PD Pattern Analysis During Induced Test of Large Power Transformers

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ABSTRACT

The partial discharge (PD) measurements on power transformers are studied with a view toward discrimination and classification of different discharge sources. For this purpose digital analysis is applied to power transformers and reactors going through acceptance testing. Furthermore, based on these measurements, PD databases have been developed to support the discharge evaluation during induced voltage tests of transformers. Using this technique, a clear distinction is possible between transformers showing different discharge behavior.

1 INTRODUCTION

It is known that based on 1 h induced voltage test of a power transformer, important conclusions are made regarding insulation conditions of the test object. It is also known that such HV apparatus is not discharge free. On the contrary, a certain level of discharges <500 pC is allowed, and most interpretation of the measuring results depends on the subjective opinion of test engineers. Basically, during an induced test two types of discharges may occur: discharges related to the setup (floating HV electrodes or connections, ungrounded parts, *etc.*) and PD related to internal sources in the insulation of a test object.

Due to the fact that testing power transformers with rated power of >200 MVA requests quite large test areas with test facilities to 1 MV, even very careful laboratory handling cannot exclude the first type of discharges. Searching for discharge sources and their location within the setup before starting induced voltage test in such laboratories may be time-consuming. Moreover during enhanced voltage level some discharges may be incited first at the higher voltage level. It is therefore of importance to compare the PD pattern before, during and after this period (see Figure 1). With the advent of digital processing (see Figure 2), the task of data acquisition and evaluation now can be performed efficiently [1-4]. In particular the time behavior of PD patterns, as well PD pattern discrimination and classification with regard to the location of the internal and external discharge sources can be supported. The main goal of this study was to investigate the possibilities of digital processing to support PD pattern recognition during induced voltage tests of large power transformers.

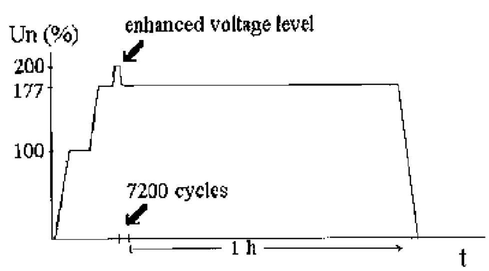

Figure 1. The time curve of test voltage during induced voltage test.

2 PD PATTERNS OF TEST SETUP

Several realistic problems were created artificially in the setup and the patterns were studied using a digital PD analyzer (TEAS-D) [2]. Here two examples will be discussed in detail, and compared to other problems. In Figure 3 two PD patterns are shown. One obtained from an aluminum rod extending from a HV sphere on an autotransformer and the other one obtained of discharges occurring on a metal ring from a cotton strap extending from a HV sphere. It follows from this Figure that both sources are characterized by similar shape of PD patterns unless there are enormous difference in the PD amplitude, which are located at different phase positions of the power frequency. To discriminate between these two setup faults and other similar problems which are quite realistic for large laboratories, fractal analysis can be applied [3]. In Figure 4 an example is shown of this analysis. It follows from this Figure that such a discrimination tool provides distinction between

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different groups of defects

1. defect 3 *vs.* defect 4,
2. defects 1 and 5 *vs.* defect 4,
3. defect 1 and 5 *vs.* defect 3,
4. *etc.*

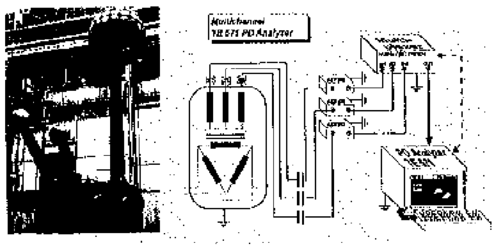

Figure 2. Off-line PD analysis of power transformers: (left) photograph of a 370 MVA auto transformer under test, (right) schematic diagram of conventional PD measuring system composed of a multi-channel PD analyzer and coupling devices each connected to HV bushing measuring screens of the test object.

