AUTOMATED DETERMINATION OF FREQUENCY PARAMETERS FOR OPTIMAL SEPARATION OF MULTIPLE PD SOURCES AND DISTURBANCES

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Abstract: The paper deals with synchronous multispectral PD measurement technique that enables separation of PD sources. Different concepts to find frequencies suitable for automated separation are evaluated. The finally proposed concept for automation is modular software subdivided in: pre-selection of frequencies, acquisition and in the evaluation of PD data. To shorten the time necessary for PD evaluation, the limitation of the initial numbers of possible combination of frequencies by frequency range of PD measurement equipment and a-priori knowledge on asset type and test set up is discussed. For comparison and rating of 3CFRD diagrams three parameters are defined but the most important appears "the number of clusters". The clustering algorithms DBSCAN and OPTICS provide a proper solution for cluster identification.

1 INTRODUCTION

In noisy environments, de-noising becomes an indispensable part to maintain sensitivity and selectivity in partial discharge (PD) measurements.

One of the numerous de-noising procedures for pulse-type signals is based on waveform analysis, separating interference and PD pulses by different pulse shapes. To clearly distinguish in between interference and (multiple) PD sources, pulse waveform analysis requires wideband or even ultra-wideband detection. PD measurements on HV equipment, however, rarely allow non-interfered wideband PD detection due to radio interference. Consequently, quality of pulse waveform analysis can suffer when radio interference is present. Furthermore, pulse waveform analysis has to trigger on individual pulses to limit the amount of data - continuous wideband acquisition and evaluation seems actually not feasible and would probably not be effective.

Another de-noising procedure became available with synchronous multi-channel PD measurements, which already proved of value as a tool for effective discrimination of interference and multiple PD sources [1,2]. Though this method (3PARD) originally was designed for three-phase HV equipment, it is not at all limited to this field of application. Several experiments showed that it is only necessary to provide a number of independent, synchronous PD observers to apply multi-channel PD evaluation. Obviously, single-channel PD measurements cannot meet this requirement.

Fusion of central ideas from pulse waveform analysis and synchronous multi-channel measurements led to a new de-noising and separation procedure (3CFRD - 3 center frequency relation diagram) for pulse-type signals based on multispectral analysis.

This paper puts the main focus on multispectral PD measurements. Like available methods based on PD pulse waveform analysis, multispectral PD measurements use spectral properties of pulses to separate PD from interferences. In contrast to existing methods, multispectral PD measurements do neither rely on broadband data acquisition nor on triggering individual pulses and need only single-channel measurements. Thereby, multispectral PD measurements overcome certain limitations of the existing methods.

The method of multispectral PD measurement offers the possibility to separate different pulse-shaped PD signals by applying three different band-pass filters simultaneously. With the three band-pass filters three impulse responses are determined and the peak values are correlated for visualisation in the 3CFRD [2-5].

Using 3CFRD the correct choice of the three band-pass filter frequencies is very important because these have direct influence to separability of the PD sources. The band-pass filters have to be tuned to frequencies with differences in spectra of the PD impulses. Depending of the type of the PD defect and test setup sometimes only a few frequencies allow adequate separation in 3CFRD. Hence finding proper frequencies, also by an experienced user, can be very time consuming, since there are a lot of combinations of three center frequencies for each PD measurement. At laboratory measurements and particularly on site the given time for PD measurement is usually strongly limited. Furthermore for PD monitoring the

3CFRD method has to be able to adjust itself automatically to the respective measuring conditions.

For optimal separation in 3CFRD a modular software for automated determination of the three center frequencies is proposed. To limit the initial number possible of combinations proper procedures have to be adopted in order to shorten the time needed for automated determination. Different aspects for the limitation of the number of frequencies are indicated.

2 MULTISPECTRAL PD MEASUREMENT

Depending on PD propagation path form PD source to decoupling position the spectra of PD pulses will be different. The method of multi-spectral PD measurement uses these differences in PD signal spectra for separation of PD sources. By applying three band-pass filters to the PD impulse the pulse magnitude is determined at three different frequencies (fL, fC, fR). These charge values are correlated in a three axis diagram by vectorial addition and are marked by a triple point (see Figure 2). If one of the band-pass filters is set to a center frequency with differences in signal spectra, PD pulses of different PD defects are located at different positions in the 3CFRD. The clusters of the PD sources can be back-transformed separately to PRPD for identification of PD type and apparent charge.

