Article

Partial discharge measurements on rotating machines – experience and innovation

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Abstract

Partial Discharge (PD) measurement is nowadays a worldwide accepted method for the condition-based assessment of stator insulation. The advantage of having a fully digital PD measuring system, with advanced hardware and software capabilities that allow improved insulation diagnosis by means of PD analysis, is shown. The sensitivity of the PD measurements can be strongly limited by a high noise level. State-of-the-art features based on synchronous multi-channel and multi-frequency techniques for signal separation of noise and PD defects are presented. The examples of data evaluation are described and the use of the automated PD pattern recognition system is also discussed.

Introduction

Rotating electrical machines (motors and generators) are among the most critical features of a properly functioning energy supply system or industrial production facility. Unscheduled downtime in the generation of electrical energy or the failure of a motor on a production line can be a very expensive matter. Damage to the stator insulation of a machine is a frequent cause of defects in such equipment. Partial Discharge (PD) measurement is an appropriate diagnosis and maintenance tool that provides reliable and timely status identification, and has proved itself in the field on countless occasions.

This article examines the benefits in more detail. A comparison of off-line and on-line PD measurement are given, as are the reasons why such measurements on rotating electrical machines are so useful. We will also examine how digital, software-assisted PD measuring systems support users in their work. This extends from the separation of the various PD sources in the machine to the automatic interpretation of the phenomena.

Measuring of partial discharges

The PD measurement of windings in rotating electrical machines provides a non-destructive and non-invasive method of identifying individual discharge sites in their insulation. In the epoxy resin mica insulation used in medium-voltage machines, such sites can result from internal discharges, delamination of insulation layers, mechanical erosion resulting from vibration or the abrading of control coatings, to name just a few. The above methods differ from others, for example, insulation resistance or loss factor measurements, in that they provide a comprehensive picture of the condition of the insulation of the entire winding, individual phases or phase belts, regardless of the extent to which the winding can be separated.

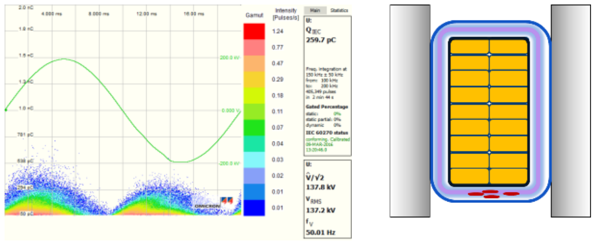
Like the other two methods, the results of a PD measurement have to be interpreted once the measurement has been carried out. Modern measuring instruments provide very elegant recording methods, such as stream files, that enable the measurement to be replayed as a film on a PC as often as required.

The physics underpinning partial discharges is a comprehensive subject and a full description is beyond the scope of this article. Nevertheless, it will be helpful to provide the brief description as follows:

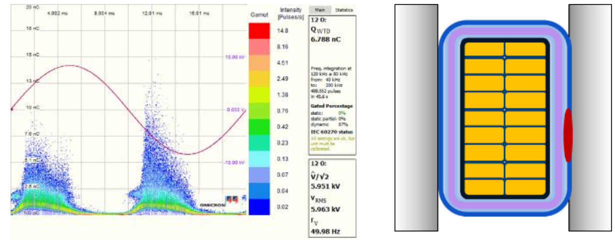
According to IEC 60270, “A partial discharge is defined as the dielectric breakdown of the insulation of high-voltage equipment as a result of a localized increase in field strength caused by contamination or discharge sites in the insulating medium. The electromagnetic pulse released as a result can be measured to provide an indication of the condition of the insulation.”

Measuring partial discharges enables manufacturing faults and aging in the insulation of electrical machines to be identified, thus enabling potential causes of machine failures to be identified in good time. The ensuing maintenance activities can then be scheduled to facilitate the targeted deployment of frequently scarce resources.

What is known as the PRPD pattern has established itself as the most reliable way of interpreting the PD measurement. PRPD stands for **P**hase **R**esolved **P**artial **D**ischarge. This approach correlates the individual PD pulses in terms of their frequency, amplitude, polarity and phase with respect to the high voltage. Its advantage lies in the mapping of typical patterns to the type of defect in the winding. This enables not just the identification of the type of fault, it also provides a classification of the risk in accordance with international standards. One example is illustrated in Figure 1, where the phase resolved pattern is correlated with the corresponding known defects.



Discharges in the insulation, or internal discharges



Discharges between conductor and the earthed metal surrounding the conductor, or slot discharges

Figure 1: Phase resolved partial discharge pattern with associated defects

Besides the phase resolved patterns of the individual measurement, interpreting the results from a number of consecutive measurements provides the most reliable evidence concerning the condition of the insulation in a machine. Any change to the pattern of the phase resolved results, or a rapid increase in amplitude, is a sure sign that further actions are needed. This necessitates taking PD measurements at regular intervals using an external high-voltage source (hereafter referred to as off-line PD measurement), or continuous measurements on the machine, with no external source, while it is running (known as on-line PD measurement). Both methods have their advantages and disadvantages, which will be looked at in more detail in this article.

