# PARTIAL DISCHARGE TESTING OF DEFECTIVE THREE-PHASE PILC CABLE UNDER RATED CONDITIONS

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**Abstract**: The ability to accurately monitor the health of power distribution plant is a very attractive prospect for utility companies. This capability would provide a system that engineers could use to assess the real-time state of the network. Analysis of the data produced could allow for more informed decisions to be made in the areas of asset replacement and maintenance scheduling amongst others. It is widely accepted that partial discharge activity is linked with the electrical ageing/degradation of high voltage equipment. Work at Southampton is focused on obtaining a better understanding of the characteristics and trends of partial discharge events associated with medium voltage cables under, 'real life' conditions. An experiment has been developed that allows for service conditions to be applied to defective paper insulated lead covered cable samples. The samples under investigation were exposed to mechanical damage designed to replicate typical problems found on an active circuit. Partial discharge measurement was undertaken during the stressing process.

## 1 INTRODUCTION

Due to increasing economic and regulatory pressures experienced by modern utility companies, the power industry has undergone a shift in maintenance philosophy. The realities of operating an ageing power network have forced utilities to begin to develop preventative maintenance tools rather than rely on unreliable traditional techniques. Methods such as regular off-line testing of HV equipment are gradually being complimented by continuous monitoring systems. This observation is applicable to the situation in London where a large portion of the 11 kV distribution network is nearing the end of its predicted lifespan. An increase in the failure rates of paper insulated lead covered (PILC) cables that make up the majority of the network has already been identified. A research project has been undertaken with the aim of identifying any unique characteristics in partial discharge (PD) activity that is generated when cable circuits are exposed to different types of stress. The focus of the research presented in this paper is to document the effects of mechanical stress on the generation of partial discharge (PD) for cables of PILC design. The eventual application of this work is to use the understanding gained from this work to develop tools that will be used to identify issues that are linked to operational challenges within the distribution network.

The analysis of PD signals has emerged as a viable method to judge the operational condition of power cables [1]. The topic of partial discharge analysis is a vibrant research area. Extensive research has been published that considers the location of PD sources, quantification and characterisation of PD signals produced by cable circuits [2-4]. An international standard has been recently revised in order to unify the PD measurement process (IEC 60270).

The primary aim of this research is to collect PD data from damaged samples that are exposed to realistic in-service conditions. A range of stressing mechanisms have been identified that are known to have reduced the operating life of PILC cables and they have been replicated on samples under controlled laboratory conditions. By closely matching the environment that is experienced by these types of cables in the field for a range of test samples, it is hoped that experiment data can be used to identify specific PD sources from sets of field data.

An experiment has been designed and constructed to allow full voltage, current and thermal control over 10 m lengths of PILC cable. Full details of the experiment are provided in [5]. The experiment provides safe testing of cable samples under rated conditions. The medium voltage (MV) cable samples are connected to the rated three-phase voltage and undergo accelerated thermal cycling for an extended period. The results presented in this paper are from three cable samples that were exposed to different types of mechanical stress. These include: repeated sharp intrusion, overbending and tree root crushing simulation. A mechanical crushing rig was designed and fabricated to provide quantifiable and repeatable mechanical stress conditions for the cable samples under test.

PD measurement was undertaken using a three unit Omichron Mtronix MPD 600 system. In conjunction witt this, a commercially available on-line PD measurement system was also implemenred to record PD data from the earth bond of the cable using a high frequency current transformer (HFCT). It should be highlighted that cables of this design are highly resistant to mechanical trauma. However, after a considerable amount of damage, the mechanical stress activated phase resolved PD patterns that were unique to each type of mechanical stress were obtained.

## 2 THE EXPERIMENT

The rated voltage for the experiment was provided by a back energised distribution transformer. In order to control the thermal conditions experienced by the cable sample, the samples were connected to themselves in a loop to allow a circulating current to flow. The sample was passed through two current transformers (CTs) to control the thermal conditions. After an initial thermal calibration experiment, it became apparent that 320 A per phase was sufficient to raise the conductor temperature of the sample to its rated value of 65 ºC within an acceptable timeframe. The induced current was supplied evenly between both CTs. In order to accurately maintain the sample temperature at the rated value, one of the CTs induced a constant current and the other used a feedback loop to maintain the sample temperature at the required value. The thermal control CTs were arranged to thermally cycle the cable samples with a six hour period. Two hours were taken to heat the sample to its rated temperature, the sample was maintained at the rated temperature for a further two hours and then left to naturally cool for two hours before the cycle was repeated.

