ASSESSMENT OF UHF PD MONITORING DATA BY MEANS OF PATTERN RECOGNITION

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Abstract: Online monitoring of power transformers which supports established diagnosis methods gains importance. Continuous measurement using trend analysis allows the detection and tracing of undesirable changes at an early state. For partial discharges (PD), ultra-high frequency monitoring represents an advantageous technique. The used measurement inside a tank is less sensitive to external noise. Additionally, it is mountable on transformers in service. The considerable amount of generated data needs suited evaluation. Partially automated analysis is inevitable. This contribution presents an approach using phase resolved PD pattern analysis. Typical patterns from known PD sources are reduced to an abstracted shape which uniquely characterizes the form of the source. This so called template is compared to measured PRPD patterns gained from the monitoring data. Comparison between pattern and template is calculated by 2-dimensional normalized cross-correlation algorithm. Source tracking over time is evaluated using continuous correlation. By introducing a set of templates for correlation the progress of individual PD sources is determined.

1 INTRODUCTION

Local failures of power transformers' insulation may lead to breakdowns and can cause high outage and penalty costs. Therefore, power transformers are tested, e.g. by established partial discharge measurement according to IEC 60270 [1]. Because common PD diagnostics are performed within hours, it only provides snapshot information about transformers' actual condition. In contrast, permanent online monitoring of PD is used to gain operational experiences and evaluate trending. Continuous data generated by (online) monitoring demands new analysis methods. To manage large amounts of data the user needs assistance. This contribution presents an approach which automatically categorizes PD sources using known PRPD patterns. Their activity over time and phase correlation becomes traceable.

2 PRINCIPLE OF MEASUREMENT

Ultra-high frequency (UHF) detection has been developed to detect and classify defects in gas insulated switchgears (GIS) through measuring the electromagnetic radiation of PD. The UHF technique has been successfully applied during the past decade to power transformers [2], [3], [4]. UHF measurement is based on the fact that PD are fast electrical processes radiating electromagnetic waves with frequencies up to the ultra-high frequency range (UHF: 300 – 3000 MHz) in the surrounding oil [5]. An UHF probe, see Figure 1, is installed in an oil valve of the transformer. The tank wall is grounded and represents a Faraday cage which shields external noise, namely corona. Due to the moderately attenuated propagation of UHF waves inside the transformer tank, the electromagnetic wave detection is usually sensitive [2]. Unlike electrical PD measurements, UHF measurements cannot be calibrated in terms of apparent charge in pico coulombs (pC) [6], because the electromagnetic field strength of UHF PD signals is measured by an antenna. However, it is possible to correlate PD to the phase angle of the applied voltage using the phase resolved PD (PRPD) pattern [7]. It has to be noticed that this correlation is arbitrarily and measured UHF PD must not originate from the chosen phase in a three phase system.

Figure 1: UHF Probe for inside tank measurement of UHF PD, designed for standard DN50/DN80 oil valve

3 DATABASE OF A USE CASE

A 50-year-old unit generator transformer with a rated voltage of 110/10 kV and a rated power of 120 MVA is monitored. An online UHF PD measurement system records data [8] using a Doble Lemke LDS-6/UHF measuring system. UHF PD signals are measured with approximately 35 dB amplification and a bandwidth of 9 MHz at a centre frequency of 505 MHz. The noise level of the system is between 1.5 and 2 mV. Therefore, all PD below 2 mV are discarded. Phase L1 is used for phase correlation.

Due to the fact the generating unit is only in operation on demand, the transformer is not continuously in service. Measurements are available for approximately 65 days from 2009 until 2012. Figure 2 shows a UHF PRPD measurement pattern. Record time is one minute. The x-axis shows the phase angle and y-axis the voltage amplitude. Colour indicates the number of PD. The PRPD pattern of the considered transformer is not stable and changes several times within a day. Therefore, the existence of multiple sources is assumed which are evaluated in the following.

