Fundamental Aspects of PD Patterns of On-line Measurements on Turbogenerators

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ABSTRACT

This paper discusses partial discharge (PD) measurements performed on turbogenerators using the VHF PD detection technique. With this technique it is possible to perform PD measurements on turbogenerators without interruption of their operation. In addition to PD in any particular phase, the recorded patterns can show crosstalk from other phases and disturbances. The membership of each signal source (phase's own PD pattern, crosstalk, disturbances) to the recorded pattern depends on the selected center frequency. By examination of some typical examples, the relationship between the center frequency and recorded patterns is discussed. Furthermore, PD measurements performed over time on the same generator are studied to discuss possible changes in the spectral responses of particular phases of a turbogenerator. By visual comparison of PD patterns as well as computer-based discrimination tools it was found that several center frequencies are suitable to tune the VHF PD detection technique. However, these center frequencies can change in the course of time for a particular phase of a turbogenerator. As a result, in order to avoid a misjudgment on the insulation condition of turbogenerators, the analysis of on-line recorded PD should not be restricted to just one single center frequency.

1 INTRODUCTION

To obtain good insight into the condition of the stator insulation of a generator, PD measurements offer a good opportunity [6, 8]. For this purpose the PD measurement can be performed in two ways.

1. During periodic revision of the generator using IEC 270 measuring circuit and applying external voltage to particular short-circuited coils/phases [1]. By periodically performing this off-line test (2 to 5 yr) a quite good impression can be obtained about the trend of the PD levels for particular phases. To analyze PD patterns, additional information of the pulse-phase as well as the pulse-intensity can be used. Comparison of different tests in time of the same generator can provide a identification of new discharge sources. Off-line PD measurement has been in use for many years. However, three main disadvantages can be found regarding this type of discharge measurements.

During off-line tests, the thermal and mechanical stresses in the stator insulation are not the same as during operation. As a result, an off-line PD measurement does not show the PD processes of the generator which it has in service.

The costs of such off-line tests (removing the unit from service, providing of an external HV source *etc.*) are quite high.

The performance of off-line PD tests in time intervals of 2 to 5 yr does not give any information about the changes of PD activity in the period between these tests.

2. During regular operation of a generator using capacitive or inductive couplers, the PD signals are measured by a scope or a specially adopted PD detector. When the PD couplers (at least one on each phase) are permanently installed on the generator, an on-line test can be performed [2–5]. This type of measurement is very easy without any interruption of the generator operation. Moreover, such a PD measurement is performed on a object under regular thermal and mechanical stresses for operation. On-line PD tests have become very popular in the last few years.

Two difficulties arise when such PD measurements have to be performed. From the power plant as well as from the rotor excitation, system interference may occur in the measuring circuit [7, 8]. Due to the fact that all three phases are energized at the same time, complex propagation processes occur of PD signals through the stator winding, resulting in reflections, attenuation and crosstalk [7, 8, 14].

Different methods can be applied to suppress external noise [19, 27]. Moreover, extensive studies in the past have shown that certain relationships exists between PD pattern sequences and measuring frequency [29–33].

In this study, a spectrum analyzer (SA) is used as tuned filter to suppress external noise [8]. For this purpose, the SA can be tuned between *e.g.* 10 and 100 MHz to a frequency where PD from the stator insulation is dominating and the level of PD signals at this frequency can be demodulated to ~250 kHz and displayed on a 50 or 60 Hz time basis.

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As a result, such a signal can be processed further by a conventional PD detector or PD analyzer with the main goal to use the wide experience on phase-resolved PD pattern recognition [9–14].

The main goal of this study is the analysis of the above mentioned problems 1 and 2. In particular, on the base of a series of tests in power plants, the following aspects have to be researched and discussed.

What is the influence of the selected resonance frequency of the SA on the measured PD patterns, and how should crosstalk effects in the PD patterns of single phases be handled and analyzed?

What is the most efficient way to compare the PD patterns measured on particular phases of a generator, or measured at different times during service life on the same generator, or else measured for known failures (slot PD, end winding PD)?

In this paper, the first experiments from on-line tests on turbogenerators are presented. In particular, the evaluation of PD measurements at different frequencies are discussed in scope of the above mentioned aspects.

2 THE VHF PD DETECTION TECHNIQUE

The discussion presented in this report is based on PD measurements using the measuring setup depicted in Figure 1. The circuit used for on-line measurements is composed of high frequency (HF) capacitive/inductive discharge-free couplers, a SA to measure the signal response at frequencies of 30 MHz and to demodulate it to 250 kHz, and a modified PD detector to display and record the measured PD signals.

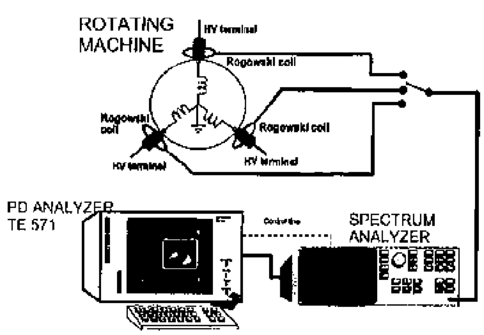

Figure 1. Measuring setup as used for VHF PD measurements on turbogenerators. The setup is composed of rotating machine in operation, high frequency discharge-free couplers, *e.g.* Rogowski coils, spectrum analyzer and digital PD detector.

The on-line measurement technique is denoted as the VHF PD detection technique, because the technique is based on measuring PD responses in the VHF range. In this Section this technique, as well as the components of the circuit, will be discussed.

2.1 COUPLERS

To measure PD during operation of generators, different methods can be utilized. Several types of couplers can be used: capacitive couplers [4], Rogowski coils [2, 4], stator slot couplers [3], and current transformers [16].

The PD measurements evaluated in this report are all performed with capacitive couplers and Rogowski coils around the HV bushings. Due to the fact that the scope of this study is the PD pattern behavior, and that the applied sensors have been developed by the authors of [4], no discussion of the sensor electrical properties will be given in this paper.

2.2 ON-LINE VHF TUNING

When a PD measurement is performed at a generator in regular operation, the signal at the terminals of the couplers is a mixture of various sources, divided in three main groups. First, the PD activity originating from the measured phase, denoted as the phase's own PD activity/pattern; second the PD activity originating from the other phases. PD signals are high frequency signals and travel by complex propagation through the stator windings. Therefore, PD signals originating from one particular phase can be revealed at a coupler connected to another phase, an effect called crosstalk [7, 8]. Third, in a power plant (the generator's natural environment) many sources of electromagnetic (EM) disturbance and noise are present, that are picked up by the couplers. One particular disturbance originating from the generator itself is the rotor excitation [7, 14].

Crosstalk patterns can be distinguished from the phase's own PD pattern by their appearance on the phase position. All measurements presented in this report are performed with the frequency of phase U as reference. With the fact that the two other phases are shifted 120 and 240° with respect to phase U, Figure 2 shows the positions of the patterns of the phases on a 20 ms base.

