Pattern Analysis of Partial Discharges in SF₆ GIS

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ABSTRACT
The measurement of partial discharge (PD) of several faults in gas-insulated system (GIS) is discussed. Phase-resolved PD patterns have been measured using three different PD detection measuring systems: according to the IEC 270 recommendations, a VHF /UHF measuring system with narrow band filtering, and the UHF measuring system with wide band filtering. PD patterns are compared using computer-based discrimination tools. The influence of the selected center frequency on the PD patterns is discussed for the narrow band VHF /UHF measuring system. The influence of the number and type of GIS components between the discharging defect and the capacitive coupler on the shape of the PD patterns is analyzed. For several GIS components the signal reduction is studied. It was found that the shape of PD patterns is independent on the used PD detection circuit and the propagation path of the PD signals. As a result, discrimination and classification of PD distributions of several studied defects are possible using digital tools.

1 INTRODUCTION
SF₆ gas-insulated system (GIS) have proven to be very reliable. However, it is known that faults cannot completely be excluded and that most faults which might lead to failure in a GIS show PD activity [1, 2]. Two kinds of electrical measuring systems are in use to detect PD in GIS: Conventional measuring systems based on the IEC 270 recommendation; most commercially available narrow or wide band PD detectors are measuring PD signals using frequency ranges of ~10 to ~500 kHz and the measurement in [pC] of actual discharge levels is based on the IEC 270 recommendations [3] and modern VHF /UHF measuring systems which are using narrow or wide band filters: detection in a frequency range to ~3 GHz which has been frequently used for the last years during on-site tests [4–6].

1.1 THE IEC 270 MEASURING SYSTEM
One of the main advantages of the standardized IEC 270 system is a very broad scale of experience and recently also the presence of digital tools related to phase-resolved PD recognition that support the evaluation of PD measurements [7–10]. Unfortunately, due to external noise which is frequently present in the field (on-site/on-line), the use of the conventional test circuit as recommended by the IEC 270 [3] is quite difficult. To solve this problem and to achieve a sensitive measuring circuit for on-line testing of GIS, a system called VHF /UHF detection has been introduced [5]. It has been shown that this detection system has about the same sensitivity as the IEC 270 system [11, 12].

1.2 THE NARROW BAND VHF/UHF SYSTEM
The main advantage of the narrow band VHF /UHF system is the possibility to suppress external noise and disturbances by selecting a frequency range with a sufficient signal-to-noise ratio and lowest influence of disturbances [5, 15]. In contrast to Figure 1(a) which shows a narrow band measurement tuned in a proper frequency range, Figure 1(b) shows a measurement tuned in a wrong frequency range.

Fast on-site inspection is possible if VHF /UHF capacitive couplers are permanently installed in the GIS installation. The occurrence of PD in GIS caused by moving particles, particles on insulators and protrusions on the conductor can be very dangerous to the insulation conditions of the GIS installation. This means that the detection and recognition of these faults at an early stage during on-site tests are important tools for condition-based maintenance of GIS. In particular, the digital tools related to recognition and classification of phase-resolved PD patterns also have been used successfully for narrow band VHF /UHF measurements [16].

1.3 THE WIDE BAND UHF SYSTEM
A wide band UHF system has been introduced also [17]. This system measures the time domain signal in a frequency range from 500 to 1500 MHz. Using wide band amplification of the signal, an increase of the signal-to-noise ratio can be expected but on the other hand more influence of disturbances cannot be excluded, see Figure 1(c).

In practice, during an acceptance test, the evaluation of PD in GIS is restricted to measuring the inception voltage (kV) and the largest discharge magnitude (pC) and comparing these to the test specifications.
However, if the maximum allowable discharge level is exceeded, it is important to know the cause of the discharge. The main goal of evaluation in GIS is to find one of the following defects:

- Protrusion on the HV conductor; protrusion on the enclosure; a particle on an insulator (spacer); free moving particles inside the enclosure;
- Internal defects in moving parts like circuit breakers and disconnectors;
- Electrically floating parts in the installation.

For this purpose different discharge related parameters and quantities have been introduced in the past and are still in use [3]. Due to the increasing automation of PD measurements, the use of computer-aided evaluation has become popular. The use of a computer-aided system offers the opportunity to store sequences of the discharge pulses and to post process these in the course of time or as a function of the power frequency cycle [18]. In this way a basis is created for further evaluation and diagnosis of PD measurements in GIS [17, 29].