A protection system was designed, constructed and integrated within the experiment in order to ensure safety. The protection system monitored the input current to the transformer, current flow to earth as well as the applied voltage to the experiment sample. This ensured rapid isolation of the power supply to the experiment in the event of sample breakdown, excessive leakage current or the event of an internal fault within the distribution transformer itself. The system also provides operator functionality including an emergency stop button and an inter-lock - to prevent access to the experiment whilst HV is applied to each sample.

Three new cable samples were prepared for testing during this schedule. The cable under investigation is of mass impregnated paper insulated three core 11 kV belted construction with a cross-sectional copper conductor area of 185 mm$^2$. The samples were cut to a length of 10 m and terminated at both ends using 1600 mm polymeric terminations of the same design that are used in the field. The primary aim during sample fabrication was to ensure that the samples were as similar to in-service cables as possible. After each sample had been constructed, it was connected to the experiment and left to thermally cycle for a number of days. This process was completed in order to reduce any PD activity that is intrinsically produced by the termination design being used. Having completed the initial thermal cycles on the sample, a PD test was undertaken in order to ascertain the "noise" threshold of the experiment. The term "noise" in this context includes the background white noise level, the PD introduced by the virgin sample as well as any "impulse like" signals introduced by the experiment itself. By ascertaining the background noise level of the experiment, it provided confidence that when PD signals larger than that level are recorded, they had to have been produced by the mechanical stressing process.

The aim of the test schedule was to mechanically stress three cable samples whilst under rated conditions and record the PD activity that was produced. The stressing of the cable was designed to replicate adverse conditions that could be experienced by a cable in the field. The first test involved investigating the mechanical limit of the cable itself as well as finding if crushing the cable would generate measurable PD activity. In order to stress the cable in controllable and repeatable manner, a mechanical stressing rig was designed and fabricated, the schematic of which is shown in Figure 1. The rig consists of an adjustable steel frame that incorporates a manually operated hydraulic ram. Given the application of the device, the contact points between the sample and the metal frame were insulated in order to reduce the chance of short circuiting the sample in the event of a breakdown. The contact surface connected to the ram is interchangeable in order to provide added functionality to the system.

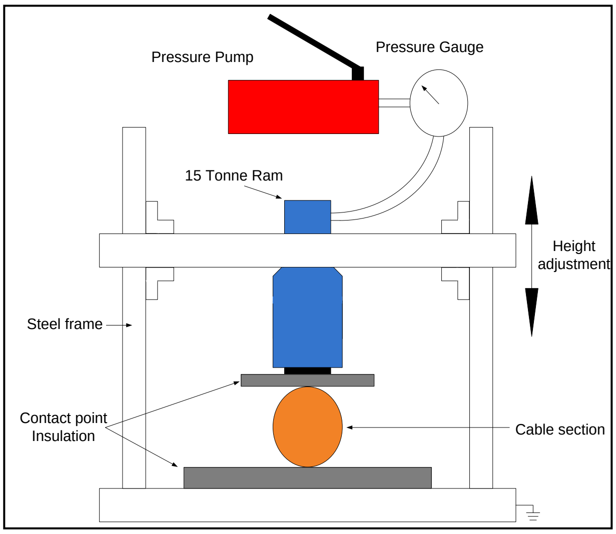

**Figure 1:** Schematic diagram of mechanical crushing device.

### 2.1 Repeated crushing

The first test that was undertaken, involved heating the cable sample to its rated temperature. This ensured that the background noise level for the experiment was ~25 pC by reducing the PD that is intrinsically associated with cables of this design [6]. A static set of PD-like pulses is introduced by the thermal control CTs, they are introduced by the electronic switching of the power supply and have a fixed phase relationship and are easily identified. A sharp contact point was attached to the hydraulic ram in order to maximise the mechanical stress experienced by the cable. This test was designed to replicate the repeated compression caused by vehicles crossing a shallow and otherwise unprotected cable. After some initial testing, the mechanical limit of the crushing rig was defined as 1360 kg. Given the contact area provided by the sharp contact point, the pressure applied to the cable was calculated as 5.4 $\text{kgmm}^{-2}$. The rated voltage and temperature were maintained as PD measurement was completed for the extent of the test process. In order to completed the testing within a reasonable timeframe, the cable compression was completed in a number of sets. Each set consisted of 10 compressions applied to the cable with a single compression consisting of increasing the mechanical pressure on the cable from zero to the rated value and back to zero.