Efforts are often made to define limiting values for partial discharges and to assess the condition of the insulation simply by noting the amplitude of the PD. This represents a misguided attempt to resolve complex processes by the use of a YES/NO criterion. Only on very rare occasions can a single measurement trigger immediate need for action.

The PD measurement is an appropriate maintenance tool that identifies the condition of the insulation of rotating electrical machines and, on this basis, helps the engineering team determine what maintenance measures to adopt across the machine park.

Propagation response of the PD pulse in the winding

As direct measurement of the PD pulses at the discharge site is not possible in complex insulation systems, such as exist in generators or motors, the apparent charge, which can be measured on the terminals, is used instead to interpret the results of PD measurements.

To interpret the results of a PD measurement on the stator winding correctly, the test engineer should be aware that the short, unipolar PD pulse is transformed as it passes to the generator terminals by attenuation, reflections, dispersion and electromagnetic coupling effects into an oscillating signal that is extended to a greater or lesser extent. Depending on the filter settings on the measuring instrument, the amplitude values of the charge may be closely connected with the source of the charge. For this reason, the comparative measurement discussed above should always be carried out using the same parameters. To demonstrate this point, several holes were drilled into the stator winding of a decommissioned hydro generator with a rated power of 5,6 MVA. The aim here was to induce into the winding an artificial partial discharge pulse with a known amplitude and to measure the pulse on the terminal using a variety of filter settings.

Figure 2 shows the experimental setup. Various pulses with a defined charge of 10nC were injected along the winding. The measurement was taken at the terminals of the lead using a coupling capacitor Cc and a measuring impedance.

The result is something referred to as an "attenuation matrix" (Figure 3), which shows the apparent charge on the terminals as a function of the injection point of the artificial discharge site. Refer to (F. Öttl, 2016) for a more detailed description of the experiment and its results.

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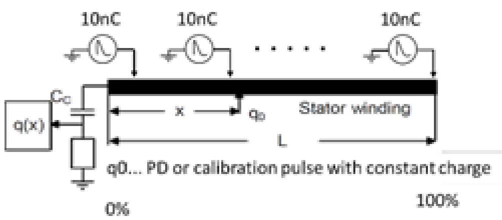


Figure 2: Equivalent circuit diagram of injection along the winding

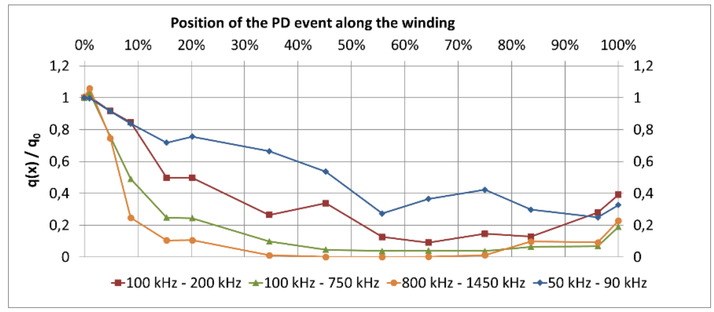


Figure 3: Attenuation matrix; result of measurement on the lead when injecting 10nC along the winding, recorded at various filter frequencies.

The result of these frequency-selective measurements confirms the well-known fact that a reliable measurement of the apparent charge on generators is only possible when the bandpass filter is set to a low mid-band frequency.

The advantage of frequency-selective measurement can be clearly seen in Figure 3. Depending on the filter frequency, the various injection locations are more or less pronounced. This feature is used by modern PD measuring systems to separate the sources.

Quasi-integration and peak detection

As already mentioned, the PD measurement determines the apparent charge. The result of the measurement is shown in coulomb. In the Anglo-American world, the values are usually expressed in mV. One frequently asks question concerning the extent to which the two measurement methods can be compared. The short answer is as follows: The nC and mV values cannot be compared with one another.

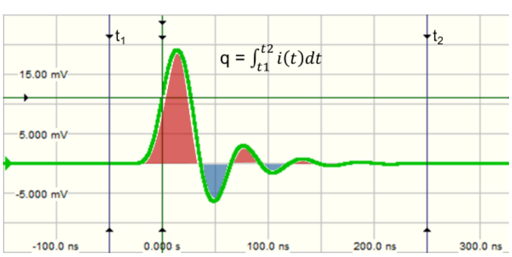


Figure 4: Integration of apparent charge in time window

Put simply, the calculation of the apparent charge can be seen as an integration of the area enclosed by the PD pulse (Figure 4). This explanation is not 100% correct, as the DC-components of the signal cannot pass the coupling capacitor. For all further explanations, the model is sufficient. This method has two major advantages:

- First, the area is proportional to the energy released at the discharge site and hence to the size of the discharge site.

- Second, other defects, whose sources lie some distance from the terminals, can be detected to a reasonable degree of accuracy (Figure 3), as, assuming the appropriate filter is selected, the "slow" frequency components of the pulse can be measured.

