Influence of Aging on Classification of PD in HV Components

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ABSTRACT

In this presentation the influence of degradation of discharging dielectric on phase-resolved patterns of partial discharges (PD) is studied. Using conventional PD detection and statistical analysis, internal discharges in a flat cavity, and in epoxy insulation of two HV components were analyzed during long term tests. The results indicate that aging progress was accompanied by few consecutive changes in the phaseresolved patterns. This observation might become important for two applications: the developing of databases of different discharging defects, and the analysis of discharge degradation of dielectrics.

1. INTRODUCTION

THE usefulness of classical partial discharge (PD) detection to recognize different PD sources is evident. Recent development has shown that combining this technique with computer-aided statistical evaluation improves significantly the PD analysis in HV constructions [1–5]. Moreover, the combination of PD detection and statistical evaluation can be used also for the evaluation of the degradation of dielectric materials [6–15].

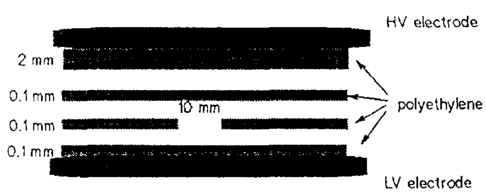

Figure 1.

Sandwich method used for preparation of flat cavity in polyethylene.

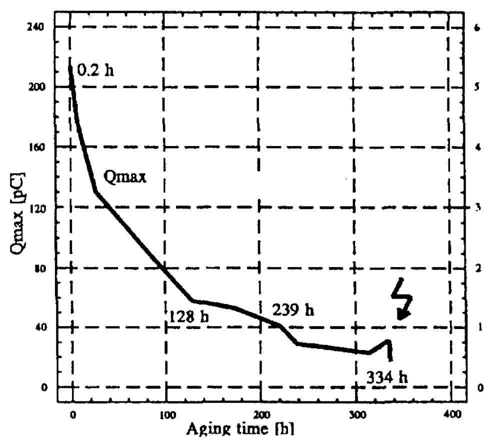

Figure 2.

Maximum discharge magnitude measured for flat cavity in polyethylene during 336 h aging to breakdown.

In this paper the usefulness of conventional detection to monitoring of insulation aging is discussed. Conventional detection in this case means the classical PD detector (according to IEC 270) which is extended by a statistical analyzer. The influence of the aging process on phase-resolved patterns as observed during aging until breakdown of a flat cavity is presented, see Section 3. Moreover, based on the fact that physical changes in a cavity can influence discharge patterns as observed using conventional detection, the results as obtained on two simple HV components containing internal discharges are presented in this paper: 30/50 kV epoxy resin current transformer, and 23 kV epoxy resin insulator, see Sections 4 and 5.

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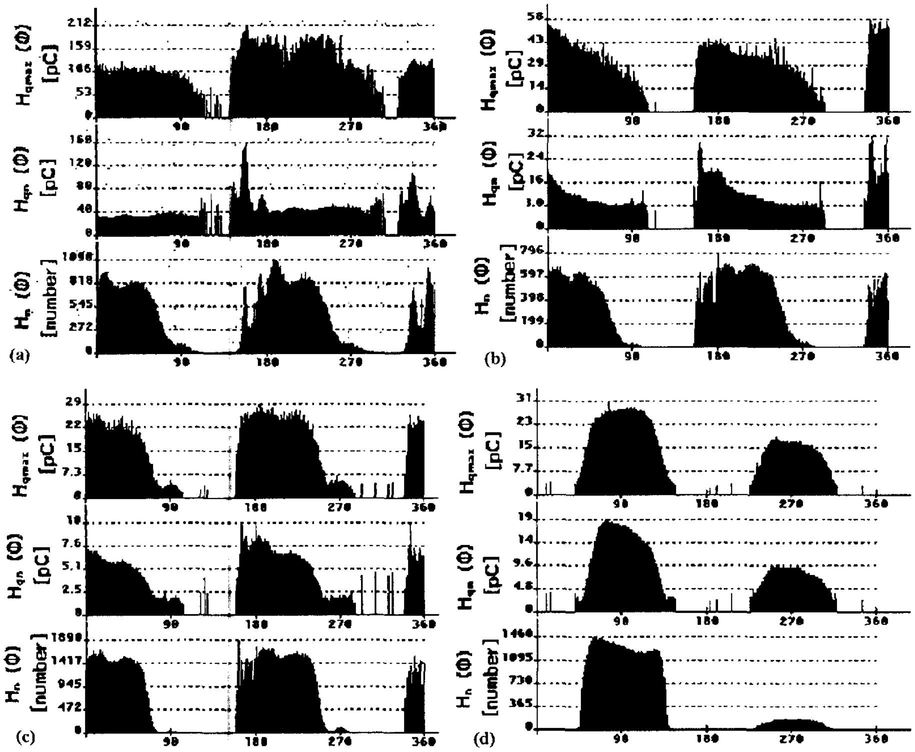