Figure 2 shows the most important stages of PD signal evaluation: discharging defect; electromagnetic wave excitation by the discharge and influence of the GIS on the transmission of the electromagnetic waves; coupling and data acquisition; and data processing. It is known that the discharge currents in SF₆ are very short in time: < 1 ns [17]. These fast pulses excite electromagnetic waves in the GIS enclosure, see (2) in Figure 2. Various components such as T-junctions, insulators, circuit breakers etc. are used to build a GIS. These components influence the transmission of the electromagnetic waves due to reflection, attenuation and dissipation. To pick up the PD signals, capacitive couplers can be used, see (3) in Figure 2. Finally the measuring data can be processed by a spectrum analyzer or a PD analyzer.

To evaluate different PD sources, digital post-processing provides a series of phase-resolved PD quantities. Sometimes it is not possible to characterize a fault by one single shape of the distribution. On the contrary, sometimes a PD source can be characterized by different PD patterns, for example in the case of a protrusion on the conductor, see Figure 3(a) to (d). In this case evaluation of the patterns becomes more difficult. Moreover, several parameters such as the geometry of the GIS test setup, the insulating materials involved in the PD process, the electric field strength and the electrode material may influence the distributions. In particular, one must distinguish between signals emitted from fixed and moving particles. Fixed particles can produce corona discharges, whereas moving particles can produce both corona discharges during flight and contact discharges when striking a surface [20].

In addition to physically related conditions, several parameters like the measuring frequency in the case of the narrow band VHF /UHF system, the choice of PD quantities as well as the statistical tools for discrimination are of importance. To contribute to the discussion on the possibilities of digital PD monitoring of GIS and statistical discrimination and classification of PD patterns, the following aspects are studied in this paper.

IEC 270, narrow band VHF /UHF and wide band UHF PD patterns are compared for a sharp protrusion on the conductor in the GIS installation; the influence of the VHF /UHF measuring frequency on the PD patterns is
Figure 3. Examples of PD patterns made by 3D $H_n(\phi, q)$ intensity distribution of the discharge magnitude $q$ and phase-angle $\phi$ observed for different typical defects in GIS [16,19]: (a) to (d) protrusion on the conductor, (e) a free moving particle, (f) a particle fixed to an insulator and (g) a protrusion on the enclosure. The PD-magnitudes are not calibrated.

analyzed; the influence of the distance and the number of insulators between the fault and the coupler on the PD patterns is studied; and a comparison of two different discrimination tools is made: the tree method and fractal analysis.

Based on these investigations it was found that the shape of PD patterns is independent of the PD detection circuit used and of the propagation path of the PD signals. As a result, discrimination and classification of PD distributions of several studied defects is possible using digital tools.

2 PD MEASURING SYSTEMS: PRACTICAL DETAILS

The PD measurements discussed in this report were obtained using two test setups. Figures 4 and 5 show commercially available 245 and 420 kV GIS. Exact information of the dimensions of both GIS is not necessary for the understanding of the discussed results in this paper.

In this Section a more detailed description of the three measuring systems is given. In all systems a digital PD detector (TE-571) is used to digitize, record and store the PD signals measured using a measuring system according to the IEC 270 recommendations or a tunable narrow band VHF/UHF filter or a wide band UHF filter. After a PD measurement, different graphical representations of the measured PD signals can be created to further analyze the PD source, see Section 3. Only in the case of the measurements obtained with the IEC 270 measuring system, the amplitudes of PD pulses are measured in pC. In both other systems no calibration is possible and the PD pulses are uncalibrated.

2.1 IEC 270 PD DETECTION

The IEC 270 PD detection circuit is composed of a coupling capacitor (60 pF), a coupling device (AKV-572) and a PD detector (TE-571). The PD signals measured using this circuit were correlated to the 50 Hz wave form of the applied voltage. In this way phase-resolved PD patterns were obtained and used to discriminate between different faults. To automate this process, several digital tools are in use to analyze the
2.2 NARROW BAND VHF/UHF PD DETECTION

The VHF/UHF detection circuit is composed of a capacitive coupler (in the case of the 245 kV setup a cone-shaped coupler with a capacitance $C' = 1.058 \text{ pF}$ [24] and in the case of the 420 kV setup disc couplers), a spectrum analyzer (SA) (Tektronix 2711) and a modified PD detector (TE-571). A capacitive coupler was used to pick up the electromagnetic waves as produced inside the GIS enclosure by each PD pulse, see Figure 2.

