EVOLUTION OF SPECTRAL CONTENT OF CAVITY DISCHARGES IN SOLID POLYMER DIELECTRICS

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Abstract: There are challenges encountered in interpretation of online partial discharge tests of equipment such as solid dielectric power cables. This paper contributes knowledge on time-dependent behaviour of cavity partial discharges spectral content in solid polymer insulation. Knowledge in this area can enhance correct interpretation of continuous online partial discharge measurements. Accelerated ageing of artificial cavity defects in polymer insulation under laboratory conditions gave partial discharge signals with frequency content that evolved distinctly as the defects aged from initial inception to total failure. The partial discharge frequency spectra were characterised by widely varying bandwidths in the initial period of ageing that eventually significantly reduced in magnitude and degree of scatter as the defects aged until total failure. Possible implications of these results on practical partial discharge diagnosis are discussed.

1 INTRODUCTION

In partial discharge (PD) diagnosis technology there is a growing interest in online monitoring and trending of PD measurements [1,2]. Furthermore online PD measurements are commonly performed in the frequency domain and using instruments such as spectrum analysers. The strengths of spectrum analysers in PD detection include:

- The spectrum analyser can be tuned to selected frequency ranges that are free from external interferences, thereby optimising S/N ratios.
- In the zero span mode and at a selected suitable frequency, the spectrum analyser displays PDs in the commonly preferred mode – the phase-resolved PD patterns (PRPDP).

While online PD spectral analysis is becoming increasingly popular in the diagnosis of equipment such as power transformers, power cable splices and terminations, gas insulated switchgear (GIS) and generators, there are challenges often encountered in the technology. One of the challenges is the inadequate knowledge in correctly interpreting trends. In literature there have been cases reported where power cables failed later in operation and yet had been judged healthy because the first periodical measurements had identified large magnitude PDs and in the subsequent measurements (after a couple of months) the PDs had diminished [3,4].

Partial discharges in polymer electrical insulation are known to change with time as the insulation ages under continuous exposure to PD activity. Literature shows that in most cases this phenomenon has been studied using time-resolved and phase-resolved discharge signals. In the frequency domain, and in particular where PD signals are detected directly as frequency spectra, the evolution of partial discharges is not yet fully explored.

This paper reports results of work performed to experimentally explore long term time-dependent evolution of cavity PDs frequency spectra in polymer insulation.

2 THE EXPERIMENTAL WORK

A laboratory experiment was set up as depicted in Figure 1. It comprised of an array of test cell sets. One set comprised of parallel plane subdivided electrodes sandwiching sheets of polymer insulation and the other set were 11 kV shielded cross-linked polyethylene (XLPE) power cable samples. In each test cell an artificial cavity was introduced at positions either adjacent to the high voltage electrode, adjacent to the earth electrode or completely embedded in the insulation. Although in the entire project other types of insulation defects were included, the scope of this paper only considers cavities.

All the test cells were designed to give frequency response bandwidth with an upper cut-off frequency of 1 GHz and a lower cut-off frequency in the kHz range. The design of the cable samples' capacitive couplers used for the wideband PD detection is presented in [5]. The test cells were designed such that with the cavity dimensions of 2 mm diameter by 1 mm depth the initial PD inception voltage was 6 kV.

The test cell array was continuously stressed at twice the inception voltage. The supply voltage frequency was set at 400 Hz to accelerate the PD induced ageing process. At suitable intervals the PD spectra was recorded using a 3 GHz spectrum

