Bewertungsregeln für die TE-Diagnostik von verschiedenen betriebsgealterten Hochspannungsanalgen

Edward Gulski
Hochspannungslaboratorium
Technische Universität Delft
Niederlande

Kurzfassung

Die Anwendung digitaler TE-Auswertung in der Diagnostik verschiedener Hochspannungskomponenten ist heutzutage keine Kuriosität. Mit Hilfe von on-site, off-line und on-line Messsystemen wird weltweit versucht den Isolationszustand betriebsgealterten Analgen zu beurteilen.
Es ist bekannt das für diesen Zweck nicht nur störungsfreie, empfindliche TE-Messtechniken ausreichend sind aber auch entsprechende leistungsfähigen Interpretationsregeln entwickelt werden müssen, um die Relation zwischen der Fehlstelle selbst, den messbaren TE-Kenngrossen, der Konstruktion der Hochspannungsanlage und der Isolationsalterung aufzubauen.
In diesem Beitrag mit Hilfe von Praxis- und Laborergebnissen die Möglichkeiten und Grenzen von Bewertungsregeln gezeigt werden.

1. General

Due to the service life of high voltage components the insulating materials are exposed to structural changes. In most cases these changes can be seen as a degradation of the insulation propertied of a particular HV equipment.
In order to detect changes in the insulation at a early stage and also to get insight to the maximum service life of a HV component, predictive maintenance is often recommenced and in several cases already in use.

In the last ten years the use of digital PD measuring techniques for quality assurance in the works, during on-site testing as well as for monitoring purposes during service life of HV components like transformers, generators, cables and GIS is getting increasing attention:

- *IEC 60270 CD Partial Discharge Measurements*. With this document of the IEC TC 42 the use of digital PD detectors for routine measurements as well as for diagnostic of HV components has become its acceptance.
- *Calibration Procedures for analog and Digital PD Measuring Instruments* (Electra No. 179 August 1998). With this paper of the TF 33.03.05 the technical background has been created to support the revised IEC 60270 document.
- *Cigre Data Format for GIS PD Software Applications* (Electra No. 177 April 1998). This format introduced by TF 15.03.08 opens new possibilities of systematic use of PD derived quantities for collecting and exchange of PD measuring data as well as developing PD data bases and possible knowledge rules to support PD diagnostic.
- *PD Measurement as a Diagnostic Tool*, (Electra No. 181 December 1998). This paper describes PD data interpretation for industrial power capacitors.

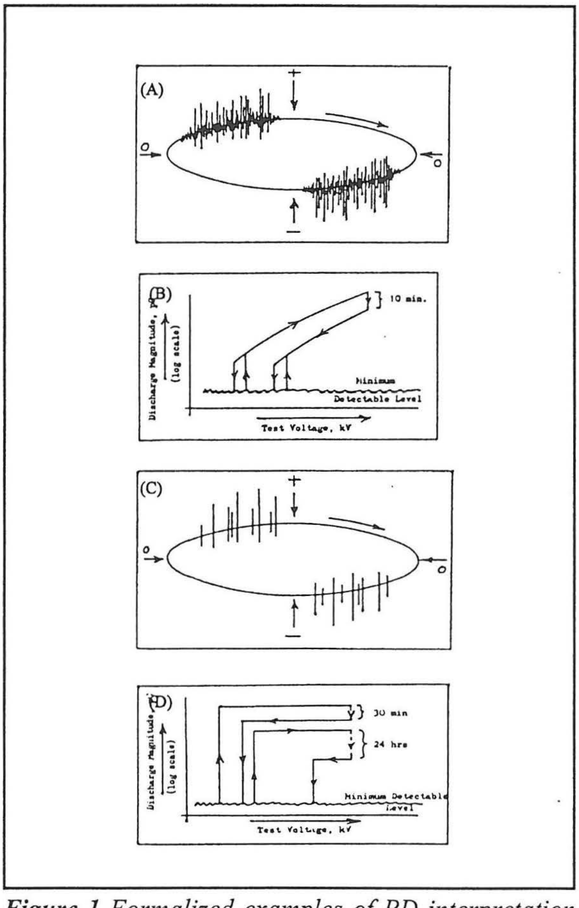

Figure 1 Formalized examples of PD interpretation rules to recognize different discharging defects in polymeric insulation [cigre WG 21.03]:
Relation between PD magnitude and test voltage (A) and the phase-resolved PD pattern (B) for fissures in the insulation
Relation between PD magnitude and test voltage (C) and the phase-resolved PD pattern (D) for multiple cavities in the insulation

Already in 1969 Cigre WG 21.03 has published a systematic indicating analog measured PD patterns, which are relevant for different defects in HV insulation **(figure 1)**. This document has established the importance of recording the PD patterns. By means of simple knowledge rules developed for *qV-curve* and the *PD ellipse* world wide technique has been introduced to support electrical engineers in interpreting PD measurements and recognizing typical insulation faults.

