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B1 Insulated cables
PS1 Learning from experiences

Development of an Electromechanical Test Technique in Dynamic Power Cables

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SUMMARY

The rise in power generation from offshore floating windfarms to meet ambitions to reduce carbon emissions is creating growing challenges for insulation reliability. Cable failures are a dominant source of offshore power outages, accounting for approximately 80% of insurance claims in this industry. Floating wind turbines use buoyancy modules to suspend dynamic cables in the water column that results in high levels of static strain. Strain is enhanced further by in-service oscillatory movement caused by wind, tidal and wave motion, and there is little knowledge of the impact of dynamic mechanical flexing on the behaviour of electrical trees. These are fine, tree-like gaseous erosion channels that grow from regions of high electrical stress within cable dielectric insulation, potentially over many years, which can ultimately provide a conductive pathway between electrodes and eventually result in the cable insulation failure.

Recent CIGRE Technical Brochures (TB) 722 and 862 have recommended methods for mechanical testing of submarine cables for dynamic applications. This paper presents a study attempting to develop electromechanical test techniques to examine the appropriateness of a sequential testing approach outlined in CIGRE TB862 and associated electrical tree characteristics. Such testing was found to be highly challenging and produced significant learning experience. Testing was conducted on 5 m lengths of 66 kV power cable core subjected to flexing using a large cable bend fatigue system whilst simultaneously electrically energized to grow electrical trees. Cables were bent along a former to a radius of 2.5 m, giving tensile strains as high as ~1% in the region of interest. Artificial defects (needles) were inserted into the cables to accelerate tree initiation. Electrical trees were successfully grown for static and dynamic strains in multiple cables. Optical microscopy allowed post-testing assessment of the trees and real-time partial discharge data was recorded. Several practical and experimental challenges were encountered when operating at large scales, including difficulties preventing voids around the needle tip during the insertion process and controlling needle-to-core gap distance. Observed electrical behaviour was consistent with companion studies conducted at smaller scales in the laboratory, supporting scalability, but trees grown in the large-scale tests were comparatively smaller in many cases. Subsequent laboratory investigations into these differences were conducted, revealing differences in process control between laboratory and large-scale that influenced the resulting tree growth. The details of test techniques, best practice, and learning experiences are presented. Optimising combined mechanical and electrical testing at scale will provide better understanding of whether a new combined testing approach is necessary for assessing the insulation reliability of dynamic cable or the existing sequential test approach is sufficient.

KEYWORDS

Power cables, combined testing, insulation, electrical tree, dynamic, mechanical strain

1 Introduction

Increasing deployment of floating offshore wind farms to generate renewable power is key to realizing the European Green Deal and the broader EU ambition to reach climate-neutrality by 2050 [1]. As these are installed in deeper waters further from shore, and the connecting array cables are effectively floating. These cables are subjected to varying tensile and compressive strains in-service which is different to land-based cables typically installed in benign environments. There is little knowledge on the impact of dynamic mechanical loading on known pre-breakdown phenomena such as electrical tree growth in cable. Electrical trees are tree-like hollow gas channels that grow within cable insulation from regions of high electrical stress, and eventually provide a conductive pathway between electrodes, resulting in large destructive currents and a source of cable failure. Cable failures account for approximately 80% of insurance claims in the offshore wind industry [2] and efforts to ensure their reliable operation is seen as critical to the financial viability of offshore and floating offshore wind projects.

For dynamic HVAC cables, the current industry practice is to design the dynamic cable based on the fatigue life of the metallic components (e.g. CIGRE TB722 and 862 [3], [4] and DNV-RP-F401 [5]), where the insulation system is not considered to be significantly affected by the dynamic strain variations seen during the cable operation in offshore environment. This lack of consideration for insulation design is also reflected in the full-scale qualification of a dynamic HVAC cable where mechanical fatigue and electrical type testing are performed sequentially. It is further highlighted in CIGRE TB862 that there is a lack of research related to combined electromechanical testing and at what strain levels the mechanical load will not have a significant effect on ageing. These insulation failure mechanisms are becoming more important to understand and form the basis of this study.

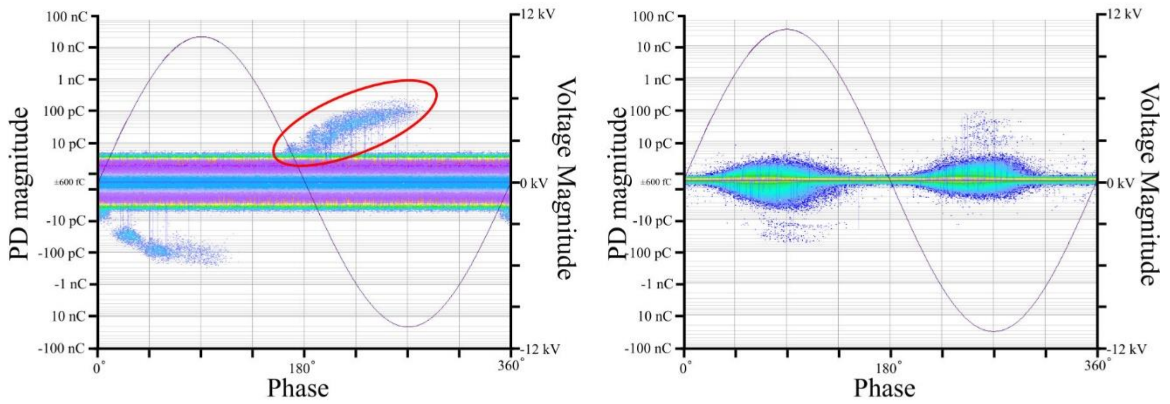
This paper investigates the combination of both mechanical and electrical testing using multi-metre lengths of 66 kV power cable subjected to dynamic bending whilst under high voltage and reports learning experiences.