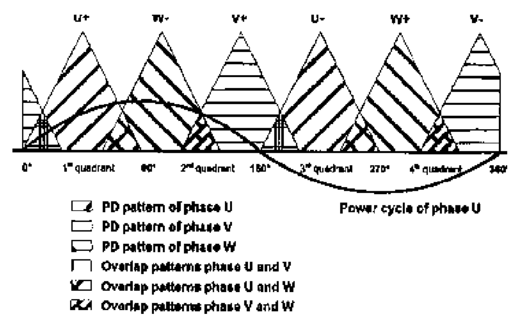

Figure 2. The positions of the single phase patterns on the 50/60 Hz power frequency of phase U.

The classic PD detection circuit as used for off-line PD measurements operates according to IEC 270 recommendation in a frequency range to 500 kHz [1]. If this type of detection would be used at a generator in operation, the result would be the sum of all signal sources at the detector side and no distinction between these various sources would be possible. Therefore, research has led to discrimination between these various sources based on their frequency characteristics in the MHz range (PD analysis on gas insulated systems even goes to ~1 GHz [25]). As a result, detection circuits have been developed that operate in the VHF/UHF range.

From the literature it is known that the spectral contents of PD activity can be used for two purposes.

PD activity can be distinguished from other signal sources, based on the spectral response. In Figure 3 a literature example is shown of

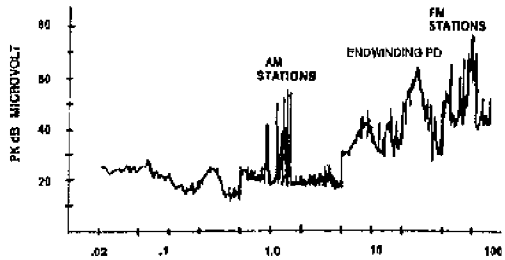

Figure 3. Example of a spectrum of a 4 kV motor. The spectrum indicates a clear distinction between end-winding PD and signals from broadcasting stations [15].

the spectrum of a 4 kV machine, where end-winding PD can be distinguished from broadcasting station signals [15].

When defects arise in the insulating system, the spectral response will change. Figure 4 shows an example of spectral measurements on a stator bar with and without defect [23].

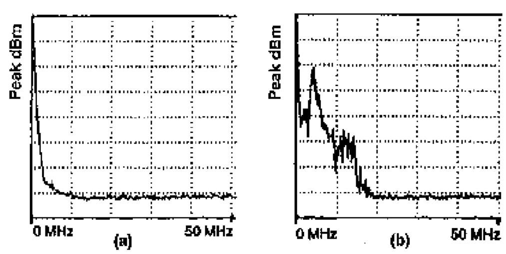

Figure 4. Example of spectral measurements on a stator bar [23]: (a) spectral response of a good bar, (b) spectral response of bar with slot discharges.

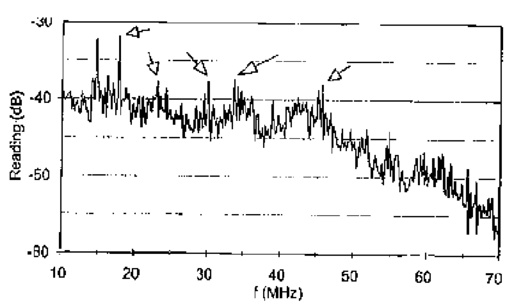

Figure 5. Example of a frequency spectrum obtained with the SA, recorded on phase U of a new turbogenerator. The arrows correspond to frequencies at which a high response is measured.

For the purpose of recording, the frequency spectrum of a particular phase, a Tektronix SA is connected to the couplers. The SA is an advanced instrument designed for spectral analysis. For the on-line measurements presented in this report two function modes of the SA are used, the specific frequency span and the zero span mode.

In the specific frequency span mode, the SA measures the frequency spectrum of the signal detected by the sensors. The upper limit of the frequency range is determined by the characteristics of the couplers and thus in this particular case does not exceed 100 MHz for the cases discussed in this paper. In Figure 5 an example of a specific frequency spectrum as obtained with the SA is shown.

In this example a number of peaks at certain frequencies are marked by the arrows. These peaks indicate that at these frequencies the measured response is above the noise level. At this stage there is no conclusion about the source of the response (phase's own PD, crosstalk or disturbances). For this purpose, the zero span mode of the SA must be used.

In the zero span mode, the SA is tuned to a selected frequency (preferably a frequency with a high response), which means that the SA acts as a bandpass filter of 300 kHz with the selected frequency as center frequency, denoted as f_0. After the SA is tuned, it is switched to the zero span mode with a time base of 20 ms (for 50 Hz). This is the demodulation function of the SA, a demodulation to ~200 kHz. In this way, signals containing the selected resonance frequency can be recorded by a PD detector, directly connected to the SA.

In addition to these two operating modes, a third mode can be utilized by a combination of the SA and the PD detector. This mode, denoted as the 'frequency scan' mode, is discussed in Section 2.3.1.

2.3 VHF PD PATTERN ANALYZER

All PD measurements discussed in this paper are obtained with the digital PD detector TE571 of Haefely Trench [10, 18]. The TE571 detector records the measured PD signals with respect to the 50/60 Hz sine wave of the applied voltage and stores the measurement for further analysis (Section 2.5). It is known that there exists a strong relationship between the shape of the measured PD patterns that occur in the 50/60 Hz sine wave and the type of defect that is causing them [12, 18]. In the case of generators this means that patterns measured at a phase in good condition differ from those measured at phases in bad condition. Moreover, patterns caused by slot discharges differ from those originating from end winding discharges [13, 19]. Analysis of these patterns is thus a good means of discrimination between different discharge sources as well as quality levels of the insulation. The following distributions are digitally processed in order to characterize the properties of a PD measurement: the maximum pulse height $H^{\pm}_{qMax}(\varphi)$, the mean pulse height $H^{\pm}_{qn}(\varphi)$, the pulse count $H^{\pm}_{n}(\varphi)$ and the discharge intensity $H(q)$, see Figure 6.

Using a IEC 270 measuring system, these quantities are processed for a fixed frequency range as defined by a PD detector. The use of a tunable SA allows processing of these quantities at different center frequencies. To observe the behavior of these quantities as a function of the center frequency, the frequency scan and the spectral response matrix are introduced.

2.3.1 FREQUENCY SCAN

The complex propagation of the PD pulses through the windings strongly influences the frequency characteristics of the PD signal as they appear at the coupler site. As a result there is need for a study on the influence of the center frequency on the measurement of PD patterns. For this purpose the frequency scan (FS) procedure of PD patterns was introduced.

During a FS the SA operates in zero span mode. Preceding a measurement, several (N) center frequencies are selected. This selection might result from a previous measured frequency spectrum by the SA, or can be a fixed step series of frequencies (*i.e.* 10, 12, 14 MHz . . .). The

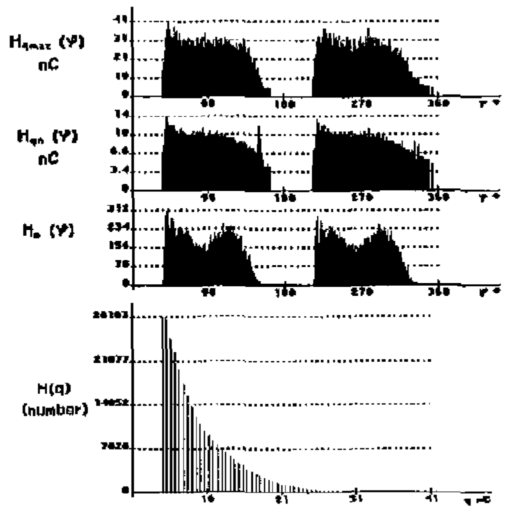

Figure 6. Example of phase resolved distributions (upper) and discharge intensity distribution (lower) as recorded off-line with the digital PD detector TE571.