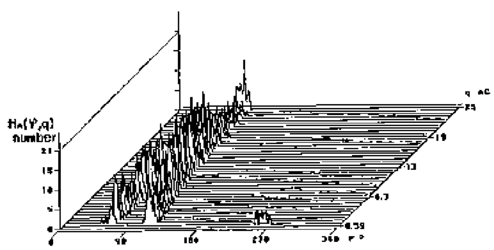

Figure 3. Example of $H_n(\phi, q)$ PD pattern as observed (top) at 100 kV test voltage on an aluminum rod extending from the HV sphere of a 370 MVA Auto-Transformer, (bottom) at 600 kV on a metal ring form a cotton strap which was left in the sphere and extending from it on the top of a 55 MVA reactor,

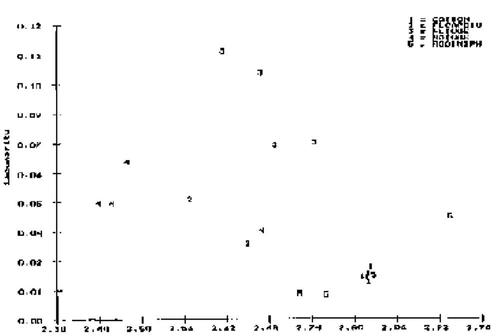

Figure 4. Result of fractal analysis as applied to six different artificially made in a setup discharge sources. 1: metal ring with a cotton strap extending from the HV sphere, 2: floating object near the test sample, 3: floating shielding electrode, 4: no shielding electrodes on the test object, and 5: an aluminum rod extending from the HV sphere.

The fact that no distinction is possible between defect 1 (metal ring extending form the HV sphere) and defect 5 (metal rod extending from HV sphere) can be explain by the fact that unless different sources in both cases the same type of defect was mentioned: sharp point on the HV electrode.

3 REGULAR PD PATTERNS IN LARGE POWER TRANSFORMERS

It is known from transformer tests that during an induced test a certain PD level is permitted. In particular the PD patterns which may occur during this test are analyzed as a function of time and the behavior of the magnitude is observed carefully with regard to their origin (see Figure 5). In addition, different PD distribution can also be processed to describe the PD patterns. In the following a few typical PD patterns are shown, which were observed on objects without any insulation problems (see Figures 6 to 8). A single PD pattern, as represented by different statistical distributions, can be processed by special tools to extract the characteristic properties [2]. To discriminate between series of such fingerprints statistical processing can be applied.

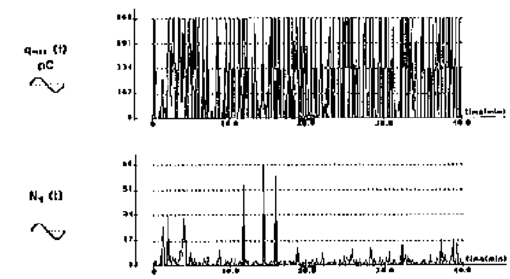

Figure 5. Typical example of PD quantities $q_{max}(t)$ and $N_q(t)$ as observed at $1.7U_n$ during 40 min induced test of a 47 MVA 3-phase transformer.

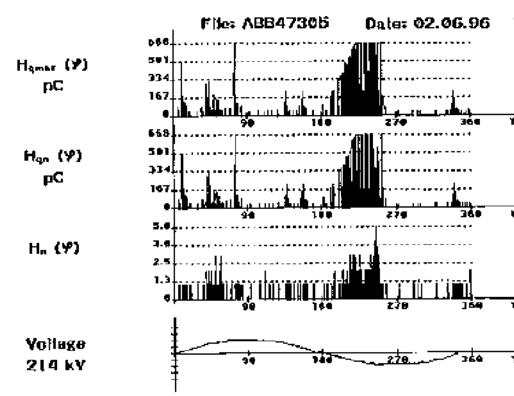

Figure 6. Typical example of phase-resolved distributions as observed during 2 min induced test of a 47 MVA 3-phase transformer.

