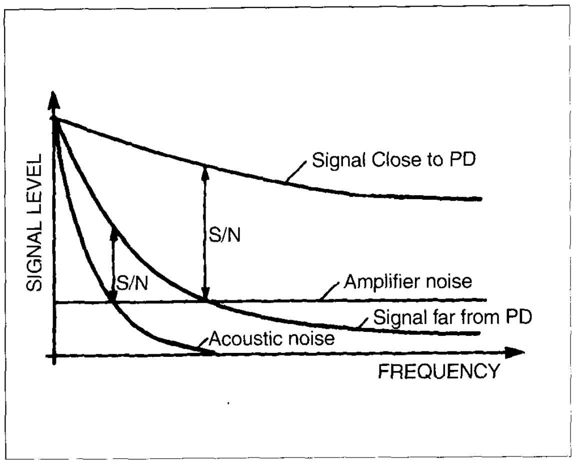

Fig. 7. Signal and noise vs frequency, indicating the basis for determining the acoustic detection bandwidth that provides optimum S/N.

AE sensors usually detect displacements only along one axis, so that only the acoustically-induced particle motion along this axis is detected. Thus such sensors are not wavetype specific.

As mentioned above and in the first article [1], the choice of frequency response influences the wave components that are detected. In a dispersive system, the frequency characteristic determines the detected "virtual velocity" of a wave, as in practice, this will be the wave component first detected by the sensor.

The efficiency of a sensor depends on the acoustic impedance matching to the system under measurement. In order to make a "distributed" sensor suitable for use in high voltage regions, fiberglass acoustic waveguides can be used. The signal is transmitted from the medium into the wave guide and then propagates along the wave guide to the sensor [3].

Noise

Properly shielded acoustic detection instrumentation is generally insensitive to electromagnetic interference provided that ground loops have been avoided. Use of differential sensors and amplifiers suppresses induced common mode noise. Thus noise in such a system is dominated by the two common forms of mechanical noise. Continuous noise dominates the lower frequency regime. Such noise can result from modal vibrations in the apparatus under test or from ambient environmental noise. Usually such noise is low above the audible range and is practically nonexistent above 100 kHz. Transient noise sources usually have a broader frequency spectrum and can appear similar to signals from partial discharges. Sources of transient noise include rain, snow, blowing sand, etc. In situations where partial discharge-induced transients are phase coherent (with the power frequency), the effect of random noise can be reduced through the use of discrimination techniques based on this known correlation. However, not all sources of partial discharge are phase coherent. Particle-induced partial discharge and acoustic signals in SF_6-insulated substations (GIS) are an example of signals which are phase incoherent.

Design of Acoustic PD Instrumentation

Acoustic partial discharge detection apparatus is very simple, consisting of a sensor, filter, preamplifier, and some type of data acquisition instrument (e.g., storage oscilloscope), as shown in Fig. 6. The system frequency response (time constant) determines most system detection characteristics, just as for a conventional partial discharge detection system. Sensitivity and signal-to-noise ratio are determined primarily by the amplitude and frequency characteristics of the signal that arrives at the sensor and the ambient mechanical background noise. Acoustic signals generally decrease at high frequencies as absorption "filters out" the higher frequencies. This effect is more pronounced for apparatus with large distances between PD sources and the sensor. On the other hand, the acoustic noise increases at lower frequencies. The system is optimized through a tradeoff among bandwidth, signal, and noise (Fig. 7). Absorption often limits the practical testpiece dimensions for a given required sensitivity.