### 2.2 Overbending

Another type of mechanical stress that has been identified to reduce the life of cable samples in the field is caused by overbending. Realistically, overbending damage to cables is more likely to occur during the period between the cable fabrication and when it is commissioned. This investigation aims to find whether bending the cables will generate any significant PD activity under rated conditions. Overbending cables of this design is known to disrupt the uniformly overlapped insulating papers that form the primary insulation for the cable. If considerable movement of the insulating papers occurs, voids could appear that may generate PD activity. As with the previous experiment, a new sample was inserted into the experiment and was heated to its rated temperature. The test process involved forming a bend in the cable, applying the test voltage for an extended period and monitoring if any PD activity was produced. If the PD activity remained unchanged, a more aggressive bend was applied to the sample and the process was repeated. After consulting the design specifications of this type of cable design, the minimum bend radius was identified as $13^*D_0$. $D_0$ is defined as the diameter of the cable which was measured as 63 mm, providing a minimum bend radius of 82 cm. Once a sufficiently small bend had been applied to the cable to generate PD activity, the sample was left for an hour under rated conditions in order to capture a significant amount data.

### 2.3 "Tree root" crushing

This test was designed to replicate the effects of a growing tree root compressing the cable and causing damage. This event is known to have caused faults in cables of the design investigated in this work. Given the long term nature of this kind of damage and the time constraints associated with this project, the damaging process was accelerated to a certain degree. The crushing rig used in the test covered in section 2.1 was modified in order to more closely mimic the compression caused by a tree root growing around a cable. The sharp point contact used previously was replaced with a flat 50 mm contact in order to spread the pressure across the cable without puncturing the outer insulation. The rig was also reinforced in order to apply a larger pressure to future cable sections.

### 2.4 PD MEASUREMENT

PD measurement was undertaken using two systems: A conventional PD measurement system with input units capacitively coupled to each phase of the sample as well as an advanced substation monitor (ASM). The conventional system was used in order to quantify the apparent charge of the PD activity whilst the ASM is a commercially available PD monitoring system that provides long term data acquisition functionality using techniques that are employed in the field. The conventional Mtronix system was configured with the IEC 60270 integration bandwidth settings ($f_c$=350 kHz, $\Delta$=300 kHz) selected and each unit was calibrated before testing commenced.

Additional PD data acquisition was also provided using the "high resolution" mode of the ASM system, with a single cycle of PD data recorded every three minutes. The ASM has a sample rate of 100 $\text{MSs}^{-1}$. The HFCT used to collect the PD pulses that propagate along the earth bond of the cable sample has an bandwidth of 50 kHz - 20 MHz and a transfer function of 5 $\text{VA}^{-1}$.

## 3 RESULTS

The results provided in this section were obtained when a significant change in PD activity was caused by each type of mechanical stressing technique described previously. All results were obtained with the sample at rated voltage and temperature.

### 3.1 Repeated crushing

During testing for the repeated crushing experiment, ten applications of the maximum pressure were applied before the rated voltage was connected and PD measurement took place. During the experiment, no significant change in PD activity was noticed until after the application of 40 crushes to the sample. At this stage, the PD activity generated by the sample rapidly increased in magnitude. An example of the PD activity that was active at this point is provided in Figure 2. Analysis of the phase resolved PD pattern generated by each phase over a 20 s time period shows the activity is dominated by a single source. This was assumed due to the distinct phase relationship of the activity visible on phase one. The patterns viewed on phase two and three relate to cross talk of the activity on phase one, where the inversion in PD polarity is evident. The peak apparent charge generated by the crushing process at this point in testing reached ~1 nC for phase one. Given the introduction of PD activity with a significant amplitude had been caused by the crushing process, the pressure was maintained on the sample in order to collect PD data. After a period of five minutes, the protection system for the experiment tripped and isolated the sample from the applied voltage. The protection system was reset and as the applied voltage was gradually increased, the protection tripped again. The conclusion that a fault had occurred was reached as the cable insulation could only withstand 3.5 kV. At this point, the mechanical pressure applied to the sample was removed, the power supply was turned off and the sample was maintained at its rated temperature for an hour. After this period, a voltage was applied to the sample. The protection tripped when the output voltage of the transformer reached 4 kV. As this was a significant increase (14%) in the breakdown voltage of the sample, it was proposed that some kind of recovery of the cable insulation was occurring. To investigate whether that was the case, the sample was left at its rated temperature for another half hour before a voltage was once again applied to the cable. At this point the cable insulation was able to support the full rated voltage without breaking down. The cable had effectively, "self-healed".