SA is tuned to the first selected f_0, is set to the zero span mode and the TE571 detector records the PD patterns until $1/N$ of the total measuring time has elapsed. Then the SA is tuned to the next selected center frequency and the process continues until the total measuring time has elapsed. By this method, patterns are obtained at each selected center frequency.

Analysis of the changes in these patterns for the selected center frequencies can give more information about the frequency behavior of the sensor response to PD activity, crosstalk and disturbances. In particular, the technique is a useful means for finding a proper center frequency in order to obtain PD patterns which are not distorted by surrounding disturbances. It also allows study of the spectral response of the phase's own PD activity as well as crosstalk, and helps in finding trends in the frequency response measured at a particular coupler by comparison of FS recorded at different times during service life. Such trends might indicate the development of defects in the insulation system.

Figure 7 depicts a frequency scan recorded at one phase of a turbogenerator (PD patterns at five frequencies are displayed). This example clearly shows the differences in the PD patterns measured at different f_0. The pattern measured at 18 MHz shows the phase's own PD activity. With a center frequency of 30 MHz crosstalk from phase V is measured. At 48 MHz no response is measured. An equal level of the phase's own PD activity and crosstalk from both phases is measured at 62 MHz, while at 64 MHz crosstalk from phase V dominates the pattern.

2.3.2 SPECTRAL RESPONSE MATRIX

To find the most suitable and sensitive center frequency to measure the phase's own PD response, a procedure denoted as spectral response matrix (SRM) is introduced. For this purpose, the highest response and its origin (the phase's own PD, crosstalk PD from each other phase, and disturbance) measured in the patterns at all N center frequencies is determined and is assigned as 100%. Subsequently, a percentage ratio of the four types of signal sources at each frequency is determined and all

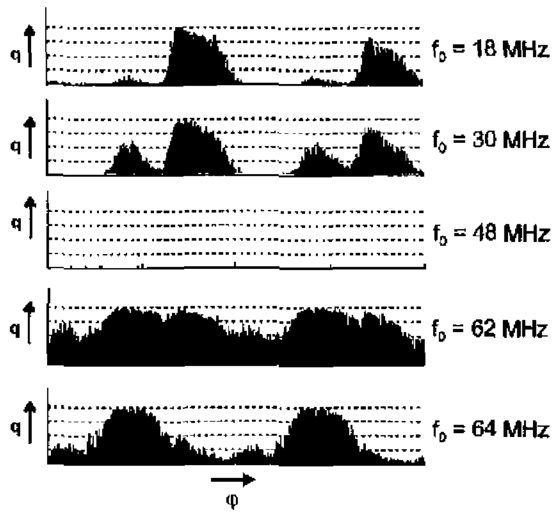

Figure 7. Example of a frequency scan measured at phase W of a new turbogenerator (only patterns at 5 of the 30 frequencies are depicted).

Table 1. SRM of the example in Figure 7, *i.e.* frequency scan at phase W of a large turbogenerator.

f_0 MHz	Phase U	Phase V	Phase W	Dist
18	0.01	0.05	1	0
30	0	0.4	0.8	0
48	0	0	0	0
62	0.4	0.5	0.5	0

are put in a $4{\times}N$ matrix. Thus a SRM is a representation of a FS measured at a particular phase. A SRM can be a useful means to evaluate the spectral responses of the various signal sources at the coupler site. Moreover it can be used to analyze changes in the frequency behavior of these signal sources measured during the service life of a generator. Table 1 shows the SRM of the example in Figure 7.

2.4 STATISTICAL ANALYSIS

After a PD measurement is finished, further analysis of the patterns is required. The TE571 detector is accompanied by the TEAS-D fingerprint technique for analysis and diagnosis of the measured data [20]. Furthermore, a number of stand-alone tools have been developed to make classifications in sets of data, based on clustering.

2.4.1 FINGERPRINT PROCESSING

At the of end of a PD measurement the characteristic shapes of the measured patterns (see previous Section, Figure 6) are quantified by the following statistical operators:

1. the asymmetry as the quotient of the mean level in the + and − phase,
2. the phase factor to study the difference in inception voltage in the + and − phase,
3. the cross-correlation factor to evaluate the difference in shape between + and − phase
4. the number of peaks to discriminate between single top and multiple top distributions,
5. the skewness as an indicator for asymmetry with respect to a normal distribution and

6. the kurtosis as an indicator for the deviation from the normal distribution.

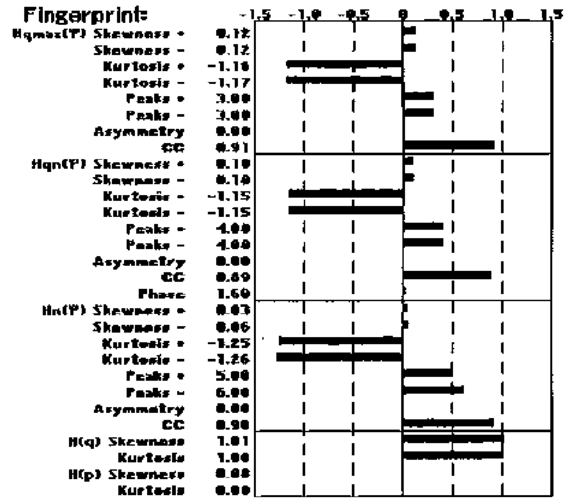

Figure 8. Fingerprint as processed for the measured data of Figure 6. A total of 29 statistical operators is processed to characterize a particular PD measurement.

In total 29 statistical operators are processed. The total set acts as a fingerprint of a certain PD measurement, see Figure 8. Measurements now can be compared with each other by comparison of their fingerprints, using mathematical techniques. A percentage is obtained that reflects the recognition of a particular measurement as a defined discharge type in the PD data bank (Figure 9).

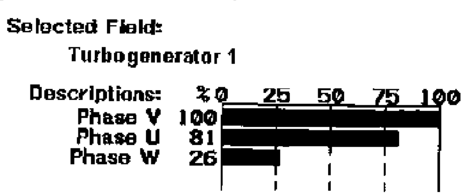

Figure 9. Percentage of recognition of an unknown measurement, compared to a turbogenerator data bank.

2.4.2 PD DATA BANK

With several fingerprints, a collection of user-specific data can be created, the PD data bank [20]. Fingerprints of discharge measurements of unknown type can be compared to the collection of known situations. A data bank is judged to be well designed if it produces a high similarity for the correct defect/situation and low or nil for the others. The recognition process strongly depends on a number of factors, such as the test conditions at which the reference data are obtained, the number of fingerprints that represent a defect and the organization of the data bank. A way of organizing is depicted in Figure 10.