The thermal noise of amplifiers increases as the square root of the bandwidth and can influence the signal to noise ratio. A reduced bandwidth reduces the temporal resolution of the system. With a high signal rate, poor temporal resolution results in a "pile-up" of

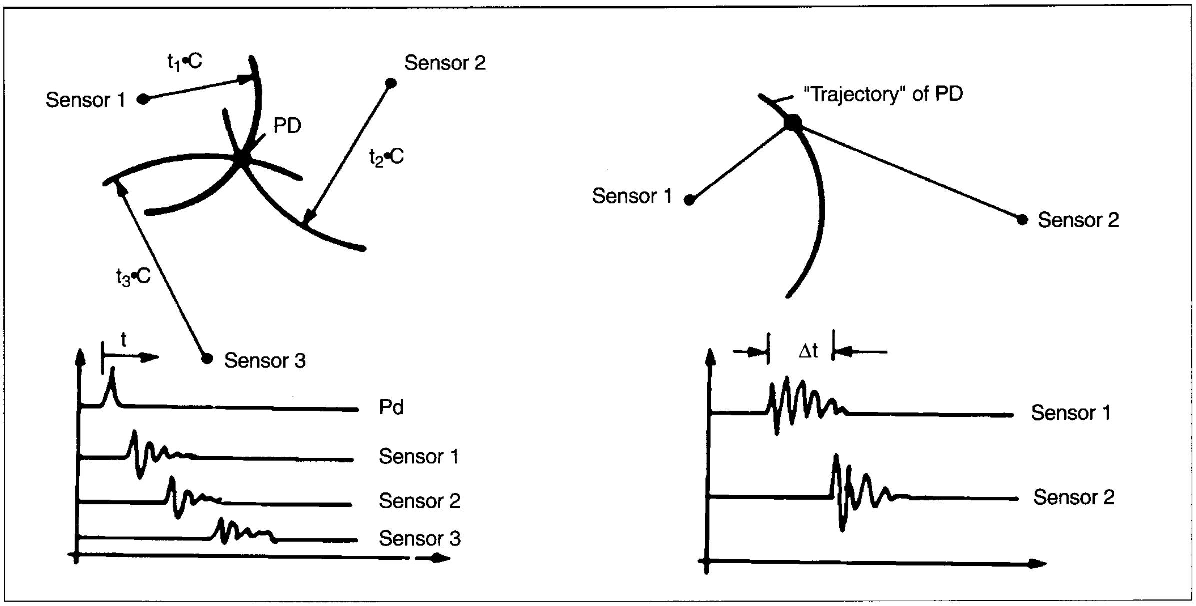

Fig. 8. Triangulation of source location based on time of flight measurements. a) Based on measurement of both electric and acoustic signals; b) based on only acoustic measurements.

the acoustic signals, which can result in errors in the indicated PD magnitude, just as for electrical measurements with too long a time constant (too small a bandwidth). To some degree, this will always be a problem, as one discharge often results in multiple signals (wave types) that propagate along different paths and interfere at the sensor. The frequency response of the system also determines which frequency components are detected. As the speed of sound and propagation path vary with wave type and frequency, the appearance of the signals is determined by the choice of sensor and bandwidth.

The coupling from the apparatus under test to the sensor should be considered as an integral part of the system, as it strongly influences system characteristics. For example, a magnetic hold-down for an accelerometer results in poorer bandwidth than a pinscrew. However, a magnetic hold-down eases system implementation.

Location of Discharges

The possibility of PD location is one of the major features of acoustic discharge detection. Location can be based on either measurement of the time of signal arrival at a sensor (Fig. 8) or on measurement of signal level. In practical situations, a location based on a time-of-flight measurement requires two or more simultaneous measurements in order to facilitate triangulation to determine the source location. The simplest approach is to measure the electrical signal simultaneously with the acoustic signal. If the acoustic propagation velocity is known, then calculation of the source location becomes simple. However, the fact that different wave components travel along different paths in a structure is a complicating factor (4,5).

If the electrical signal cannot be detected, a triangulation can be carried out as a simultaneous measurement with several acoustic sensors. In a continuum, the source must be located on a hyperboloid between the two sensors, which can be determined from analyses of time lag of the signal. All locations on such a hyperboloid will result in the same time lag between the signal arrival at the two sensors. These methods can be used during commissioning tests where time is limited.