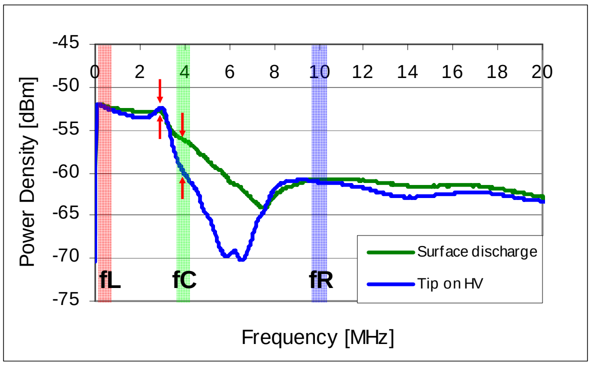

Figure 1: FFT of surface discharge and tip on HV in a test setup

This method is especially useful for single channel PD measurement where multi-channel separation procedures like 3PARD [6] cannot be used.

Finding center frequencies with differences in PD signal spectra sufficient for separation in 3CFRD can be very time consuming, since this requirement is often fulfilled only by few small frequency ranges. In Figure 3 the 3CFRDs of two different combinations of the center frequencies fL, fC, fR (frequency triples) are shown. They were measured at a laboratory test setup with surface discharge arrangement and a tip on HV. The decoupling was done by a coupling capacitor with measuring impedance. The 3CFRDs vary only in one frequency, fC = 3MHz or respectively 4MHz, but in the 3CFRD on the left side the clusters of the two PD sources are superposed while the clusters in the 3CFRD on the right side can be separated easily. The reason for that can be seen in the FFTs in Figure 1. At 3MHz no appreciable difference in magnitude of the FFTs exists. In contrast at 4MHz considerable difference in magnitude of the FFTs can be seen.

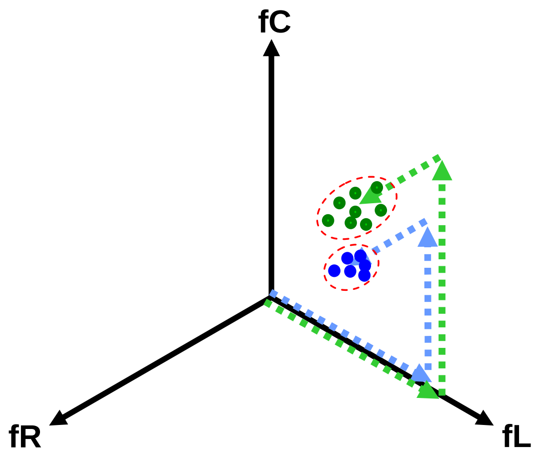

Figure 2: Construction of 3CFRD

With increasing number of PD sources, complex setups and measurements in noisy environment it becomes more difficult to find center frequencies suitable for separation in 3CFRD.

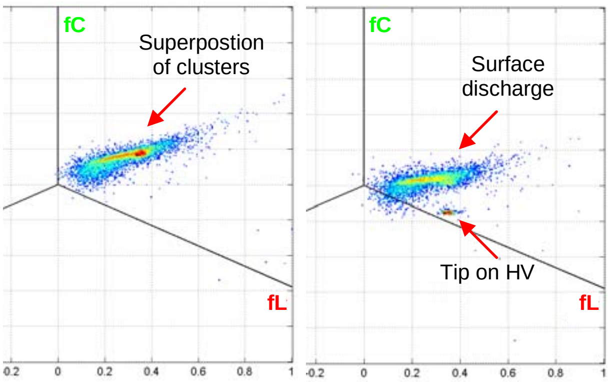

Figure 3: 3CFRDs for center frequencies 0.5, 3, 10 MHz (left) and 0.5, 4, 10 MHz (right), BW 650kHz

3 CONCEPT FOR AUTOMATED DETERMINATION OF FREQUENCIES

Frequencies suitable for separation in 3CFRD theoretically can be found by comparison of spectra of the single PD pulses. In practice, however, this procedure is not possible because of superposition of PD impulses and interferences.

Figure 4 shows the general procedure for automated determination of three frequencies for best possible separation of 3CFRD clusters. The three steps are explained in detail in the following sections.