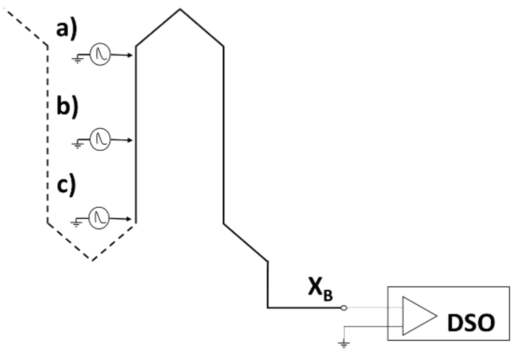
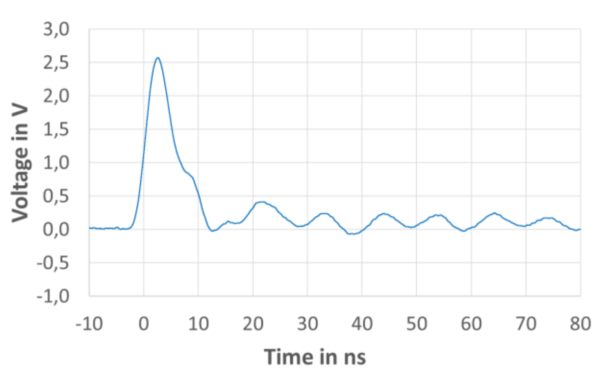
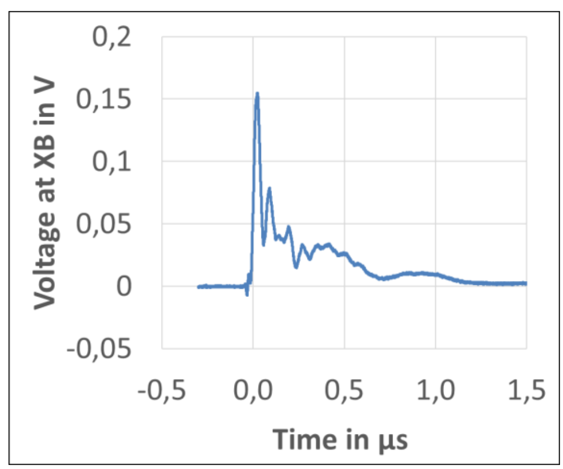


Figure 5: Winding diagram showing injection points and digital oscilloscope on the measuring point.

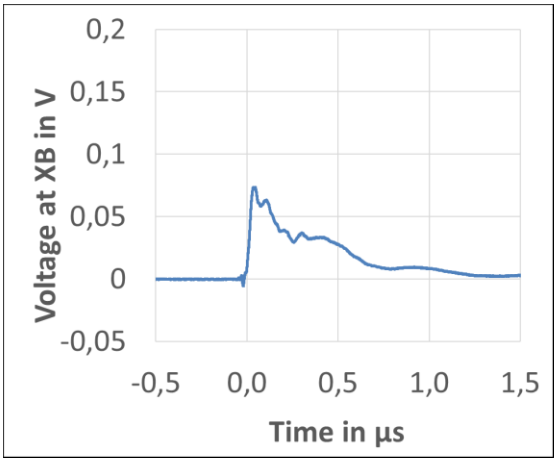
Peak detection, on the other hand, measures the highest peak of the time signal in mV and, therefore, requires a very wide broadband filter. The high-speed components of the signal dominate, but are very strongly attenuated after just a few sections of winding. This is illustrated in Figure 6 using a practical measurement on a stator winding of a decommissioned hydro generator with a rated power of 102 MVA. The winding was made accessible in the straight portion and an impulse was injected on three positions close to the terminal where the measurement with a digital oscilloscope is taken. A comparison of the signals in Figure 6 shows a "stretching" of the signals, which, after flowing through a single bottom bar and sections of a top bar, are already exhibiting much longer rise/decay times than the short calibration pulse. The amplitude drops from 2.5 V to 155 mV (!) after just one Roebel bar. A measurement of the signals injected at points b) and c) shows a further reduction to 75 mV and 60 mV peak.



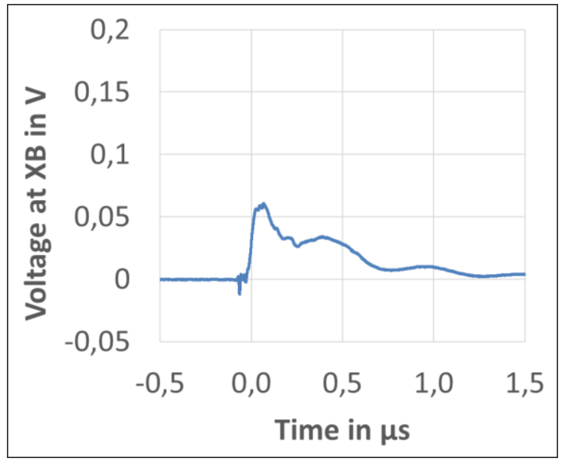
Injection pulse



Measurement on terminal X_B when injected at a)



Measurement on terminal X_B when injected at b)



Measurement on terminal X_B when injected at c)

Figure 6: Injection of the pulse at three different locations along the top bar in slot 2 (2nd bar after the star point) as shown in Figure 4. Attention: Note the different scales used for the injection signals.