In Figure 9 an example of comparison to other samples of power transformers is shown. Most of the samples with 90% recognition were characterized by the fact that no problems or irregularities were observed during induced voltage level (exception has to be made in the case of 55 MVA reactor and 203 MVA transformer, see next Section). It follows from this classification diagram that the discharges observed in this particular 47 MVA 3-phase transformers are similar with probability of >90% to other test objects which were in good condition. This result is reasonable, since all these transformers were accepted after induced voltage test.

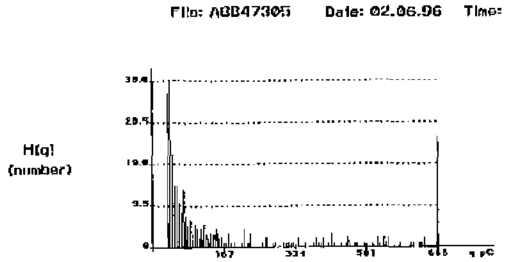

Figure 7. Typical example of PD intensity distribution $H(q)$ as observed during 2 min test of objects in good condition; 47 MVA 3 phase transformer.

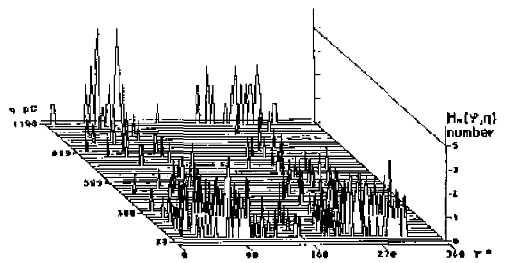

Figure 8. Typical example of $H_n(\phi, q)$ PD pattern as observed for a transformer in good condition; a 370 MVA autotransformer. This pattern was also observed during the enhanced voltage level test as well as after 1 h voltage test at $1.7U_n$.

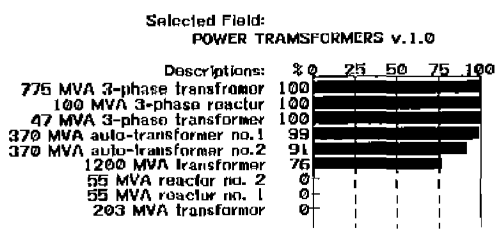

Figure 9. Recognition by a computer-aided data bank 'Power Transformers v.1.0' of PD patterns as observed for a 47 MVA 3-phase transformer in a good shape. Typical is the overlap in the recognition with other test samples also showing regular PD patterns.

4 IRREGULAR PD PATTERNS IN LARGE POWER TRANSFORMERS

In the following, two examples will be discussed where additional discharges were observed (1) after enhanced voltage level of discharges in the connectors of a 370 autotransformer, (2) internal discharges on a damaged screen inside a 55 MVA reactor. It follows from Figure 10 that in contrast to Figure 8 the PD pattern has been changed permanently due to increased voltage stress. In Figure 11 an interesting example is shown, where the presence (cases 3 and 4) and the absence (cases 1, 2 and 5) of a particular defect are visible by fractal analysis plotting. In particular the fractal analysis shows that the inception of setup discharges as well as the effect of removing the discharges source (see Figure 12) can be observed in the behavior of fractal parameters. As shown in this example, the additional information as obtained from fractal analysis can support the decision process during PD testing end evaluation of measuring results.