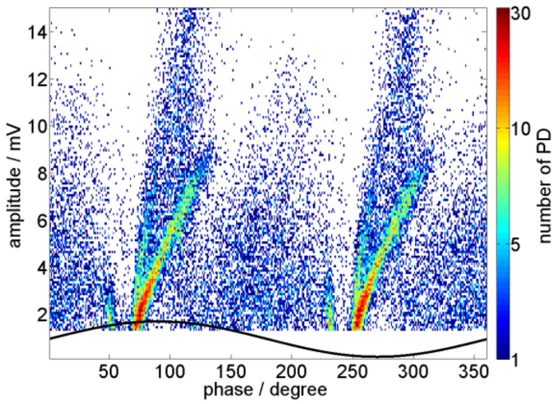

Figure 2: PRPD pattern from UHF measurement (one minute record time), called pattern 1

4 PRINCIPLE OF EVALUATION

4.1 Normalized cross-correlation

Cross-correlation is an algorithm for pattern recognition within an image. The higher the similarity between two images, the higher is their correlation factor. In this contribution, the normalized cross-correlation is used providing values of correlation coefficients between -1 and +1 for each matrix element [9]. Thus, cross-correlations of different images become comparable. A correlation coefficient of 1 indicates an exact match of the template (never occurs in practical pattern analysis). -1 represents an area where image intersection and template are opposed (negative image, never occurs in practical pattern analysis).

The algorithm is given in (1). Matrix *A* represents the image, Matrix *B* the template. $\bar{A}$ and $\bar{B}$ are the geometric mean values of both matrices. They are subtracted from the matrices to remove offsets. The offset free correlation is divided by RMS-value of the offset-free cross-correlation for scaling. *C* is the resulting correlation matrix.

$$C(x_1,y_1)=\frac{\sum(A(x,y)-\bar{A})(B(x-x_1,y-y_1)-\bar{B})}{\sqrt{\sum(A(x,y)-\bar{A})^2}\sqrt{\sum(B(x-x_1,y-y_1)-\bar{B})^2}} \quad (1)$$

For evaluation a part of the entire pattern is defined as search parameter, being a significant detail characterizing the pattern. It defines the so called template. Two examples for templates generated to fit pattern 1 (Figure 2) are shown in Figure 3. In this case the characteristic is the top edge of the pattern.

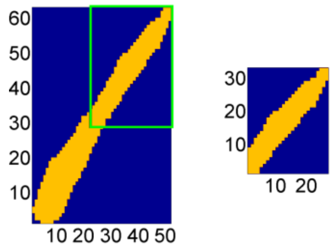

Figure 3: Examples of two binary templates of different size. Left: larger template defining the entire shape of the considered pattern. Right: smaller template generated as cut-out of the large template [9].

Template and image are cross-correlated. The result is the correlation factor of template and image for each position of the image. Therefore, the template and the image must overlap.

Mathematically it is a measure for the similarity between the entries of two matrices. The intersections of both matrices are multiplied, the result is provided by a 2-dimensional correlation matrix, whose coordinates represent the correlation factor of template and image at each position of the original image. For the given example the resulting cross-correlation matrix is shown in Figure 4. The colour indicates the correlation between the small template from Figure 3 and the pattern from Figure 2.

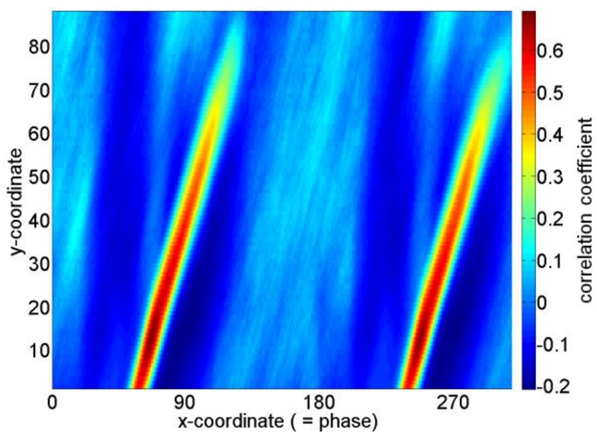

Figure 4: Visualization of the correlation matrix of normalized cross-correlation vs. phase in degree. Colour indicates the similarity between template and picture [9].