2.4.3 CLUSTER ANALYSIS

As stated, a data bank is well designed for classification purposes if it produces a high similarity for the correct defect and a low one for all the others. Due to the fact that users of PD analyzer TE571 can create their own data bank, they should be trained to create well designed

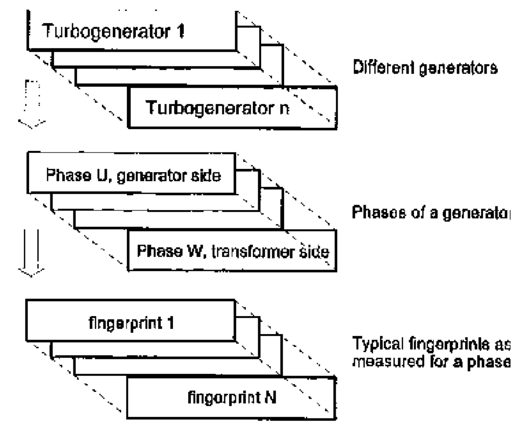

Figure 10. A possible structure of a data bank. In this example, the hierarchical structure starts with a collection of generators, followed by the single phases and ends with PD measurements.

data banks. For this purpose, discrimination techniques can be used [19]. With these techniques recognition of clusters can be performed without *a priori* knowledge of the type of the single measurements. Two techniques are discussed here, the group average analysis technique (Ward's minimum) and the fractal method.

TREE ANALYSIS

To analyze the PD measurements discussed in this report Ward's minimum clustering method is used [20]. With this analysis technique the distances between all fingerprints of a group of PD measurements is examined. The result is a tree structure that illustrates the relationship between individual fingerprints, see Figure 11.

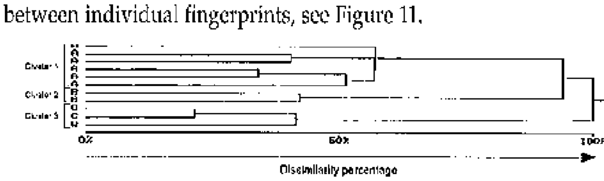

Figure 11. Example of cluster analysis using the tree method, each letter corresponding to measurements from one single phase.

The percentage scale in this Figure represents the dissimilarity between the fingerprints that were fused together. Similar fingerprints connect at a low dissimilarity level, different fingerprints connect at relatively high dissimilarity levels. By cutting such a tree at a certain level, a number of clusters is formed, each cluster consisting of fingerprints of the same defect.

FRACTAL ANALYSIS

In addition to the tree technique, the fractal method is used. It is shown [21, 22] that the 3-dimensional distribution $H_n(\varphi, q)$, see Figure 12, can be analyzed on fractal features. The fractal method processes two operators: fractal dimension, as indicator for the roughness of the surface and lacunarity, as indicator for the density of the surface.

Figure 13 shows the result of fractal analysis represented in a XY-plot. The same numbers correspond to measurements from one single phase. The different clusters are marked with the ellipses.

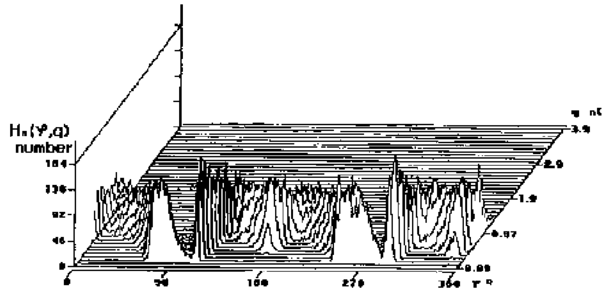

Figure 12. 3-dimensional distribution $H_n(\varphi, q)$. This example shows crosstalk.

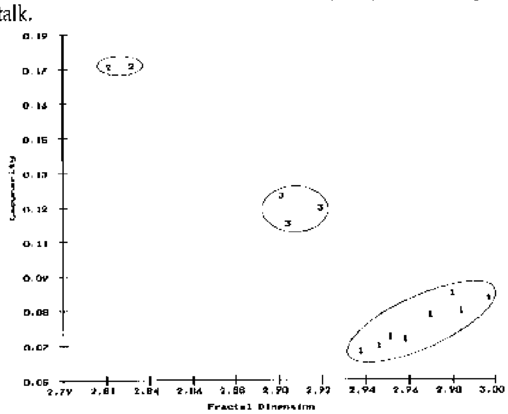

Figure 13. Example of fractal analysis, each letter corresponding to measurements from one single phase.

3 PURPOSE OF PD PATTERN ANALYSIS

3.1 OFF-LINE PD MEASUREMENTS

It is known from the literature that phases of a turbogenerator in good condition can be characterized by PD patterns in the first and third quadrant of the sine wave with a typical sinusoidal shape [12, 23]. The $H_n(\varphi, q)$ distribution depicted in Figure 14 shows the typical shape of an off-line PD measurement on a generator in good condition. Furthermore, knowledge exists on changes in and characteristics of patterns of off-line PD measurements when faults are present in the phases of the generators [12, 13]. As an example, the $H_n(\varphi, q)$ distribution of a PD measurement on a turbogenerator suffering from slot discharges is depicted in Figure 15.

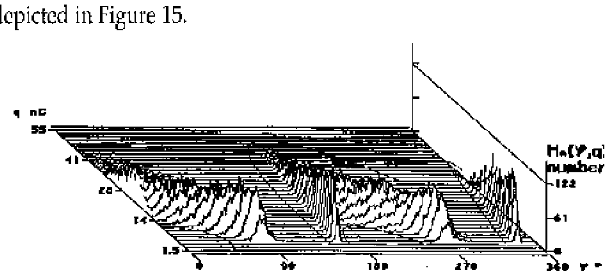

Figure 14. $H_n(\varphi, q)$ distribution of an off-line measurement of a turbogenerator. The characteristic sinusoidal shape is emphasized by the contour lines.

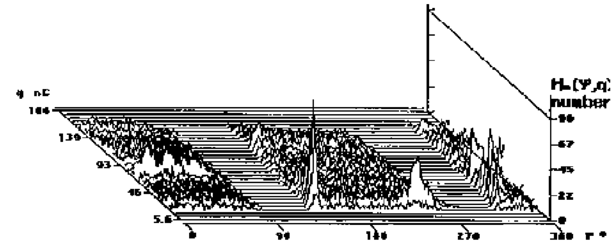

Figure 15. $H_n(\varphi, q)$ distribution of an off-line measurement on a turbogenerator. This pattern is typical for turbogenerators showing slot discharges.

3.2 PROCEDURE FOR ON-LINE PD MEASUREMENTS

The application of the on-line PD measurement technique as discussed in the previous Section, has as purpose to monitor the insulation condition of a generator by using knowledge from off-line PD measurements [28]. In other words, the examination is focused on finding a procedure for on-line measurements to obtain the same characteristic patterns as would be obtained by off-line measurements. However, as was mentioned already in Section 2.2, at on-line measurements several signal sources influence the measured patterns: The phase's own PD activity, PD activity originating from the other phases due to crosstalk, and disturbances inside and outside the generator.