Figure 3.

Typical phase-resolved distributions measured during 336 h aging at 10 kV to breakdown of a flat cavity in polyethylene. (a) 0.2 h, (b) 128 h, (c) 239 h, (d) 334 h.

2. CONVENTIONAL PD DETECTION AND STATISTICAL ANALYSIS

Actual HV equipment usually is tested for discharges using classic PD detectors (bandwidth *e.g.* 40 to 400 kHz). Due to increasing automation of PD measurements, the use of computer-aided evaluation has become very popular. TEAS 570 is an example of such a discharge analyzer that has been introduced recently [16].

To avoid presentation of material already published in [4, 16, 18], only the most important aspects of PD acquisition and processing as used to obtain measuring results are discussed here.

Using this system and statistical techniques as developed in the past [3, 4], the properties of a PD source can be quantified in a fingerprint. Such fingerprint of a discharge can be used for comparison with other discharge sources. For this purpose the magnitude q of each discharge and its phase-angle ϕ on the power frequency are recorded by discharge analyzer during a certain time, *e.g.* ~ 5 min. These recordings, which form the basis of the method, are used to make statistical distributions, such as the maximum discharge magnitude H_{qmax} as a function of phase angle ϕ. Also the average discharge magnitude H_{qn} and the number of discharges H_n are recorded, see *e.g.* Figure 3. These distributions give different results for the positive and the negative half of the

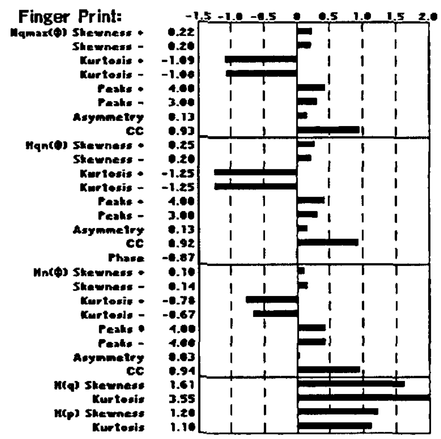

Figure 4.

Fingerprint at 0.2 h aging, as processed for the measured data in Figure 3(a).

50 Hz (or 60 Hz) period, so that six different distributions are obtained. In addition, two spectra are made: $H(q)$ representing the intensity discharge magnitude and discharge energy $H(p)$. Altogether 8 distributions are obtained in this way. The shapes of these distributions are characteristic for different types of discharges. Extensive experience has been obtained when comparing cavity discharges, corona *etc.* [4, 16]. For recognition purposes the shapes of the distributions are analyzed with 'operators'. Such an operator is for instance the *skewness* of a distribution, which expresses the asymmetry of that distribution in a single number or the kurtosis which describes the sharpness of a distribution [17, 21]. A total of 29 operators can be used [16]. A set of 29 of those operators records the shape of a distribution as a list of 29 numbers; this set of operators is called the fingerprint of a discharge. In Figure 4 examples of such fingerprints are shown. Techniques have been developed to compare the fingerprints of different discharges, so that discharges of unknown origin can be compared with (and possibly recognized from) a collection of known discharges. One of these techniques is the use of 'centour score' [18, 19]. The centour score indicates how well two fingerprints resemble each other. The centour score varies between 100% for a perfect fit and 0% for complete absence of resemblance.