In this contribution, only the shape of the pattern is taken into account. It would also be possible to integrate the information of accumulation of PD in one area.

4.2 Pattern tracing

Patterns should be traceable over time. Therefore, the constant PD data stream is divided into segments with constant duration. For each segment the PRPD pattern is generated and then cross-correlated with a template. The adequate duration depends on the behaviour of the source over time. Pattern 1 from Figure 2 shows high volatility. Therefore, duration is set to 1 minute. Correlation is calculated with the small template from Figure 3. The maximum value of the correlation matrix represents the correlation coefficient for the time segment. An example is plotted in Figure 5. In red, aligned to the left axis the correlation coefficient is shown. For comparison, the number of PD per minute is also plotted (black, right axis).

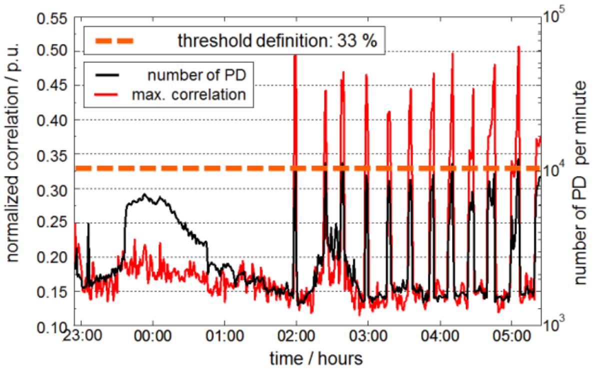

Figure 5: Number of PD per minute (black) and maximum normalized cross-correlation per minute (red)

From 23.30 h to 1.00 h, there is a temporary rise in the number of PD per minute. The correlation coefficient remains low (maximum 22 p.u.). Therefore, data implies that the considered source is not responsible for the peak. Manual comparison between the correlation coefficients and the PRPD pattern confirm the results of cross-correlation. After 2.00 h, the specific pattern occurs regularly. Every peak in the number of PD is caused by the source, no other sources are present. In this case, correlation works properly. Therefore, a threshold level can be defined. Here, it is chosen to 33 p.u. (Figure 5, dashed line). Correlation coefficients above this level indicate the occurrence of the pattern.

4.3 Filtering

Depending on the available PRPD patterns, image pre-processing can help to improve correlation. If a pattern consists of few PD (e.g. if accumulation time is too short) similarity to the template is too low. Hence, correlation coefficients are low. If only few PD events are available, the pattern has to be pre-processed. Single pixels by PD have to be transformed into closed surfaces before cross-correlation. Averaging filters are used for this approach. The filter joins nearby small areas containing PD by blurring them together. It calculates the value of a single matrix element of a PRPD pattern by the mean value of its surrounding elements. For this contribution, filters sizes of 3x3 and 5x5 were used and tested. Figure 6 shows the result from a 3x3 averaging filter of a pattern.

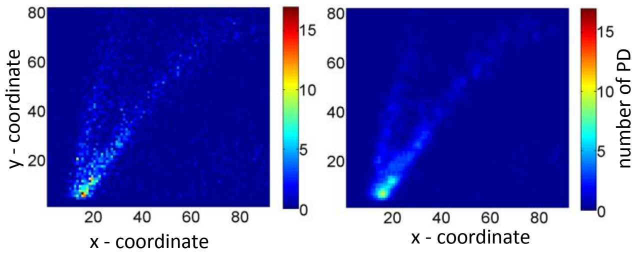

Figure 6: Original PRPD (left); filtered pattern by 3x3 averaging (right)

A drawback of this method could be the sensitivity for noise in the PRPD pattern. It is possible that falsifications occur depending on the filter size. Using an average filter, small, scattered PD result in an enlarged area. In a worst case scenario, a new pattern could be generated by filtering having a high correlation with the template.

5 APPLICATION

5.1 Physical interpretation of the pattern

Several types of defects in transformer insulation may lead to PD. It could be located at almost every place inside the transformer. Additionally, electrical events from outside the transformer can affect the measurement. Typical sources of PD in a transformer are e.g. particles, gas bubbles, tips, surface discharge alignments, bad contacts and not connected metallic parts.