The first step in finding a proper measuring frequency for a VHF/UHF PD measurement is to measure the full frequency span (ranging from 0 to 1.8 GHz in the case of a Tektronix 2711 spectrum analyzer). The SA can be seen as a tunable narrow band bandpass filter and the center frequency of the tunable filter is swept across the desired frequency range [25]. As a result, the frequency spectrum can be measured.

Using a SA, there are several methods to obtain a frequency spectrum.

1. The spectrum can be measured during one sweep of the SA.
2. The spectrum can be measured during several sweeps of the SA and the frequency spectrum is composed of the maximum amplitudes at each frequency, and
3. The spectrum can be measured during several sweeps of the SA and the frequency spectrum is composed of the averaged amplitudes at each frequency.

2.3 METHOD 1

For proper use of a SA it is assumed that during the sweep of the SA across the frequency band, the input signal is continuous and unchanging. However, it is known that a PD process cannot be considered as a continuous, unchanging, signal and in most cases it is characterized by stochastic behavior. Therefore, in an extreme case, the frequency spectrum of the PD process might change after each sweep. However, a stable spectrum is required for further analysis of the PD process and therefore this method is not suitable.

![Figure 6. Example of a frequency spectrum measured at a capacitive coupler of a GIS installation. Dashed line: background spectrum Solid line: background plus PD spectrum](image)

Depending on the frequency spectrum of a particular PD event and the amount and type of random noise pulses (Figure 6) a choice has to be made between methods 2 and 3.

2.4 METHOD 2

This can best be used to detect PD pulses with a low repetition rate, Figure 7(a). The disadvantage of this method is that random noise pulses can strongly influence the measured frequency spectrum of the PD event. Another disadvantage is that nothing can be concluded about the intensity of the detected pulses at peaks in the frequency spectrum.

Therefore, no conclusion is possible whether the detected pulses were from continuous PD pulses or random noise pulses.

2.5 METHOD 3

This method can best be used in situations with a high PD repetition rate, Figure 7(b). Moreover, the method can suppress randomly occurring noise pulses because the measured signals at each frequency are averaged over all $x$ sweeps. Therefore the amplitude of a noise pulse can be reduced to $1/x$ of its original size. Obviously, for the same reason, this method is not suitable to measure PD pulses with a low repetition rate.

It has been shown that using both methods 2 and 3 at least 10 sweeps of 5 s are required to obtain a stable frequency spectrum [19].

The SA measures a frequency spectrum (solid line in Figure 6) which can be composed of signals from PD pulses, large random noise pulses...
and continuous noise, for example from radio transmitters. To make a distinction between noise and PD signals the measured frequency spectrum can be compared to a frequency spectrum without PD signals (dashed line in Figure 6). In particular this method can be used in a laboratory with a test setup. As an example, see Figure 8. First the background noise level was measured, see Figure 8(a). Then voltage was applied to the GIS test setup with a protrusion fixed on the conductor. The resulting frequency spectrum is shown in Figure 8(b). Visual comparison of both spectra shows no clear difference and therefore it was not possible to select measuring frequencies for a VHF/UHF PD measurement based on these spectra. Therefore, the difference between both spectra was processed, resulting in the frequency spectrum shown in Figure 8(a).

For further analysis of the processed frequency spectrum of Figure 8(a), a frequency scan (FS) can be made. During a FS the SA operates in the zero span mode. In the case of Figure 9(a) five measuring frequencies are further analyzed. During measuring time $T$ the SA is tuned to each selected measuring frequency. At each frequency the maximum PD magnitude is obtained during $t$, see Figure 9(b).

To determine the most sensitive and suitable measuring frequencies for a narrow-band VHF/UHF PD measurement, the obtained PD pulses are processed and shown as a point-on-wave (POW). Therefore analysis of the changes in the measured POW for different measuring frequencies can give more information about the frequency behavior of the fault and measuring setup, see Figure 9(c). Although the PD event has the highest amplitude in the frequency spectrum and frequency scan at frequency $f_1$, the POW in Figure 9(c) shows that this frequency also is strongly sub-

![Figure 7. Frequency spectra obtained 10 sweeps of 5 s using (a) hold maximum amplitudes and (b) averaging of a free moving particle of 10 mm in the GIS enclosure. The applied voltage was 260 kV and the gas pressure was 420 kPa.](image1)

![Figure 8. Frequency spectrum analysis to select measuring frequencies for narrow band VHF/UHF PD detection. (a) Background noise spectrum, (b) spectrum with protrusion on the conductor.](image2)

From the measured frequency spectrum and the frequency scan, a frequency well above the noise level can be selected for a narrow band VHF/UHF PD measurement. For further analysis of the signals at this selected measuring frequency, a SA can be used to demodulate the signals into narrower range.