Since more than twenty years this document is still the only one, which describes systematically the different insulation defects and their individual manifestation by PD quantities.

In the last years more than ten different digital PD analyzers are commercially available and are in use in the field of PD diagnostics. It is also known, that with modern PD off-line and on-line measuring techniques the discharge process occurring in the insulation can be described by means of several digitally processed 1-, 2- and 3 dimensional PD quantities. As compared to analog PD detection, in this way much more data from PD measurements are available. Nevertheless no systematic interpretation rules have been developed to use the combined information as provided by particular PD quantities.

The goal of this paper is to discuss the possibility of interpretation (knowledge) rules to support PD diagnostic of HV components.

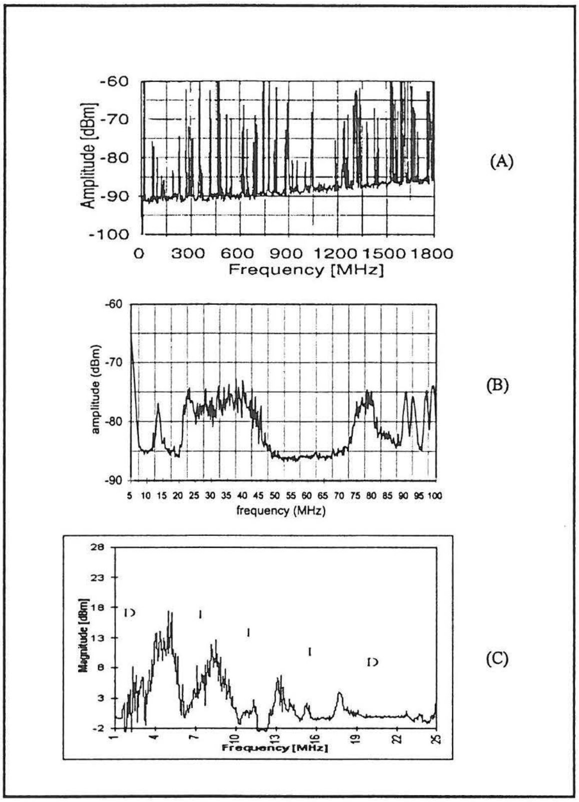

Figure 2 Examples of PD spectrum observed using VHF/UHF PD detection methods for different discharges in HV components:

a) off-line detection of Free moving particle in 345 GIS,

b) on-line detection of internal discharges in 11 years old 50 MVA turbogenerator,

c) off-line detection of internal discharges in a 47 years old 50kV/10kV, 14 MVA power transformer.

2. PARTIAL DISCHARGE QUANTITIES

The use of a computer-aided system offers the opportunity to store sequences of the discharge pulses and to post-process these in the course of time or as a function of the power frequency cycle. In this way a complete data recording is made, and a basis is created for further evaluation and diagnosis of the insulating systems.

2.1 Basis quantities

A digital instrument which provides registration of the discharge signals and the test voltage may process in general the PD pulse in frequency and time domine. As a result for a PD phenomenon several parameters can be determined (**figures 2-4**):

- PD pulse spectrum; in [dBm]

- Discharge magnitude q_i; in [pC]. [nC], [µV]
- Discharge phase ϕ_i; in [ms], [°]
- PD intensity;

2.2 Time functions of derived quantities

It's known that the behavior of discharges may be very complex due to their dependency to a wide range of conditions at the discharge site, and to the voltage level. Moreover, depending on 'aging effects' at the discharge site different types of behavior can be observed in the course of time. In figure 3 an example of PD magnitude observed for discharging defect in a cable termination till breakdown is shown. Observing the PD magnitude no indication of breakdown was present.