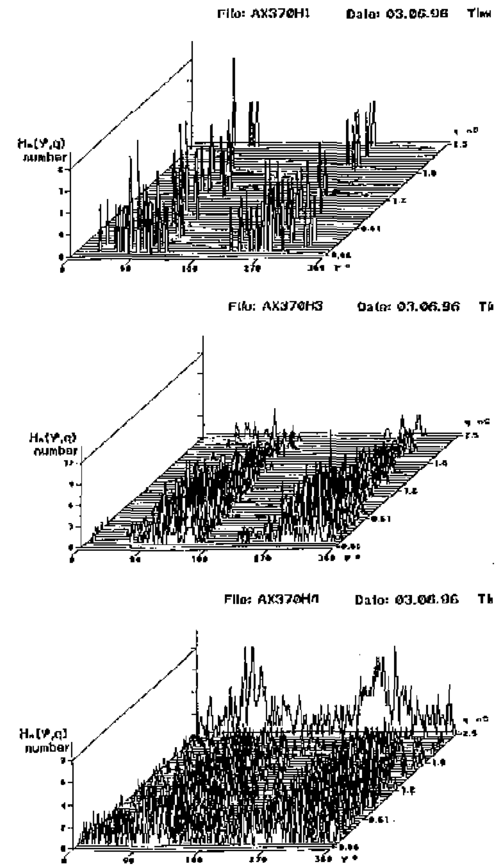

Figure 10. $H_n(\phi, q)$ PD pattern as observed before (a), during (b) and after (c) enhanced voltage level of a 370 MVA autotransformer.

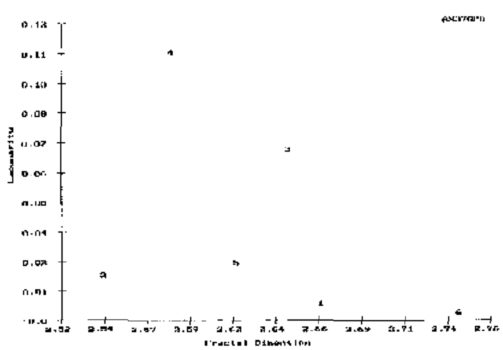

Figure 11. Result of fractal analysis as applied to six PD tests of a 370 MVA autotransformer. 1 and 2: regular PD pattern before enhanced voltage level, 3: irregular PD pattern during enhanced voltage level (ignition of discharges in the setup), 4: PD test after enhanced voltage level (discharges in the setup), 5 and 6: PD test after removing of discharge source.

In Figure 13 the PD intensity is shown from an induced test of a 55 MVA reactor containing internal discharges on a damaged screen. In Figure 14 the phase-resolved 3D distribution is shown. As compared to PD patterns from Section 3 it is evident that discharges, caused by specific faults like a damaged screen, are characterized by specific pat-

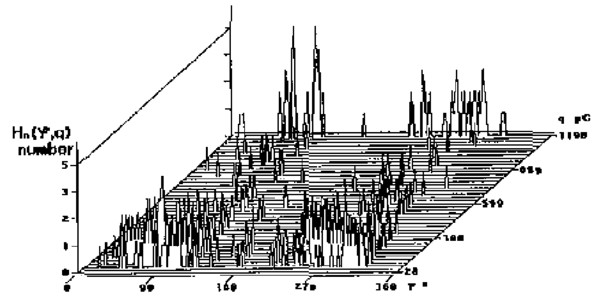

Figure 12. $H_n(\phi, q)$ PD pattern of a 370 MVA autotransformer observed after enhanced voltage level, and after removing the PD source in the setup which was ignited during enhanced voltage level, see Figures 10 and 11.

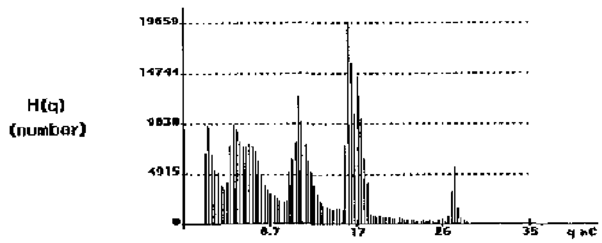

Figure 13. PD intensity distribution $H(q)$ as observed within 2 min for a 55 MVA reactor containing discharges on a damaged screen inside the test objects.

terns. To describe these differences visual comparison of PD patterns or numeric classification tools can be used (see Figure 15). Experience has been obtained during application of the following discrimination techniques: fractal analysis which is applied to evaluate the 3 dimensional phase resolved PD patterns; and tree structure which is based on group average analysis.