2 Small-scale preparation testing

Preliminary experiments were conducted in the Manchester laboratory on more manageable short 10 cm lengths of the same cable used in the larger-scale testing (Figure 1). These tests were designed to understand the typical partial discharge characteristics observed under unstrained conditions. Growth of electrical trees is typically conducted on samples containing an inserted needle acting as an artificial defect. This is necessary to accelerate the initiation and growth of electrical trees to practical timescales. While a needle in a cable is unrepresentative, the physical processes occurring likely are, even if accelerated, and the use of a higher field stress to accelerate testing is a well-established approach. Even without needles, electrical trees can still grow from sharp field-enhancing points and even water trees [6].

Observations showed typical partial discharge behaviour that was comparable to experiments typically conducted on extracted XLPE material, as shown in Figure 2. Separate research on XLPE under strain also showed tree geometry is affected by the application of tensile strain (Figure 3) [7] applied globally to samples, warranting further investigation at scale. Tensile strain produced narrower trees, and vice-versa for compressive strain.

Figure 1. Offcuts of 66 kV XLPE cable were prepared into shorter-length samples for laboratory testing and the brass end-cap design is to minimise electrical noise.



(a) (b)

Figure 2. (a) Initial phase resolved partial discharge pattern which suggested tree growth in which partial discharge magnitude increases with point-on-wave magnitude as voltage increases producing an arc-like pattern (circled in red) (electrical noise band also present), and (b) the phase-resolved partial discharge pattern after the partial discharge free stage showing a more lemniscate-like patterning.

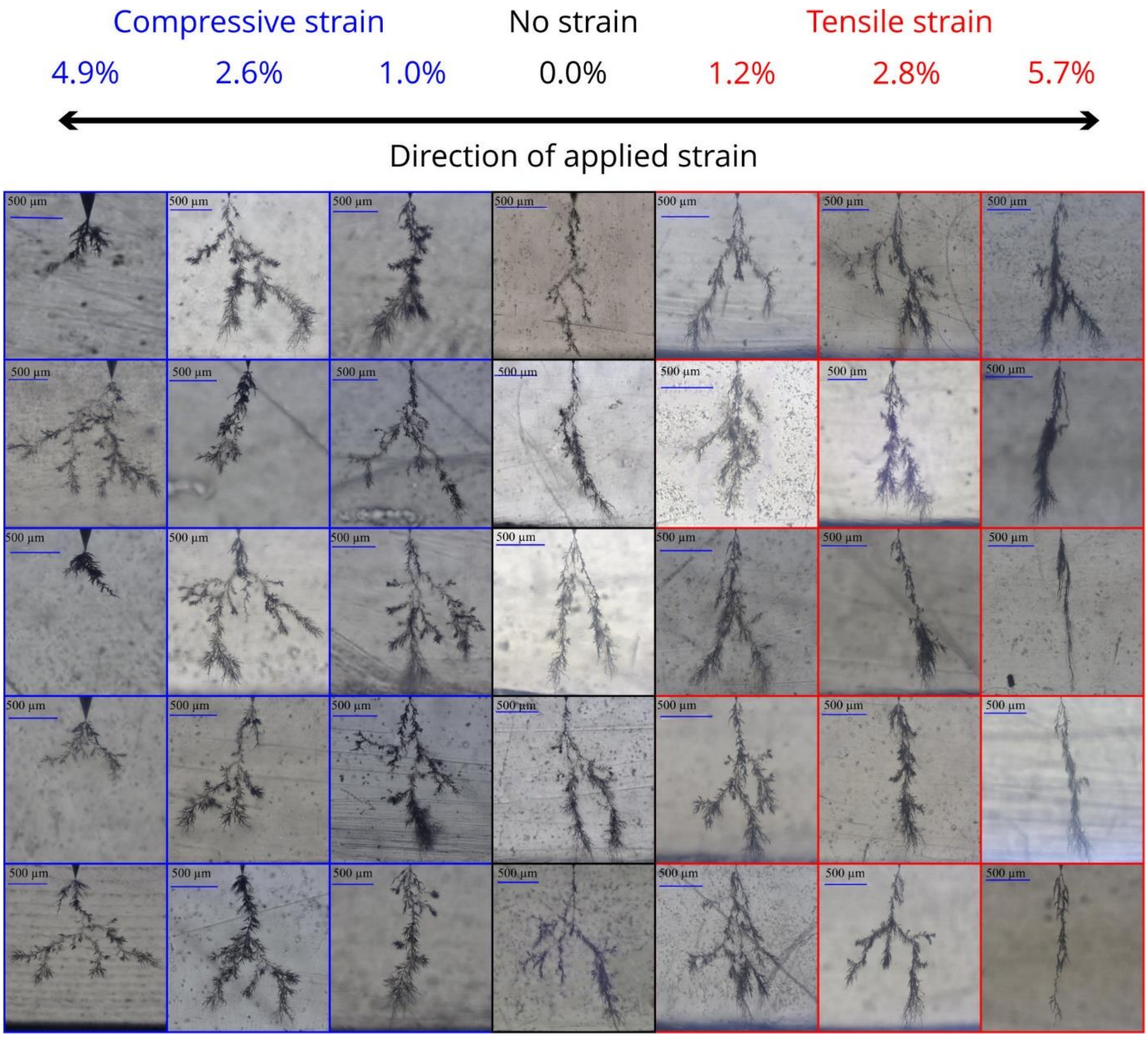
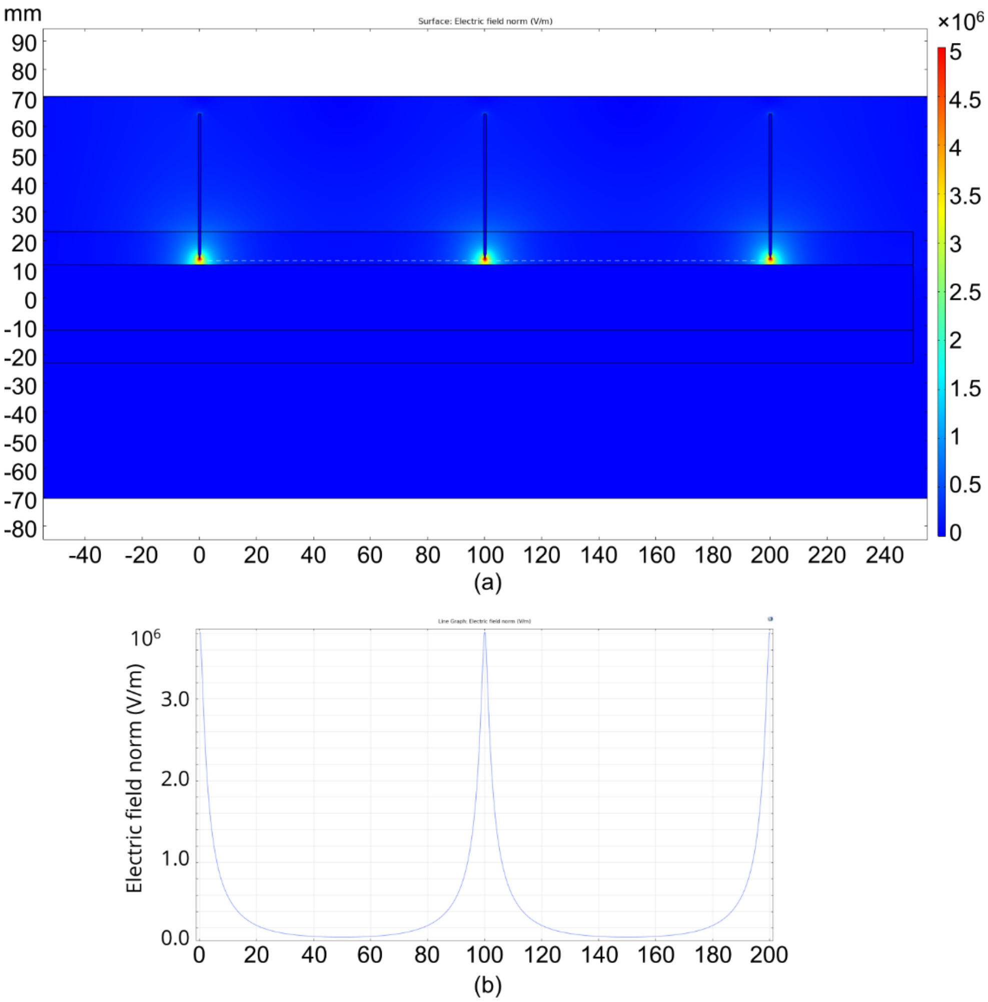