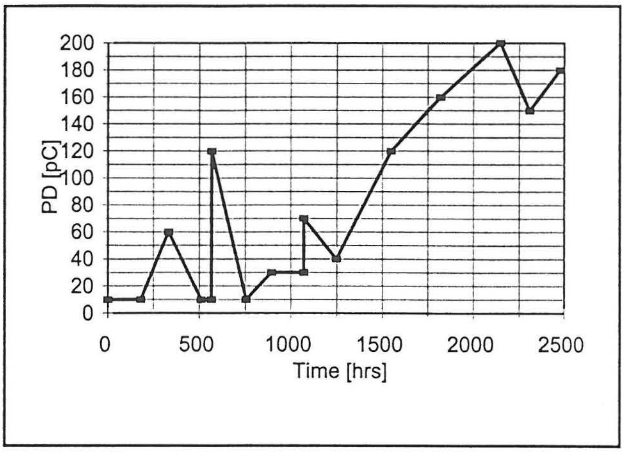

Figure 3 *Time behavior of PD magnitude as observed on a 12/20 kV cable termination during 2500 hours aging till breakdown.*

2.3 Intensity histograms of discharge and energy magnitudes

The observation of these PD intensity spectra can give interesting additional information about discharge sources. In figure 5 intensity spectra are shown of discharge magnitudes observed for a transformer in a 'good' condition and for a transformer showing internal defects. It follows from this example that the differences in the shape are clearly visible and it's clear that using this PD quantity additional information can be obtained to analyze different PD sources.

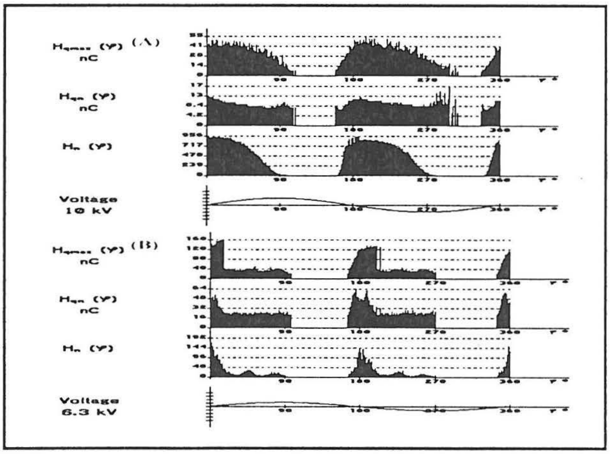

Figure 4 *Examples of PD patterns observed for 63 MW turbogenerators*
(A) regular PD pattern: the sinus envelope of the two phase-resolved distributions $H_{qmax}(\Phi)$, and $H_n(\Phi)$ as well as the flat shape of the $H_{qn}(\Phi)$ are typical for turbogenerators without insulation degradation.
(B) irregular PD pattern: the phase-resolved distributions $H_{qmax}(\Phi)$, $H_{qn}(\Phi)$ and $H_n(\Phi)$ are typical for 6MW and 63MW turbogenerators showing discharges in HV bushing.

2.4 Distributions of phase-related derived quantities

Most frequently used PD quantity is the phase-resolved PD pattern. These quantities observed throughout the whole cycle (0..360°) result in the following types of distributions:

- $H_q(\phi)$: distribution of the discharges magnitudes ,

- $H_n(\phi)$: distribution of the number of discharges,
- $H_n(\phi,q)$: combination of PD magnitude and its intensity

In figures 6 examples of phase distributions are shown as observed for turbogenerators 'good' condition and with a presence of winding discharges. Looking at these distributions it's clear that each distribution is characterized by its specific shape. These shapes can be explained in terms of PD inception conditions.