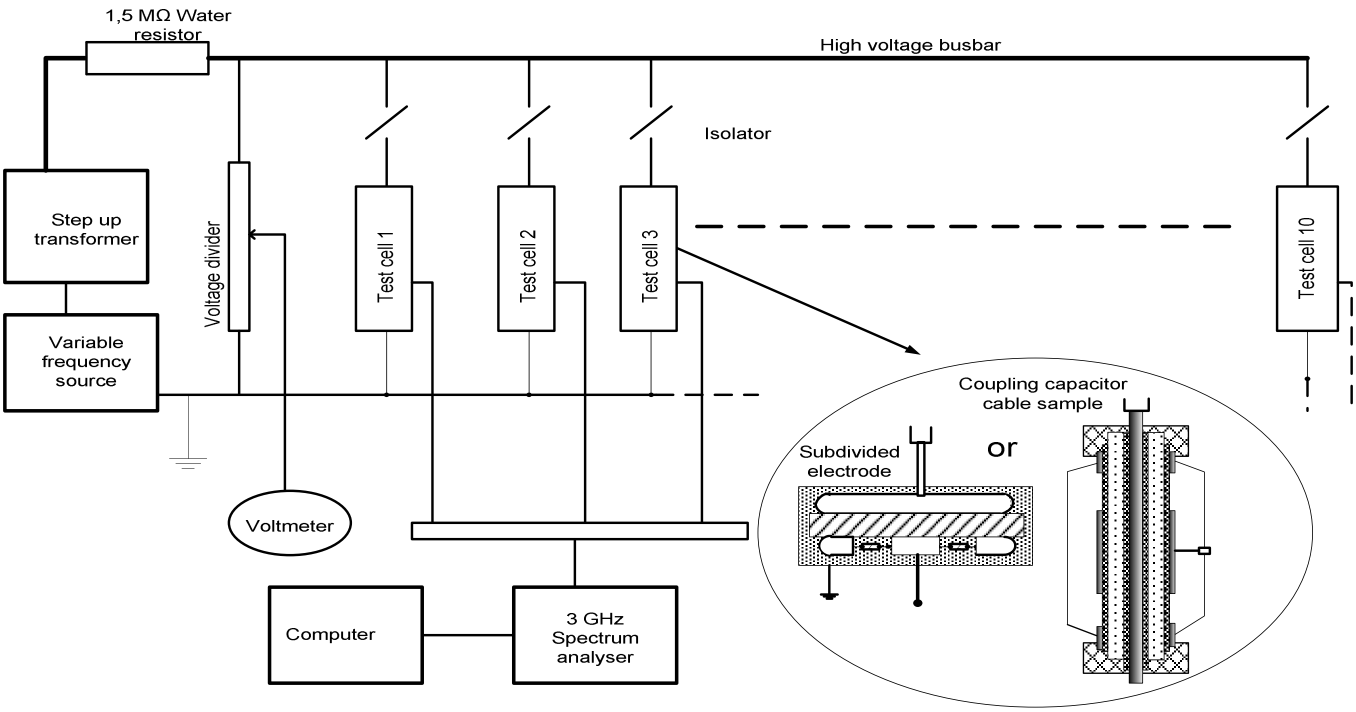


Figure 1: The accelerated ageing test rig for the PD defects. The inset shows some details of the two test cell types used

analyser from each test cell in isolation from the rest of the test cells and at a test voltage of 7 kV and 50 Hz frequency. The process was repeated until all the test cells had failed. All tests were performed in a screened high voltage laboratory. The temperature and humidity were on average 20^0C and 50% respectively and varied within ±10% throughout the duration of the tests.

3 RESULTS

3.1 Spectral Bandwidth Measurements

The PD spectral bandwidth and magnitude variance are the spectral parameters that distinctly responded to the cavity ageing under continuous exposure to PD activity. This paper however focuses on discussions regarding the spectral bandwidth. Spectral bandwidth in this work is defined as the highest frequency component discernable above the background noise level.