For a long term evaluation, three typical PRPD patterns from the use case are chosen. The physical interpretation of the pattern is demanding. Comparison with pattern descriptions from literature [11], [12], [13] led to the following conclusions.

Figure 2 shows the initially considered pattern at an accumulation time with one minute. Colour indicates the number of PD; x-axis is the phase angle and y-axis the voltage amplitude of the UHF signal. In the following it will be called pattern 1. It could be a void (e.g. a gas bubble) in the insulation of the transformer [13]. It has two similar curved branches with 180° phase interval. Its origin is at approx. 75° and 250°, respectively. Thus, it is likely not a pattern from phase L1. The amplitude is quite stable at 10 mV.

Pattern 2 shown in Figure 7 could be a floating potential (e.g. a not well-connected shielding electrode) [13]. It has one straight branch. The amplitude is volatile from 8 mV up to 25 mV.

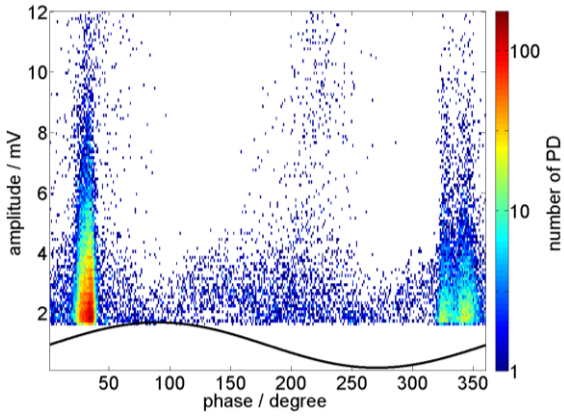

Figure 7: PRPD pattern 2 accumulated during one minute

Pattern 3, see Figure 8, could be a void or a surface discharge without contact to an electrode [13]. It has two hills starting at 80° and 250°, respectively. The amplitude is stable with a maximum of 7 mV.

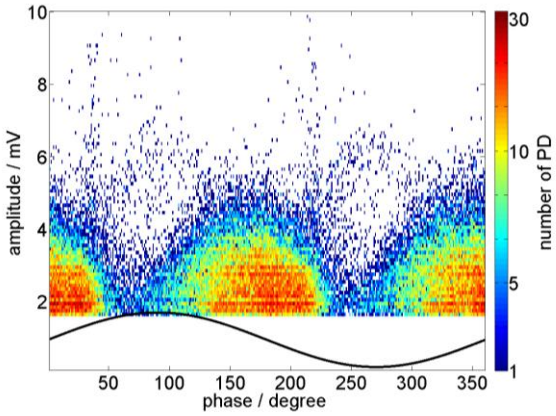

Figure 8: PRPD pattern 3 accumulated during 15 minutes

Pattern 1 und 2 are generated by accumulating PDs for one minute. Pattern 3 is less active; accumulation time therefore is 15 minutes. Table 1 shows a summary of the used parameters for pattern analysis.

Table 1: Summary of the used parameters

Pattern	Used filter size	Accumulation time	Threshold level
Pattern 1	3 x 3	1 min	64.6 %
Pattern 2	None	1 min	52 %
Pattern 3	5 x 5	15 min	70 %

For these three patterns, templates are defined and correlated with the dataset described above. Using threshold levels as trigger, times are identified the patterns occur.

5.2 Appearance of the pattern

Figure 9 shows in the upper plot the number of all PD measured during the monitoring. In this view, only operating days of the transformer are shown resulting in 65 days of data. The measured PD per minute are plotted in grey, showing high volatility. For better survey, a moving average in brown is introduced. Data around day 50 cannot be evaluated due to measurement errors.

The lower plot in Figure 9 shows a bar graph for each pattern. Colour indicates times the patterns are detected by cross-correlation. Pattern 1 is only present at 15% of the time showing intermitted behaviour. Pattern 2 has a higher appearance and can be detected at 40% of the measurement time. Pattern 3 is the dominating source which can be detected at 60% over the entire period. However, it is not the source contributing the most PD per interval because PD from 15 minutes are needed to calculate an applicable pattern.