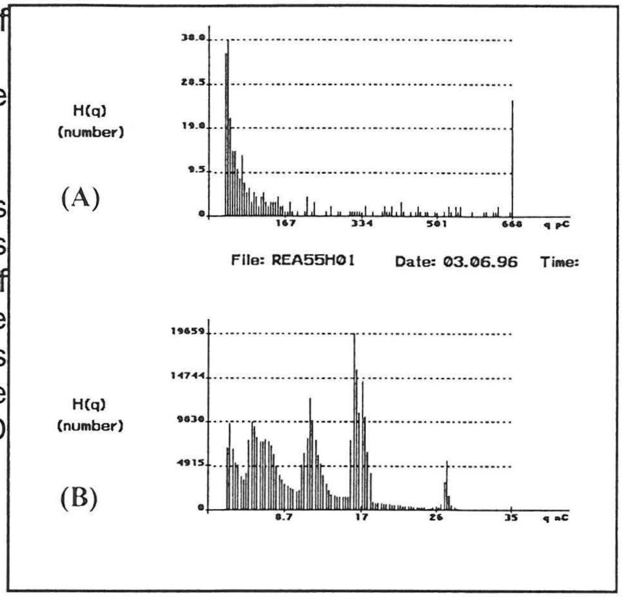

Figure 5 *PD intensity distribution H(q) as observed within 2 minutes for a 55 MVA reactor containing discharges on a damaged screen inside the test objects.*

3. EVALUATION CRITERIA

As shown in previous chapter a lot of experience is available to evaluate PD measurements. With regard to the PD pulse spectrum, discharge magnitude and discharge phase-position, as well as the repetition rate, different quantities have been discussed and their usefulness in the analysis of insulation defects is shown.
With regard to particular type of HV component combining information about characteristics observed for each PD quantities can be used to support the interpretation of measuring data. In the following sections examples of applying combination of different PD quantities characteristics to obtain additional information about the discharging site in the test object.

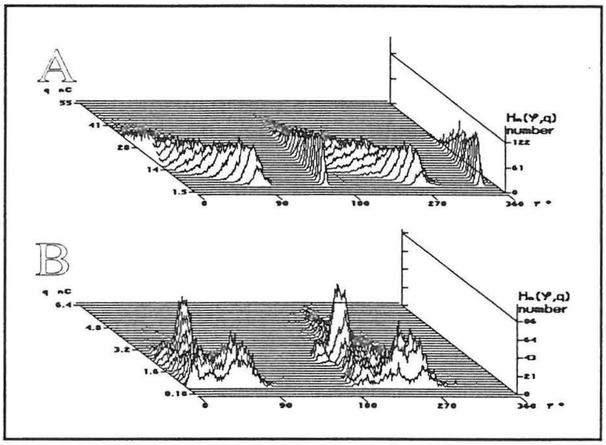

Figure 6 *Examples of PD patterns observed for turbogenerators:*

A) *regular PD pattern; the outer and inner sinusoidal shapes of the 3D phase-resolved distribution $H_n(\Phi,q)$ are typical for turbogenerators in good condition,*

B) *irregular PD pattern; this $H_n(\Phi,q)$ phase-resolved distribution was observed for endwinding discharges.*

3.1 Diagnostic of Power Transformers

It is know that on the base of one-hour induced voltage test of a power transformer important conclusions are made regarding insulation conditions of the test object. It is also known that these HV apparatus are no discharge free. On the contrary, a certain level of discharges <500 pC is allowed and most interpretation of the measuring results depends on knowledge of test engineers. The main goal of digital diagnosis support was to provide addition information about the PD process.

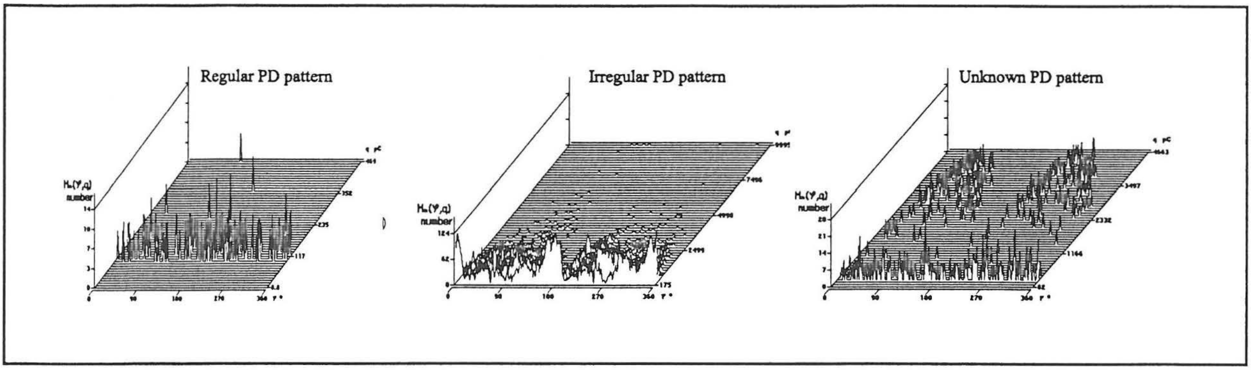

Figure 7 Example of discrimination criteria for PD pattern analysis during induced voltage test of power transformers.