If the signal is repetitive, one of two sensors can be moved until the acoustic pulses arrive simultaneously at the two sensors. The source will then be located in a plane midway between them [6]. This method is only suited to apparatus in service, as it is time-consuming.

The simplest location technique is based on the fact that the signal will be largest close to the source. Then only one sensor is required and is moved around until the position for maximum signal is located. The shape of the detected signal can also be informative as high frequency content will be greater near the source, which results in "sharper" transients.

Detection and Evaluation of Signals

The simplest detection system is based solely on registration of the signal magnitude, which can be

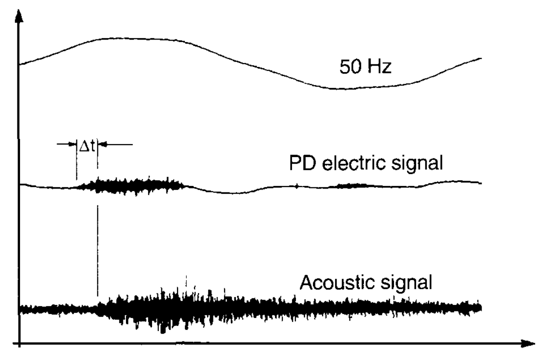

Fig. 9. Acoustic signal from HV electrode in GIS.

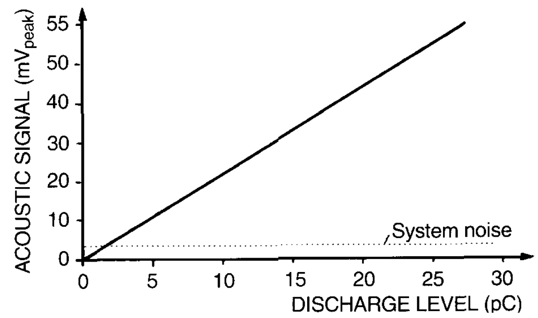

Fig. 10. Sensitivity of acoustic PD detection in 300 kV GIS.

measured as either a peak or RMS value. For all but the smallest systems, measurements are required at multiple locations on the apparatus. A signal level above the noise indicates acoustic activity at a specific location. Such a measurement is usually sufficient for a rough scan. Further inspection of detected signals is required to improve the quality of the diagnosis. An oscilloscope is invaluable for signal evaluation. A storage oscilloscope allows for observation of single pulses. Pulse shape and duration of PD is usually different from that of noise pulses. An envelope display mode is also useful. If an oscilloscope is synchronized to the line voltage, the envelope of the discharge signal should have a periodicity of 50 (60) or 100 (120) Hz depending on whether the discharges appear in one or both half periods (Fig. 9). The phase correlation of a discharge signal can be concealed by dispersion if detected far away (usually some meters) from the source. As the wave components arrive out of phase, the resulting signal can appear like continuous noise. This effect can be reduced by moving the sensor closer to the PD source. Another way of improving a hidden correlation to the power cycle is filtering of the wave components where dispersion dominates. For a flexural wave in a plate this can be achieved by using a high-pass filter. In a plate where the velocity depends on both frequency and plate thickness, a suitable filter frequency is about 500/d kHz, where "d" is the plate thickness in mm. As the travel time of an acoustic wave from a PD source to the sensor is usually appreciable relative to the power frequency period, interpretation of the PD signal based on the signal phase relative to the power frequency waveform is not straightforward unless the distance to the source and speed of sound in the medium are known.

The amplitude of a PD-induced pressure wave from a single discharge is proportional to the square root of the mechanical energy released in the discharge. However, the discharge rate is often so high that "pile-up" of the acoustic signals occurs, as such signals generally have a duration in the millisecond range (Fig. 9). Consequently, the peak value of the detected signal will not be directly related to the energy as might be expected. The RMS value of the detected signal will depend on both the energy in the single pulses and the pulse rate. The RMS signal level therefore depends on the total energy released in the discharge. As the signal level depends on the propagation path, absolute measurements are not considered possible if the structure of the apparatus is complex.