The center frequency $f_c$ of the SA is set to the selected frequency; the measured span is set to zero: the zero span mode of the SA, and the sweep time is set to 20 ms to obtain phase-resolved patterns related to the 50 Hz power cycle.

In zero span mode the measured frequency band is determined by the resolution bandwidth (RBW). In fact, the VHF/UHF signals are passed to a bandpass filter with a bandwidth equal to the RBW and the frequencies between $f_c - 0.5b_w$ and $f_c + 0.5b_w$ are further processed. Therefore, the SA can be seen as a bandpass filter with a tunable center frequency $f_c$. In this study an RBW $b_w = 5$ MHz was used.

### 2.6 WIDE BAND UHF PARTIAL DISCHARGE DETECTION

The wide band UHF detection circuit is composed of a capacitive disc coupler, a signal conditioning unit (SCU) controlled by a PC and a modified PD detector (TE-571). A capacitive coupler was used to pick up the
Figure 9. Analysis of a measured frequency spectrum: (a) from the frequency spectrum 5 different measuring frequencies were selected; (b) at these measuring frequencies the maximum PD level was measured for $t$ (a frequency scan) and (c) the phase-resolved patterns can be further analyzed; in this case $H_{q_{\text{maZ}}} (\phi)$ distribution of the maximum values of discharges. Electromagnetic (EM) waves. The SCU measures the signals between 500 and 1500 MHz, see Figure 6. The envelope of the measured UHF signals is passed to a peak-detect circuit. Although the maximum value of these signals depends on the frequency characteristics of the GIS and the coupler, it is taken as indication for the PD magnitude. The data can be transferred between the SCU and a PC. The same signals from the SCU can also be used as input signals for the PD detector. Using this configuration, the digital tools used to analyze PD patterns can be used also for PD patterns detected with the wide band UHF system.

3 PD DISCRIMINATION TOOLS

It is known that a strong relationship exists between the shape of phase-resolved PD patterns and the originating discharge source (type of defect) [18]. Each discharge source with its geometry, location, dielectric properties and applied field, is characterized by a specific sequence of PD. Analysis of these sequences is thus a good means of discrimination between different discharge sources. The PD pulses are grouped with respect to their intensity and their phase-angle. Different phase-resolved PD distributions or patterns can be processed, e.g.: the maximum pulse height $H_{q_{\text{maZ}}} (\phi)$; the mean pulse height $H_m (\phi)$; and the pulse count $H_n (\phi)$.

After a PD measurement has been finished, 29 statistical operators are processed to describe the properties of the PD measurement: a 'fingerprint' [23]. When several fingerprints are available, it is possible to develop a collection containing user specific data: the PD data bank. In this way an unknown discharge measurement can be compared to a collection of known situations, represented by their fingerprints. A data bank is judged to be well designed if it produces a high similarity for the correct defect and low or nil for all the others. If no recognition is possible, the result should be low for all defects.

Of course, the result of such a recognition process strongly depends on the test conditions at which the reference data are obtained, the number of measurements used to represent a defect and on the way the data bank is organized.

Figure 10. Example of cluster analysis of fingerprints using the tree method as obtained from different defects. 1: Electrically floating part; 2: Free moving particles.

For this purpose, several discrimination techniques can be used [23]. The main goal of all these methods is the recognition of clusters within the group of measurements without a priori knowledge. This means that no indication of the membership of an individual measurement to a particular cluster is present beforehand. To analyze the measurements discussed in this report, the group average analysis technique was used [23]. The result of the analysis is a tree structure, which illustrates the relationships between individual fingerprints, Figure 10. The percentage scale in the lower part of this Figure shows the dissimilarity between fingerprints that were fused together. In the example shown in Figure 10, the last two groups were measurements of an electrically floating part, each fingerprint indicated by A, and measurements of free moving particles, each fingerprint indicated by B. It follows that similar fingerprints will be connected at relatively low dissimilarity levels (e.g. all A levels in Figure 10), while different fingerprints will be connected at relatively high dissimilarity levels (1 and 2 in Figure 10). By cutting such a tree structure at a certain level, the data can be divided into different clusters.