As already noted, the effects of attenuation, reflection, dispersion and electromagnetic coupling cause the "stretching" of the signals, which are injected at distances of just 3 m and 5 m from the terminal.

On-line or off-line partial discharge measurement

If the above mV measurement is repeated by measuring the apparent charge at the same injection locations, the injected 10 nC will be detected as 9 – 9.5 nC at the terminals. Clearly, this depends on the filter settings in Figure 3, but applies to every "low frequency" filter bandwidth.

We have already seen that there are two possible ways of measuring partial discharges: Off-line measurements, where the machine is disconnected and the test voltage comes from an external source, and on-line measurements, where the machine is kept running and sporadic or continuous measurements are made using pre-installed coupling capacitors (Figure 7).

Figure 7: On-line measurement with installed coupling capacitors

In the case of an on-line measurement, data can be generated at various operating points and under varying load or temperature conditions without having to shut down the machine. The measurements are, therefore, being made under real operating conditions (Badicu, 2016). This advantage is affected however by a much higher likelihood that external interference is present. This does not come from the insulation system in the machine, so it must not be included in the diagnosis. To circumvent this problem and to ensure an adequate distance between useful signal and unwanted signal, higher filter frequencies will normally need to be used.

As described earlier, the measured high frequency components will be attenuated very rapidly between their source and the measurement location, which means that only parts of the winding can be properly diagnosed. By way of compensation, the voltage distribution of the winding towards the star point decreases when the machine is in operation.

Off-line measurements differ in that the entire winding is raised to the same high-voltage potential so that any discharge sites that do not appear during operation will be seen in the phase resolved pattern, greatly increasing the chances of early detection. Another advantage is the generally very low noise level, which means that much lower filter frequencies can be used. This enables slow pulses to be measured, which results in the detection of partial discharges along most of the winding. Off-line measurements also allow the test setup to be calibrated. These advantages are offset by the fact that the measurement is more expensive and time-consuming, as the machine has to be disconnected and an external source installed (Figure 8). On the other hand, this type of measurement is normally carried out while servicing is in progress.

As another disadvantage of off-line measurements, the influence of humidity has to be taken into account. This can have significant influence on the outer discharges such as slot discharges and/or surface discharges.

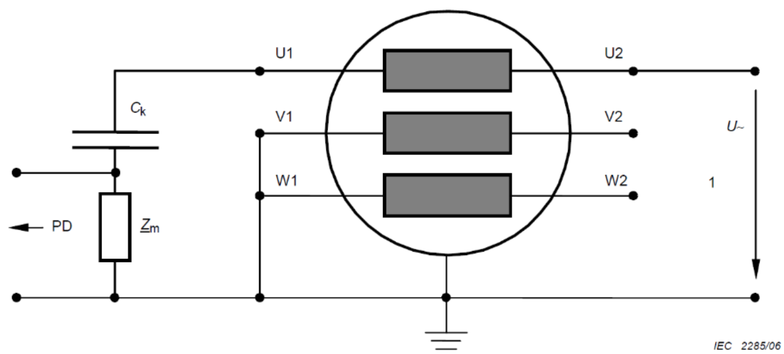


Figure 8: Equivalent electrical circuit of the off-line measurement for a channel on phase U.

As the two types of measurement have their advantages and disadvantages and offer differing diagnostic possibilities, Off-line and on-line measurements can be viewed as complementary ways of determining the condition of the insulation.

Separating the partial discharge phenomena

Anyone who has performed any PD measurements on a motor or generator will know only too well that the results are normally taken from two or more PD sources. To make a reliable assessment of the risk arising from the individual phenomena, it is therefore important to separate these individual PD sources. The test engineer is normally confronted by three challenges:

1) External interference
2) Superimposition of various PD phenomena
3) Cross-coupling from neighboring phases (on-line measurement)

To reduce signal interference as much as possible, the signals can be digitized at the point of acquisition. The long-distance transmission of analog signals is no longer done, which makes the measurement as robust and as reliable as it can be. Frequency-selective measuring systems also offer the ability to choose different filter settings and even measure at higher frequencies where noise levels are much lower. This should be done with the utmost caution, however, as the sensitivity of the measurement is strongly affected by this parameter (Figure 3).

Items 2) and 3) above can be considered as a whole. It can be very difficult to differentiate between the various phenomena in a single phase resolved pattern. In addition to experience, the insertion of the individual PD sources at various voltage intervals in an off-line measurement can, for example, help with the interpretation. If the latter is not possible, or high noise levels are present during on-line measurement, frequency-selective, synchronous, multi-channel measuring systems offer software-based tools that make it easier for the user to draw justifiable conclusions. Examples of these include:

- 3PARD (3 **P**hase **A**mplitude **R**atio **D**iagram)
- 3CFRD (3 **C**enter **F**requency **R**atio **D**iagram)

3PARD

A schematic representation of how 3PARD works can be found in Figure 9. Three synchronous channels – in this case the phases L1, L2 and L3 – detect the same partial discharge pulse at varying amplitudes within a user-defined time window. If we assume that the phenomenon occurs in L1, this is where the intensity will be highest. The two other channels also measure the pulse by cross-coupling in the winding. The amplitude is now transformed into a vector which, when graphically aggregated, gives a point, in the 3PARD star diagram. If the PD source crops up regularly, the various points form a cloud, also referred to as a "cluster". Differing PD sources form various clusters in the diagram. These clusters can then be separated and transformed back into a phase resolved pattern for further analysis.