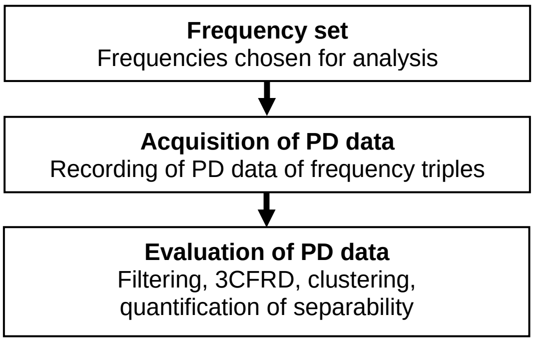

Figure 4: Block diagram modular software for automated determination of frequencies for 3CFRD

3.1 Frequency set

First of all, frequencies used for analysis of test setup have to be set and all possible frequency triples (combinations of fL, fC, fR) have to be calculated. The total number of different frequencies for 3CFRD depends on the frequency range and the bandwidth of the bandpass filter. For a frequency range of 20 MHz (available for the MPD600) and a bandwidth of 500 kHz, the total number of frequencies n would e.g. be 40 ([0.5, 1, 1.5,…, 20MHz]). Three different frequencies (combinations of fL, fC, fR, so-called 'triples') are used for 3CFRD, so the number of possible orderless combinations is calculated according to equation (1) with n = 40 and k = 3.

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \tag{1}$$

For the given example the number of all possible combinations (triples) would be 9880. Of course, the result of such a brute-force attack is not applicable in practice. To acquire PD data of all 9880 triples for subsequent evaluation and a very short acquisition time of only 5 s for each triple would already lead to 13 h total acquisition time. Consequently, the number of triples has to be narrowed in a reasonable way. This can be done by taking a-priori knowledge into account.

Frequency characteristics of sensors and measurement system set one boundary. For all presented data a MPD600 (Omicron) with a PD input frequency range of 9kHz to 20MHz was used. The test object and the test circuit as well as radio interference may restrict the available frequency range. Figure 5 shows the FFT of PDs generated in a machine stator. Due to strong attenuation above 7MHz it is not reasonable to take into account frequencies above this value for analysis. On site in most of cases high disturbances are superimposed. Frequencies with a high level of disturbances can also be disregarded. Another restriction is given by IEC 60270 since for determination of the apparent charge according to the standards one frequency has to be set in the range up to 1MHz.

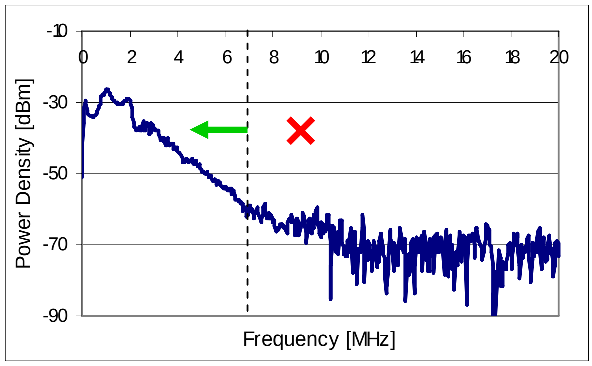

Figure 5: FFT of PDs of machine stator at 7.7kV test voltage

According to [4,5] for proper separability in 3CFRD the frequencies fL, fC, fR have to be set to different frequency ranges. Proposed is a sub-division in: fL = 0 to 2MHz, fC = 2 to 10MHz, fR = 10 to 20MHz.

A further reduction of frequency triples can be reached by using frequency steps of different width. The spectra of the PD impulses in many cases have a higher dynamic for the lower frequencies. Here it is meaningful to choose smaller frequency steps. For the higher frequencies the dynamic in the spectra often decreases so that the frequency steps can be chosen larger.

An example taking this into consideration is given with: fL = [0.5, 1, 1.5 MHz], fC = [2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, 9, 10 MHz], fR = [10, 12, 15, 18 MHz]. With a Matlab calculation from this frequency set about 130 different frequency triples result. Again assuming a duration of PD data recording of 5 seconds for each frequency triple this would lead to a total acquisition duration of about 11 minutes, what satisfies requirements of practicability much more.

3.2 Acquisition of PD data

For acquisition of PD data the frequency parameters fL, fC, fR as well as measurement bandwidth and record duration of PD data has to be set automatically in the PD measurement system. The control of the PD measurement system is system specific and hence not discussed in this context. For each frequency triple PD data are recorded and stored for subsequent evaluation.

3.3 Analysis of PD data

In some cases a pre-processing of the recorded PD data is meaningful e.g. by de-noising. On the one hand this reduces time for further processing of data, especially for clustering. On the other hand in 3CFRD noise clusters are generally of high density and large extension and thus can influence the determination of the best frequency triples.