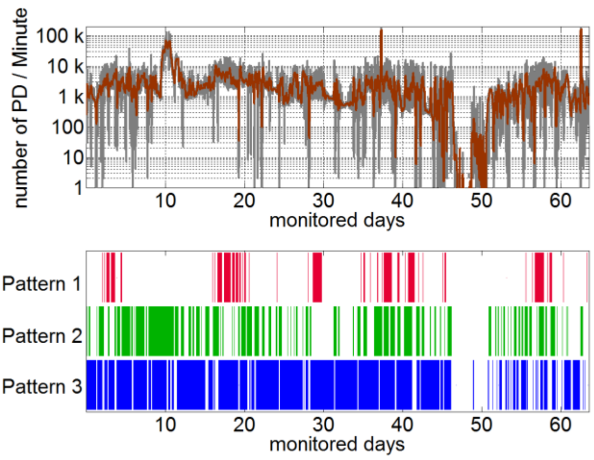

Figure 9: PD activity and occurrence of patterns. Upper plot: number of PD per minute (grey) and moving average (brown)
Lower plot: results of recognition algorithm of determined patterns 1 - 3 over the monitored time.

5.3 Phase position of the pattern

For pattern identification literature usually includes the information provided by the reference to phase of patterns [11], [12], [13]. The absolute value of the phase is used as well as the information about the drift over phase. Also, in case of patterns occurring in both half waves, the stable phasing relative to each other is considered. Therefore, the phase information is included for long time evaluation.

Initially, it has to be mentioned, that the UHF method measures the antennas feed point voltage generated by the electromagnetic radiation of PD. Compared to electrical PD measurement the direct galvanic coupling between the PD event and the electrical phase is missing. Therefore, UHF events are chosen to be correlated to phase L1 of the transformer. With this definition, an assumption of the actual electrical phase can be made. Nevertheless, information about the stability of sources with respect to phase is easy to obtain.

To extract the phase information, the correlation matrix calculated for each time step is scanned for the maximum correlation coefficient. The x-coordinate represents the phase angle of the maximum correlation and hence of the considered source (if maximum correlation is above the pattern specific threshold level). It has to be mentioned, that erroneous detections are possible due to the recognition method. E.g., if several overlapping patterns are active at once, template correlation could fail or the superimposed pattern could match the template best at an incorrect phase angle. This has to be considered in the following evaluation.

Figure 10 shows the phase angle of pattern 1 referenced to L1 of the transformer. The pattern is phase stable between 60° and 120° and the second pattern between 240° and 300°. Single detections at other phase angles are erroneous. Which is confirmed by manual checks of several control samples.

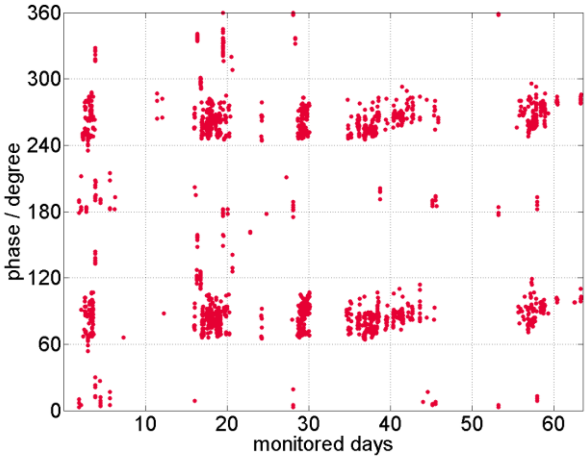

Figure 10: Phase angle of pattern 1 over time

Figure 11 shows the phase angle of pattern 2. In contrast to pattern 1, no stable correlation to a phase is possible. The pattern shifts over the phase. According to [13], this behavior in combination with the pattern shape can be associated with floating potential sources.