a)	*Regular PD pattern;*	*low PD magnitude;*	*low PD intensity*
b)	*Irregular PD pattern;*	*high PD magnitude;*	*high PD intensity*
c)	*Unknown PD pattern;*	*high PD magnitude;*	*low PD intensity*

In particular to indicate if the PD is a regular one (no deviation form a normal situation) or that the PD process is irregular which measn that discharging defects are present). To support this decision and based on different PD quantities three discrimination criteria have been defined:

***Table 1** PD quantities and their characteristics used in interpretation rules for induced test on power transformers.*

PD magnitude; pattern reading	*< 1 nC*	*> 1 nC*
PD intensity; pattern reading	*low*	*high*
PD pattern based on PD database	*regular*	*irregular*
PD pattern change during and after enhanced voltage level	*no significant change*	*significant change*
PD magnitude during entire test	*low*	*high*
PD intensity during entire test	*low*	*high*
Number of the PD processes; pattern reading	*one*	*several*

The information about particular PD quantity was collected from the measurement and classified by the test engineer. For regular PD behavior, for irregular PD behavior examples are shown (**table 1, figure 7**. The questions asked in the data protocol have been designed to obtain an answer about the presence of discharging defects in the transformer insulation.

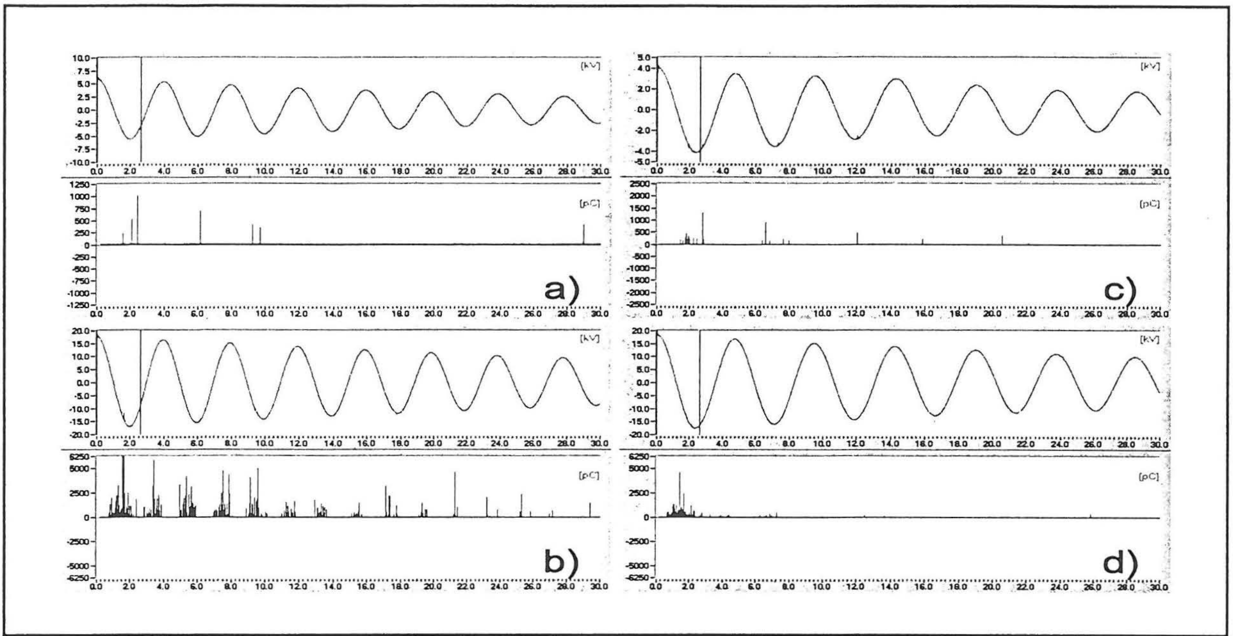

Figure 8 *Examples of MV power cable PD diagnostic on-site. PD quantities: PD inception, PD level, PD pattern of two cable sections of different age of the same type of paper/oil cable insulation and oil filled joints are compared here. In both cases using traveling wave method the discharges were located in oil filled joints.*
a) 2870m long section from 1960: 1 nC PD inception at 6 kV; PD intensity low; PD pattern single pulses,
b) 2870m long section from 1960: 6 nC PD at 18 kV; PD intensity high; PD pattern repetitive,
c) 1606m long section from 1973: 1.5 nC PD inception at 4 kV; PD intensity low; PD pattern repetitive,
d) 1606m long section from 1973: 4 nC at 18 kV; PD intensity high; PD pattern no repetitive.