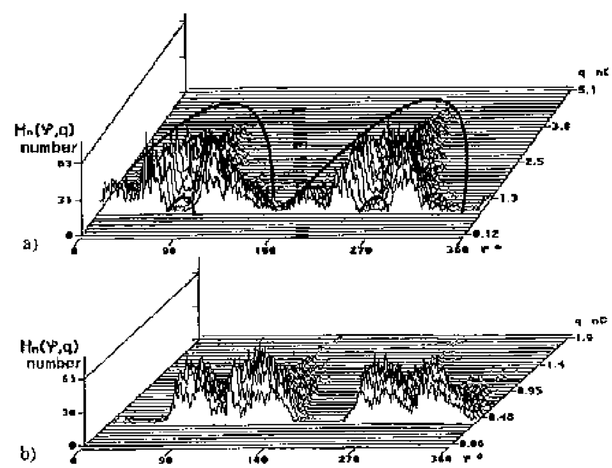

Figure 16. $H_n(\varphi, q)$ distributions of an on-line measurement at phase W of TG2, measured at different f_0. (a) $f_0 = 63.5$ MHz, phase's own PD activity with characteristic sinusoidal shape is recorded. (b) $f_0 = 32.3$ MHz, phase's own PD activity and crosstalk of phase V, both with no inner envelope, is recorded.

In Figure 16 two $H_n(\varphi, q)$ distribution are shown of an on-line VHF PD measurement on a turbogenerator. Figure 16(a) is from a measurement with the SA tuned at 63.5 MHz, Figure 16(b) is from a measurement with the SA tuned at 32.3 MHz. This example clearly indicates the issue of tuning the SA correctly for a useful PD measurement. Therefore, considering the goal of this report as stated in the beginning of this Section, the evaluation of the measurements that will be presented in the next sections are concentrated on the following aspects. What is the influence of f_0 on the measurement of phase's own PD response/pattern? What is the influence of f_0 on the measurement of crosstalk

PD response/pattern? And finally, what is the influence of f_0 on the measurement of disturbances response/pattern?

Visual comparison of patterns as well as statistical analysis will be used for this purpose. Moreover, another aspect will be examined: Does the spectral response measured at the phases of a particular generator change during service life?

Before proceeding towards the evaluation it should be noted that all patterns presented in this paper are obtained with the VHF detection method, a method that lacks a calibration procedure. Thus, all discharge magnitude values that the axes show are uncalibrated.

4 EVALUATION OF VHF PD MEASUREMENTS

To discuss the issues of study as stated in Section 3.2, on-line PD measurements of two large turbogenerators are evaluated, denoted as TG1 (155 MW/15 kV) and TG2 (650 MW/21 kV).

4.1 INFLUENCE OF f_0 ON OWN PHASE PD PATTERN

In the following, using two typical examples, the meaning of the phase's own PD pattern is discussed.

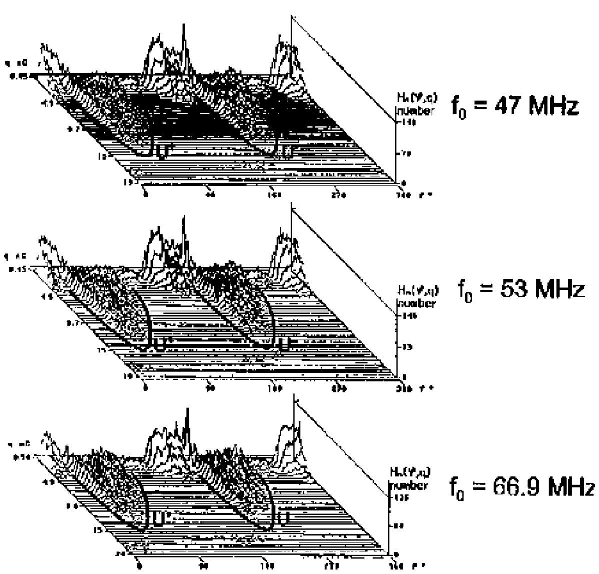

Figure 17. $H_n(\varphi, q)$ distributions of a measurement at phase U of TG1, measured at $f_0 = 47, 53$ and 66.9 MHz. The SA is well tuned.

Figure 17 depicts the $H_n(\varphi, q)$ distributions measured at phase U of TG1 at three different center frequencies, $f_0 = 47, 53$ and 66.9 MHz. The phase's own PD patterns are marked by curved lines. This example shows that measuring at different f_0 can produce equal patterns for the phase's own PD activity.

Another case shown in Figure 18 shows a different picture than the above. These distributions are measured at phase V of TG2. As can be seen from this Figure, the particular phase's own PD pattern is measured at center frequencies 10 and 22 MHz. However, when measuring at $f_0 = 18$ MHz and $f_0 = 44$ MHz the phase's own PD pattern is

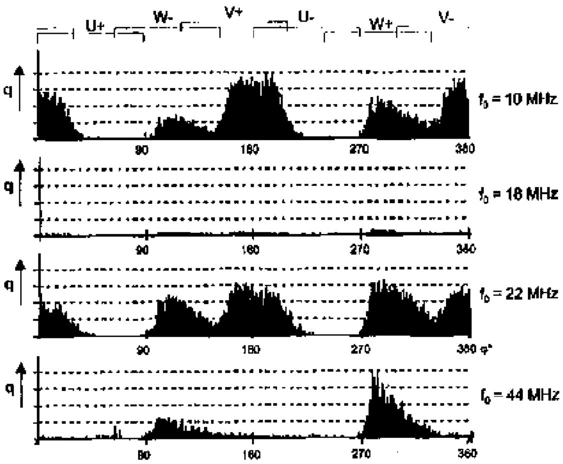

Figure 18. $H_n(\varphi)$ distributions of a measurement at phase V of TG2, measured at $f_0 = 10, 18, 22$ and 44 MHz.

not recorded; the measurement at 18 MHz shows no patterns at all, the measurement at 44 MHz shows a pattern due to crosstalk from phase W. Thus this case indicates that the center frequency can influence the measured PD pattern.

Based on the above the following can be concluded. The measurement of phase's own PD pattern is influenced by the center frequency, and there is more than one center frequency to measure the phase's own PD pattern.

4.2 INFLUENCE OF f_0 ON CROSSTALK PD PATTERN

With the following examples, the influence of the center frequency on the crosstalk PD patterns is discussed.

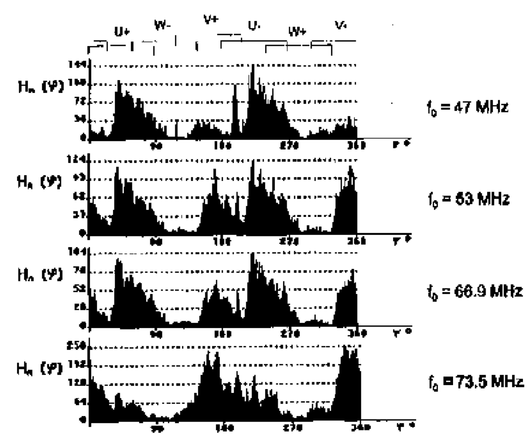

Figure 19. $H_n(\varphi)$ distributions of PD measurement on phase U of TG1 at $f_0 = 47, 53, 66.9$ and 73.5 MHz.

Figure 19 shows the $H_n(\varphi)$ distributions of the measurements discussed in Section 4.1.1 of the previous Section, with an addition of a measurement performed at $f_0 = 73.5$ MHz. The distributions show that, next to the phase's own PD pattern, a crosstalk pattern is recorded at phase V. Furthermore, the Figure shows that the relative intensity of the measured crosstalk patterns increases with increasing center frequency. At 73.5 MHz the crosstalk pattern even dominates over the phase's own pattern.