3. EXPERIMENTAL RESULTS ON AGING A FLAT CAVITY IN POLYETHYLENE

In order to analyze the influence of dielectric aging on phase-resolved distributions of PD pulses, an extended study was done in the past [13]. To illustrate this study results of 336 h aging until breakdown of a cylindrical flat cavity in polyethylene are discussed in this paragraph. This cavity was prepared by punching a hole with diameter of 10 mm in PE sheet with thickness of 0.1 mm. The sample was prepared by the sandwich method, see Figure 1. To guarantee the height of the cavity 0.1 mm the sheets were fixed to the electrode with silicone grease. The surface of PE sheet was cleaned with soft cotton tissue and dried in air for at least 20 min. The sample were aged at average field strength of 15 kV/mm and the phase-resolved distributions were collected over a period of 10 min at average field strength of 4,3 kV/mm. In Figure 2 the time behavior of the maximum discharge magnitude until breakdown is shown. It can be seen from this Figure that from the beginning of the test a slow decrease in the discharge level has been observed, and no remarkable variations are registered until breakdown. During the whole aging period, 12 measurements of 10 min were carried out resulting in 360 sets of phase-resolved distributions. In Figure 3 typical phase-resolved distributions as observed at different moments during the test are shown: 12 min, 128, 239 and 334 h. It follows from these Figures that not only a decrease in the discharge magnitude occurs but àlso that significant changes in the shape of all three phase-resolved quantities are visible.

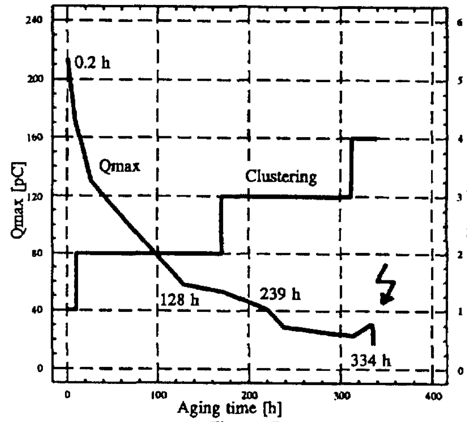

Figure 5.

Maximum discharge magnitude measured for flat cavity in polyethylene during 336 h aging to breakdown extended by clustering of phase-resolved distributions.

If all these distributions as observed at different points in the aging time are processed using statistical operators as mentioned above the significant properties of discharge process at a certain aging time are quantified. In Figure 4 the result of this processing is shown. Comparing the numeric values of all 29 statistical operators as processed for phase-resolved distributions, distinct changes during the test are observed. As mentioned above, during the entire aging period, 360 sets of phaseresolved distributions were observed. Based on the processing of these distributions, 360 fingerprints were obtained (one 10 min measurement is represented by 30 fingerprints). These fingerprints were also further analyzed in order to see whether and in what measure they could be distinguished from each other. The relationship between all fingerprints was analyzed in the following way.

All available fingerprints were individually declared as unknown, removed from the data base and compared to each others (using groups of 30 fingerprints).

Using this classification, all 360 fingerprints could be divided in four categories. The first group appears between 0 and 0.2 h, the second between 0.2 and 180 h, the third between 180 and 330 h and the fourth from 330 h until breakdown. Based on this clustering all fingerprints were combined into consecutive groups called Stage 1, Stage 2, Stage 3 and Stage 4. Based on these groups, a new data bank 'Clusters: aging flat cavity' was developed.

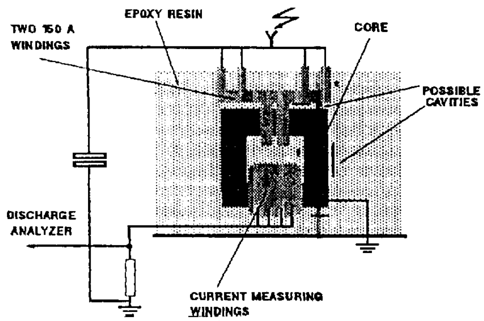

Figure 6.

Cross section of the 2×150A/5A current transformer with indication of possible discharge sources.