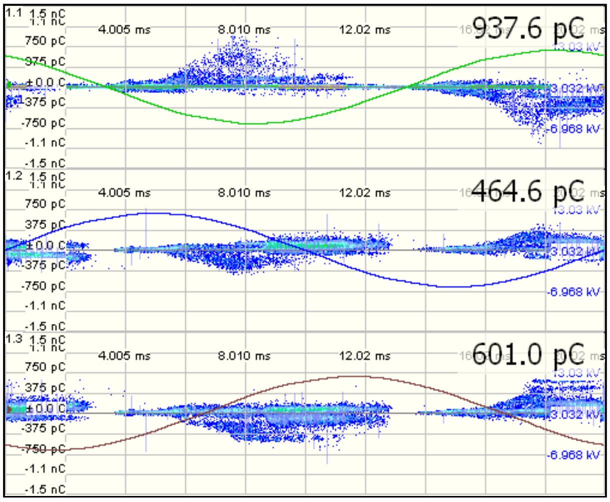

**Figure 2:** Phase resolved PD pattern of "repeatedly crushed" sample for phases 1, 2 and 3.

### 3.2 Overbending

The overbending test involved bending the cable to a certain degree, monitoring the PD activity and if no significant change had occurred, reduce the bend radius as appropriate. The PD magnitude remained below the noise threshold until the bend radius was reduced to 22 cm. Two bands of PD activity appeared on phase one and three with a peak apparent charge reaching ~60 pC. The phase resolved PD pattern that was captured over 20 s is shown in Figure 3. It should be noted that the visible damage to the cable was considerable, at the apex of the cable bend, the sample was clearly compressed by ~20% of the cable diameter.

A smaller bend radius of 19 cm was then applied to the sample. At this stage of the test, it was becoming increasingly difficult to bend the sample. The cable was heated to 45 ºC and the rated voltage was applied to the sample as previously. Analysis of the persistence plot generated at this point showed an increase in the peak magnitude observed from the sample. When comparing the PD results from the bend with a radius of 19 cm to the bend with a radius of 22 cm, The new conditions exhibited a peak charge magnitude of ~170 pC with the previous activity peaking at ~55 pC. The later results also show PD activity on phase two of the sample although this pattern is likely caused by the cross-talk from the other phases increasing to a value greater than the noise threshold.

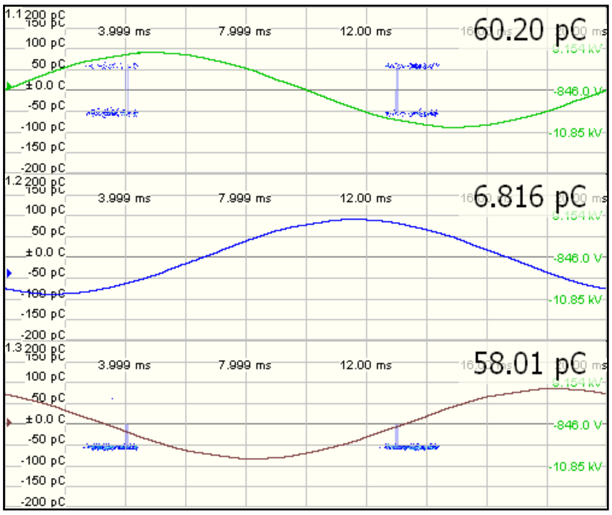

**Figure 3:** Phase resolved PD pattern for a sample with a bend radius of 22 cm for phases 1, 2 and 3.

### 3.3 Tree root compression

This test involved maintaining the sample surface temperature at the rated value of 51 ºC and increasing the pressure applied to the cable in discrete steps. The temperature was held at the rated value in order to isolate PD generated by the mechanical crushing process. The noise threshold for this experiment was recorded at 35 pC. The pressure applied to the mechanical ram was increased to 3175 kg before any distinct PD activity was observed using the conventional PD measurement system above the noise threshold. Under these conditions, a distinct PD pattern was noticed from the sample. The phase resolved pattern of the PD activity over a 20 s period is shown in Figure 4. The PD pattern shows the majority of activity occurring on phase 2 and 3 with a smaller number of larger magnitude pulses observed on phase 1. The majority of PD activity on phase 2 and 3 occurs at a specific phase angle with an apparent charge magnitude of ~60 pC. There is confidence that this activity is caused by the mechanical crushing process as there were a limited number of PD pulses of this magnitude at lower mechanical pressures.

