HubNet Position Paper Series

Interfaces in Solid Dielectric Insulation Systems

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- Development of a mega-grid that would link the UK's energy network to renewable energy sources off shore, across Europe and beyond.
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- Management of transition assets: while a significant amount of new network equipment will need to be installed in the coming decades, this new construction is dwarfed by the existing asset base.
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The University of Manchester

Position Paper on Interfaces in Solid Dielectric Insulation Systems

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Abstract:

High power and high voltage electrical plant require high reliability to provide economic solutions for energy generation, transmission, distribution and conversion. Interfaces between dielectric materials are inevitable in real systems, and are required as a result of the need to improve material performance, enable plant fabrication and connect various components.

Interfaces may be characterised into three types: macroscopic, micro-scopic, nano-scale. These are roughly associated with lengths of: larger than mm, 10's to 100's of micrometres, and sub-micron. Each has a different impact on equipment performance and is at a different state of research development. This report is structured so that firstly modifications to materials are considered, and secondly the macroscopic joints between materials are reviewed. Many recent reviews cover the former, whereas few reviews have been written regarding macroscopic interfaces. For that reason this review focuses on the latter.

It is concluded that there continues to be a high level of research and development activity in the nano-scale composites, but that there is a lack of research aimed at larger scale interfaces between materials. This is an important area to develop for improved reliability and the transition to DC systems.

1 Introduction

Recent activity within both the EPSRC Supergen HubNet research consortium [1],[2] and CIGRE WG D1.59 'Methods for dielectric characterisation of polymeric insulating materials for outdoor applications' [3] has identified a need to review research and understanding of the performance of interfaces in dielectrics for power systems. This requirement stretches from the nano scale, concerning nano-composite polymers in which the interaction between nano-fillers and a host polymer matrix can profoundly affect dielectric properties, to interfaces between different polymer systems in overhead line insulators. The interfaces between solid surfaces and liquids and between solids and gases are not considered in this report.

This report provides a top-level review of activities is this area. It is not intended to provide a detailed literature review – the topics are too diverse for that: rather it is intended to bring out the commonalities and differences in the systems concerned. In particular a number of recent reviews on nano-composites have recently been published and these are referred to in the text. More primary references are used in the review of macroscopic interfaces since no review has yet been written in this area. Rather than base this review on material-type or specific application, the review considers the broader generic situations of interfaces. These situations are:

1. micro-fillers and nano-fillers used to modify macroscopic properties of polymers
2. Macroscopic interfaces between insulating materials

These two situations might also be regarded respectively as modification of materials per se, and assembly/fabrication of components. However, the role of processing is key in both.

2 Filled polymers

The use of fillers in polymers is well documented and the generalities of using fillers as active ingredients to radically improve performance and/or to reduce cost will not be considered here. This has been done many times before [5],[6] and work continues in that area [7]. Indeed the area of nano polymers is the most active in the dielectrics community, as reflected by the contents of conferences such as CEIDP and ICSD. But it is useful to review the breadth of filled systems employed, and the long track record of such technologies.

Micro-particulate filled polymers

The range of micro-fillers used commercially is very wide. Examples include silica or clay in epoxies for improved thermal and mechanical performance, reduced shrinkage and reduced cost. Chopped glass is traditionally used as a low cost method of increasing strength. Mica flakes are well established to improve electrical reliability particularly for thin layers in the presence of discharges (in windings for example). ATH has particular roles in fire resistant materials and overhead line insulation. Such material have been commercially deployed over may years [4].

Typically micro-fillers improve or change the characteristics of a compound through their own macroscopic properties. However these advantages can be lost if the filler is not well bound to the polymer, in which case poor mechanical and chemical properties can result. Although not strictly microfiller systems, filament winding and pultrusion are examples where excellent interfaces between filler and polymer are required for optimal

performance, and where delamination can introduce significant shortcomings. Considerable work has also be done in this area for coatings of optical fibres for cable applications.

Nano-filled Materials

The use of nanofillers in conventional polymers has transformed the research landscape. The wide activity in carbon nanotubes and other conductive fillers is not considered here, but the level of activity in that area will have a major impact on our understanding of processing issues, including management of polymer-filler interfaces.