Figure 3. Examples from University of Manchester research [7] showing influence of strain on tree geometry.

For large-scale testing, owing to limited samples of 5 m length, a multi-needle setup was anticipated to be used in some larger-scale tests. Electric field modelling using finite element analysis was conducted to examine whether the fields from adjacent needles would interfere. Results showed field magnitudes dropped by over an order of magnitude with 100 mm needle spacing and adjacent needles were thus unlikely to adversely interact (Figure 4).



(a)

(b)

Figure 4. Finite element modelling of peak electric field strength associated with needles 100 mm apart. (a): Geometry and electric field strength (kV mm^{-1}), (b): Electric field strength profile between needles about horizontal while dashed line in (a).

During large-scale testing, it was anticipated that in cables with multiple needles inserted, some would need to be left electrically floating rather than being removed to avoid damaging the electrical trees grown. Testing showed that floating needles did not initiate trees nor allowed continued tree growth after initiation. Before operating at larger scale on the bending test rig, it was unclear whether having earthed needles and an energised core would be more practical, or the opposite electrical configuration. Additional testing was also conducted to determine whether the alternative electrical configurations influenced tree growth behaviour. Both configurations showed identical tree growth behaviour, and it was later determined that earthed needles would be more practical and help avoid short circuit to the dynamic bending rig.

3 Large-scale setup and testing

The dynamic cable bend fatigue test rig, shown in Figure 5(a), was used to conduct bending fatigue tests on combining mechanical fatigue and electrical treeing investigation concurrently on 66 kV power cable samples with the core energised under high voltage. The primary aim was to examine whether observations of electrical tree growth on the small scale translate to larger scale testing on real-world samples. Three principal tests were conducted with cable samples: unstrained conditions, statically strained, and dynamically strained.

66 kV power core cables approximately 5 m in length were used as test samples shown in Figure 5(b). Ends were prepared as shown in Figure 5(c) by exposing the core, stripping back the semiconductive layer to prevent surface flashover, and earthing the screen. Brass end caps were placed over the core ends to minimise peak fields and silicone sealant was used at the cap-cable interface to eliminate small air gaps and corona (Figure 5(f)). A hole with 1 cm in diameter nearer the centre of the cable length was drilled through the outer sheath and screen to a depth sufficient to reveal the insulation layer (Figure 5(d)). A square-ended drill bit was used to minimise insulation penetration. Cables were heated using a heating blanket to reach 70°C (Figure 5(e)). A 50 mm needle with 3 µm tip radius was inserted centrally into the drilled hole using a press. The needle was heated to 140°C using a modified soldering iron and needles could be inserted normal to the surface to a depth sufficient to give an approximate gap size of 2 mm between the needle tip and semiconductive layer covering the core. This depth was gauged beforehand using a customised needle insertion rig. This process of sample preparation was as similar as possible to that followed for smaller-scale laboratory samples often tested.