In total 18 typical PD patterns have been used to support the data discrimination between regular and irregular PD patterns. All information about PD magnitude, the PD time behavior, PD patterns etc. have been analyzed and weighted using some expert system. Finally the based on defined knowledge rules discharge condition of transformer in question was reported.

3.2 PD Inspection of Medium Voltage Power Cables

The detection, location and recognition of partial discharges (PD) at an early stage of possible insulation failure in medium voltage is of great importance for maintenance purposes. As a result, maintenance actions can be planned more precisely to prevent unexpected discontinuities in operation of the cable network.. To obtain a sensitive picture of discharging faults in power cables the PD should be ignited, detected and located at power frequencies which are comparable to operating conditions at 50 or 60 Hz..
From the recent research is known, that stressing cables with oscillating waves provides ignition conditions for partial discharges which are similar to 50 Hz AC energizing conditions. In this way the PD inception voltage, PD magnitudes as well as the phase-resolved PD patterns are representative for discharging defects. Moreover, based on the traveling wave principle particular discharge sites can be traced back. In this study two examples are shown of PD diagnosis applied to service aged cable sections. In particular

combining information form the test provides better insight in to discharge processes in the test object (**table 2, figure 8**).
Unless the fact that at this moment based on these data are not sufficient to judge the seriousness of the discharge source for the insulation condition of a particular cable or an accessory this information can be used for periodic inspections in the future and studying aging and degradation effects in the insulation and their manifesting by partial discharges.

Table 2 *PD quantities and their characteristics used in interpretation rules for induced test on power transformers*

PD inception voltage;	*< operation voltage*	*> operation voltage*
PD magnitudes;	*< typical values*	*> typical values*
PD intensity;	*low*	*high*
PD pattern;	*single pulses*	*(no) repetitive*
Location in the cable section;	*cable insulation*	*cable accessories*
PD mappings;	*local concentration*	*distributed along the cable*

3.3 Risk assessment of particles in GIS

Foreign particles inside the GIS enclosure may contribute to the failure of the whole installation. It is known that using UHF PD detection consisting of a UHF couplers, spectrum analyzer and a PD detector sensitive detection, analysis and recognition of discharges is possible.
Table 3 *PD quantities and their characteristics used to evaluate PD measurements on GIS*

	PD pattern magnitude	**PD pattern intensity**	**PD spectrum magnitude**	**PD spectrum intensity**
stage I: electrical field= $E_{stage\ I}$; particle starts to discharge	*low*	*high*	*low*	*selective*
stage II: $E_{stage\ II} > E_{stage\ I}$; particle starts to move	*high*	*less*	*high*	*full*
stage III: $E_{stage\ III} > E_{stage\ II}$; particle is jumping	*high*	*less*	*high*	*selective*