The above mentioned four measurements representing certain moments in the aging of the flat cavity in polyethylene were further evaluated by comparison to these four clusters, Table 1. It follows, that the individual results which were obtained during the course of 336 h test until breakdown can be classified clearly in one of the consecutive clusters. In Figure 5 the time behavior of the discharge magnitude is extended by the clustering of the phase-resolved distributions. This observation confirms the results of extensive analysis as presented in [14, 15] where using ultra-wide band PD measuring technique and conventional detection degradation changes in a flat cavity were studied. In this study a significant correlation has been found between both outcomes. As a result of the presented study and results published in the past [13–15] the conclusion may be drawn that the consecutive changes in the PD patterns are fundamental and not just random.

Table 1.
Clustering (%) in aging flat cavity as function of time.

	Time			
Stage	0.2	128	239	334
1	100			
2		100	30	
3			100	
4				100

4. EXPERIMENTAL RESULTS ON AGING A CURRENT TRANSFORMER

An epoxy resin current transformer which contains two windings of 150 to 5 A as used in a 50 kV transmission network was continuously aged for 1361 h at 52 kV. These transformers are tested for 1 s at 30 kA short circuit current. Because of mechanical stresses during this test the epoxy insulation sometimes cracks. This results in cavities around the transformer core igniting at a voltage lower than the phase voltage of 29 kV. The discharge measurement was carried out after such shortcircuit test. Discharges occurred from the very beginning, possibly located in multiple cracks in the epoxy near the conductor, see Figure 6. These discharges were not identical to a flat-cavity discharges as studied in Section 3, and their fingerprints differed significantly.

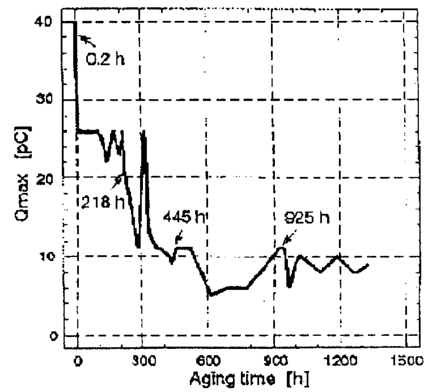

Figure 7.

The maximum discharge magnitude measured during 1361 h aging at 52 kV of epoxy resin current transformer.

During the entire aging time of 1361 h, discharge detection was carried out in regular intervals where one such PD measurement was preformed for 10 min. Unfortunately no breakdown was registered after 1361 h aging and therefore the investigation was stopped. To represent in a proper way the development of the discharge process, altogether 54 measurements were carried out. In total 1620 sets of phase-resolved distributions were processed. In Figure 7 the time behavior of the maximum discharge magnitude is shown. It can be seen from this Figure that after 300 h aging significant decrease in the discharge magnitude has been observed, and after this change no remarkable variations are registered.

In Figure 8 typical phase-resolved distributions as observed at different moments during the test are shown: 10 min, 218, 445 and 925 h. It follows from this Figure that not only a decrease in the discharge magnitude occurs but also remarkable changes in the shape of all three phase-resolved quantities are visible. The statistical analysis of the phase-resolved distributions were made in a similar way as for the data in the previous Section.

Also the numeric values of all 29 statistical operators as processed for phase-resolved distributions show distinct changes in character during the test.

