WHITE PAPER

Partial discharge

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Introduction

The IEC-60270 standard defines the partial discharge (PD) as a localized electrical discharge, which partially bridges the conductors' insulation. In electrical engineering, PD is defined as the localized dielectric breakdown of a small section of an electrical insulation system when there is high-voltage stress. In general, PDs occur due to local electrical stress on the insulation's surface or in the insulation, such as a gas bubble in an insulator, a gas-filled void in an insulating material, or around an electrode in a gas.

Partial discharges can characterize the majority of the deformations within the transformer insulation systems. Partial discharges may lead to damage of a high-voltage device. The damage may happen in a short time or develop for years. Therefore, the assessment of changes in PD intensity is essential, and it can be realized by monitoring systems.

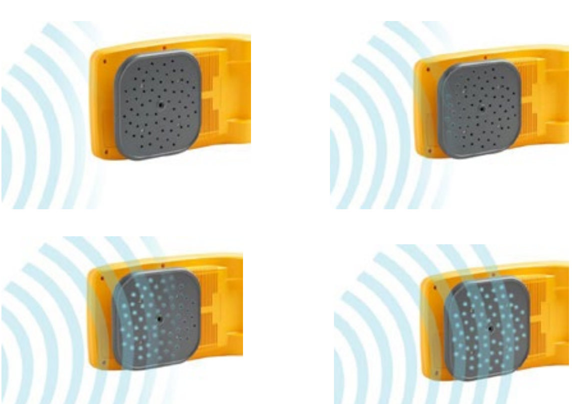
The electrical discharge (Q or q) has the SI unit of is the coulomb (C). It is defined as the charge carried by a constant current of one ampere in one second.

Refresher on the operation of the ii910

The ii910 uses 64 microphones arranged in a specific array pattern. It has a visible camera in the middle of the array providing an image of the scene. The device uses complex algorithms to generate a sound map or image of the sound sources and then overlays the generated sound map on to the image. Depending on the sound source's position concerning the ii910's field of view, each microphone receives the sound slightly different times. The inter-microphone time differences allow locating the sound source's position: If the sound is coming from the right side of the device, the microphones on the right side of the array will receive the sound a fraction of a second earlier than the microphones on the left side. The ii910 would display the image for that sound on the right side of the screen.

How does the ii910 detect partial discharges?

Some parts of electric energy (1–5 %) is converted into mechanical energy during PD, and the conversion generates acoustic emission (AE) waves. The AE waves are produced as a result of the intermolecular bond energy release when materials are deformed. Processing AE waves are commonly used to assess conditions of civil structures, diagnostics of cutting machines and the cutting process, and detection of material defects. In electrical engineering, the acoustic emission waves serve as the cue for detecting PD sources' location in large power transformers. The AE method in PD detection is relatively new. However, the AE method was referred to as the most applicable and the least expensive PD detection method when compared with the traditional methods (Sikorski and Ziomek, 2012, Table 1). The ii910 detects the acoustic emission waves generated by electrical discharges.



Factors affecting PD detection

The radiated sound field in insulation parts, under ideal conditions, propagates as a spherical pressure (longitudinal) wave. The generated acoustic waves disseminate through the high voltage apparatus' inner parts and reach the external surface.
When the acoustic waves reach the solid insulation parts, the structure-borne propagation paths are formed, described by a vector of velocities.
There are reflections and refractions at the boundaries of the structure-borne propagation paths, resulting in absorption, attenuation, and scattering. The complex propagation structure turns the PD detection procedure into a case-specific process: The PD detection device should be positioned differently for each case to gain a high signal-to-noise ratio. Moreover, the optimum detection position does not always correspond to the shortest optical path between the PD source and the device. To overcome the transmission path issues and the acoustic effects (absorption, attenuation, and scattering), the mobility and the properties of the acoustic sensor (sensitivity and the frequency range) are critical aspects for efficient PD detection.

Transmission path

The following characteristics in IEC 62748 summarize the impact of the acoustic transmission path between the PD source and the acoustic sensor:

1. Variable propagation modes of the acoustic wave along the transmission path from source to the acoustic sensor;
2. The changes in the acoustic velocity based on different materials and conditions (e.g., for insulating oil: comparatively high-velocity variation with temperature, only minor velocity variation with humidity);
3. Acoustic dispersion and dispersive attenuation: Frequency-dependent decomposition of acoustic waves as it passes through a medium. Depending on the insulation material, some of the decomposed frequencies get attenuated. Hence the frequency characteristics of the acoustic waves generated by the PD vary for each case.
4. Mismatch of the acoustic impedances at the sensor and the high voltage apparatus housing;
5. Distance between the acoustic sensor and the PD source.