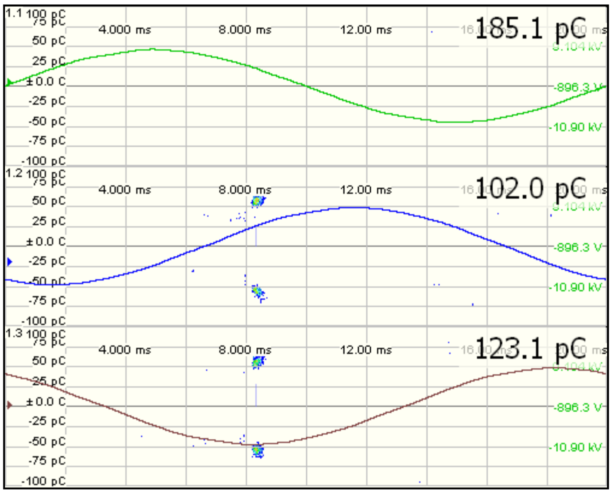

**Figure 4:** Phase resolved PD pattern of "Tree root" sample for phases 1, 2 and 3.

## 4 FORENSIC ANALYSIS OF THE SAMPLES

In order to fully understand the damage that had been inflicted on each cable sample, the sections of interest were systematically dissected and analysed for visual evidence of damage.

### 4.1 Repeated crushing

Before the cable sample was disposed of, it was cut into sections, one of these included the section damaged by the repeated crushing process. Thorough forensic analysis was undertaken on this section as it was thought to be the site of a cable fault. The first observation when studying the sample was that it had received a considerable amount of external damage. The PVC oversheath had sizeable holes in the location which the crushing mechanism contacted the sample. Once the oversheath had been removed from the sample, the steel wire armour and lead sheath were uncovered. The initial conclusion was that the lead sheath had been structurally compromised. Several of the wire armour strands had been forced into the lead and left deep impressions, two of the strands had fully punctured the sheath. It was also found that one of the armour wires had snapped at the contact point. The broken wire was located on the top of the cable where the moving part of the compression rig touched the cable. The broken wire had been forced through the lead sheath and was embedded in the paper insulation associated with phase one of the cable. Under close inspection, the impression of a single armour wire was identified on the phase insulation paper for phase one.

As the paper insulation under the impression were removed, a clear conduction path was seen passing through each layer of insulation. This manifested itself as a small incision with associated charring through each paper layer. As the sample had been rapidly (5-6 power cycles) isolated after the detection of a fault. Due to fast acting protection operation, the fault current only flowed instantaneously and the fault site remained in relatively good condition. In order to explain the "self healing" response of the cable, it should be taken into account that the sample under test in this experiment was new and had only experienced rated conditions. Given that a reduction in insulating performance is thought to be associated with the ageing process for this design of cable, this property may not be possessed by "old" cables in the field. Clearly, the removal of the mechanical pressure on the sample modified the conditions at the fault site. The most obvious explanation for the insulation recovery is that the distance separating the broken wire and the phase conductor increased to a point that breakdown was no longer likely.

### 4.2 Overbending

The initial thought when viewing the cable sample was the considerable amount of mechanical force that was required to damage what is a very mechanically resilient cable design. As previously described, the sample was heated to the rated temperature and a mechanical force was applied to the cable in order to bend it in ever reducing radii. The minimal bend radius reached during testing was 19 cm which is 23% of the minimum bend radius advised by the cable manufacturer.

The first visual inspection of the cable section showed no damage to the cable oversheath. The only physical difference to the sample that was noticed at the start of the forensic process was the bend in the sample that had remained as it cooled.

After the cable oversheath had been removed, the steel armour was revealed, the armour remained fully intact with a number of small gaps between several wires. No obvious damage was noticed to the internal materials of the cable until the phase insulation was exposed. At the apex of the bend, the paper insulation was noticeably paler than the rest of the insulation. On closer investigation, it proved that the mineral oil used to impregnate the insulation paper had been forced away from this region. The separation of adjacent papers on the outside of the bend and compression of papers on the inside of the bend was observed. A few small (5 mm) rips were seen on the inner paper layers.