Three-dimensional pictures can also be analyzed with fractal features [22]. The fractal method processes two parameters. The fractal dimension corresponds to the roughness of the surface. A smooth surface has a low fractal dimension. A flat surface has the lower limit 2, and a very rough surface has a high fractal dimension with upper limit 3.

The lacunarity corresponds to the density of the surface. An empty surface has a low lacunarity (lower limit 0), a dense surface has a high lacunarity (upper limit 1).

Figure 11 shows the fractal method applied to the same defects as in Figure 10. Again, two different clusters with similar 3 D-patterns are formed.

4 STUDIED FAULTS

In this paper the following faults are studied. Besides the protrusion on the enclosure which was only studied in the 245 kV GIS setup, all faults were studied in both GIS setups.
A metallic protrusion was fixed to the conductor, resulting in a long sharp point protruding into the gas of 10 mm length and 0.5 mm in diameter, see Figure 12.

A free moving particle in the GIS enclosure can stick to an insulator if the insulator is not perfectly clean. After some time of voltage application the particle can produce PD and even initiate flash over. To simulate this situation, a metallic particle was located on the insulator of 10 mm length and a diameter of 0.2 mm, see Figure 14.

A protrusion of 15 mm long and 0.4 mm in diameter was fixed to the enclosure at the same location where the free moving particle was located as shown in Figure 13.

To compare the PD patterns, as measured using an IEC 270 detection circuit and a VHF/UHF detection circuit in a GIS setup, a protrusion on the conductor was used. Figure 15 shows the frequency spectrum that was produced by a protrusion on the conductor present in the 245 kV setup. In this particular case the applied test voltage was 172 kV. In this Section three groups of measurements are compared: IEC 270, narrow band VHF/UHF and wide band UHF measurements. Within the frame of this study measurements at several VHF and UHF measuring frequencies have been performed, at different voltage levels and in both GIS setups. From frequency spectra and frequency scans several measuring frequencies were selected: in the case of the 245 kV setup 170, 294, 460 and 617 MHz and in the case of the 420 kV setup 361, 829 MHz and 1.2232 GHz. Concerning the 245 kV setup voltage levels of 128, 172 and 216 kV were applied and concerning the 420 kV setup the voltage levels were 110, 140 and 160 kV.
Figure 16. Phase-resolved distributions from a protrusion on the conductor as measured using three different measuring systems: IEC 270, VHF and UHF narrowband. The PD magnitudes are not calibrated.

Descriptions:

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Figure 17. Statistical analysis applied to a fingerprint of a PD pattern of a protrusion on the conductor measured with the UHF detection circuit.

Comparison of the measurements was performed in two steps, comparison of IEC 270 vs. narrow band VHF /UHF detection and comparison of narrow band VHF /UHF vs. wide band UHF detection.

Unfortunately it was not possible to use the different detection circuits simultaneously, but all measurements were done under exactly the same measuring conditions. Typical patterns as measured with the IEC 270 system, VHF and UHF narrowband system are gathered in Figure 16. Due to the fact that a subjective judgment was not possible on the base of visual interpretation of the measurements, numerical discrimination was applied, see Figure 17.

Figure 18. Phase-resolved distributions from a protrusion on the conductor as measured using narrow band and wide band UHF PD detection. The PD magnitudes are not calibrated.

Descriptions:

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Figure 19. Statistical analysis applied to a fingerprint of a PD pattern of a protrusion on the conductor measured with the narrow band UHF method.

For comparison of the narrow band and wide band UHF detection system, a protrusion was fixed on the conductor of the 420 kV GIS setup. Typical measuring results as obtained with both narrow and wide band systems are shown in Figure 18. As can be seen, the measurement obtained with a wide band UHF system has several peaks in the $H_{q\max}(\phi)$ and $H_{an}(\phi)$ distributions. However, these signals disappear in the intensity distribution $H_{an}(\phi)$. Therefore it can be concluded that these signals are single disturbances. Although the wide band system is more sensitive for disturbances, it can be concluded that, leaving these disturbances out of consideration, there are no significant differences between the measuring results. To check this conclusion, statistical analysis was applied for further analysis of the PD patterns [7-9]. Statistical recognition confirms the small differences between narrow band VHF, narrow band UHF and IEC 270 measurements, see Figure 17, and between narrow and wide band UHF, see Figure 19. Figure 17 show the result of statistical comparison of a narrow band VHF PD measurement and a PD data bank that consists of narrow band VHF, narrow band UHF and IEC 270 PD measurements. As a result the VHF PD measurement is recognized for 100% as a VHF, a UHF and an IEC 270 PD measurement. These experimental results show that in this particular case no differences between the PD patterns as measured with the three different systems can be concluded. To generalize this conclusion, more careful investigation is necessary.