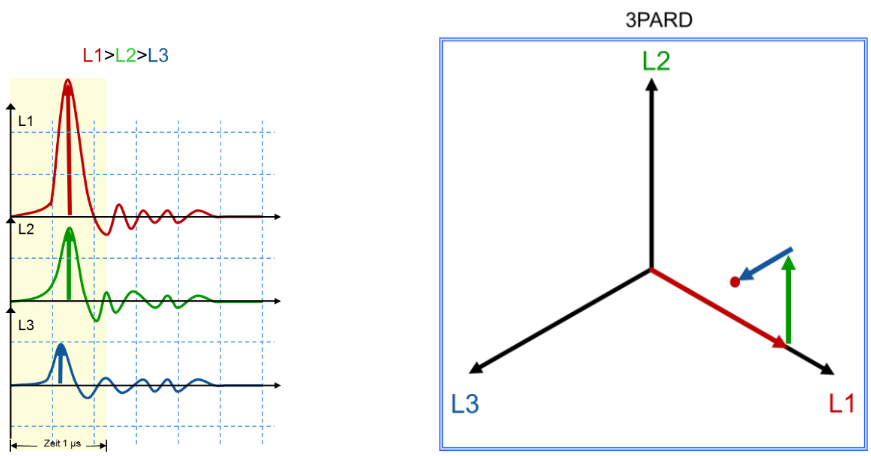


Figure 9: How 3PARD works; Left: The pulse is detected at varying amplitudes in the three channels; Right: Graphical aggregation of the vectors in a 3PARD diagram.

The practical example shown in Figure 10 will help clarify matters. The three individual, synchronous channels and their phase resolved PD patterns are shown on the left. As this is an on-line measurement, the phase of each one is shifted 120°. The amplitude of the charge in the individual phase resolved patterns is the instantaneous value in coulomb. The presence of numerous PD sources, some of which overlap, can clearly be seen. The 3PARD view is depicted on the right-hand side of the figure.

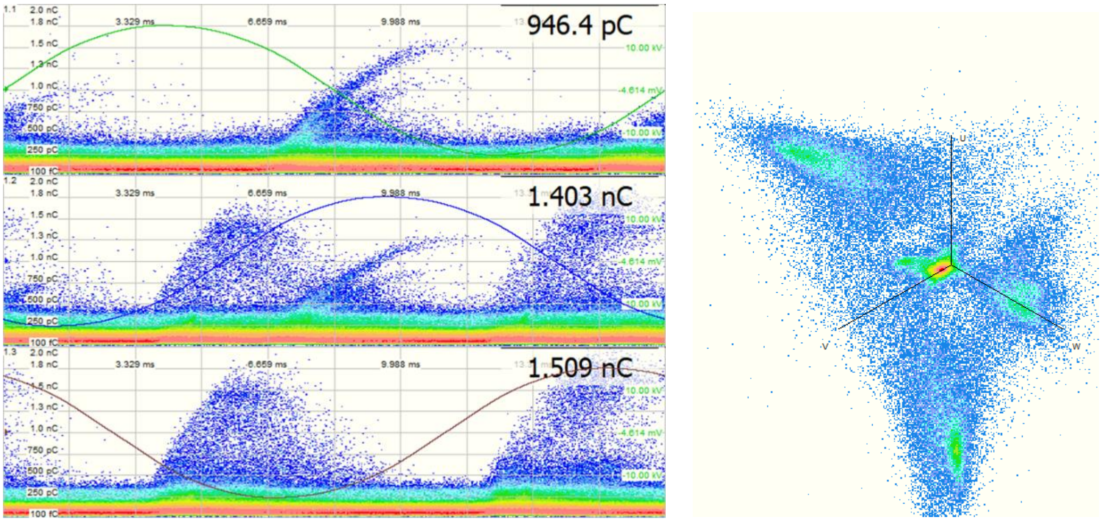


Figure 10: 3PARD, practical example with output measurement and 3PARD view.

The four clusters in this view can now be identified and transformed back into their phase resolved PD patterns. Figure 11 explains the procedure. The individual phenomena can then be identified and a risk assessment carried out. With a little experience, the delamination in cluster 2 and the winding head discharges between phases V and W will also be apparent from the original measurement. However, the internal discharge in cluster 4 cannot be seen in the original measurement, as it is completely concealed by the noise identified by cluster 1.