The frequency range of PD

As mentioned in the section above, the frequency characteristics of PDs differ mostly based on the transmission path properties. The variability of the peak frequencies was investigated in the PD literature. The present section summarizes the peak/dominant frequencies observed while analyzing the AE waves of PDs in the literature.

Harrold (1975)–The AE waves of different types of PDs in oil were investigated. A wideband transducer was used for measurements.

- No unique frequency with high energy was detected.
- The successful frequency range of the resonant transducers: 20 kHz-100 kHz.

Harrold (1980)–The AE waves generated by sparks and arcs in oil were recorded with narrow and wideband transducers.

- High energy arcs radiate maximum levels in the range of 120 Hz-10 kHz,
- Low energy micro sparks create maximum acoustic emission at high frequencies: 10 kHz-400 kHz.

Howells and Norton (1978)–The AE waves generated by power transformers were observed using a resonant transducer with a resonance peak of around 140 kHz.

- Most of the AE wave energy is transmitted in the 20 kHz-80 kHz.
- Rest is transmitted within the range of 140-170 kHz, close to the transducer's resonant frequency.

Zhu et al. (1988)–Several types of PDs in power transformer insulations were investigated. Wideband and narrowband piezoelectric sensors were used.

- Peak frequencies covered a wide range (70-150 kHz),
- Barkhausen noise frequencies are lower than 20 kHz.
- The frequency bandwidth of 70-180 kHz was recommended for detecting PD.

Sakoda et al. (1999)–Frequency response of the AE waves of a single PD pulse in oil was measured with a broadband ultrasonic transducer.

- Almost all of the energy of the AE pulse from PD in oil was transmitted below 100 kHz. The dominant frequency was 25 kHz.

Bozcar (2001)–The AE waves emitted by surface discharges in oil, gas bubble discharge in oil, and discharges in potential particles were analyzed. A wideband piezoelectric transducer was used (10 kHz–1 MHz).

- Creeping discharges (a term used for surface discharge) created low-frequency AE signals (<100 kHz), with the most significant portion is carried between 70–90 kHz.

Sikorski and Ziomek (2012)–Ten different PD types occurring in oil-paper insulation were examined.

- Each of the investigated PD forms generates repeatable and unique AE signals,
- Results of frequency-domain analysis strongly depend on the type of the applied sensor,
- The low-frequency (30 kHz) sensor is more sensitive in the detection of high-energy PD like surface discharges than the wideband sensor,
- High-energy creeping sparks generate AE signal in the 20 to 40 kHz frequency band,
- Low-energy PD, like discharges in gas bubbles or internal gas voids, emit short AE pulses in the high frequencies (100–300 kHz).
- The conclusions from the model tests were confirmed by measurements carried out on power transformers.

Sikorski (2019)–Peak frequencies of four PD types were investigated.

- Four PD forms were investigated: two types of surface discharges, partial discharge, and inter-turn discharge.
- The frequency of the AE signals generated by one of the surface discharge type B ranged between 20 kHz and 110 kHz, wherein 95 % of the energy was transferred in a narrow band from 22 kHz to 42 kHz.
- The type A surface discharges produced AE signals of higher frequencies where 95 % of the acoustic wave energy was transmitted in the band between 48 kHz and 100 kHz.
- The inter-turn discharges generated AE signals with slightly higher dominant frequencies than the type B surface discharge slightly higher. 95 % of the AE signal's energy was transmitted between 20 and 68 kHz.
- The partial discharge in oil had a broadband frequency characteristic. The largest part of the acoustic energy (90.3 %) was emitted in the frequency band of 80–117 kHz, where the peak frequency was equal to 98.1 kHz.
- The dominating frequencies observed in the four discharge types' normalized summed spectrum are 40 kHz, 68 kHz, and 90 kHz.

What PD properties does ii910 measure?

Electrical discharge type classification in ii910

The ii910 classifies the types of partial discharges using artificial intelligence algorithms. Four types of discharges are classified: External discharge, internal discharge, tracking discharge, and other.

1. **External discharge:** The external discharge classification is based on the two subclassification algorithms in ii910: Electric arc and corona discharge. Acoustic data of both external discharge types were collected from power transformer measurements.

   a. **Electric arc:** An electric arc, or arc discharge, occurs when an electrical discharge is perpetuated in a gas that results in an electric breakdown (Fig. 1). The produced plasma can generate visible light. It is often categorized as a *two-electrode discharge*: when an ionized path is formed from one electrode to another, a massive magnitude of energy is released.