### 4.3 Tree root compression

Firstly, it should be noted that the extent of damage applied to the cable was considerable and at all points in the test and yet, the cable remained operationally functional. The test involved incrementally increasing the mechanical pressure applied to the cable without puncturing the insulation. Analysis of the compression site showed superficial damage to the outer layers of insulation, the separation of armour wires and a small amount of deformation to the lead sheath. After the removal of the lead sheath around the crushing site, a considerable amount of damage was revealed at the top of the cable. The phase conductors were orientated with phases two and three above phase one. The orientation of the phase conductors at the crushing site resulted in phase one acting as a wedge and was driven between phases two and three. This action separated the phases, causing the paper surrounding them to rip longitudinally by 170 mm. As noticed in the previous sample, the region around the damaged area was considerably drier than the remainder of the cable. The movement of mineral oil coupled with the mechanical stress to the cable could promote the creation of voids within the cable that could be generate PD activity. The damage to the phase insulation for phases consisted of the innermost layers of paper insulation of phases two and three being ripped. The rips were up to 5 mm in length and were situated on the protrusions formed by the individual copper strands that make up the conductor. The outer phase insulation paper of phase three were slightly roughened - that was the only damage observed on phase three.

## 5 CONCLUSION

An experiment was developed to assess PD due to mechanical damage of PILC cable samples exposed to their rated temperature and voltage conditions. Three mechanical stressing methods were developed that were designed to replicate situations that are known to damage cables in the field. The three types of mechanical damage that were applied to different cable samples include repeated mechanical crushing, overbending and long term compression.

It was observed that all three types of mechanical damage introduced PD activity within the cable samples at rated voltage. These tests were of necessity over a very short period compared with expected field lives of 50 years and confirm that PD events can be initiated by extreme and repetitive stresses over comparatively short timeframes on new cables.

The repeated crushing experiment caused a phase to earth fault to occur between the cable armour and phase one of the cable. After the fault tripped the experiment protection system, the cable was heated for an hour and a half, the voltage was reapplied and the cable insulation withstood the electrical stress. The cable exhibited, "self healing" properties. The PD activity recorded during the crushing process exhibited a clear phase resolved pattern and the largest magnitude activity was associated with the phase that eventually failed. An increase in PD magnitude was observed as the sample approached failure.

Distinct phase resolved PD patterns were identified for all of the mechanical stressing mechanisms described in this work. Compression of the cable lead to a movement in the oil impregnate within the cable, it also effectively blocked the future flow of impregnate through the contact point. The lack of impregnate could lead to a localised reduction in the dielectric performance of the cable, acting as a weak point in the cable insulation.

## 6 ACKNOWLEDGMENTS

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## 7 REFERENCES

[1] H. S. A. Halim and P. Ghosh, "Condition assessment of medium voltage underground PILC cables using partial discharge mapping and polarization index test results," Procs. from the IEEE International Symposium on Electrical Insulation Conference, pp. 32-35, June 2008.

[2] F. J. Wester, E. Guilski and J. J. Smit, "Detection of partial discharge at different AC voltage stresses in power cables," IEEE Electrical Insulation magazine, vol. 23, pp. 28-43, July-Aug 2007.

[3] S. Boggs and J. Densley, "Fundamentals of partial discharge in the context of field cable testing," IEEE Electrical Insulation magazine, vol. 16, pp. 13-18, Sept-Oct 2000.

[4] W. L. Weeks, J. P. Steiner and W. Lafayette, "Improvement in the instrumentation for partial discharge in cables," IEEE Trans. on Power Apparatus and Systems, vol. PAS-104, pp. 753-760, July 1985.

[5] J. A. Hunter, L. Hao, D. J. Swaffield, P. L. Lewin, N. Cornish, C. Walton and M. Michel, "Partial discharge in medium voltage three-phase cables," Procs. from the IEEE International Symposium on Electrical Insuation, pp. 1-5, 2010.

[6] N. Ahmed and N. Srinivas, "Can the operating conditions of the cable system effect the data of the field PD Testing?" Annual report on Electric Insulation and Dielectric Phenomena, pp. 311-314, 2001.