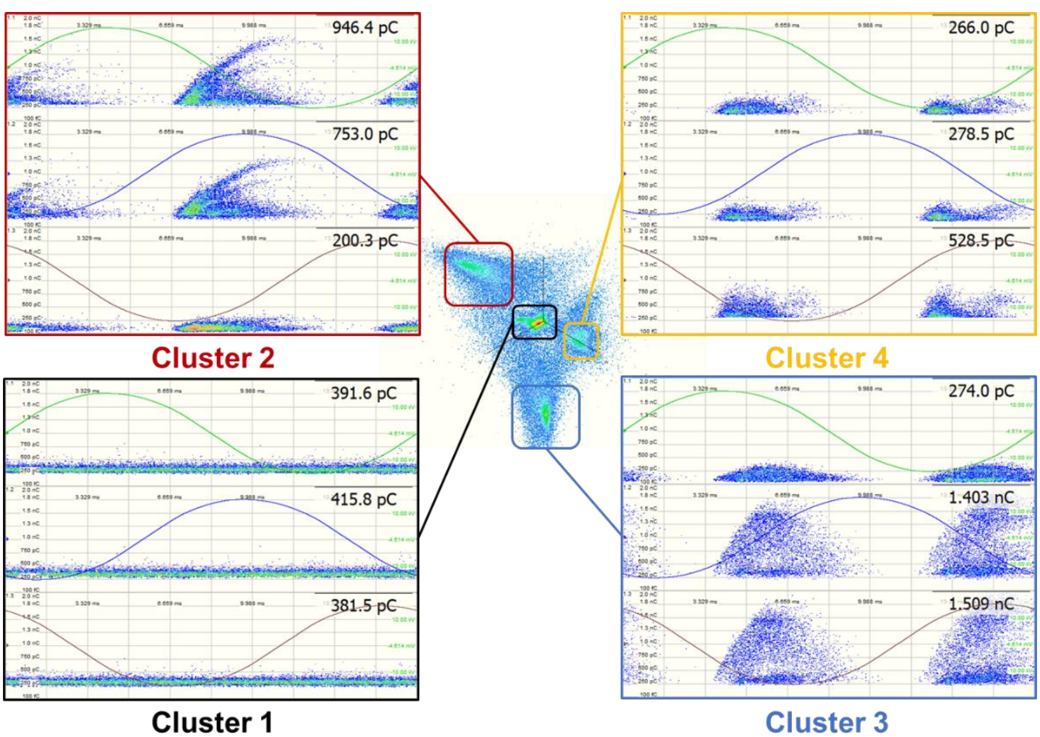


Figure 11: Separating the PD sources in Figure 10.

3CFRD

The 3CFRD method separates the PD sources in a similar manner and is primarily used in situations where it is not possible to measure using three channels, or where an additional decision criterion apart from 3FREQ is required. This method measures the PD pulses at the same time using three different filter bandwidths. Depending on the creation mechanism, signal propagation and attenuation, different PD sources also have different amplitudes in the respective filter settings (Figure 12).

These in turn are entered into the star diagram described above and, after graphical aggregation, form clusters for the various PD phenomena.

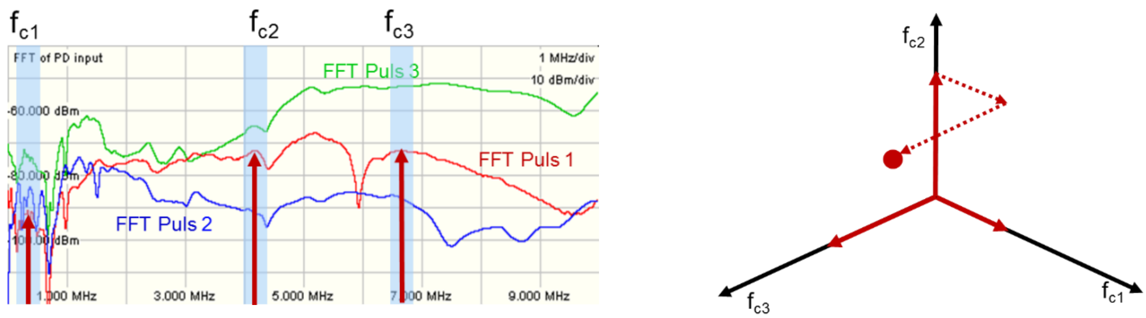


Figure 12: 3CFRD principle; once they have been graphically aggregated in the right-hand diagram, which shows the red PD pulse, each of the three PD sources in the diagram on the left form different clusters.

Automatic cluster recognition

Software tools that support the cluster separation described above are available. Automatic separation is a precondition for the next stage to provide as much support as possible during the evaluation. As described above, it can be assumed that each cluster represents a PD source. The various defects generate partial discharges whose phase resolved patterns have long been familiar. Following the automatic separation of the PD sources is presented, these patterns can be interpreted automatically using the software.

However, the result of this software-assisted interpretation does depend on certain system parameters, one of the most significant being the measuring time, as this must be long enough to generate sufficiently clear PRPD patterns. Assuming this is the case, the procedure can be split into the following five stages:

1. Creating the 3PARD with the separated clusters
2. Differentiating between PD source in the machine and other signals
3. Classification – Knowledge-based evaluation
4. Classification – Pattern recognition
5. Reporting

Cluster identification is performed using OPTICS (**O**rdering **P**oints **T**o **I**dentify the **C**lustering **S**tructure), a density-based algorithm for identifying clusters. Only those clusters with a sufficient point density are included. Individual points or clusters that are not dense enough will slip through the net due to their lack of data points.