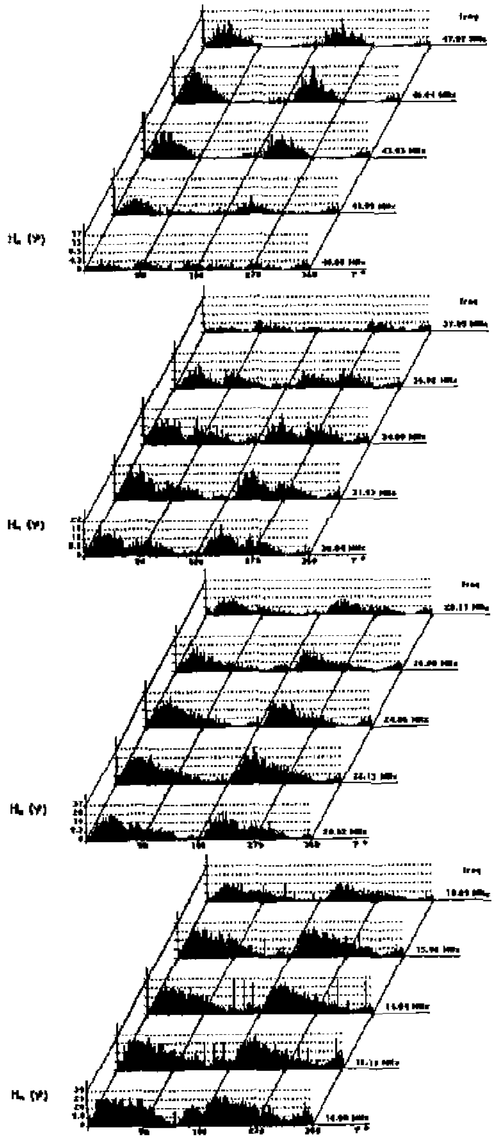

Figure 20. Phase resolved patterns of a measurement at phase U of TG1, at 20 successive center frequencies.

Figure 20 depicts a frequency scan measured at phase U of TG1, in the range from 10 to 48 MHz. To analyze the influence of the center frequency on the amount of of crosstalk in the measured patterns, a modified SRM was calculated. Instead of determining the SRM based on the highest response of all patterns (see Section 2.4), each SRM-line was determined based on the phase's own PD response of the corresponding pattern. By this, the relation between crosstalk pattern and phase's own PD pattern can be evaluated per each center frequency. The procedure to determine such a modified SRM is as follows. First, determine the maximum phase's own PD response measured at the first center frequency of the range. Then, determine the percentage ratio of maximum crosstalk and disturbance response compared to the maximum phase's own PD response, and finally repeat the procedure for the patterns at all center frequencies.

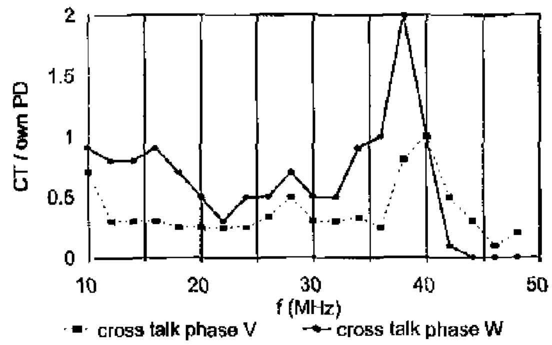

Figure 21. Graphical interpretation of the SRM data regarding crosstalk.

Figure 21 depicts the modified SRM for the crosstalk memberships in graphical form. From the Figure it can be concluded that the membership of crosstalk in the measured patterns strongly depends on the center frequency, and the membership of crosstalk in the measured patterns differs for each phase. ⩽40 MHz the recorded crosstalk of phase W is roughly twice as high as the measured crosstalk of phase V, while >40 MHz little to no crosstalk from phase W is measured.

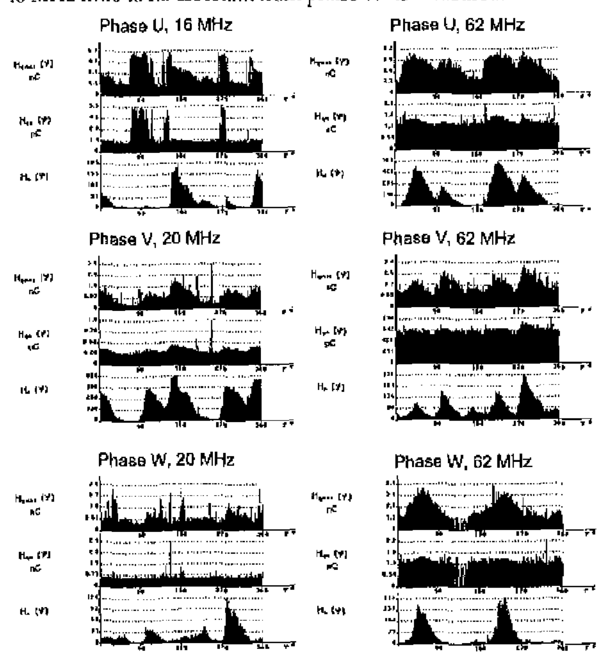

Figure 22. Phase resolved patterns of a measurement on TG2.

Another case that shows the influence of the center frequency on the measured crosstalk patterns is shown in Figure 22. The phase resolved distributions are from a measurement on TG2. The characteristics of the distributions are summarized in Table 2. From this table it can be seen that depending on the used center frequency, all sorts of combinations of signal sources are revealed in the recorded patterns.

Table 2. Summary of evaluation of the phase resolved distributions in Figure 22.

Meas. phase	f_0 MHz	Pattern dominated by
U	16	crosstalk from phase V + disturbance
U	62	phase's own PD + crosstalk from phase W
V	20	phase's own PD + crosstalk from phase W
V	62	crosstalk from phase W
W	20	phase's own PD + disturbance
W	62	crosstalk from phase U

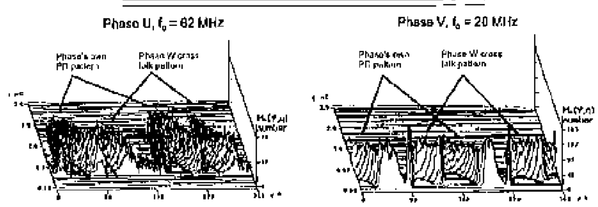

Figure 23. 3-dimensional distribution which shows the sinusoidal shapes, characteristic for a good insulation, measured on TG2.

In Figure 23 the $H_n(\varphi, q)$ distributions are depicted of the measurement on phase U at $f_0 = 62$ MHz and the measurement on phase V at $f_0 = 20$ MHz. Not only do the patterns show the characteristic sinusoidal shape with inner envelope (marked by the curved lines) of the phase's own PD pattern, this shape is also present in the crosstalk patterns. This event shows that the center frequency can be a useful means to measure crosstalk patterns that show the typical shapes known from the experience with off-line PD analysis.

The above discussion results in the following conclusions. The center frequency can influence considerably the measurement of crosstalk patterns. This influence depends on the generator where is measured, as well as the particular phase.

The presence of crosstalk patterns can be unfavorable for general pattern analysis of a particular measurement. However, in some cases the crosstalk patterns give conclusive information about the insulation state of the phase from which the crosstalk is measured.