The first publication explicitly concerning nano-composite dielectrics came from Lewis in 1994 [8]. He was the first to conclude that the use of interfacial properties on the nano-scale would be in the focus for developments in this field. A recent article [9] provides a historic review of nanodielectric materials. In the literature there are numerous other recent reviews [10]-[15] where the advances in nanocomposite materials and the enhancement of the properties of the base materials are pointed out in detail. Advantages may include:

- Permittivity decrease
- Dielectric loss decrease
- Low field DC conductivity reported to both increase and decrease
- Space charge decreases at high field
- High field conductivity decreases
- Breakdown strength increases.
- Time to breakdown increases in treeing experiments
- PD resistance improves
- Tracking resistance increases
- Thermal endurance increases

however, a great variability in results is reported probably due to variability in dispersion and interfacial properties.

The differences between nano- and micro-fillers are two-fold. Firstly, the micro-filler changes the composite's macroscopic properties through its own macroscopic properties, whereas the nano filler modifies the composite's macroscopic properties through the morphological changes it generates in the host polymer. The second difference is then that the nano filler requires a low filler level of a few percent compared to the 10's of percent used in micro-filled systems.

In micro-filled systems the interface requirement is one of good bonding between the polymer and the filler particles. This provides for good transfer of mechanical stress, heat etc. In addition, a good bond is required to prevent the interface becoming a mechanical or chemical weakness. In the nano-filled system a good interface is required so that the nano filler modifies the morphology of the surrounding polymer [7]. Although such a modification is initiated over a smaller surface area per filler particle, the structural changes within the polymer occur over much larger distances than the diameter of the nano-particle [8]. Thus a small loading of fillers (say 5%) can profoundly change the whole polymer system. Here again, however, is a requirement for a highly controlled interface between polymer and filler. Two further requirements arise for the nano-system: and that is good dispersion of the filler particles, and providing circumstances which allow optimal morphology to develop in the nano-composite.

3 Macroscopic Interfaces between Polymers

In contrast to the issues concerning interfaces between filler particles and a host polymer, the interfaces between polymers in equipment can present large areas to engineer. Often the reliability of a system is determined by such interfaces. Most notably, joints and terminations in cable systems are frequently the 'weak' points of a network. This is partly due to the necessity of the interface itself, and partly because of the requirement to fabricate joints and terminations in the field, in sub-optimal conditions.

In joint structures, interfaces are often managed by including semiconductive or non-linear resistive regions, creating geometries which prevent fields parallel to the interfaces, and by extending the length of the interface. These methods effectively control the fields to which the interface is exposed. As commercial pressure increases to reduce the size of plant, and the move to DC systems improvements are now necessary including the removal of over-engineered designs.

The methods of designing insulation systems with interfaces have been hugely improved by introduction of finite element techniques. These readily allow complex geometries and non-linear elements to be modelled. Also, the ability of the community to directly measure space charge accumulation on simple geometries and simple materials has allowed direct measurement of space charge accumulation at interfaces [16]. This provides a tool for probing large interfaces unavailable on polymer-filler systems. It is also these measurements for example which show directly that nano-fillers can modify space charge accumulation in HVDC systems.

In 1996 the cable jointing community developed a list of experimental test cell requirements through CIGRE WG 15-10, to enable laboratory bench testing of material interfaces. These requirements were that cells designed for interface testing should:

1 - have a simple configuration that is easy to reproduce;
2 - have no metal electrode surfacing at the interface;
3 - allow various defects to be introduced;
4 - enableone to study mechanical pressure effects;
5 - enable one to study surface roughness effects;
6 - enable one to study the effect of silicone oil or other liquid insulants;

KEMA [17] also added

7 - enable one to study shear effects (including motion and rubbing)

The resulting test samples used by Kema are shown in Figure 1.

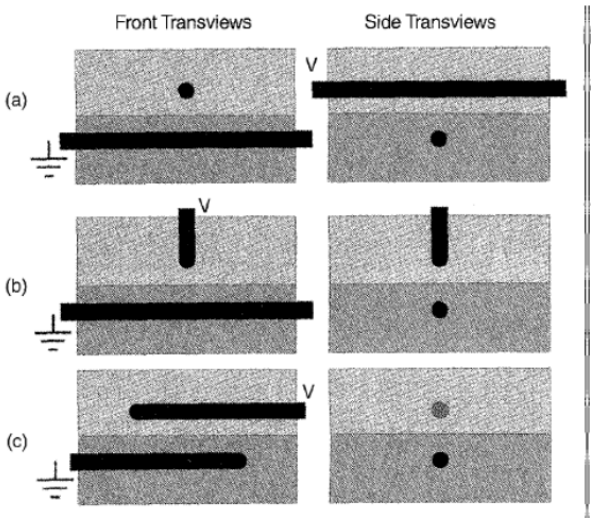

Figure 1: Electrode arrangements to study cable joint interfaces. These are arranged to give a variety of tangential stresses at the interfaces [17]