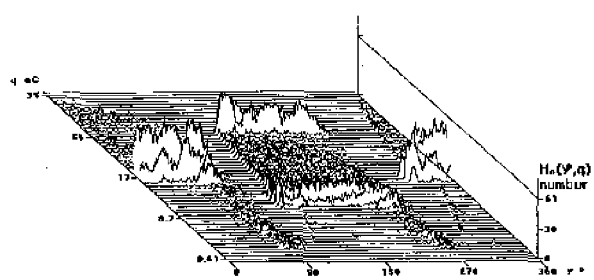

Figure 14. $H_n(\phi, q)$ PD pattern as observed after enhanced voltage level of a 55 MVA reactor containing PD on a damaged screen inside the test object.

To evaluate a large number of fingerprints obtained for several different PD sources or different types of transformers, or to investigate the clustering of the measuring results in order to discriminate between different discharges the 2nd method (tree structure) is suitable.

To investigate the differences between different PD measurements or discharge sources as obtained for the same type of transformer, the first

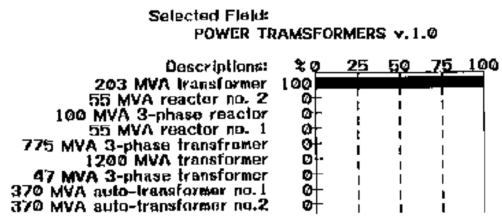

Figure 15. Recognition by a computer-aided data bank 'Power Transformers v.1.0' of PD patterns as observed for a 55 MVA reactor containing PD on a damaged screen inside the test object. In contrast to Figure 10 no resemblance was observed to other tests objects showing regular PD patterns.

method (fractal analysis) seems to be promising.

5 PD DATABASE FOR DIAGNOSIS SUPPORT

When a measurement is made on a power transformer, it can be compared to the PD measurements obtained from such objects in the past (see Figure 16) which have been collected in a database. The previous Sections have investigated the possibilities of digital processing to support PD pattern recognition during induced voltage tests of large power transformers [4]. In the following, the importance of developing a PD database to support PD evaluation is discussed on the basis of 80 PD measurements made on power transformers and reactors in the period of four years. These measurements were analyzed using statistical tools as discussed in [2, 5].

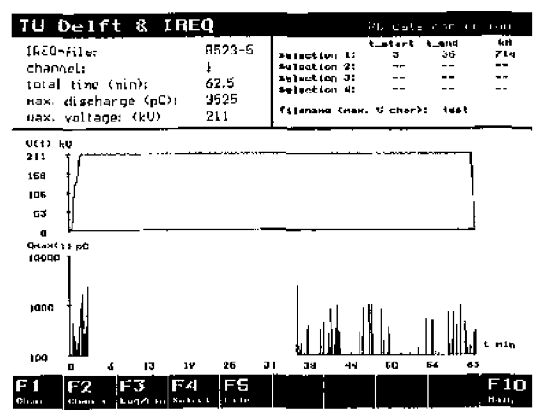

Figure 16. Measuring data example of a 1 h induced voltage test of a power transformer. The marks are between 3 and 35 min and represent the time sequence of PD measuring data which were used in this particular case for further PD data base processing.

For reasons of clarity, the entire PD database has been divided into two separate parts. The first part has been made on the basis of measurements made on reactors, whereas the second part concerns autotransformers and three-phase transformers only. The main goal of this PD database was to answer the question about general trends in PD patterns in the case of regular or irregular PD patterns which occur during induced voltage test of power transformers and reactors.