The subsequent identification of unwanted signals and the ability to distinguish them from the useful signals of the machine insulation system eliminates all of the data points that are irrelevant as far as the interpretation is concerned. The software can identify a range of different noise phenomena, including asynchronous signals, such as the frequent "noise carpets" in the PRPD patterns, or synchronous interference, such as excitation pulses.

Once all the irrelevant clusters have been removed from the measurement, the software concentrates on interpreting those that remain. The first pass involves checking each cluster for attributes, such as those listed in Table 1.

Table 1: Example of attributes used to classify partial discharges

Attribute Name	Attribute Property
Pulse-charge variation on positive half	Wide
Pulse-charge symmetry on positive half	Symmetric
Pulse-charge behavior on positive half	Peaking
Polarity ratio	Equal polarity
Pulse-phase symmetry on positive half	Right-biased
Charge-phase regularity on positive half	Not flat
Charge-phase symmetry on positive half	Right-biased

The software executes a number of iterations along a decision tree. If one of the attributes is detected, the next criterion is then examined. The decision tree provides a deterministic procedure for identifying unique, clear instances. If one cannot be found, the software then resorts to pattern identification.

The patterns being examined are compared with a number of reference patterns stored in a database. The similarity between a measured phenomenon and an existing pattern is determined with the help of a Euclidean distance algorithm

$$d(x,y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)}$$

in which the distance x_i represents the property vector of the current PRPD pattern and y_i represents the property vector of the reference pattern. The index i is a placeholder for the various properties. If the distance is close to zero, it can be assumed that the measured phenomenon corresponds to the reference and that the type of defect has been identified.

A detailed report listing the various types of PD sources is output at the end of each automatic identification session.

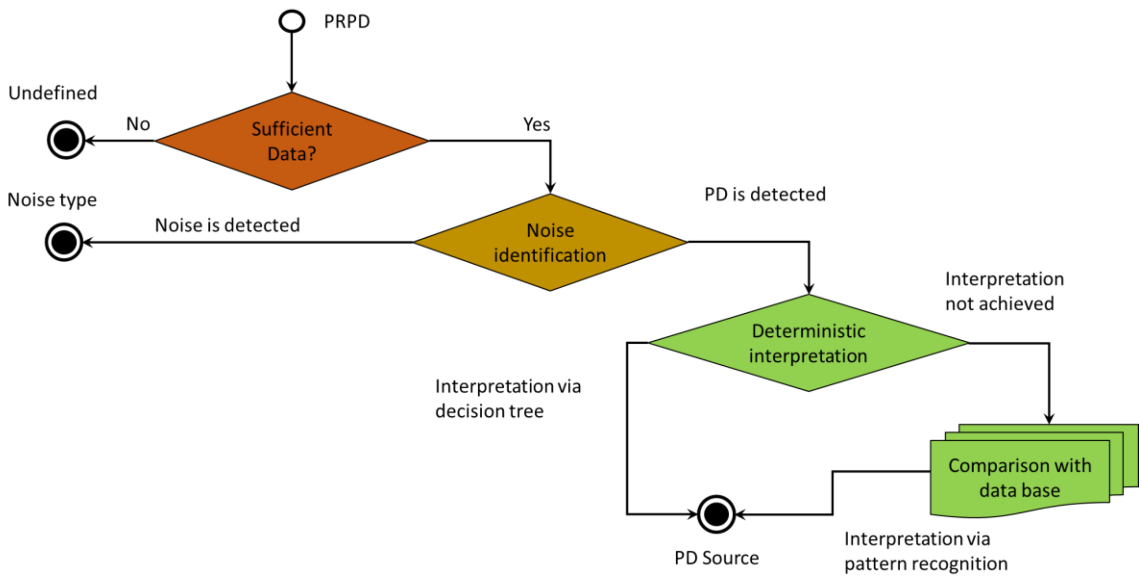


Figure 13: Overview of the process used during automatic interpretation.

We will now use another practical example to illustrate the described decision process. This uses a monitoring system for a 1160 MVA turbo rotor with a nominal voltage of 27 kV installed in 2012. The historical data is identified and evaluated using pattern recognition. The analyzed cluster is highlighted in red in Figure 14.

The analyzed cluster was identified as such by the program and determined to have enough data points. Classification on the basis of the attributes showed that it was a borderline case between two phenomena. For each of the three measurements, the system resorted to making a comparison with one of the phenomena stored in the database.