6 INFLUENCE OF THE COUPLER LOCATION ON THE FREQUENCY SPECTRA AND THE PD PATTERNS

6.1 INFLUENCE ON THE MEASURABLE FREQUENCY SPECTRA

Using a free moving particle as shown in Figure 13, the influence of the coupler location on the frequency spectra was studied.

The frequency spectra from a free moving particle shown in Figure 20 are spectra measured at three different coupler locations as indicated in Figure 4. To obtain the frequency spectra, the data measured during 10 sweeps of 5 s were averaged. It follows from Figure 20 that the frequency spectrum measured at coupler S2 shows no spectral content between 900 and 1100 MHz; no explanation can be given for the fact that coupler S2 shows a different behavior in this frequency range compared to S1 and S3. Moreover, for the mean value of the frequency spectra measured at different coupler locations it can be concluded that the mean value of S1 > S2 > S3. However, the differences are very small so that it is not possible to draw any specific conclusions regarding the influence on the measured frequency responses of the location of the capacitive coupler or the number of insulators between the fault and the coupler.

To obtain the frequency scan (FS), the same free moving particle in the test vessel was used as injection source. In particular FS was measured at three different coupler locations, see Figure 21, which shows the PD magnitude (not calibrated) as function of different frequencies. From the results of the FS can be concluded that in general the highest PD signals are measured at coupler location S1, that different couplers show peaks at different resonance frequencies, that in the frequency range
from 1200 to 1400 MHz, an overlap in the frequency scans of all three couplers is observed, and that the insulators between the PD source and the different couplers attenuate the electromagnetic waves, especially at the lower frequencies.

6.2 Influence of the Coupler Location on the Shape of the PD Patterns

Using a protrusion on the conductor as shown in Figure 12, the influence of the coupler location on the shape of the PD patterns was studied. It has been shown by frequency spectra and frequency scans that insulators introduce signal reduction. Furthermore, the signal reduction depends on the frequency: lower frequencies are more subjected to signal reduction than higher frequencies. To compare the influence of the coupler location on the shape of phase-resolved patterns PD measurements were done at the three different coupler locations using the VHF/UHF narrow band system, see Figure 5. An overview of the GIS components between the defect and the capacitive coupler used for UHF PD detection is given in Table 1. As an example PD measurements as obtained at a measuring frequency in both VHF and UHF ranges are shown in Figure 22.

From visual comparison no differences in the phase-resolved patterns measured in the VHF range can be concluded. In the UHF range, the PD patterns measured at S1 differ from the PD patterns measured at S2 and S3. Due to the fact that S1 is located inside the test vessel, no signal reduction between the defect and the coupler is introduced.

Therefore, a higher measuring sensitivity can be obtained at coupler location S1 compared to S2 and S3. This explains the possibility to detect...
Descriptions:

Table 2. Signal reduction $R$ (dB) between couplers $S_1$ and $S_2$ resp. $S_3$.

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<tr>
<td>S2</td>
<td>0.4</td>
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<td>S3</td>
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Figure 23. Statistical recognition applied to a fingerprint of a PD pattern measured at coupler $S_1$ and a measuring frequency in the VHF range.

Figure 24. Phase-resolved distributions of four typical defects in GIS: (a) to (d) protrusion on the conductor, (e) a free moving particle, (f) a particle fixed to an insulator, and (g) a protrusion on the enclosure. The PD magnitudes are not calibrated.

7 ANALYSIS OF PD PATTERNS

It has been shown in the previous Sections that the PD patterns obtained from measurements using three different detection systems and different test voltages show no differences for a particular fault. As a result it is possible to define a typical phase-resolved PD pattern for each single fault which is independent of the PD detection system used and of other parameters such as measuring frequency. The PD patterns as measured from the four studied faults are compared and cluster analysis is applied to investigate the possibility to discriminate between different faults.