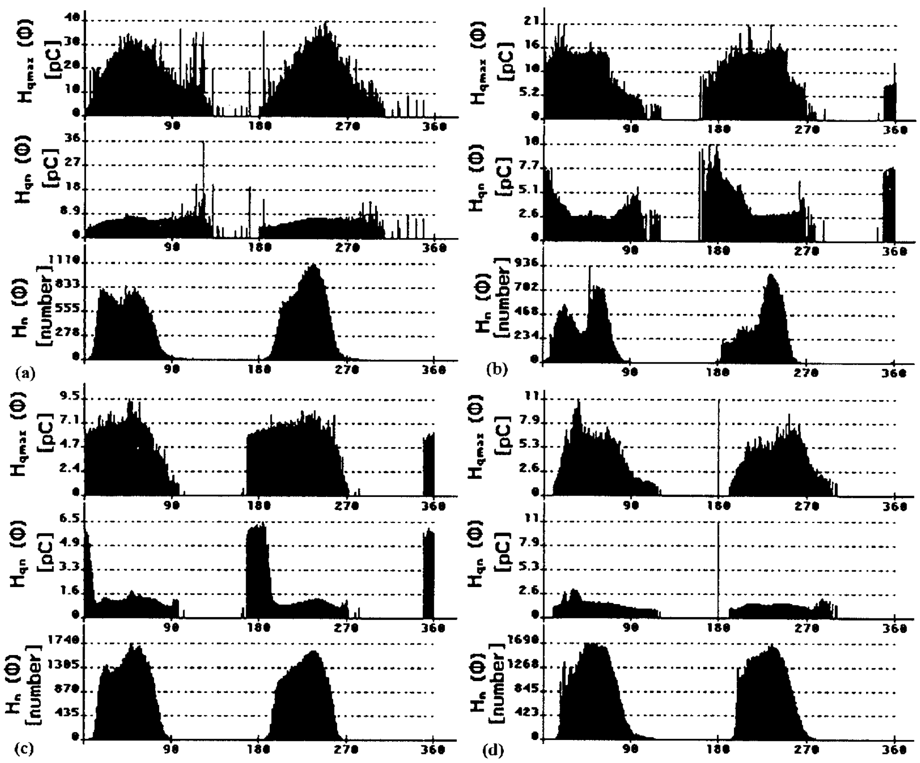

Figure 8.

Typical phase-resolved distributions as observed during 1361 h aging at 42 kV of an epoxy resin current transformer. (a) 0.2 h, (b) 218 h, (c) 445 h, (d) 925 h.

As mentioned above during the whole aging test 54 measurements represented by 1620 fingerprints were processed. These fingerprints were further analyzed in order to see whether and in what measure they could be distinguished from each other. To analyze the relationship between fingerprints different methods can be used.

In Section 3 the data were compared to each other to find out the internal relationship. In the case of many fingerprints this way of comparison is out of question. Therefore an other way of comparison has been made. For instance the principal component analysis could be one of possible solutions [19, 20]. But also using mutual comparison of fingerprints in the course of time can produce a very good insight into the relationship between all fingerprints.

On the basis of such comparison four consecutive clustering were found during 1361 h aging. The first group appears between 0 and 100 h, the second between 100 hours and 330 hours, the third between 330 and 530 h and the fourth from 530 h until the end of the test. Based on this clustering, all fingerprints were combined into consecutive groups called Stage 1, to Stage 4. Based on these groups new data bank 'Aging stages of CTR' was developed. 2 Statistical evaluation of mutual comparison of all 54 measurements was made in order to see whether and in what measure they could be distinguished from each other. In Table 2, results of this classification are shown. In particular individual measurements were compared with its own group and with the other three. To evaluate results of classifications, the following outputs were used.

Table 2.

Classification results (%) of 4 aging stages for a 30/50 kV current transformer. Classes are: A correct recognition, B semi-correct recognition, C no recognition, and D incorrect recognition.

Stages	A	B	C	D
1	66	34		
2	100			
3	91		9	
4	78		22	

1. correct recognition: the fingerprint is correctly classified. The following rules were applied. The classification of the known fingerprint must be > 30% and the

difference between the first and second classification must be $\geqslant 30\%$.

2. Semi-correct recognition: the fingerprint is assigned to several categories including the correct one. The first classification of the known fingerprint is $> 30\%$ and the difference between the first and second classification is $< 30\%$.
3. No recognition: the fingerprint is not assigned to any of the known categories. We propose that the first classification should be $< 30\%$.
4. Incorrect recognition: the fingerprint is incorrectly classified.

It can be seen that sufficient distinction between the four stages exists. In none of these cases mis-classification occurred, that is: in neither case the wrong stage of discharge was indicated.

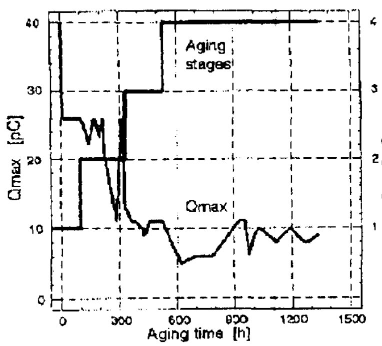

Figure 9.

The time behavior of the maximum discharge magnitude as shown in Figure 8 extended by clustering of phase-resolved distributions which were determined during 1361 h aging at 52 kV of epoxy resin current transformer.