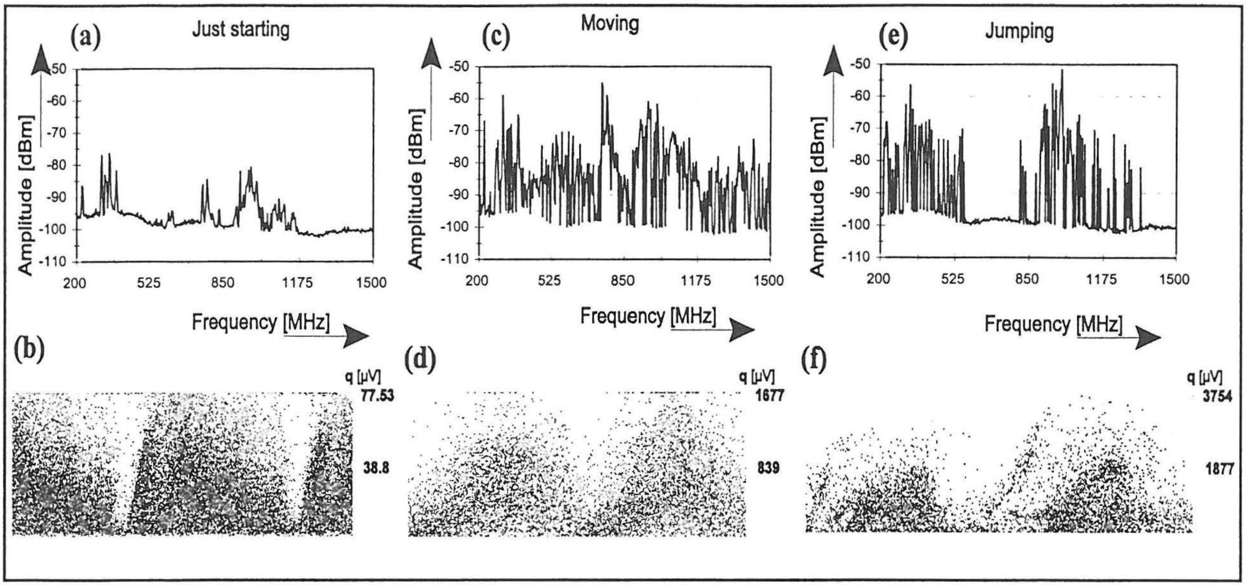

Figure10 *Examples of PD based interpretation of defects serousness in a GIS. PD spectrum, PD pattern of different stages of a bouncing particles are compared here.*

a) PD spectrum of stage I; low amplitude, selective intensity
b) PD pattern of stage I; low amplitude, high intensity
c) PD spectrum of stage II; high amplitude, full intensity
d) PD pattern of stage II; high amplitude, less intensity
e) PD spectrum of stage III; high amplitude, selective intensity
f) PD pattern of stage III; high amplitude, less sensitivity

At the moment a ab-normal discharge activity has been found inside the enclosure, the major question which arises is about the dangerousness of the defect. In particular, important in the case of bouncing particles is the information about the movement of the particle. As soon the particle is jumping between the electrodes the dangerousness of the defect is serious.

For this purpose, information is necessary which can support the test engineer in his evaluation of measuring results. In the following an examples is shown where using combing different characteristics of particular PD quantities addition information can be generated to support the decision process of the test engineer (**table 3, figure 9**).

4. Interpretation (Knowledge) Rules

As shown in previous chapters the use of digital PD analysis can benefit interpreting discharges in HV components in different ways:

a) By relating particular defects to characteristics of particular PD quantities (Chapter 2)
b) Based on a) making interpretation rules to describe discharging sites

In general terms depending on particular experiences with different types of HV apparatus collecting all PD quantities, their origin, seriousness as well as to determine insulation condition can be considered for three levels of IF-THEN rules:

Level 1
IF {result (**characteristics**) of a PD measurement [PD quantities, PD patterns, PD trends]}
THEN {**actual situation** [no defect, defect type 1, defect type 2 etc},

Level 2
IF {**defect recognized** [type 1, defect type 2, etc]}
THEN {**seriousness of defect**, aging stage [no worry, severe]

Level 3
IF {**serousness of defect**, aging stage}
THEN {**insulation condition** [good, moderate, bad, near breakdown]}

5.Conclusions

In this study based on several examples possibilities of interpreting (knowledge) rules for PD diagnosis on HV components have been discussed. As a result using experiences with digital PD diagnosis the following steps should be considered to develop a systematic of PD knowledge rules to support diagnosis of service aged materials:

1. Systematic of digitally processed PD quantities which are meaningful in diagnosis of HV components;
   In particular, to investigate the systematic of digitally processed PD quantities which are of importance to evaluate different defects in service aged insulation of HV components: switchgear, GIS, transformers, cables & accessories and generators.

2. Development and collecting of PD knowledge rules of different insulation defects and if possible degradation stages for particular HV components.

3. Depending on particular experiences with different types of HV apparatus collecting all PD quantities, their origin and seriousness for IF-THEN rules

4. Inventory of diagnosis support system suitable for application in the praxis of PD knowledge rules mentioned in 2.
   For the purpose obtaining as complete as possible information about the discharge process, all measurable information need to be linked together. While a human expert can obtain such a reliable insight on basis of few characteristic PD quantities, the use of a diagnosis support system (knowledge rules + expert system) can give the possibility to use all significant information from periodic measurements or continuos monitoring during the whole service life of a component.