A data bank is well designed for classification purposes if it produces a high similarity for one defect and a low one for all the others. If no classification can be made, it should produce a low similarity for all defects. Due to the fact that the user of a digital PD detector type TE571 also can create his own data bank, it was important to know how a well-designed data bank can be made.

For this purpose, several discrimination techniques can be used [5]. The main goal of all these methods is the recognition of clusters without a priori knowledge. This means that no labels indicating the membership of an individual measurement to a particular cluster are present beforehand.

To analyze the measurements discussed in this report group average analysis technique was used [2]. Using this method discrimination between possible clusters can be made. In the case of several measurements each represented by a fingerprint this method examines the distances between all fingerprints. The results of the analysis is a tree structure, which illustrates the relationships between individual fingerprints, see Figure 18. The percentage scale in the lower part of this graphic shows the dissimilarity between fingerprints that were fused together.

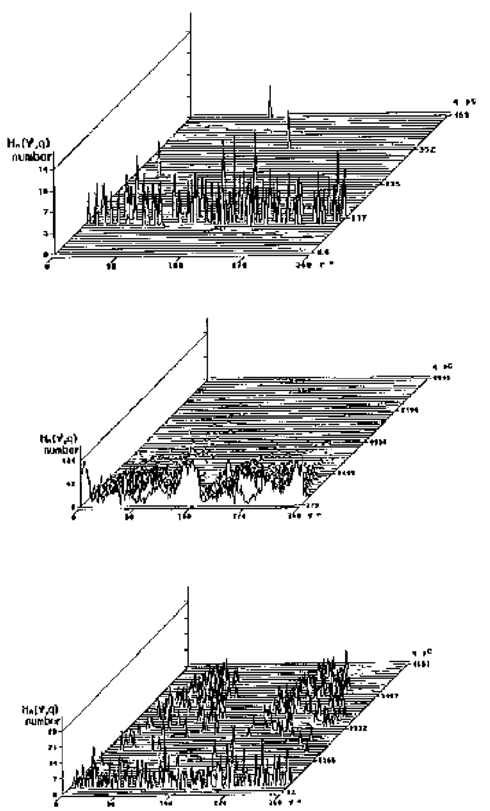

Figure 17. PD pattern as observed for a transformer showing (top) regular PD evaluation regular, (middle) irregular PD evaluation irregular, (bottom) unknown PD evaluation unknown.

6 EVALUATION CRITERIA FOR PD MEASUREMENTS

When discharge data as measured during 1 h voltage application, using a multichannel system, is evaluated, the following two important points have to be considered.

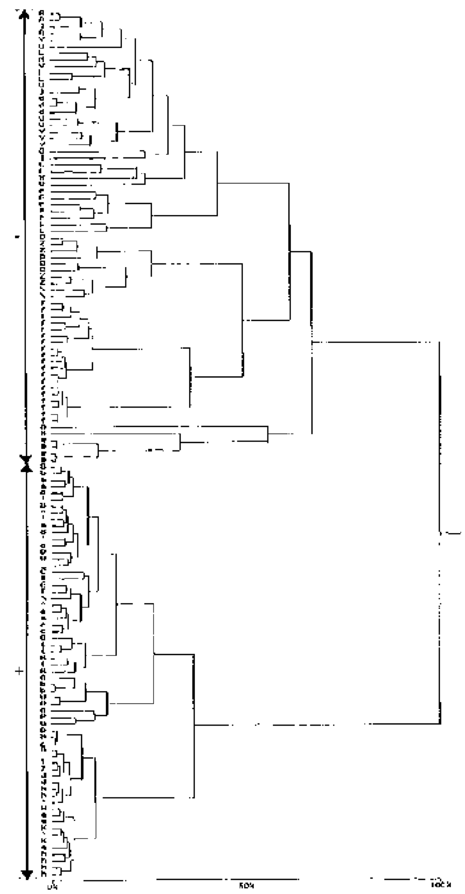

Figure 18. Result of cluster analysis as applied to PD patterns measured on 40 different power reactors.