Cables with needles inserted were crane-lifted onto the large bend rig. The centre of the cable length was placed across the centre of a lower former of bend radius 2.5 m, giving tensile strains of approximately 1% in the region of interest around the needle tip, and ratchet strapped down. The ends were placed through the rig's collars (Figure 5(g)) and cleats were used on both sides of the collar on one end of the cable to secure it to the rig and prevent horizontal sliding during flexing (Figure 5(h)). This was necessary because the cores had smaller diameter than the larger parent cables the rig was designed for. The secured end not subjected to flexing was connected to the test circuit; the core was connected to high voltage via a hole drilled in the end cap for a standard 4 mm banana lead, and the screen was earthed (Figure 5(f)). The other end of the cable was free to be subjected to bending by the rig. The hole and needle were positioned to be in a region of the cable that was above the former and away from the centre where it was ratchet strapped (Figure 5(i), Figure 6). The rotation of the cable in the rig was such that the hole and needle pointed upwards, normal to cable's surface.

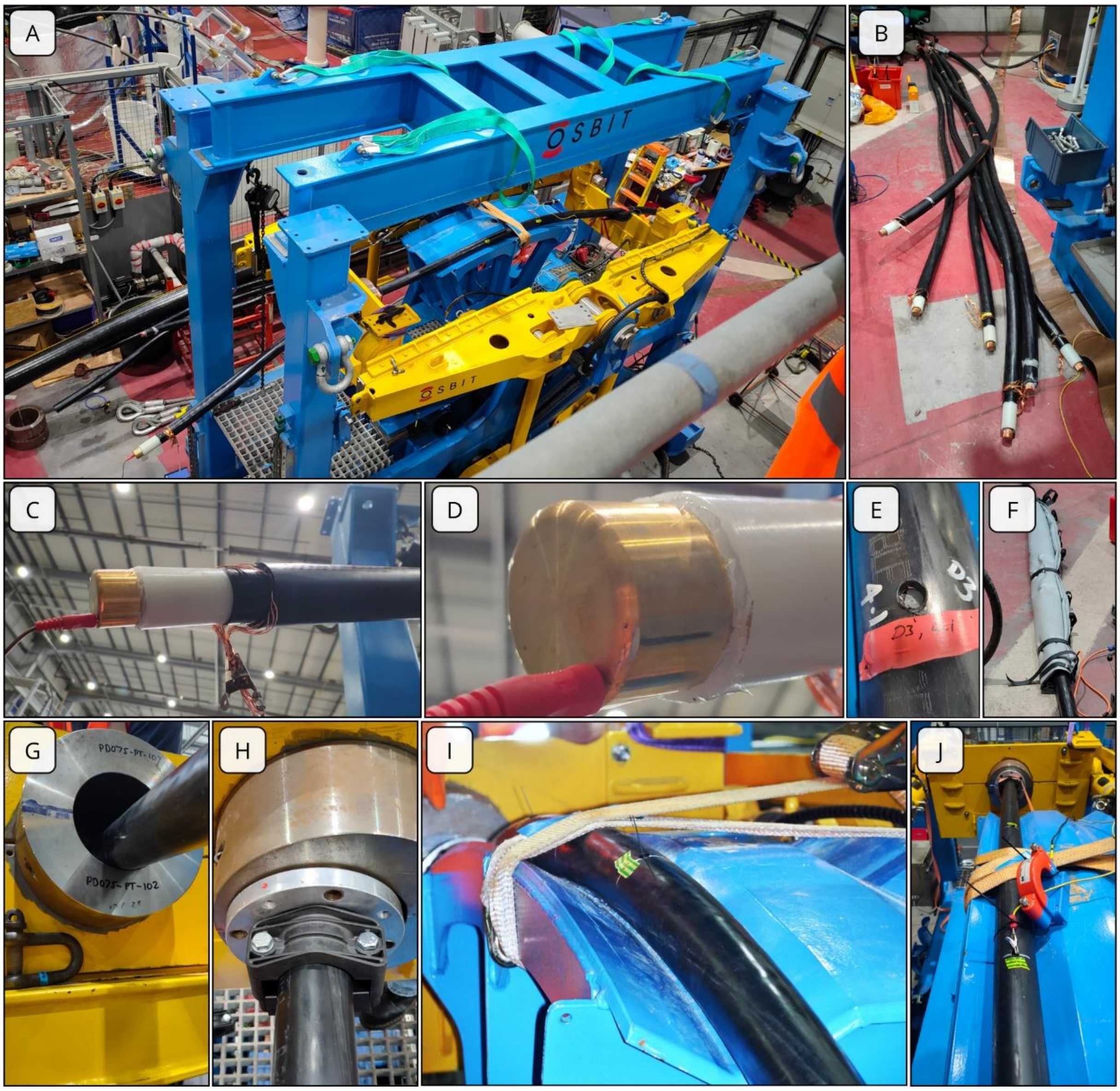


Figure 5. Various images of the test setup.