Of particular interest to CIGRE WG D1.59 is the interface between pultruded core and polymeric sheath of an overhead line insulator. This presents an interface necessarily principally parallel to the field. As in the case of cable joints and terminations, these interfaces are protected by managing the field to which they are exposed. In particular care is taken to avoid contamination and voids at the interface, and to manage the fields at metallic fittings. The outdoor application also presents the threat of moisture penetration and stress-corrosion cracking of the core and of internal tracking processes.

Some of the similarities between the chemistry of filler-polymer interactions and more general interfaces are illustrated by the experiments and considerations of Bolliger and Boggs [18]. Interestingly they also referred to the presence of filler in the respective polymers as important even in the case of macroscopic interfaces.

A key parameter is pressure between polymer layers; this is well established in short-term breakdown tests [19] and a point developed more recently by Du and Gu [20]. Du and Gu proposed a simple reproducible small-scale sample with metallic electrodes, and transparent silicone to allow camera recordings of discharges and track development. They showed that an increase of interfacial pressure can effectively restrain the carbonization to appear along a narrow channel and reduce the complexity of tracking patterns, and also increase discharge inception voltages. However, the smoothness of the interface is also seen as significant [21] and, as might be expected, this is exaggerated at lower pressures – indicating the presence of voids or low density material may be the cause. The apparatus which has been used with two electrode configurations by Du, Gu et al is shown in Figures 2 and 3.

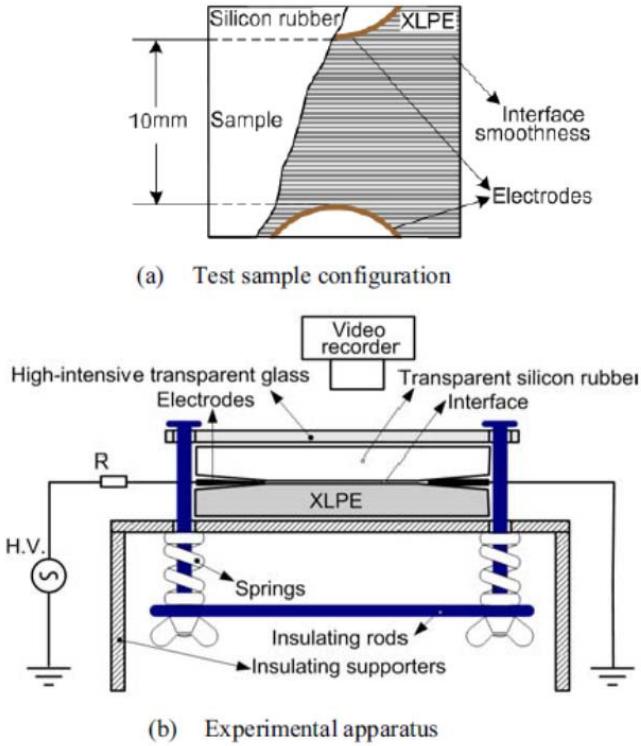

Figure 2: Apparatus to visually see discharges and track growth at under transparent silicone layers. Flat round copper electrodes of diameter 10 mm are sandwiched in the interface and separated by 10 mm [21]