7.1 VISUAL ANALYSIS

Figure 24 shows examples of PD measurements with typical phase-resolved PD patterns of the four studied defects. In Figure 24(a) to (d)
Table 3. Overview of the membership of a specific PD measurement to one of the three (visually formed) groups.

<table>
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<td></td>
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<td></td>
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been the reason for the three different groups.

Table 3 indicates the relation of the test voltage, the measuring frequency and the percentage of PD measurements that are part of one of the indicated groups. The Table shows that the membership of a PD measurement to one of the three groups is independent on the applied test voltage. The PD measurements in group 4 were measured using a protrusion on the HV conductor of the 420 kV GIS setup. Therefore it can be concluded that the four PD patterns as shown in Figure 24(a) to (d) are typical PD patterns for a protrusion on the HV conductor.

Figure 25. Typical phase-resolved distributions for the four studied faults: a protrusion on the conductor, a free moving particle, a protrusion on the enclosure and a particle fixed to an insulator. Protrusion on conductor — — —, free moving particle . . . , protrusion on enclosure . . .

Typical phase-resolved PD patterns of the three other studied faults are shown in Figure 24(e) to (g). Visual comparison of all PD patterns results in the following.

The phase-resolved distributions of a protrusion on the conductor show four different typical patterns where the PD are concentrated mainly around the positive peak and differences in the number of PD can be found around the negative peak or the PD are concentrated mainly around the negative peak. The phase-resolved distributions of a protrusion on the enclosure and a particle fixed to an insulator are similar and the PD distributions are concentrated around the negative top of the applied test voltage, while the phase-resolved patterns of a free moving particle are very typical: the patterns follow the sine wave of the applied test voltage. Figure 25 summarizes these observations.

From visual comparison of PD patterns it is possible to recognize a free moving particle and a protrusion on the conductor. However, it is not possible to distinguish between a protrusion on the enclosure and a particle fixed to an insulator. To study the possibility to use computer-based discrimination tools two methods have been applied to the PD measurements: fractal analysis and the tree method.

7.2 FRACTAL ANALYSIS

The result from the fractal analysis [29] is shown in Figure 26. Fractal analysis shows that two clusters can be formed: A and B. From analysis of both clusters it is found that cluster A contains only PD measurements as obtained from a free moving particle. As explained before, the PD patterns of a free moving particle are very typical whilst patterns of the other three faults show some overlapping parts. The second cluster consists of measurements of a protrusion on the conductor (marker 1), a particle fixed to an insulator (marker 3) and a protrusion on the enclosure (marker 4). Because fractal analysis analyzes the surface of the 3D distributions, it is not sensitive to asymmetry in the patterns. As can be observed in Figure 24, the only difference between a protrusion on the conductor on one side and a protrusion on the enclosure and a particle fixed to an insulator on the other side is the asymmetry in the PD patterns. Therefore, these three faults are clustered in one and the same cluster.
Table 4. Comparison of both discrimination tools to discriminate between the four studied faults.

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<td>Free part.</td>
<td>-</td>
<td>fractal/tree</td>
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<td>Part. sp.</td>
<td>tree</td>
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<td>Prot. enc.</td>
<td>tree</td>
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7.3 TREE ANALYSIS

The result from the tree analysis [18] is shown in Figure 27. With the tree method five different clusters can be observed. Although the phase-resolved PD patterns of a particle fixed to an insulator (A) and a protrusion on the enclosure (C) show similarities (see Figure 24) both faults can be discriminated using the tree method.

Cluster 3 combines measurements of a free moving particle (B) and group 5 of a protrusion on the conductor (F). Cluster 4 consists of measurements of group 4 of a protrusion on the conductor. Cluster 5 combines measurements of group 1 and 2 of a protrusion on the conductor.

7.4 COMPARISON OF FRACTAL AND TREE ANALYSIS

Within each cluster no influence of different parameters such as the GIS components where the PD signals propagate, such as insulators and T-junctions, different signal reductions were observed. However, no changes in the shape of PD patterns were observed.

This study shows that both discrimination methods, the tree method and fractal analysis, are complementary. In the case that one of the methods fails, the other one can be used for discrimination. For example, no discrimination is possible between a protrusion on the conductor and a particle fixed to an insulator using fractal analysis. Using the tree method, a clear distinction between these faults is shown.

Of course, to generalize these conclusions, more systematic and careful investigations and convincing demonstrations are necessary.

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REFERENCES


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