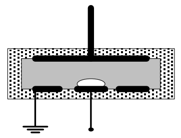
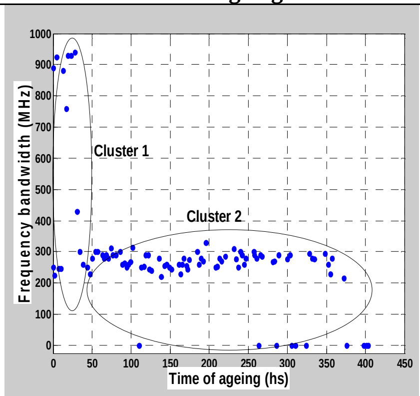
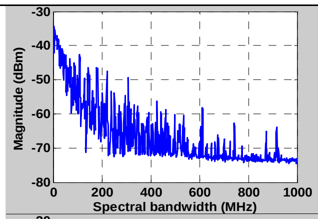
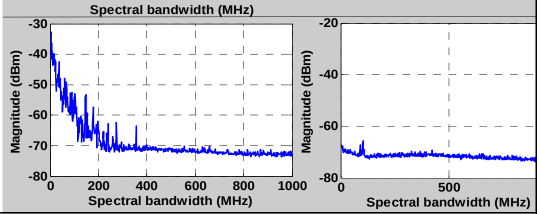
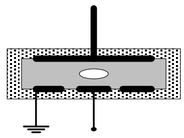
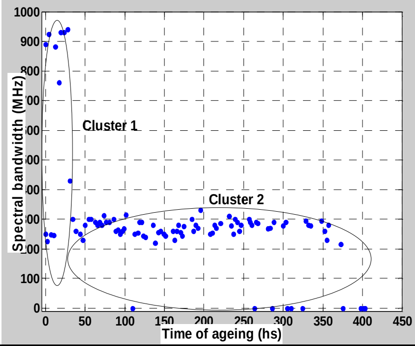
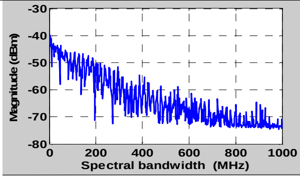
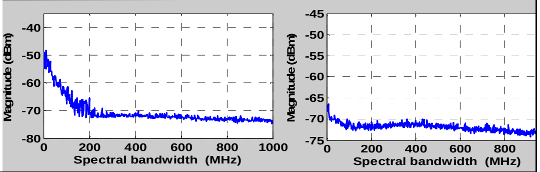
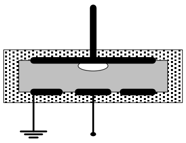
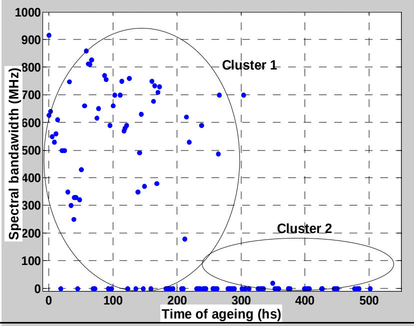
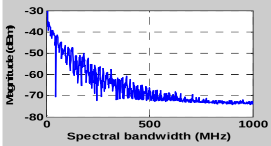
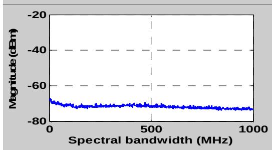
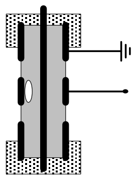
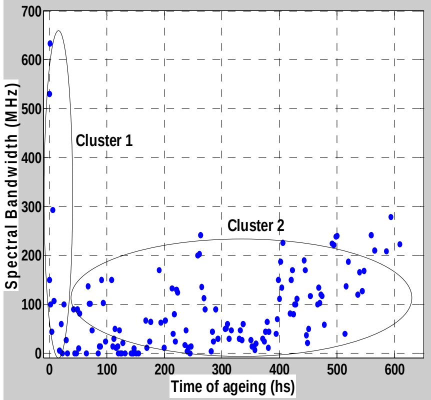
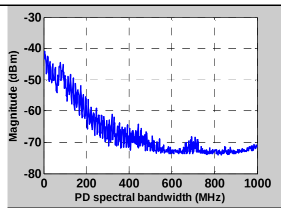
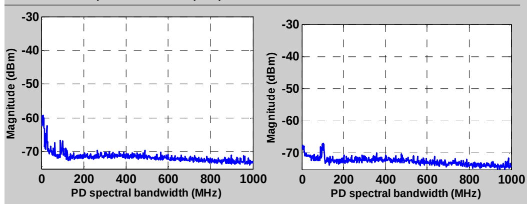
The variations of the PD spectral bandwidth as the PD aged from initial inception to total failure is as shown in Table 1. The frequency spectral descriptor (bandwidth) clustered distinctly when plotted against the ageing time. The bandwidth changed randomly and over a wide range between 200 MHz and 950 MHz in the first 50 to 100 hours of accelerated ageing. In the subsequent periods up to total failure, the PD frequency spectral bandwidth variations narrowed with standard deviations of 1.5 to 2.5 times less than that in the first 100 hours. Moreover there were instances where there were no PD signals detected in prolonged periods of up to tens of hours.

Although the actual maximum and minimum bandwidths varied from one test cell to another, the overall trend of the two clusters in the time distribution of spectral bandwidths was consistent in all the test cells used. The results were independent of cavity positions and whether it was a parallel plane electrode setup or power cable sample.

3.2 Analysis and Discussion

The observed time-dependent spectral behaviour of PD spectral characteristics is consistent with the commonly agreed theory of cavity PD mechanisms in solid polymer insulation. The gap overvoltage magnitude in a cavity discharge process influences the electron avalanche intensities that in turn manifests as variations in the frequency content of the resultant PD signal. Gap overvoltage is defined as the difference between the theoretical and actual discharge inception voltage. The actual PD inception voltage is normally higher due to the delayed availability of the seed electron [6,7]. The gap overvoltage at the instant of discharge inception can change as illustrated in Figure 2 depending on the cavity surface conditions. Time and ageing dependent phenomenon such as accumulation and transformation of PD physiochemical by-products in the discharge area changes the magnitude of gap overvoltage.

Table 1: Cavity discharges bandwidth scatter plots and typical frequency spectra at various ageing phases

Defect type	Scatter plots of the spectral bandwidth as a function of time of ageing	Ageing phase	Typical PD spectra
 Earth electrode bounded cavity		Moderately aged Severely aged	 
 Insulation bounded cavity		Moderately aged Severely aged	 
 HV electrode bounded cavity		Moderately aged Severely aged	 
 Earth electrode bounded cavity in a power cable		Moderately aged Severely aged	 

In the initial period of PD activity (clusters 1 in Table 1), there are minimal or no PD physiochemical by-products on the cavity surface. The availability of the seed electron is therefore dependent on natural random processes such as ionisation of air molecules by cosmic radiation. The resultant gap overvoltage at which each PD event initiates becomes random and this gives a randomly varying spectral bandwidth as observed in the tests. There are instances where the seed electron availability is significantly delayed – giving rise to high bandwidth (up to 1 GHz) and instances where it is readily available resulting in much reduced bandwidth (in the order of 200 MHz).