After 3CFRD determination for every single frequency triple the 3CFRDs have to be clustered. Due to the structure of the 3CFRD a density-based clustering notion offers a suitable solution. Two clustering algorithms implemented and tested are DBSCAN ([7, 8]) and OPTICS ([9]). Both clustering algorithms enable adequate clustering of 3CFRDs. An accurate clustering is very important since all further calculations are based on this clustering data.

For comparison and rating of 3CFRDs of the different frequency triples the separability has to be quantified. This can be done by the parameters 'number of clusters', 'average cluster density' and 'average cluster distance' calculated on basis of the clustering data (see section 4). High values for these three parameters are equivalent to a good separability while lower values mean worse separability. An example is shown in Figure 8. For better reliability of this method not only best but the best five frequency triples should be taken into account.

4 PARAMETERS FOR QUANTIFICATION OF 3CFRD

The number of cluster refers to the number of separable clusters in 3CFRD and is given directly by the clustering results. In Figure 3 (right) two clusters can be identified while on left side only one cluster can be seen due to superposition. The clusters of all PD sources are supposed to be identified and separated, hence the number of clusters should have a high impact on the rating of the frequency triple in analysed frequency set.

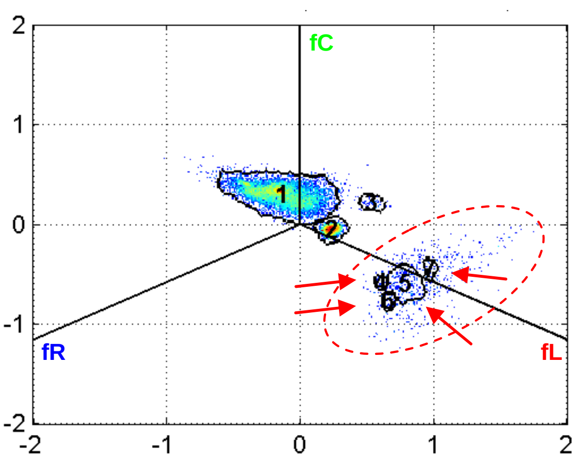

Figure 6: Clustering – cluster divided in four partial clusters

Clustering of 3CFRDs with low density proved to be critically, since this can lead to subdivision of the cluster (see Figure 6). This causes a higher value of the 'number of clusters' and thus an overestimation of the separability.

The cluster density is the amount of triple points of a cluster in relation to the area of the cluster. Many triple points in small area would lead to high density and thus to a high rating. The amount of triples is given by the clustering data and can be determined by the sum of the PD triple points of a cluster. If for one coordinate in the 3CFRD several PD triple points arise the sum is getting bigger. The area of the cluster is the whole area inside the cluster borders given by the clustering. For diffuse clusters also the coordinates without PD triples have to be taken into account. After determination of the single cluster densities the average of density of all clusters in the 3CFRD has to be determined for quantification and better comparability.

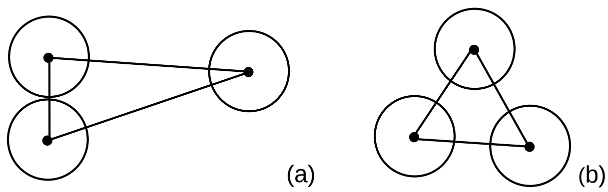

Figure 7: Configuration of clusters with different distances

The distance of two clusters is defined as the distance of the core of one cluster to the core of the other cluster. One possible definition of the 'core' of a cluster is given by the highest value of the cluster. Further options are centroid and medoid. Determination of the core of the cluster for all three definitions can be done on the basis of clustering data. Choosing the highest value as core has the advantage of a more simple calculation and of being less affected by small changes of the clustering boarders. As for the cluster density the average of the cluster distances for each 3CFRD is determined. Figure 7 shows two configurations of each three clusters. The example (a) on the left side has the bigger cluster distances but regarding the separability of all three clusters example (b) on the right provides the better configuration. To take this into account in quantification smaller distances should have a higher weighting in calculation of the average cluster distance.

For a final quantification of the 3CFRDs the values of all three parameters have to be combined. Depending on the clustering of the 3CFRDs varied weighting of the parameters is necessary to find the optimal frequency triple.