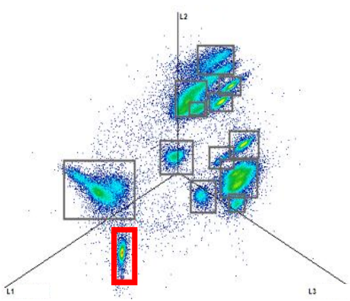
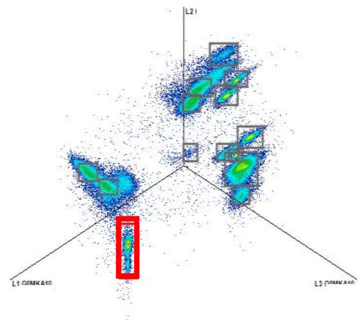
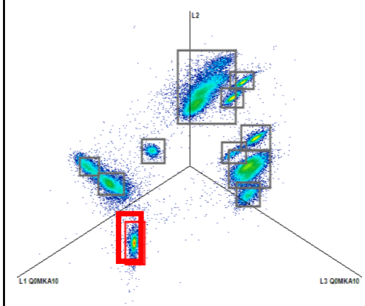
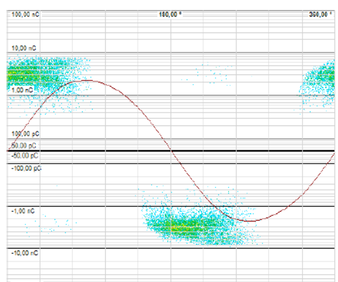
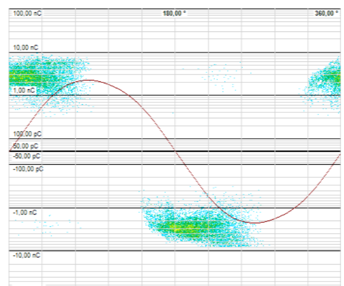
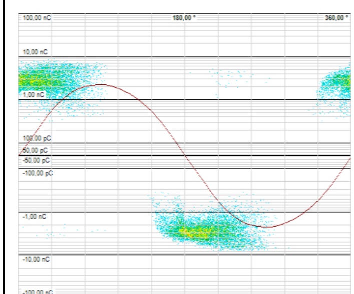
		01/2017	02/2017	03/2017
Example of an identification	3PARD			
	PRPD			
	Result	**Surfaces-Winding Head-Discharge – E1** Decision process: Sufficient data → Useful signal → Decision based on attributes – No firm conclusion → Comparison with PRPD database (E1 50%)	**Surfaces-Winding Head-Discharge – E1** Decision process: Sufficient data → Useful signal → Decision based on attributes – No firm conclusion → Comparison with PRPD database (E1 100%)	**Surfaces-Winding Head-Discharge – E1** Decision process: Sufficient data → Useful signal → Decision based on attributes – No firm conclusion → Comparison with PRPD database (E1 100%)

Figure 14: Cluster identification from a number of measurements with decision process.

Summary

The measurement of partial discharges in rotating electrical machines is today considered to be the electrical measurement method that enables the most detailed conclusions to be drawn regarding the insulation condition in a machine. Many different types of defects can be reliably identified and classified according to the risk they pose.

Despite the numerous advantages offered by this type of measurement, one must remain alert to the peculiarities of the measurement method when interpreting the results. Such peculiarities include the distributed capacitance of the winding, the type of connection, the interference caused by unwanted signals or the simultaneous occurrence of several PD phenomena.

Digital, frequency-selective PD systems provide users with a range of tools to control these peculiarities and enable justifiable conclusions to be drawn. These extend from digitization at the point of acquisition to measurement using various filter settings and the automatic interpretation of the different PD sources.

Authors

Fabian Oettl is Product Manager for the testing and measuring of rotating electrical machines at OMICRON electronics in Klaus, Austria. Before joining OMICRON, he worked as an insulation engineer in the research and development department of ANDRITZ Hydro, which is also based in Austria. He studied electrical engineering at the Technical University of Graz and graduated in 2011.

Michael Krueger is Principal Engineer for the testing and diagnosis of electrical equipment for OMICRON electronics in Klaus, Austria. He studied electrical engineering at RWTH in Aachen and at the University of Kaiserslautern, graduating in 1976. He obtained his PhD in engineering from the Technical University of Vienna in 1990. Michael Krüger has more than 40 years' experience in the field of high-voltage engineering and the diagnosis of transformers, instrument transformers, rotating electrical machines, cables and gas-insulated switchgear. He is a member of VDE, CIGRE and IEEE and is involved with several working groups of the ÖVE, CIGRE and the IEC.

Wojciech Koltunowicz graduated with a degree in electrical engineering in 1980, in 1985 and in 2004 respectively. He obtained a doctorate and a postdoctoral qualification in high-voltage engineering from the Technical University of Warsaw in Poland. Between 1987 and 2007 he worked for CESI in Italy, where he was involved in the testing and diagnosis of high-voltage systems. He has been a Senior Technical Consultant for OMICRON Energy Solutions in Berlin since 2007 and is engaged in the monitoring of high-voltage equipment. He is the Austrian representative on CIGRE Study Committee D1 “Materials and Emerging Test Techniques” and Chair of the CIGRE Working Group WG D1.66 “Requirements for Partial Discharge Monitoring Systems for Gas Insulated Systems”. He is also a member of IEC TC42 WG14.

Laurentiu Viorel Badicu graduated with a degree in electrical engineering in 2008. In 2012 obtained a doctorate in electrical engineering from the “Politehnica” University of Bucharest in Romania. He joined OMICRON Energy Solutions in Berlin as a test engineer in 2012, where he was involved in the maintenance of monitoring systems and assumed responsibility for the analysis of PD files and subsequent reporting. Since 2015, Badicu has been a Product Manager at OMICRON, where he is responsible for on-line monitoring systems and their development.

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