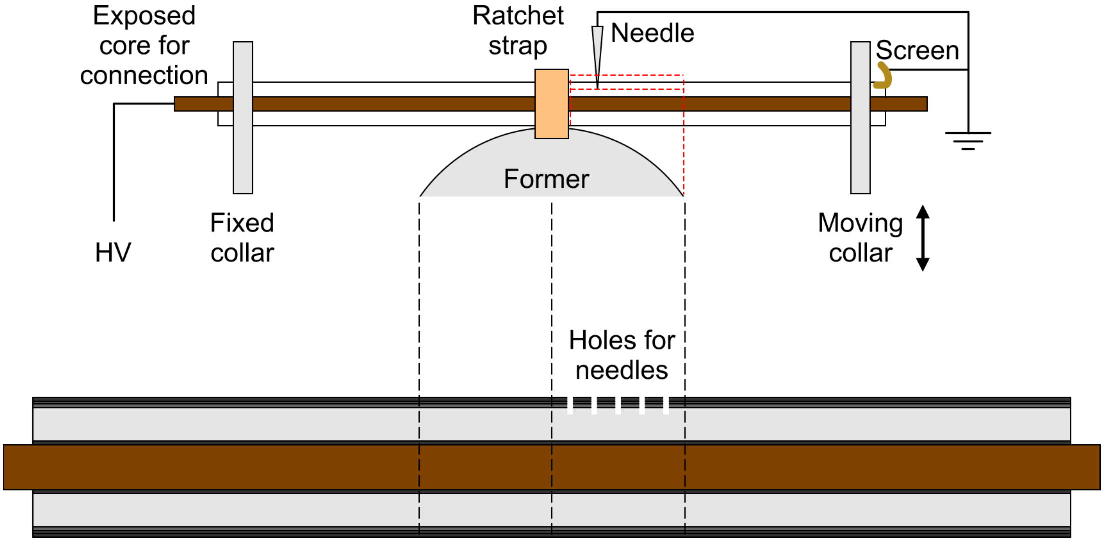


Figure 6. Sketch of cable sample in rig. The former has bend radius of 2.5 m, cables were approximately 5 m in length, and needle spacing was 10 cm.

The test circuit used is shown in Figure 7. Power was supplied using a supply and transformer, protected by a 4.1 kΩ current limiting resistor. Voltage was measured using an AC/DC HV divider and calibrated against a Multimeter. The circuit was modelled in software to quantify waveform phase shifting. A high frequency current transformer was used to detect partial discharges to earth and was placed as close to the needle as possible to minimise any antenna effect and electrical noise (Figure 5(j)). Background noise levels could be reduced to approximately 1 pC this way, allowing data signals to be detected (Figure 8). The needle was connected to earth using a fine earth wire and a crocodile clip. The fine wire was cable-tied onto the main cable along its axis to avoid torque on the needle to dislodging during dynamic oscillations on the rig (Figure 5(j)).

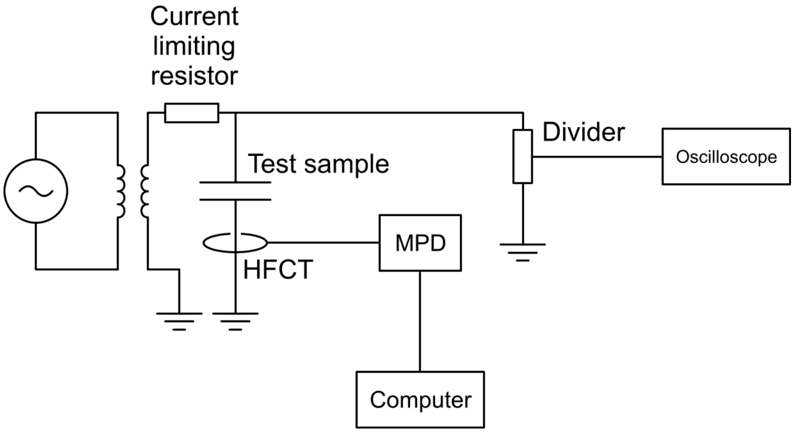
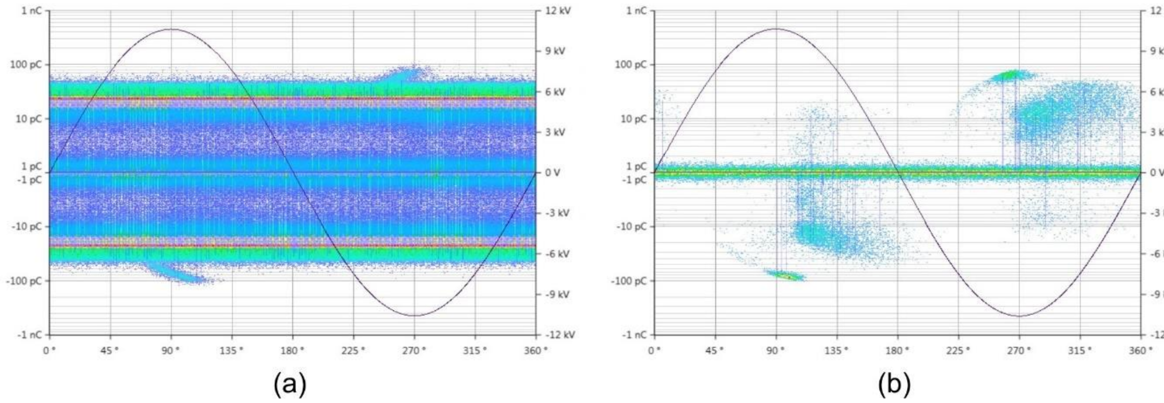


Figure 7. Circuit diagram for large-scale testing



(a) (b)

Figure 8. Example of reduction in background electrical noise levels from large bending rig when current transformer is moved as close to the needle as possible to minimise antenna-like noise on earth cable from needle. (a) before transformer is moved, (b) after it is moved.

Partial discharge charge magnitudes were calibrated against 50 pC pulses across the current transformer. The voltage was increased at approximately 250 V s^{-1} ramped up from 1 to 7.5 kV_{rms} and partial discharge activity was monitored until tree-like patterns were observed. Trees were allowed to grow for 2 hours, which initial laboratory testing in Manchester suggested that this will allow sufficient growth in the test cables without leading to a breakdown.