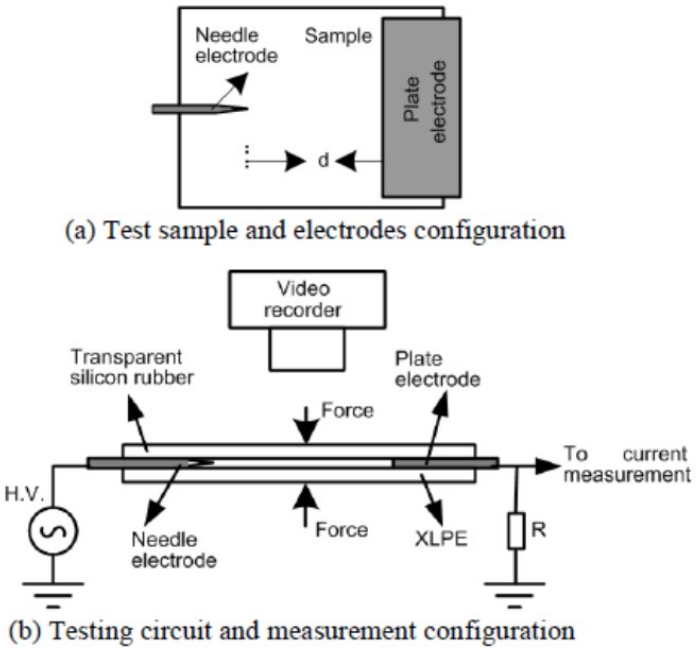

Figure 3: Apparatus to visually see discharges and track growth at under transparent silicone layers using needle-plane geometry [20], [22]

Work between Chalmers and ABB [23] developed an alternative small scale test to study the importance of the primer between silicone rubber and epoxy. This did not result in any clear

conclusions, but the apparatus used is shown in Figure 4. This features a 75 µm radius wire as the HV electrode - providing the field enhancement.

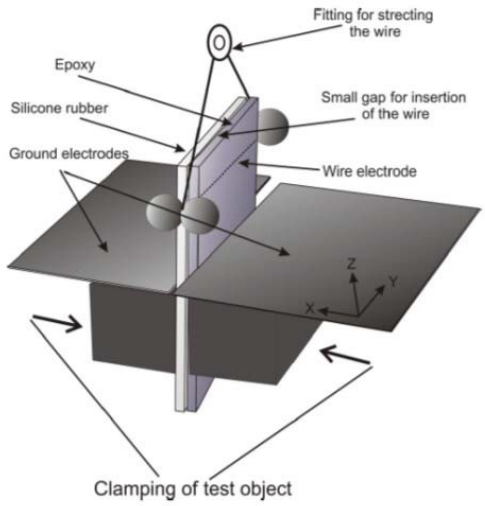

Figure 4: Apparatus to investigate interfacial tracking. The wire used as the HV electrode is 75 µm radius and 30 mm from the ground plane [23]

To study the impact of repairs and joints in HTV silicone rubber, Gubanski et al used the IEC 60587 standard inclined plane test and IEC 61109 'salt fog inclined plane test' on butt-jointed materials [24]. This is illustrated in Figure 5. In this case the samples' tensile strength was found to be the best method of ranking interface electrical strength.

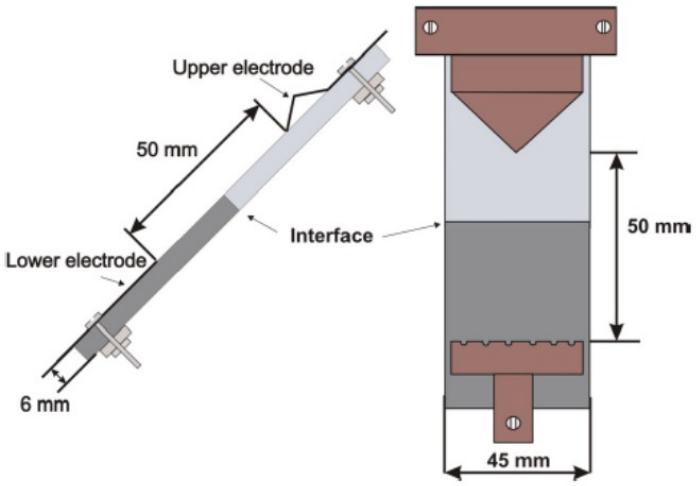

Figure 5: Apparatus to investigate interfacial integrity [24]