5 MEASUREMENT RESULTS

Based on the presented recommendations a software for automatic determination of optimal frequencies separation in 3CFRD was implemented and tested. The results of a test on an 110kV cable system with GIS compartment are shown below. In the cable test setup system, consisting of an 110kV XLPE cable, outdoor termination, cross-bonding joint and GIS part, four artificial PD defects were implemented. These were tip on HV in air, surface discharge, internal PD and tip on earth in GIS. For the test a frequency set with 89 frequency triples was used. Figure 8 shows the rating of the frequency triples on the basis of the determined parameters 'number of clusters', 'average cluster density' and 'average cluster distance'. The frequency triples with high rating (pink, e.g. 33), frequency triples with lower rating (yellow, e.g. 36) and frequency triples with worse rating (red, e.g. 16) are marked. The clustered 3CFRDs of these three frequency triples are shown in Figure 9.

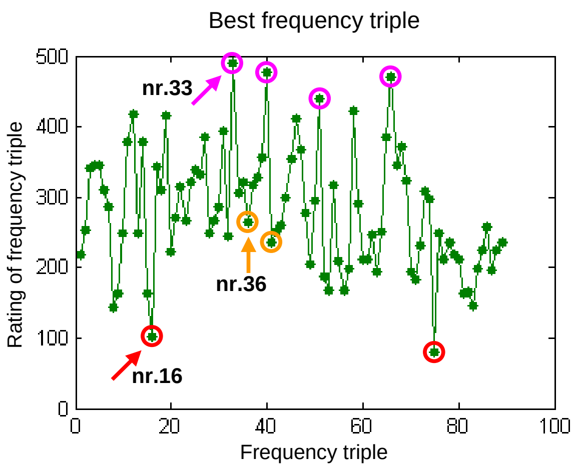

Figure 8: Rating of 89 different frequency triples for test setup with four artificial PD defects

In the 3CFRD (A) rated as best, six clusters were identified. Back transformation showed that cluster 3 belongs to the surface discharge and cluster 4 to the tip on HV in air. The clusters 1 and 2 on the left side could be related to the internal PD while clusters 5 and 6 next to the center belong to the tip on earth in GIS. Both PD defects cause two clusters, one for PDs in every half cycle of the test voltage. The 3CFRD (B) has a lower rating. Here four clusters could be identified, one for each PD defect. In contrast to 3CFRD (A) the distances between the clusters are much smaller and hence the separability is worse. The 3CFRD (C) was rated worst. Here the clusters are superposed. A separation is not possible.