Unstrained tests were achieved with a straight cable mounted into the bend rig, whereas static strained tests had the sample bent across the former and held statically. Dynamic bend tests involved the cable flexing between a straight horizontal position to curved across the former at a frequency of 10 Hz. Unstrained and static tests were conducted on the same test sample using multiple holes and needles along the sample above the former region with a spacing of 100 mm. Only a single needle was used per sample of dynamic testing because of the possibility of tree damage if flexed repeatedly after creation.

Once tests were completed, needles were removed, and sections of the test samples containing the needles and electrical trees were cut out and polished down to a physical size allowing examination under the microscope.

4 Large-scale testing results

This section presents the observations made during testing on longer lengths of cables using dynamic flexing whilst energised. Unstrained, static, and dynamic testing was conducted and Table 1 summarises the test results on electrical tree growth.

Table 1. Summary of testing and results

Test	**1**	**2**	**3**	**4**	**5**
Strain	Unstrained	Static	Static	Static	Static
Result	< 500 µm	< 500 µm	< 500 µm	< 500 µm	> 500 µm
Test	**6**	**7**	**8**	**9**	**10**
Strain	Static	Dynamic	Dynamic	Dynamic	Dynamic
Result	< 500 µm	< 500 µm	< 500 µm	< 500 µm	< 500 µm
Test	**11**	**12**	**13**	**14**	**15**
Strain	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
Result	< 500 µm	Breakdown	< 500 µm	Breakdown	< 500 µm

Unstrained

Unstrained samples were tested first to examine any differences that might be introduced by the dynamic bending rig. Partial discharge behaviour for unstrained samples was very similar to that observed on the short test 10 cm test samples examined in the laboratory, confirming that no additional complications were being introduced by the dynamic bend fatigue test rig used for the testing of 5 m cable length.

Statically strained

Five static strained tests were then conducted, revealing partial discharge behaviour that was similar to expectation, but also suggested the presence of voids in the system. The pattern that evolved was also atypical, sometimes with longer initiation times and transitions between phases. While patterns showed no features that hadn't been observed before, it is most likely that variations in needle-core gap size, which were inherently difficult to control on the large scale in unsectioned cables, were responsible.

Dynamically strained

Many of the dynamic tests resulted in failure or were rejected, either due to lack of initiation, or because samples broke down. This was again most likely to be caused by gap distances being too large or too small, preventing an appropriate field strength for controlled electrical tree growth. The tests which were successful showed generally similar partial discharge evolution to expectation, with minor deviations again being most likely attributable to gap size and other differences inherently difficult to control on large cables, relative to laboratory samples (Figure 9).