6.1 THE TIME SPAN OF A MEASUREMENT

Comparing all measuring data no uniform measuring time was used. A PD measurement used in this evaluation may represent measuring data measured only for a certain period in time on a certain channel of the test object. The duration of this time period may be different for each test object. As a result this diversity in the acquisition time may influence the interpretation of particular PD patterns.

For example when during an induced voltage test only a few PD pulses occur this can lead to a different conclusion by analyzing the PD pattern from only one minute period and by analyzing PD patterns from the 1 h test period.

6.2 THE MEASURING CHANNEL

As mentioned above, for one test object, measurements can be taken on a number of channels. It is known that in such a large test object as a power transformer cross-talk effects may occur between different channels and that also multiple discharge phenomena in the test object are possible.

Table 1. Four possible combinations of the two criteria and their evaluation.

Q_m nC	Int. y	Eval.
$\leqslant 1$	low	regular, +
$\leqslant 1$	high	unknown
>1	low	unknown
>1	high	irregular, –

As a result separate evaluation of PD signals of a respective channels would be necessary. In this study no distinction was made between test objects with one and more measuring channels. Each PD pattern showing measured data was evaluated with equal importance.

6.3 DISCRIMINATION CRITERIA

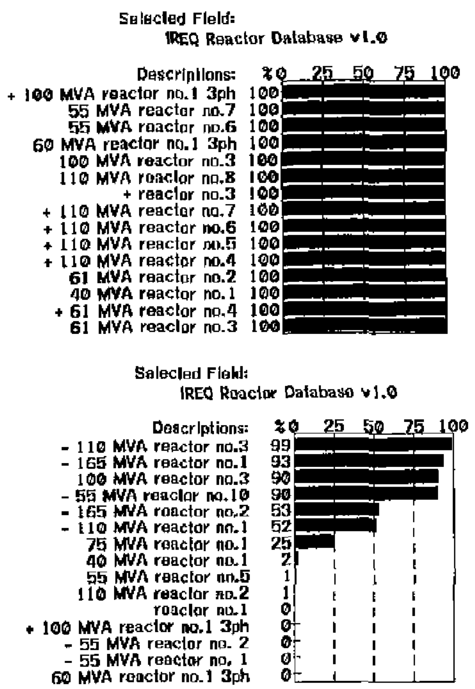

Figure 19. Examples of recognition to the reactor database (top) in case of an acceptable PD pattern, (bottom) in case of a PD defect causing discharge. (+), (—), () represents a test object in the database characterized by a (regular), (irregular) (unknown) pattern.

No *a priori* knowledge was available about the used IREQ PD test-data, of which the database is built. Therefore the data has been evaluated using the following two criteria: discharge magnitude, and discharge intensity.

In Figure 17(a) typical examples of 3-dimensional phase resolved PD patterns are shown. In particular the differences in PD magnitude as well as in the PD intensity are shown here. Based on this experience, the above mentioned criteria have been defined. For the first a level of 1 nC has been used, for the second criterion no quantitative level could be defined. As discussed in previous Sections, the PD patterns of power transformers have to be evaluated on the base of experience. In the following, four examples will be given, showing the four possible combinations, as listed in Table 1.

Table 2. List of power reactors (MVA and number) used for cluster analysis in Figure 18.

Code		MVA	No.
A		55	4
B		40	1
C		55	5
D	+	100	2
E		100	3
F	-	100	4
G	+	5	1
H	+	5	2
I	+	5	3
J		38.5	1
K		25	1
L	-	165	1
M	-	165	2
N		61	2
O	-	110	1
P		55	6
Q		55	7
R		55	8
S		110	2
T		75	1
U			1
V	-		2
W		205	1
X	-	55	9
Y	-	55	10
Z		61	3
:	+	61	4
/		40	1
;	-	110	3
?	+	110	4
—	+	110	5
,	+	110	6
a	+	110	7
b	+		3
c		110	8
d	-	110	9
e		60	1
f	-	55	1
g	-	55	2
h	+	100	1

In the example shown in Table 2 and Figure 18 two main groups can be observed. It follows that similar fingerprints will be connected at relatively low dissimilarity levels, while differing fingerprints will be connected at relatively high dissimilarity levels. By cutting such a tree structure at a certain level, the data can be divided into different clusters.