Application to Specific Apparatus

Outdoor Insulation

Detection of corona in air from protrusions at high voltage or from broken insulators is probably the application for which acoustic methods have gained greatest popularity [7]. In some cases, the discharges are even detectable as audible noise, although they are difficult to locate accurately by ear. Improved sensitivity and directivity are obtainable using ultrasonic microphones and parabolic reflectors. Such equipment is commercially available from several manufacturers. Detection of PD in air is simple as it can be described as propagation of sound through infinite space. The sound absorption of air is negligible over practical distances; only spatial attenuation reduces sensitivity.

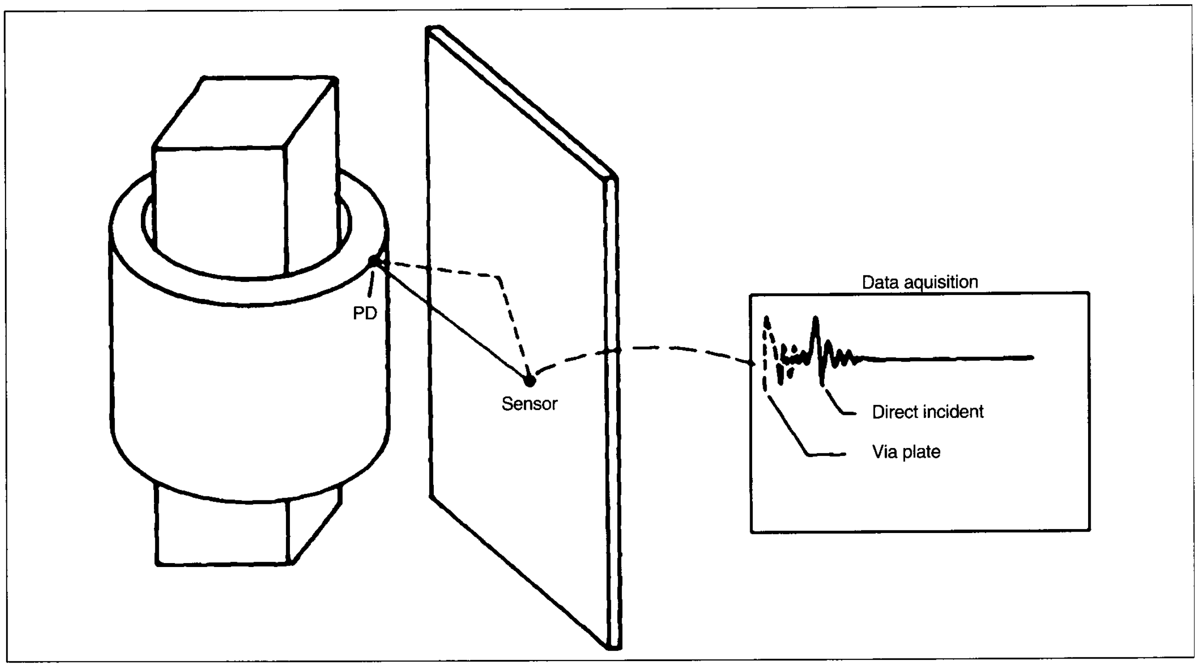

Fig. 11. Propagation of an acoustic wave from a transformer winding to the enclosure (plate).

Gas-Insulated Switchgear

Acoustic PD detection has been applied to SF_6-insulated switchgear (GIS) for many years [8-11]. PD detection sensors are mounted externally on the metal enclosure. In order to provide a thorough check of the GIS, every enclosure section (i.e., between flanges) is measured by moving the sensor on the GIS. The sensitivity has proved reasonable (Fig. 10). The comparatively high absorption of SF_6 relative to other gases and the increase of absorption with frequency reduces the high frequency content of a PD signal generated on the high voltage electrode. A sensor bandwidth of about 10 kHz to 80 kHz appears optimum [12]. Periodicity of the acoustic signals at 50 (60) Hz or 100 (120) Hz is a good indication of PD (but not free conducting particles). The periodicity of the acoustic signal depends on whether PD occurs in one or both half cycles [13].