4.3 INFLUENCE OF f_0 ON DISTURBANCES

The following discussion of two typical examples shows the effect of disturbances on the measured PD patterns in relation to the center frequency.

The measured $H_n(\varphi, q)$ distributions of the PD measurement previously discussed at Sections 4.1.1 and 4.2.1 are re-shown in Figure 24. The relative high level activity in the encircled groups originates from disturbances. The origin of the disturbances was not known, but from Figure 25, the $H_{qMax}(\varphi)$ distributions of the same measurement, it can be concluded that their membership in these patterns increases with increasing frequency. Their intensity, *i.e.* their number, does not increase, as can be seen from Figure 24.

PD measurements were performed at several center frequencies on phase W of TG1. At one particular center frequency, $f_0 = 60$ MHz, signals from a disturbance source were measured, see Figure 26. This

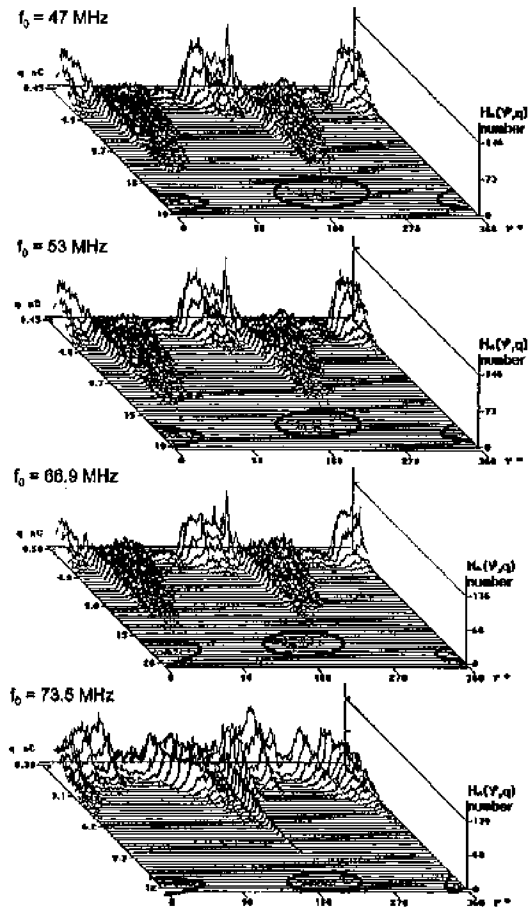

Figure 24. $H_n(\varphi, q)$ distributions of a measurement at phase U of TG1, measured at $f_0 = 47$, 53 and 66.9, 73.5 MHz. The encircled groups are disturbances.

disturbance pattern was not measured at other f_0. Closer examination of the measured pattern shows that the disturbances occur with a repeat rate of ≈1200 Hz. A plausible explanation for this occurrence is that there is some equipment (*i.e.* a pump) nearby the generator that emits pulses at a frequency of 1200 Hz. The spectral energy of these high frequency pulses should then be concentrated around the 60 MHz signal.

From the above it is concluded that the measurement of present disturbances is dependent on the center frequency. Depending on the spectral properties of the disturbance signal, they can be revealed either at just one or at a range of center frequencies.

4.4 TIME BEHAVIOR OF SPECTRAL RESPONSE

To discuss possible changes of the spectral responses in the course of time, examples of PD measurements on TG1 are examined. Two phases, U and W are considered, see Figures 27 and 28. In both Figures patterns are depicted of two measurements that have been performed in a time period of 18 months.

Visual comparison of the measurements performed on phase W (Figure 27) shows that the frequency response is practically unchanged.

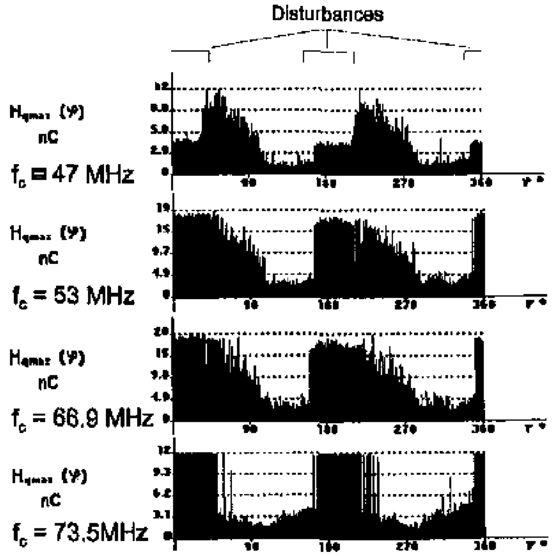

Figure 25. $H_{qmax}(\varphi)$ distributions of the measurement corresponding to Figure 24.

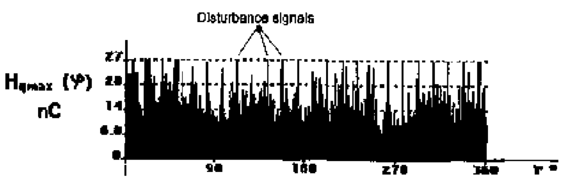

Figure 26. The PD measurement at $f_0 = 60$ MHz on phase W of TG1 shows a pattern of disturbances.

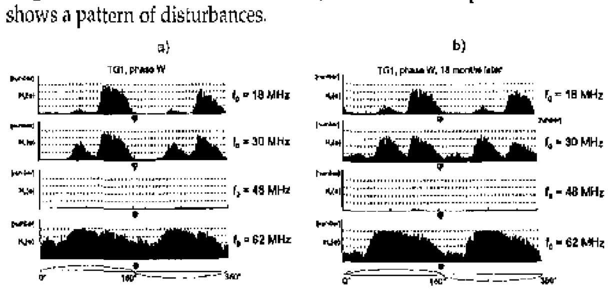

Figure 27. PD patterns at 4 resonance frequencies selected from the frequency scan, measured at phase W of TG1. (a) initial measurement, (b) measurement performed 18 months later.

Although only the patterns of 4 center frequencies are depicted here, this conclusion is supported over the entire frequency scan, which covers the range from 10 to 68 MHz. Thus, it may be concluded that no effect whatsoever arose in this particular phase in the time period of 18 months, which would be likely to change the frequency response, such as PD activity due to defects.

Figure 28 shows a different picture. In particular, the patterns at 34 and 44 MHz are substantially changed in the course of time. This is also observed at other resonance frequencies in the range from 10 to 68 MHz besides the ones depicted here. This example indicates the care one should take when analyzing on-line PD measurements using the responses of a particular phase at one single frequency. Although it has been shown that typical defects in the stator insulation can be identified by the spectral responses of a phase [26], variations in the spectral response should not be associated automatically with changes in the insulation condition.

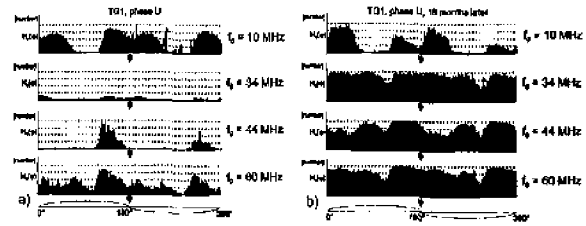

Figure 28. PD patterns at 4 resonance frequencies selected from the frequency scan, measured at phase U of TG1. (a) initial measurement, (b) measurement performed 18 months later.