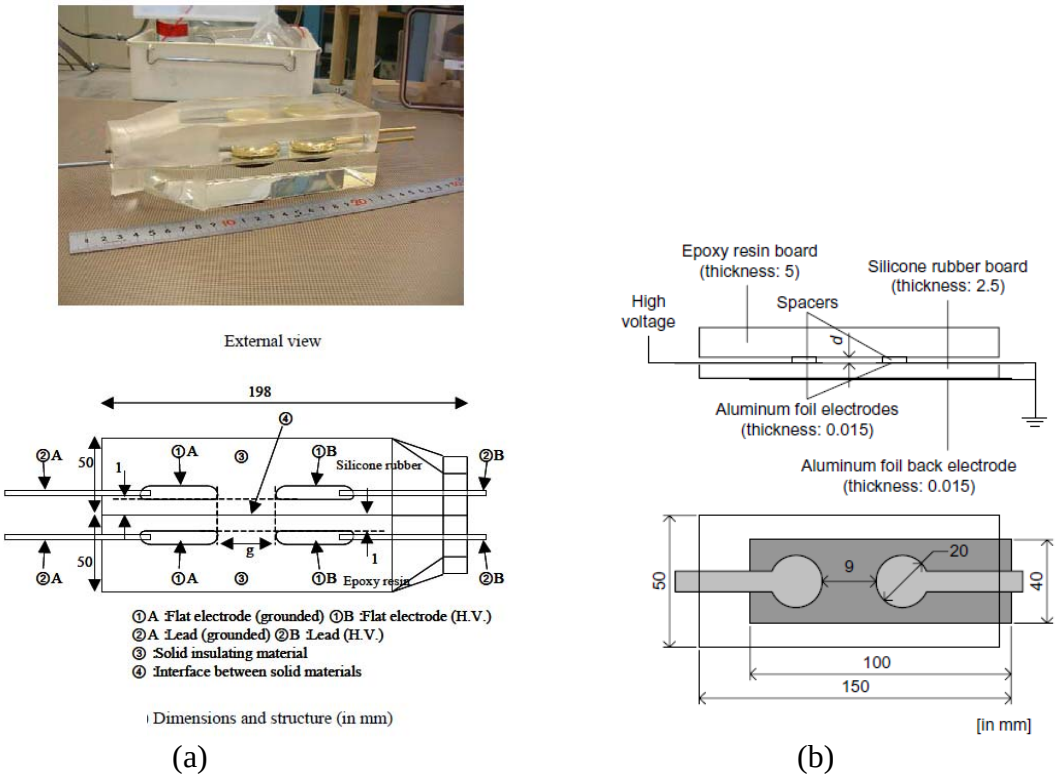

Figure 6: Two apparatus used to investigate (a) discharges and (b) breakdown at interfaces [25]

Figure 6 shows a well-controlled arrangement used to study interfaces with a controlled electrical stress [25]. This sample form has the disadvantage of being expensive of materials and preparation time, but was used for investigating the impact of air-gaps on discharge inception. The second sample in Figure 6 was presumably developed to reduce this cost, and enable repeated tests for breakdown measurements. This is similar in nature to the sample used by Dang, which tested the impact of greases in particular, this is shown in Figure 7 [26].

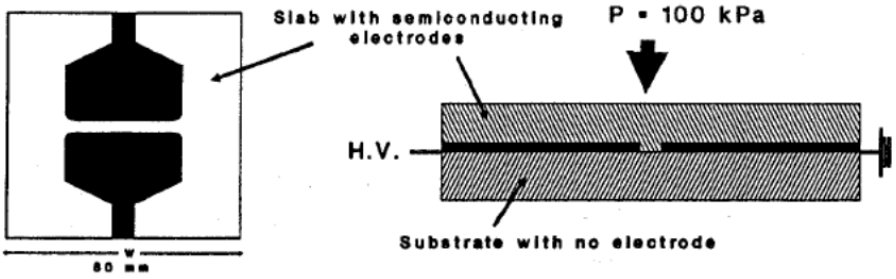

Figure 7: Sample arrangement to test greases and the impact of sliding [26]

In an approach taken similar to that with standard electrical treeing testing, cable joint interfaces have been tested by direct needle insertion into interfaces. In [27] for example, a 4 mm separation was used between needles with end radii of 60 µm.

A different approach is taken by some who consider early reduction in interfacial adhesion to be a prerequisite for failure. In this case, reduction in peal strength and even reduction in resistivity after boiling in saline solution can be used as a guide to ageing [28]. This approach has the attraction that such ageing tests are standard in type testing of overhead line insulators.

4 Conclusions

There is a high level of activity globally developing and studying composite polymers. This includes studies of filler surface interactions. Activity is apparent in commercial and academic organisations. A number of reviews are available on nano-composite systems. Rapid advancement is expected in the carbon-nano technologies which will spin into the dielectrics areas.

For macroscopic interfaces, analytical techniques are still primarily focused on partial discharges, mechanical and chemical characterisation. Surprisingly, there does not appear to have been much effort to develop interfacial tracking growth models, and this is a clear area where work is required. Work which has been reported so far is mainly using very short term tests, sometimes following longer environmental ageing regimes.

No standardised tests for macroscopic interfaces, unlike the standards for surface tracking, and common practices adopted for treeing experiments. There would be considerable advantage to developing such a standard.

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