Sound propagation in a GIS is quite complicated even though the geometry is simple. The sound transmittance from gas to enclosure is governed by features of the enclosure, which act as a plate (Fig. 7). Thus dispersion is important, as are reflections from flanges, etc., which can create many echoes and extensive ringing in the enclosure.

Medium Voltage Air-Insulated Switchgear

In a medium voltage air insulated substation, PD is a significant failure mechanism for cable terminations, connections and feedthroughs, and for flashover of polluted dielectric surfaces. Commercial acoustic PD detectors are available with a high frequency microphone mounted at the end of a hot-stick, which permits the microphone to be brought close to the apparatus under test. Such detectors are well suited to detection and location of PD in air.

In a termination, PD can occur in internal cavities introduced during mounding or assembly. For detection of internal discharges in a cable termination, sensitivity is improved if the sensor is placed in mechanical contact with the cable or termination to provide improved acoustic impedance matching. Use of insulating wave guides can facilitate access to locations close to high voltage parts.

In metalclad air-insulated distribution substations, one microphone can detect signals from a range of locations within one cell. A system for continuous monitoring based on correlation of acoustic and radio frequency signals has proved highly sensitive and immune to false alarms [14].

Capacitors

Conventional electrical discharge detection methods suffer from a reduced sensitivity when measuring apparatus with a high capacitance [15]. An instrument for acoustic PD detection in capacitors has been developed [16]. This instrument, which is based on use of an acoustic waveguide and an 80 kHz acoustic emission sensor, provides sensitivity in the range of 10 pC. The instrument meter displays the signal level in pC, although the instrument is only considered suitable as an indicator of discharge activity as sensitivity depends strongly on sensor location. Variations in signal level of up to 30 dB have been observed as a function of sensor location relative to the sound source [17]. In order to get a better indication of the nature of the detected signal, an oscilloscope should also be used for waveform monitoring. Several capacitor manufacturers use this or similar techniques routinely for quality control in order to assure adequate impregnation and elimination of gas-filled cavities.

Transformers

Acoustic techniques are routinely used by many manufacturers to locate any discharges that occur during high voltage factory testing. The methods are feasible both for ac and for impulse testing [7]. An accurate location of the discharge or breakdown location saves time in the subsequent repair of the insulation. Acoustic methods have also been proposed for in-service monitoring of transformers [18,19].

In transformers, magnetostriction-induced core noise dominates the 50 kHz to 60 kHz region so that sensors with resonance at either lower or higher frequency should be employed [18].

The simplest method of discharge location is based on simultaneous recording of the electric and acoustic signals from the discharge and computation of the distance from the sensor to the discharge therefrom. In the case of discharges at a terminal or outside the windings, the propagation path is quite simple (Fig. 11) [5]. The acoustic signals travel through the oil and couple to the plate (enclosure) at certain combinations of frequency and incident angle, as discussed in the previous paper[1]. Both a semi-longitudinal and a flexural wave will be generated in the plate; however, the flexural wave is the more significant. When externally mounted sensors are used for location purposes, a low pass filter is employed to remove all frequency components that move faster in the tank than in the oil. All distances can then be calculated based on the propagation in the oil alone, as the direct incident wave from the oil arrives first at the sensor [5]. When testing during commissioning, several sensors should be applied in order to have a reasonable sensitivity over the entire transformer. For an in-service test, a single sensor moved around on the transformer is sufficient.

Another commercially available method of detecting PD-induced acoustic signals in a transformer is based on the use of acoustic waveguides [3]. The speed of sound in a waveguide is close to the speed of the longitudinal wave (i.e., 4150 m/s for polyester fiber). However, because of the different speed in oil and in the waveguide, uncertainties appear when calculating the location of a discharge. Waveguides made from glass fibers will not harm the transformer insulation system and can be fitted permanently to the transformer.