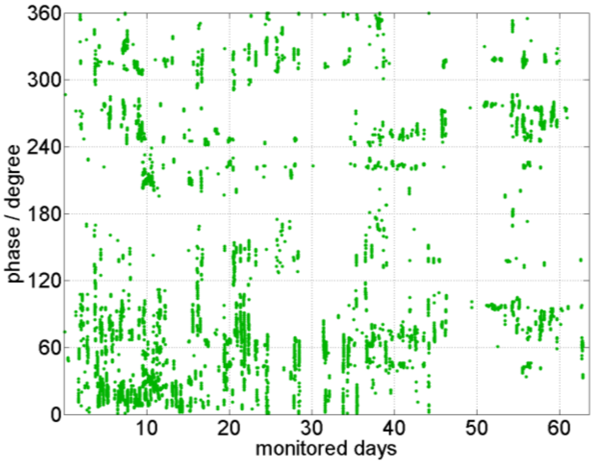

Figure 11: Phase angle of pattern 2 over time

Figure 12 illustrates the phase angle of pattern 3. Like pattern 1 it is phase stable in both half waves but at a slightly higher phase angle between 100° to 150° and 270° to 320°, respectively. Its stable correlation to phase confirms the previous interpretation as a void or floating potential according to [13].

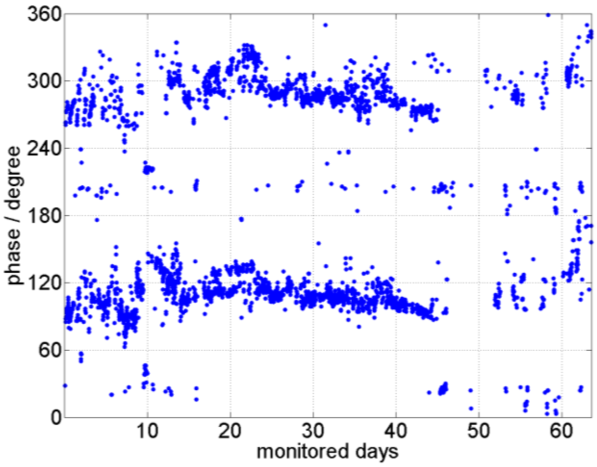

Figure 12: Phase angle of pattern 3 over time

6 CONCLUSION

PD data can be evaluated using normalized cross-correlation for PRPD pattern recognition. Therefore, the characteristic shape of a pattern is defined by a template matrix. The data is segmented into constant periods of time which are used to generate PRPD patterns. Each pattern is cross-correlated with the template. The result of a correlation is a matrix whose coefficients define the similarity between template and pattern. The quality of correlation depends on several parameters. Filtering can improve correlation outcome; results strongly depend on the chosen filter method and its parameterization. If preconditions are met, a threshold level can be defined. The maximum value of the resulting matrix is used as trigger indicating the presence of the determined pattern. Its x-coordinate represents the phase angle the pattern occurs. Combination of both allows long term tracking of PD and thus its behavior over time. Comparison of pattern shape and phase angle with known PD sources from literature can be made. In this contribution, only the relative phase can be considered due to the UHF measurement. Nevertheless, presented cross-correlation method can be applied on any PD measurement method which includes PD phase angle.

The essential benefit of the presented method is its application on large PD datasets, e.g. from monitoring systems. In the presented use case 65 days of monitoring data is evaluated. Therefore, three PRPD patterns being typical for the determined transformer are evaluated. Using cross-correlation, it is possible to track patterns over the monitored period in terms of their appearance and the phasing.

Although the used UHF PD measuring method does not provide the actual phase angle of PD, it is appropriate for long term monitoring of PD in power transformers.

7 OUTLOOK

The principle of pattern recognition using cross-correlation can be used for automated tracking of PD sources. For erroneous detections filtering can be extended with further methods. Also templates could be preprocessed before cross-correlation. E.g. a normalized template has to be scaled or rotated to fit the specific amplitude range. Hereby, a standard template collection can be introduced applicable on all transformers. Such a template collection can include typical known PRPD shapes of physical PD sources [11], [12], [13].

Automated time resolved PD monitoring data from individual PD sources can be compared with operational data, e.g. on-load tap changer position, load, top-oil temperature, load factor, etc. Thus, power transformer assessment can be supported using monitoring system combined with automated PD recognition.

8 REFERENCES

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