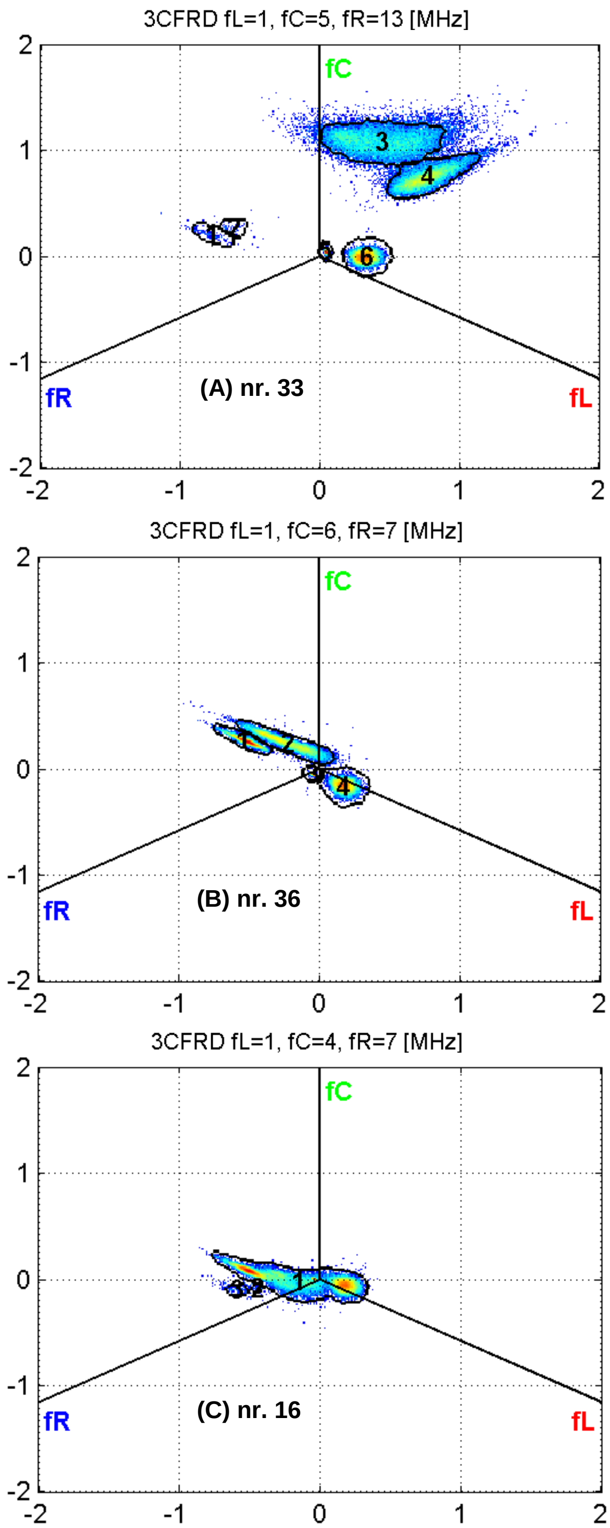

Figure 9: Clustered 3CFRDs for (A) frequency triple 33, (B) frequency triple 36 and (C) frequency triple 16 (see Figure 8)

6 CONCLUSION

- For separation of different PD sources and disturbances in 3CFRD an automated determination of the frequencies is meaningful.
- The presented concept for automation is subdivided in the pre-selection of frequencies, the acquisition of PD data and the evaluation of PD data.
- A limitation of the initial number of possible combinations of frequencies is necessary to shorten the time needed for analysis. The limitation by frequency range of PD measurement equipment and a-priori knowledge on asset and test setup are some of the most important ones.
- A pre-processing of the recorded PD data by means of de-noising is meaningful. It reduces time for further processing of data and improves the reliability of the method.

- For comparison and rating of the 3CFRDs three parameters for quantification were defined. The most important parameter for quantification is ‘number of clusters’ and should have the highest influence to the rating of the 3CFRDs.
- The quality of quantification of the 3CFRDs strongly depends on right clustering. The clustering algorithms DBSCAN and OPTICS provide a proper solution for clustering of 3CFRDs.
- With presented method at different test setups the frequency triples for optimal separation could be determined.

It is planned to test the new method of automated determination of frequency parameters at different assets under on-site conditions and to implement the method in a commercial available PD measuring system.

7 REFERENCES

[1] R. Plath: “Multi-channel PD measurements”, 14th International Symposium on High Voltage Engineering, pp. J-04, Beijing, China, August 2005

[2] W. Koltunowicz, R. Plath: ”Synchronous Multi-channel PD measurements”, IEEE Trans. Dielect. Elect. Insulation, Vol. 15, Issue 6, pp.1715-1723, December 2008

[3] A. Obralic, C. Balkon, W. Kalkner, R. Plath: “Potential of a multispectral PD-measurement on HV-machines”, 2008 International Symposium on Electrical Insulating Materials, Mie, Japan, pp. 621-624, September 2008

[4] Balkon, W. Kalkner, A. Obralic, R. Plath and K. Rethmeier: “Potential of Multispectral PD Measurement for Differentation of Interfering Impulses and Multiple PD sources” ,16th International Symposium on High Voltage Engineering, Cape Town, Southafrica, pp. 1003-1008, 2009

[5] Rethmeier, A. Obralic, A. Kraetge, M. Krüger, W. Kalkner, R. Plath: “Improved noise suppression by realtime pulsewaveform analysis of PD pulses and pulseshaped disturbances“,16th International Symposium on High Voltage Engineering, Cape Town, Southafrica, pp. 318-323, 2009

[6] S. Schaper, A. Obralic, R. Plath, W. Kalkner: “Synchronous Multi Terminal On-Site PD Measurements on Power Transformers with an Enhanced Time Differential valuation Method”, 15th International Symposium on High Voltage Engineering, Ljubljana, Slovenia, T7-535, 2007

[7] M. Ester, H.-P. Kriegel, J. Sander und X. Xu: „A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise”, 2nd Int. Conf. on Knowledge Discovery and Data Mining (KDD’96), Portland, OR, pp. 291–316, 1996

[8] Alija Obralic: „Wicklungsdiagnose an rotierenden elektrischen Maschinen mittels digitaler, synchroner Mehrstellen-TE-Analyse“, diploma theses, Technische Universität Berlin, 2008

[9] M. Ankerst, M. M. Breunig, H.-P. Kriegel und J. Sander: „OPTICS: Ordering Points to Identify the Clustering Structure”, ACM SIGMOD Int. Conf. on Management of Data (SIGMOD’99), Philadelphia, PA, pp. 49–60, 1999