Based on such clusters, reference data for a particular PD problem can defined in the PD database [2]. The PD database made for power reactors shows a clear separation between two clusters. The first cluster (—) contains measurements marked as 'bad' or 'unknown'.

The second cluster (+) contains measurements evaluated as 'good' or 'unknown'. Both clusters also contain 'unknown' measurements. This category represents measurements which are characterized by low intensity discharges >1 nC.

To draw any conclusion about these measurements more background

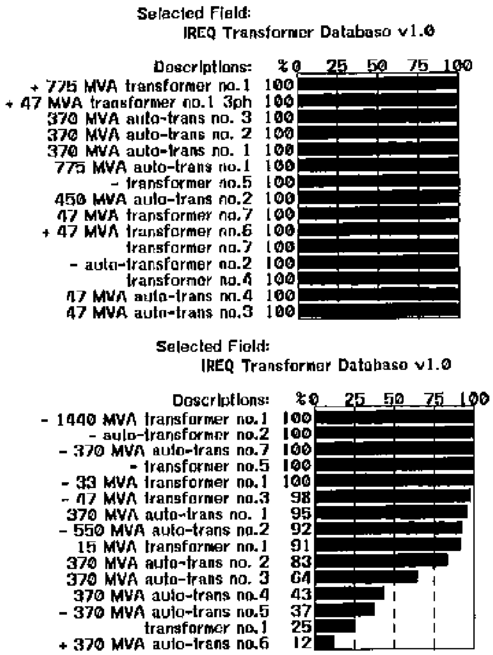

Figure 20. Examples of recognition to the transformer reactor database (top) in case of an acceptable PD pattern. (bottom) in case of an unacceptable PD pattern. (+), (--), () represents a test object in the database characterized by a (regular), (irregular) (unknown) pattern. (+), (—), () represents a test object in the database characterized by a (regular), (irregular) (unknown) pattern.

information would be necessary. Anyway due to the fact that 'irregular' and 'regular' measurements are clearly separated the presence of 'unknown' data in both clusters is interesting and shall be investigated in more detail. In similar way PD measurements on power transformers have been evaluated. Using clustering by means of tree analysis similar distinction has been observed between the first group (+) and the second (—).

7 USE OF THE PD DATABASE

When a measurement has been made on a test object, it can be compared to the database, using the centour score method, available on the TE-571 PD analyzer. In the following four examples are given showing an application of both databases during classification of an unknown measurement. As observed in previous Sections, the recognition of an acceptable PD pattern by a database (Figure 19) gives a multiple recognition for many cases. In most of these cases a low discharge magnitude as well as a low discharge intensity was observed (+). No recognition of unacceptable PD problems is found. When a typical defect is classified, recognition of only a few problems is found (Figure 20), most of which are unacceptable PD patterns.

8 CONCLUSIONS

THE digital classification of PD patterns during induced voltage test of power transformers can be useful for the following purposes:

1. identification of discharges in the test setup,
2. analysis of changes in PD behavior before, during and after the period of enhanced voltage level,
3. comparison of PD patterns of different transformers to identify the different discharge sources
4. to develop further a PD database for power transformers the following has to be considered that a database should contain two types of information: PD patterns characteristic for this type of transformers, and PD patterns representing certain un-permitted discharge sources.

Using digital processing of PD patterns distinction between different discharging test objects like power transformers and reactors is possible. Using this technique a discharge based decision supporting tool can be developed for induced voltage tests of power transformers and reactors.

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