Subsequent accumulation of PD by-products such as conductive acidic films on the cavity surface can completely short circuit the voltage across the

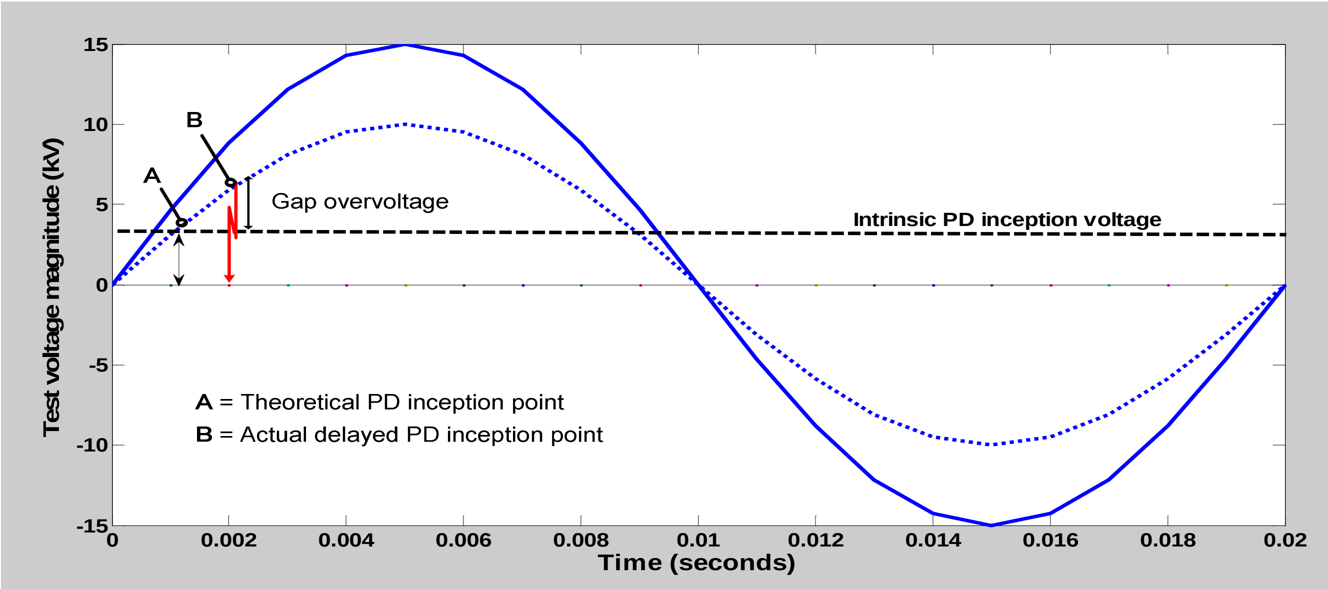


Figure 2: An illustration of the overvoltage that develops in a discharge gap due to the statistical delay of seed electron availability

cavity [8-10]. The short circuiting of the discharge gap results in prolonged PD evanescence as observed in the tests. Due to heat in the cavity, the acidic films may breakup into small islands and therefore allowing the PD activity to resume. The acidic droplets however capture and function as reservoirs of seed electrons making them readily available for initiating discharges whenever the voltage stress conditions become conducive. Most PDs under such conditions initiate at the lowest gap overvoltage. The corresponding spectral bandwidth becomes relatively small and within narrow variations as shown in clusters 2 in Table 1.

The evolution trends of cavity PD spectral characteristics have implications on PD diagnosis technology as follows:

- PD tests of new equipment such as in factory tests may be the most sensitive and reliable as the PD signals from un-aged defects have highest possible frequency content and magnitude.

- PD measurements, especially under online conditions after the system has been in operation for longer than a couple of days, have a high risk of giving misleading results. This is because these tests assess the PD condition in the later PD evolution phase where the discharge activity, particularly in void defects, has a high probability of being in a state of prolonged extinction or low magnitude and low repetition rate. At the instant of measurement, the absence or low magnitude may be erroneously regarded as an indication of good equipment condition. It can therefore be argued that PD diagnostic measurements that are conducted for purposes of maintenance or operational decisions should be interpreted in the context of previous continuous PD trending records of the equipment under test.

4 CONCLUSION

The frequency content of cavity PDs in solid polymer insulation evolve over time in distinct trends. The knowledge needs to be taken into account in interpretation of continuous online PD measurements.

5 ACKNOWLEDGMENTS

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