In Table 3, results of recognition using this new data bank are shown. Similar to previous comparison (Figure 5) the measuring data for 10 min, 218, 445 and 925 h aging are compared to the data bank 'Aging stages of 50 kV CT'. It follows, that the individual results which were obtained during the course of 1361 h test can be classified clearly to one of the consecutive stages. In Figure 9 the time behavior of discharge magnitude is extended by the clustering of the phase-resolved distributions. It follows from this Figure that the progress in the dielectric degradation is accompanied by consecutive changes in these distributions. Because no breakdown was occurred at the end of the aging period no final evidence exist for this relationship. To obtain a breakdown inside the HV construction further investigation was made, see Section 5.

Table 3.
Clustering (%) in current transformer as function of time.

	Time (h)			
Stage	0.2	218	445	925
1	100			25
2		97		
3			100	
4				61

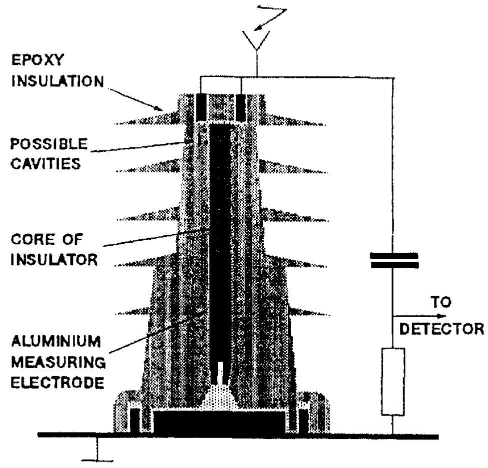

Figure 10.

Cross section of 23 kV epoxy insulator with indication of possible discharge sources.

5. EXPERIMENTAL RESULTS ON AN AGING INSULATOR

A 23 kV epoxy insulator, see Figure 10, was aged during a period of 1606 h. This insulator showed discharges below operating voltage. In this case the origin of discharges was related to air pockets around ceramic core of the insulator which remained after casting.

In contrast to the constant aging voltage of the current transformer (see Section 4) in this case the aging voltage was increased in 5 kV steps (from 28 to 82 kV) about every 150 h, see Figure 11. The test voltage for collecting fingerprints was 23 kV, the operating voltage of the epoxy insulator. The behavior of the maximum discharge magnitude during the aging time is shown in Figure 12. It remained constant at level 40 pC to $\sim$ 1000 h, then it increased to $\sim$ 100 pC and in the end of the test it dropped to 30 pC. In total 45 measurements were carried out during 1606 h, and 1350 fingerprints were collected during the aging period. The differences between fingerprints were analyzed in a similar way to the data of the current transformer. As a result six clusters of fingerprints were distinguished. In Table 4 results of this classification are shown. In particular individual measurements

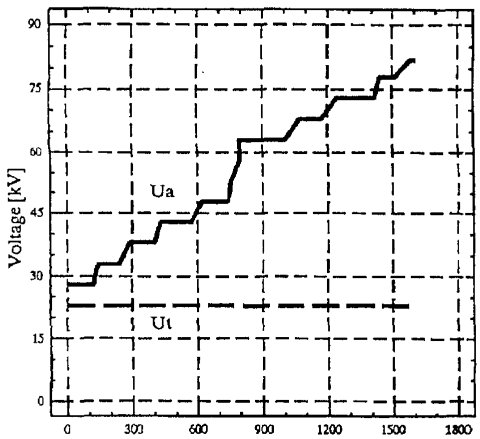

Figure 11.

Time behavior of the aging voltage U_a as used during 1606 h aging of the 23 kV insulator. All phase-resolved distributions as used for the evaluation were measured at $U_t = 23$ kV.

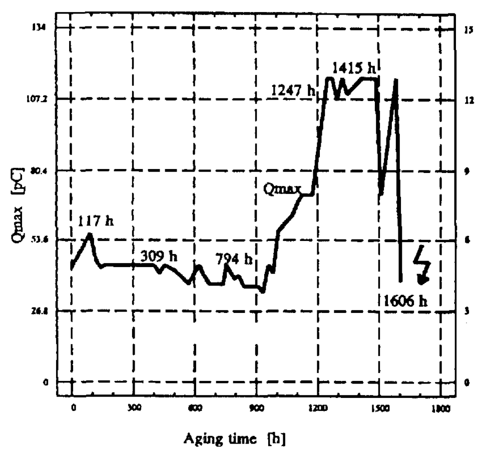

Figure 12.