In the case of PD from inside the windings or barriers, the wave propagation is more complex. Even though acoustic absorption in impregnated paper and pressboard is quite moderate, sensitivity can be reduced significantly if the source is located in a structure such as a winding. Apparently, the structure characteristics become more important than the characteristics of the material from which the structure is fabricated.

Simultaneous recording of electric and acoustic signals has been proposed as a basis for on-line PD monitoring of transformers [19]. PD is diagnosed through the correlation of acoustic and electrical signals. This avoids false alarms from acoustic signals caused by rain and electrical signals caused by corona in air.

Cables

Acoustic methods are not well suited for discharge detection in cables as a result of the large reduction in sensitivity with distance from the source. The absorption in the cable insulation also reduces sensitivity. As a result, the acoustic sensor must be in contact with the cable to provide any hope of reasonable sensitivity. The frequency spectrum of the detected acoustic signal has a maximum at a characteristic frequency, f, determined by the elasticity ($1/s$) of the column of insulating material under the sensor and the mass (m) of the sensor.

$$f = \frac{1}{2\pi\sqrt{m/s}}$$

The characteristic frequency is in the range of 2 kHz [20]. A narrow band detection circuit tuned to this frequency will improve sensitivity. The sensor should be moved along the cable and will give an increased signal level in the proximity of the discharge. However, the sensitivity for practical systems is reported to be limited (i.e., about 100 pC for XLPE cable). Sheath and armor in an XLPE cable reduce acoustic coupling from the insulation to the sensor as a result of the poor acoustic transmission through the air-filled cavities in these parts of the cable. For three-phase cable, a similar problem occurs. However, for detection and location of discharges in cable accessories, acoustic techniques are feasible.

Conclusion

Acoustic discharge detection methods are well-demonstrated for several applications. The main advantages compared with conventional discharge detection methods include immunity to electromagnetic interference and the possibility of PD source location. The simple instrumentation, the non-intrusive nature of the technique, and reduced dependence on high voltage test equipment characteristics are also advantages.

Acoustic methods compete with electrical methods only in cases where conventional methods are unsuitable as a result of EMI, access to the high voltage electrode, excessive test object capacitance, or where PD location is required. The simultaneous application of electric and acoustic techniques can provide increased sensitivity and greatly increased immunity to false alarms in an operating environment. Simultaneous measurement also offers the possibility of isolating a particular discharge source (location) and using temporal discrimination to follow the discharges from this specific location.

The benefits of acoustic techniques are not limited to commissioning and on-site testing. Acoustic techniques are also applied to material studies and have potential for development and production testing. However, an understanding of the relevant acoustic theory, as reviewed in the previous article [1], is required in order to understand both the limitations of the technique as well as the potential benefits.

Lars E. Lundgaard was born in 1952 in Copenhagen. He received the M.Sc. degree in electrical engineering from the Norwegian Institute of Technology in 1976 and worked for the Oslo Electricity Works from 1978 to 1980. Since 1980, he has been with the Norwegian Electric Power Research Institute (EFI) in Trondheim, Norway, where he has carried out extensive research into acoustic partial discharge detection.