Figure 1: An electric arc generated using two electrodes. Image courtesy of Achim Grochowski–Achgro, own work, CC BY-SA 3.0

   b. **Corona discharge:** A corona discharge is a process by which a current flows from an electrode with a high potential into a neutral fluid (e.g., air) by ionizing that fluid to create a region of plasma around the electrode (Fig. 2). The corona is often called a *single-electrode discharge* and tends to occur at sharp points and edges.

Figure 2: A corona discharge on an insulator string of a 500 kV overhead power line. Image by Nitromethane, own work, CC BY-SA 3.0

2. **Internal discharge:** Partial discharges can occur in liquid, gaseous or solid insulation parts. Typically, it starts in the gas voids or transformer oils since the dielectric constant of the void is smaller than the surrounding dielectric. For internal discharge classification, the acoustic data of void discharges were collected from laboratory and field measurements.

3. **Tracking (surface) discharge:** There are several terms used for tracking discharges, such as surface discharge, creeping discharge, or surface tracking discharge. Surface discharge (Fig. 3) is considered the most dangerous type of PD, which may lead to the power transformer's sudden failure (Sokolov et al., 1999). The tracking (surface) discharge occurs in the oil/pressboard barrier system, a problematic area in the power transformer insulation system. Several field measurements were conducted for developing the tracking (surface) discharge classification in ii910.

Figure 3: Tracking (surface) discharge damage. Image by Manning225, own work, CC BY-SA 3.0

4. **Other discharges:** There are several other electrical discharges, such as brush discharge, a single electrode discharge, and inter-turn discharge. Currently, ii910 classifies these electrical discharge types as other.

Phase-resolved data pattern

The PD attributes are commonly quantified using a method called a Phase-resolved data pattern (PRDP). The PRDP represents the PD's magnitude as a function of the phase degrees of the chosen supply voltage frequency.

The PRDP data pattern computation begins with segmenting the data into $1 / f_v$, where f_v is the supply voltage frequency. Each segment's amplitude values are then visualized as a function of the phase degrees of the supply voltage frequency. Phase degree is computed by 360 x (t_i / T) where t_i is the time information of the PD pulse, and T is the duration of the one cycle of the supply voltage frequency. Lastly, a threshold is applied before the representation of the PRDP pattern.

The ii910 applies an initial-phase prediction algorithm, which decides on the beginning sample for the PRDP computation. The initial-phase prediction algorithm results from data-driven development and successful at providing visuals that are familiar to the users who have PD detection experience with conventional methods.

The PRDP representation of one of the measurements conducted in the field is presented in Fig. 4.

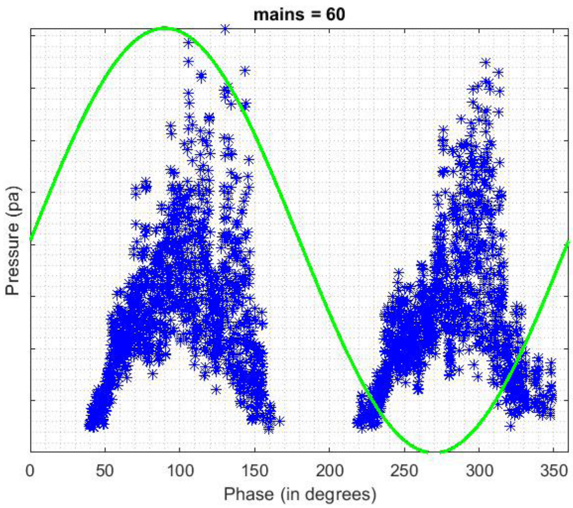


Figure 4: The PRDP analysis of an electrical discharge detected on a power transformer. The supply voltage frequency is 60 Hz and denoted with the green sinusoid.

Pulse per minute (PpM)

In addition to the PRDP analysis, ii910 provides a real-time prediction of the PD pulse count, Pulse per minute. The algorithm is developed based on the PD data collected in both laboratories and the field. The pulse count prediction algorithm is a novel algorithm developed for ii910. The algorithm analyses the temporal resolution and the smoothed PD waves' patterns for estimating the number of PD pulses per minute in the measured AE signal.

Both the PRDP analysis and the pulse count estimation are computed using the beamformed data, hence advantageous concerning environmental noise.

Conclusions

Detecting electrical discharges using acoustic sensors is a challenging task mostly due to the impact of PD's transmission path and the requirement of sensors with high-frequency range. As a hand-held device, ii910 overcomes the challenges that the transmission path brings. The acoustic properties of the ii910's microphones are chosen based on the literature summarized in the present document. The ii910 is configured to maximize the signal-to-noise ratio of the AE signals of the PDs. An extensive set of data was collected in laboratory and field settings to validate the classification and PpM algorithms. The PD position, type, number of pulses, and the PRDP analysis provide a complete and easy reporting procedure.

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