The maximum discharge magnitude measured during 1606 h aging test of 23 kV epoxy resin insulator.

were compared with its own group and with the other five. In Figures 13 and 14 typical phase-resolved distributions are shown, and in Table 5 the corresponding classification results are presented.

These aging stages are shown in Table 5 as a function of the aging time. In the last stage, after ~ 1600 h of aging, a partial breakdown of the insulator has been considered. The insulator could withstand its operating voltage but intense acoustic noise was heard along the body of the insulator.

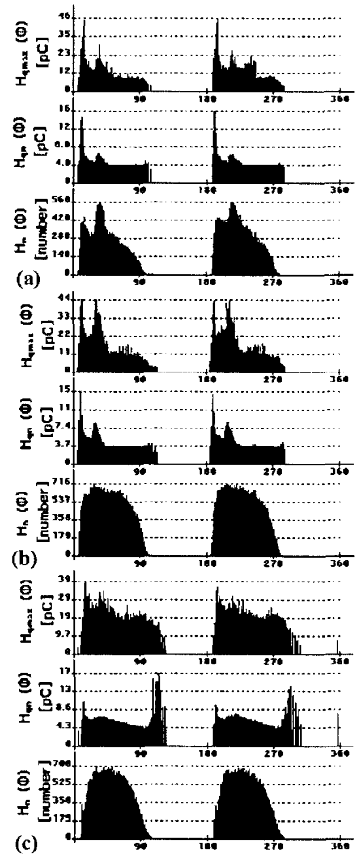

Figure 13.

Typical phase-resolved distributions as observed during 0 to 794 h aging of 23 kV epoxy resin insulator.

Table 4.

Classification results (%) of 6 aging stages for a 23 kV epoxy insulator. Classes are: A correct recognition, B semi-correct recognition, C no recognition, and D incorrect recognition.

Stages	A	B	C	D
1	100			
2	80		20	
3	94		6	
4	100			
5	100			
6	100			

6. CONCLUSIONS

USING conventional PD detection and statistical analysis the phaseresolved discharge patterns of internal discharges in an artificial flat cavity as well as in two epoxy resin insulated HV constructions were observed at ac voltages during aging tests. The following conclusions

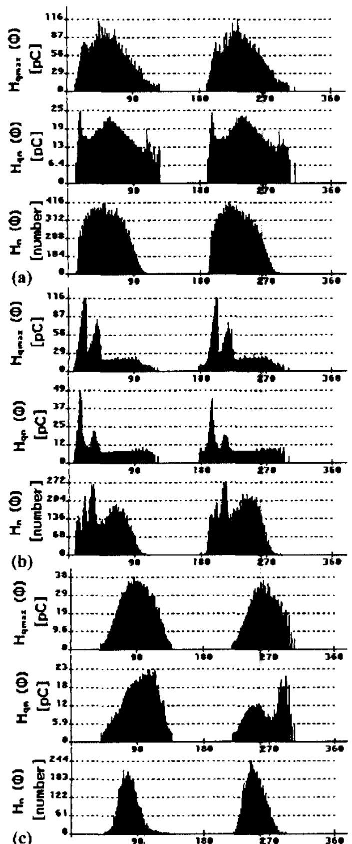

Figure 14.

Typical phase-resolved distributions as observed to breakdown during 794 to 1606 h aging at 23 kV of an epoxy resin insulator.

Table 5.

Classification (%) from 'clustering 23 kV insulator', Figures 13 and 14.

	Time (h)					
Stage	117	309	794	1247	1415	1605
1	100					
2		91				
3			100			
4				96		
5					78	
6						100

can be drawn.

As observed on the tested samples, the degradation of discharging dielectric has resulted in consecutive changes in the phase-resolved patterns of PD.

This relationship between phase-resolved patterns and degradation changes in the insulation might become relevant in the development of databases of different discharging defects.

Without any question, systematic tests on a number of other specimens with similar defects until breakdown are needed to confirm the possible usefulness of this analysis to monitor the aging of HV insulation.

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