References

1. Lundgaard, L.E. "Partial Discharge - Part XIII: Acoustic Partial Discharge Detection - Fundamental Considerations". IEEE Electrical Insulation Magazine, *8*, No. 4, July/August 1992.
2. Harrold, R.T. "Ultrasonic Spectrum Signatures of Under-Oil Corona Sources". IEEE Trans. *EI-10*, No. 4, Dec. 1975. p. 109-112.
3. Harold, R.T. "Acoustic Waveguides for Sensing and Locating Electrical Discharges in High Voltage Power Transformers and Other Apparatus". IEEE Trans. *PAS-98*, No. 2, March/April 1979. p. 449-457.
4. Ogihara, H. "Detection and Location of Coronas in Oil-Immersed Transformer with Corona Detector". Electrical Engineering, Japan, *84*, Sept. 1964. p. 12-21.
5. Lundgaard, L.E., W. Hansen, and K. Dursun. "Location of Discharges in Power Transformers Using External Acoustic Sensors". Proceedings of the 6th International Symposium on High Voltage Engineering (ISH), Paper No. 15.05, New Orleans, 1989.
6. Allen, D.J., J.A.C. Forrest, E.L. Howitt, and A.D. Petcess. "Electric and Acoustic Location of Discharges in Transformers". IEE Conference on Diagnostic Testing of High Power Apparatus in Service, Publ. No. 94, part 1, London, 1973. p. 65-70.
7. Harrold, R.T. "Acoustical Techniques for Detecting and Locating Electrical Discharges". *Engineering Dielectrics Volume I: Corona Measurement and Interpretation.* ASTM Special Publication 669, Philadelphia, 1979. p. 327 - 408.
8. Graybill, H.Q., J.C. Cronin, and E.J. Field. "Testing of Gas Insulated Substations and Transmission Systems". IEEE Trans *PAS-93*, Jan/Feb 1974. p. 404-413.
9. Lundgaard, L.E., M. Runde, and B. Skyberg. "Acoustic Diagnoses of Gas Insulated Substations: A Theoretical and Experimental Basis". IEEE Trans. *PD-5*, No. 4, Oct. 1990. p. 1751-1759.
10. Lundgaard, L.E., G. Tangen, B. Skyberg, and K. Fagustad. "Acoustic Diagnoses of GIS: Field Experience and Expert Systems". IEEE Trans. *PD-7*, No. 1, Jan. 1992. p. 287-294.
11. Wahlstrom, B., K. Petterson, W. Lord, and M. Leijon. "Approaches and Experiences in Sweden of Reducing GIS Maintenance Costs - Especially by Application of Periodic Acoustic Measurements". CIGRE Paper No. 23-106, 1990.
12. Lundgaard, L.E. and B. Skyberg. "Acoustic Signal Propagation from Discharges in GIS". *1991 Annual Report of the IEEE Conference on Electrical Insulation and Dielectric Phenomena* (CEIDP). p. 449 - 456. IEEE Publication No. 91 CH 3055-1.
13. Albiez, M. and M. Leijon. "PD Measurements in GIS with Electric Field Sensor and Acoustic Sensor". Proceedings of the 7th International Symposium on High Voltage Engineering (ISH), Paper No. 75.08, Dresden, 1991.
14. Van Haeren, R., G.C. Stone, J. Mechan, and M. Kurtz. "Preventing Failures in Outdoor Distribution Class Metalclad Switchgear". IEEE Trans. *PAS-104*, No. 10, October 1985. p. 2706-2712.
15. Boggs, S.A. "Partial Discharge - Part II: Detection Sensitivity". IEEE Electrical Insulation Magazine, 5, Sept/Oct 1990. p. 35.
16. Harrold, R.T. and T.W. Bakin. "Ultrasonic Sensing of Partial Discharges within Microfarad Value AC Capacitors". IEEE Trans. *PAS-98*, No. 2, March/April 1979. p. 444-448.
17. Lundgaard, L., R., Hegerberg, and P.H. Spaeren. "Acoustic Measurements of Partial Discharges in Power Capacitors". Nord-IS 86, Paper No. 26, Esbo, 1986.
18. Howells, E., and E.T. Norton. "Detection of Partial Discharges in Transformers Using Acoustic Emission Techniques". IEEE Trans. *PAS-97*, No. 5, Sept/Oct 1978. p. 1538-1549.
19. Kawada, H. M. Honda, T. Inoue, and T. Amemiya. "Partial Discharge Automatic Monitor for Oil-Filled Power Transformer". IEEE Trans. *PAS-103*, No. 2, Feb. 1984. p. 422-428.
20. Kreuger, F.H. *Partial Discharge Detection in High Voltage Equipment.* Butterworth & Co., London 1989. ISBN 0-408-02063-6, p. 39.