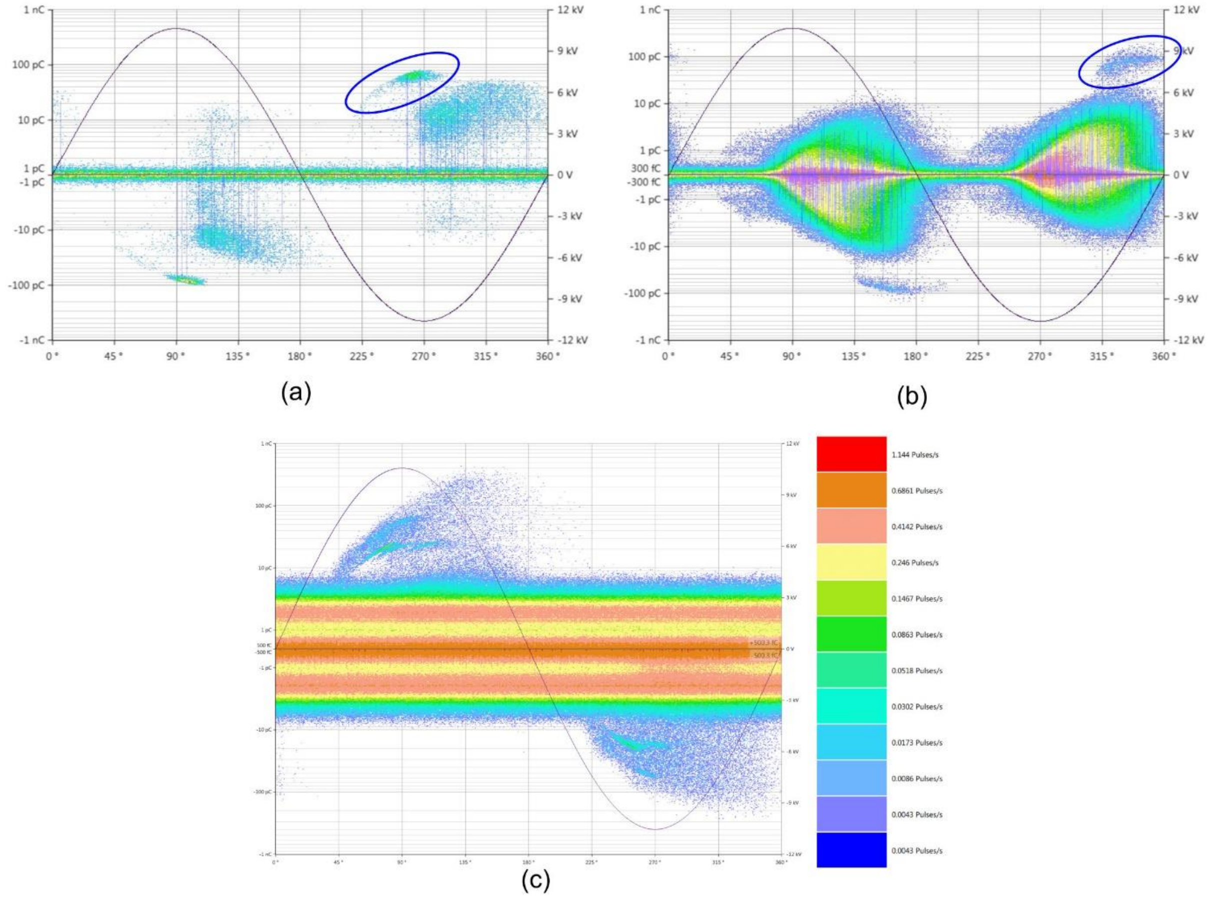


Figure 9. Typical examples of partial discharge activity from dynamic testing on large bend rig. (a) and (b): Example dynamic test partial discharge behaviour analogous to Figure 2 with additional void-like features (circled in blue); (c) A second example of a dynamic test showing more characteristic behaviour analogous to Figure 2 (a) (the central band is environmental electrical noise).

4.1 Material characterisation

Cable test samples were cut, and microscopy revealed a void was present in all test samples approximately 0.7 ± 0.1 mm in length from the needle tip. Only 3 out of 15 samples achieved the target gap distance (from needle tip to semi-conductive layer) of 2 mm ± 0.1 mm, and all other samples had larger gap distance than intended. 8 out of 16 samples initiated electrical trees, out of which 5 were extremely dense in structure and only grew to a maximum of 300 μm in length, as shown in Figure 10.

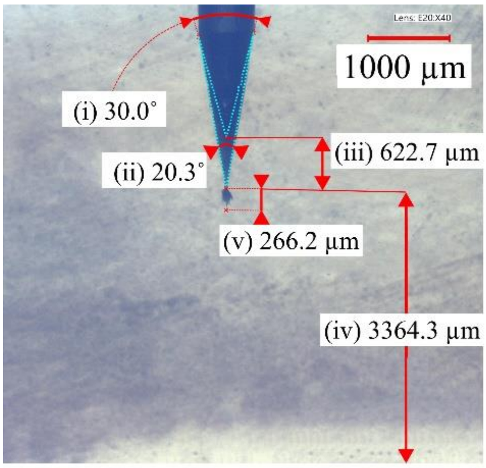


Figure 10. a) Example of sample from large-scale testing with large gap distance, void, and small tree structure (i) needle taper angle, (ii) air gap taper angle, (iii) distance from the needle tip to the air gap, (iv) distance from the air gap to the inner semi-conductive layer, (v) height of the tree.

Microscopy images from all tests are shown in Figure 11.

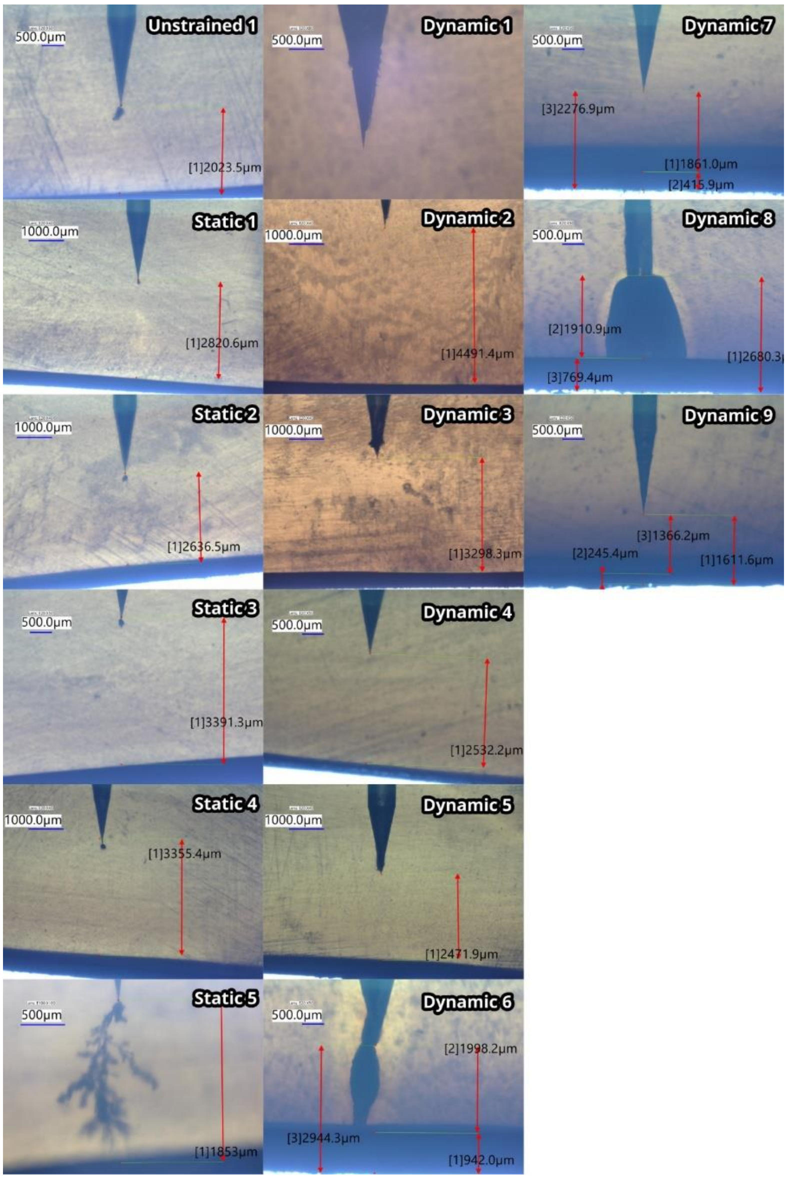
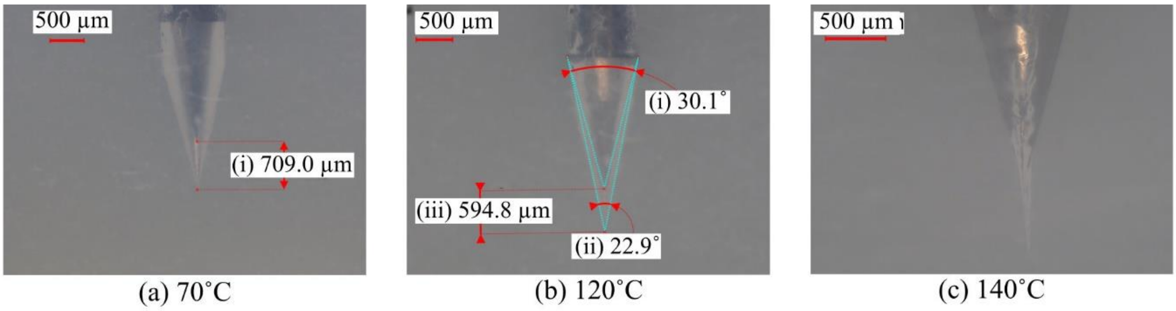