5 STATISTICAL ANALYSIS

The discussion in Section 4 results in the general conclusion that the image of the measured patterns strongly depends on the center frequency. In this Section statistical analysis of the patterns measured at TG1 is evaluated. The evaluation is concentrated on finding clusters of measurements at specific center frequencies that separate themselves by their patterns.

5.1 PATTERNS OF DIFFERENT SIGNAL SOURCES

The recorded patterns of the first measurement of TG1 are statistically processed and analyzed by the tree method, Figure 29. Three clusters can be distinguished: A cluster of measurements where the pattern is dominated by the phase's own PD pattern, clusters of measurements where the pattern is dominated by cross talk PD pattern, and clusters of measurements where the pattern is dominated by a disturbance pattern.

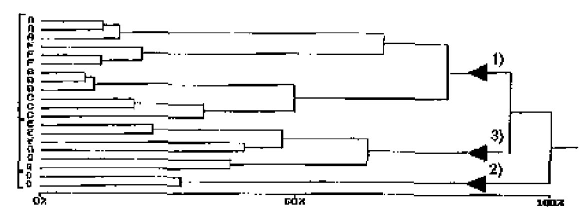

Figure 29. Cluster analysis by the tree method of the PD measurements performed on TG1.

Figure 30 shows the results of the fractal analysis. The results are similar to the tree method. Three separate clusters are formed as seen in Figure 29, marked 1, 2 and 3. Besides the distinction in measurements of different signal sources, both the tree and fractal analysis show another important result. The measurements at phase U and W, where the phase's own PD pattern dominates the measured pattern, cluster with one another (the measurements are in Figure 29 denoted by A, B, C for phase U and F for phase W, and in Figure 30 by $U47$, $U53$ and $U66.9$ for phase U and $W45$ for phase W).

The results is that the phase's own PD patterns are similar in both phases, and that the insulation shows similar PD behavior.

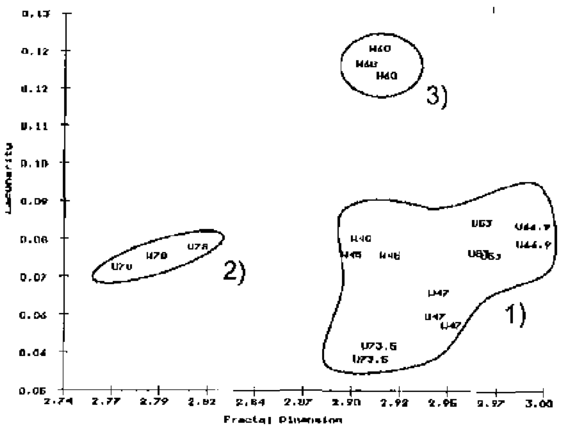

Figure 30. Fractal analysis of the PD measurements performed on TG1.

With respect to measurement of different signal sources, statistical analysis of the VHF PD patterns results in measurements that are dominated by patterns of a specific signal source cluster with one another. For each signal source a cluster is found. Moreover, measurements of the phase's own PD pattern from phases U and W cluster with one another, and thus the phases show similar PD behavior.

5.2 PATTERNS MEASURED AS FUNCTION OF TIME

In Section 4.4 it was concluded that the spectral response of phase W of TG1 was not changed in a time interval of six months. Statistical analysis as shown in Figure 31 confirms this conclusion. The pattern of the measurement performed 18 months later (as also discussed in Section 4.4) is added to the tree that was discussed in the previous Section. This measurement (denoted by H in the tree) clusters with the group of patterns that were dominated by the phase's own PD pattern.

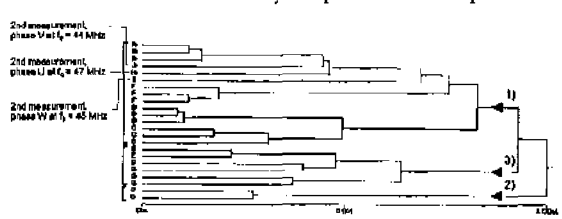

Figure 31. Tree of Figure 29, expanded with statistical results of the measurement performed 18 months later on the same generator.

Although the spectral response of phase U did change (see previous Section), patterns at some individual center frequencies still resemble the patterns measured 18 months earlier. One measurement performed at a center frequency $f_0 = 47$ MHz (denoted by I in the tree) clusters with the group of the phase's own PD activity.

So far, only measurements of phase U and phase W of TG1 have been discussed. During the measurement performed 18 months later at this generator, VHF PD measurements were also performed on phase V, where mainly phase's own PD pattern was recorded, *e.g.* at $f_0 = 44$ MHz. The measured pattern at this center frequency is depicted in Figure 32. After statistical analysis of this measurement, it was added to the tree in Figure 31. It clusters with the group of measurements

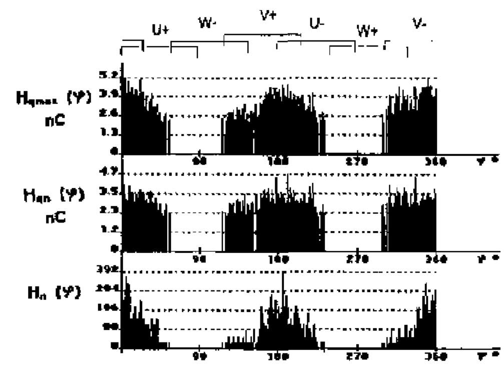

Figure 32. Phase resolved pattern of phase V of TG1, measured at $f_0 = 44$ MHz.

of phase's own PD activity. Thus, the PD behavior phase V shows, is similar to the other two phases.

Statistical analysis concludes that no change in PD patterns measured at the phases of TG1 appeared.

Measurements of phase's own PD pattern from all phase of TG1 cluster with one another, thus the phases show similar PD behavior.

6 GENERAL CONCLUSIONS

With regard to turbogenerators involved in this investigation the discussion results in the following conclusions.

1. For the measurement by VHF detection of the PD processes in the insulation of a particular phase of a generator, several center frequencies are suitable to tune the SA.
2. To find suitable frequencies to tune the SA for the measurement of the phase's own PD pattern, the following procedure can be followed. Measurement of the frequency spectrum by specific span mode of SA, selection of a specific series of center frequencies, and measurement of PD patterns at each of the selected frequencies (frequency scan). Use must be made of several techniques, *e.g.* visual comparison, tree analysis, fractal analysis, and spectral response matrix, to find and analyze the phase's own PD pattern
3. PD responses at specific resonance frequencies can change in the course of time for a particular phase of a turbogenerator. In consequence, analyzing the PD patterns of the same phase on just one single resonance frequency is not sufficient to get insight in the PD processes inside the insulation.

The authors realize that the analysis of PD patterns obtained by the on-line measuring technique from phases of generators is very complex due to influences of crosstalk and disturbances. Moreover, to obtain confirmation of general applicability of these results, further systematic study is necessary and the following steps should be considered. More systematic online tests on generators in service (if possible in good and bad condition). Fundamental studies of PD signal propagation effects in the stator insulation on the resonance frequency of the SA. Using the above-mentioned tools for analysis of PD patterns of well defined discharge sources such as slot discharges and end winding discharges.

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