Figure 11. Microscopy images from all tests

4.2 Supplementary investigations

Supplementary investigations were conducted to further clarify the observations from large-scale sample testing and identify whether certain features could be reproduced without mechanism strain. Under controlled laboratory conditions, preparation of samples to avoid the presence of voids at the needle tip is a careful process. 3 mm thick samples were cut from cores for traditional needle-plane test configuration to allow imaging of the tree structure during growth. Samples were cut from the same 66 kV power cables into 3 mm thick half-ring samples. These samples were heated to 140˚C for 1 hour in an oven before the stainless-steel needles were inserted to leave a 2 mm gap. Samples were then left at 140˚C for another hour before being left to cool overnight. This process was not directly achievable when testing on the larger scale and so replication of what was likely to have occurred was attempted. In two samples, needles were inserted as described above but after cooling the needles were retracted by 0.6 mm and then placed back into the oven for 5 minutes at a range of temperatures. It was found that at 120°C, the void geometry was similar to that seen in the large-scale testing (Figure 12). Subsequent testing with several of these void-filled samples initiated electrical trees with similar dimensions and characteristics observed in the testing on the bending rig (Figure 13).



(a) 70°C (b) 120°C (c) 140°C

Figure 12. Void geometries after reheating a sample with 0.6 mm void to (a) 70°C with no difference to the void geometry, (b) 120°C with (i) needle taper angle (ii) void taper angle and (iii) void height similar to that seen in the large-scale 5 m long cable samples, and (c) 140°C with a very thin void.

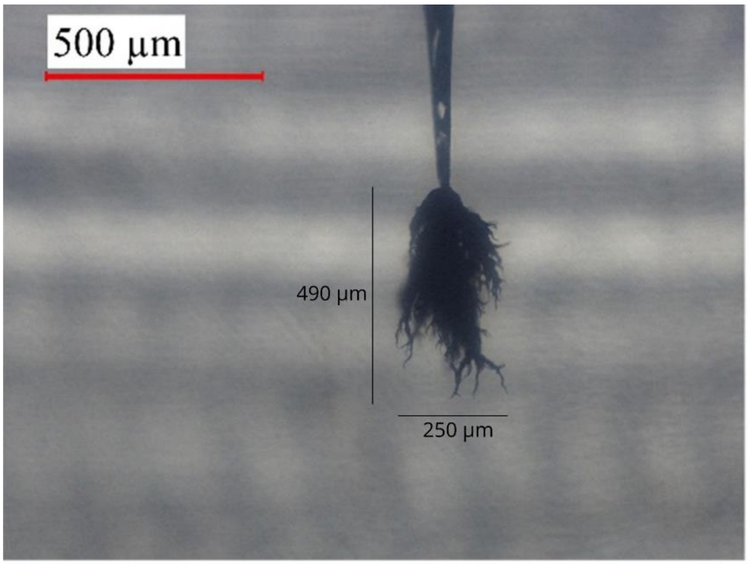


Figure 13. Example of dense tree structure initiated from the void in small samples, retracted and reheated to generate a void representative of large-scale testing

These observations suggest that in the large-scale testing, the needle retreated from the insulation on large cables during the cooling process, creating a void around the needle tip and influencing the subsequent tree growth.

5 Conclusions

Microscopy analysis of cut-out samples revealed growth of electrical trees in power cables tested under combined dynamic mechanical load and high voltage energisation. Testing on larger scales and bending rigs in a controlled manner comparable to laboratory environments is challenging. Process control was the dominant factor affecting the initiation and propagation processes in electrical trees, mainly because of void formation associated with the needle insertion. Understanding how to comparably reproduce the rigorous control found under controlled laboratory environments is essential for reliable and reproducible larger-scale testing when combining mechanical and electrical tests techniques. Owing to the difficulty in getting data with highly controlled needle-core gap distance from samples subjected to dynamic mechanical strain, no conclusions can be confidently drawn here about its influence on tree development. However, the study has shown where difficulties lie and the need to be able to control gap distance in such testing. Importantly, observations from the larger scale, and subsequent investigations in the laboratory showed that nothing fundamentally different was observed to be occurring on the large scale, and that testing was comparable to laboratory conditions where control is more easily achievable.

Separate but related testing under controlled laboratory conditions [7] has revealed application of static mechanical strain influences electrical tree geometry and that the evolution of phase-resolved partial discharge patterns is characteristic of tree development between electrodes within a cable.

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