HubNet Position Paper Series

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The Supergen Energy Networks Hub

Opportunities for Improvement of Power Plant through New Materials

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About HubNet

HubNet is a consortium of researchers from eight universities (Imperial College and the universities of Bristol, Cardiff, Manchester, Nottingham, Southampton, Strathclyde and Warwick) tasked with coordinating research in energy networks in the UK. HubNet is funded by the Energy Programme of Research Councils UK under grant number EP/I013636/1.

This hub will provide research leadership in the field through the publication of in-depth position papers written by leaders in the field and the organisation of workshops and other mechanisms for the exchange of ideas between researchers and between researchers, industry and the public sector.

HubNet also aims to spur the development of innovative solutions by sponsoring speculative research. The activities of the members of the hub will focus on seven areas that have been identified as key to the development of future energy networks:

- Design of smart grids, in particular the application of communication technologies to the operation of electricity networks and the harnessing of the demand-side for the control and optimisation of the power system.
- Development of a mega-grid that would link the UK's energy network to renewable energy sources off shore, across Europe and beyond.
- Research on how new materials (such as nano-composites, ceramic composites and graphene-based materials) can be used to design power equipment that are more efficient and more compact.
- Progress the use of power electronics in electricity systems though fundamental work on semiconductor materials and power converter design.
- Development of new techniques to study the interaction between multiple energy vectors and optimally coordinate the planning and operation of energy networks under uncertainty.
- 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.
- Energy storage: determining how and where storage brings value to operation of an electricity grid and determining technology-neutral specification targets for the development of grid scale energy storage.

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1. INTRODUCTION

The HubNet program contains a work theme on Power System Plant, which focuses on solid state insulation, including the development of nano-composite electrical insulation [1,2]. Another key theme concerns asset management, which requires understanding equipment design, ageing mechanisms and prognostic methods [3,4].

Design of power plant is controlled by the need to manage thermal, mechanical and electrical stresses in insulation systems, and doing so with great reliability. One opportunity presented for new designs of plant are material developments, and it is intended that this document reviews potential opportunities for such progress.

At present the drivers for progress in plant performance are similar to those throughout the power system. For example, the desire for more compact plant (i.e. substations [5] and overhead lines [6-8]) tends to increase electrical stresses and raise equipment temperature. Similarly the need to optimise utilisation of existing plant, generally requires raised operating temperatures, and identifying operational bottlenecks and reliability implications. However, as will be seen, new technologies may provide opportunities for self-healing [9] or self-cleaning [10] systems. Other opportunities afforded might enable reduced power quality requirements, without impacting reliability, thereby providing system cost savings.

This document is a snap-shot of the present position. The authors have sought input from experts in a number of institutions, and during conferences at poster sessions (such as HubNet's Smart Grid Symposium 2015 and UHVNet 2015). The emphasis has been on dielectrics and conductor systems which are the authors' areas of expertise, but has embraced other concepts were ever possible. Other contributors are too numerous to thank, but we are grateful to our community for their openness and willingness to share.

This report is about opportunities presented by new materials. However we have tried to link these directly to potential applications, if only to illustrate where technologies might be applied. For this reason the Report falls into three parts: firstly, generic material improvements are considered; Secondly, potential end uses of emerging materials sre considered with more detail provided; finally, recommendations for future research directions are given.

2. GENERAL DEVELOPMENTS ACROSS MATERIALS TECHNOLOGIES

Developments in chemistry, often driven by biochemistry and medical applications have led to ready fabrication of molecules on demand [11-13]. This is particularly true for polymers. Similarly, high-end applications in aerospace have led to metallic and non-metallic composite technologies [14], resulting in high strength, low weight materials. In insulation systems, the use of micro fillers is well established and nano-filler technology – whilst being well established in the laboratory [15,16], is an emerging technology.

One key feature of the power network plant market is that large volumes of material are required. In addition, high reliability is essential and, generally, long established and successful systems already exist. As a result, the drivers of development are often for reasons of cost or other improvements rather than technical operational improvement. A good example of this is the replacement of mineral oils with organic oils in transformers [17,18] and cables [19] for reduced environmental impact; an area the UK leads the world. Other cases of environmental drivers are to reduce SF6 use in gas insulated substations and lines [20,21], and to reduce the use of thermoset polymers which cannot be recycled. Another environmental driver is the need for fewer or less visible overhead lines. The consequence of many developments being 'just' improvements on a proven technology, in a sector requiring high reliability, is the need for a 'killer application' which warrants the investment required to make a technology change.

In the context of large material volumes, many of the new materials seem some distance from application, Graphene [22] and its many derivatives [23] are examples of this. Equally important though are the manufacturing and process/fabrication methods, some of which may provide improved product design leading to technical and commercial improvement. In particular, other sectors, such as aerospace [24] can lead to rapid, developments, or commoditisation, such as self-cleaning glass [25] which may change the landscape rapidly. The following sections list some key materials which are being developed.

a. Composite dielectrics

Two key areas in composite dielectrics are presently being developed in composite dielectrics. Firstly nano-composites are a key area of study in academia [26], and it has been demonstrated that these can provide improved dielectric strength [27], and discharge resistance [28]. Equally importantly they can provide improved thermal conductivity [29-31], and temperature withstand [32]. The combination of these properties may allow plant compaction. There is active work within HubNet and the Top and Tail projects in this area [1,2].

The second area of interest is the development of non-linear composites. In these the dielectric permittivity or the electrical resistivity is a function of applied field [33-35]. This can be used to self-modulate the field around the end fittings of an insulator [36], [37] or bushing [36], [38]. Such solutions may reduce the length of insulators, reducing cost and size of plant. However the fabrication process must give reliable and reproducible properties, and this has not proved easy to date.

b. Superconductors

Superconductors are not a new technology, but are included in this review for completeness. The issue for these materials is raising their operating temperature sufficiently high to make plant operation economically competitive. At present the need for cryogenic apparatus makes use in a dispersed setting too expensive for any economic gain over conventional cable or GIS technology. Localised use is possible as can be seen from their use in commercial fault current limiters [39-44].

c. Carbon nanotubes, graphene and its derivatives

Graphene [22] is an EU flagship technology (1B€ funding committed), and a UK focus is provided by The National Graphene Institute and The Graphene Engineering and Innovation Centre in Manchester. Work on graphene has been extended into many two-dimensional structures. Graphene famously has very high electron mobility [45] (15,000 $cm^2V^{-1}s^{-1}$), and high tensile strength [46] (130 GPa – 300 times that of steel). Commercially, to date, the mechanical and thermal properties of graphene have been more important than its electrical characteristics.

Graphene's derivatives can be very different: fluorinated graphene [45] for example is an extremely good insulator (a band gap of~3eV) and is extremely hydrophobic [46]. The potential in graphene has also led to a considerable body of work in other two-dimensional materials. A common example is h-BN (Boron Nitride) [47] an excellent insulator (a band gap of 5.97 eV), with both high mechanical strength and thermal conductivity.

These materials have been evaluated in isolation and in the context of finding applications as nano-composites (dispersed in polymers) and coatings [48]. Some, but not all, of these applications may be marketing driven rather than technically driven at present. The large investment in layered 2D structures for electronic and photoelectronic applications are not impinging in power network applications at present.

Carbon nanotubes are, in themselves, a mature technology. Their large aspect ratio makes compounding into conductive composites through percolation relatively easy at low levels of fill [49]. A key feature is that the width of the percolation zone can be controlled and a high temperature coefficient of resistivity can be engineered into a material [50].

d. SF_6 replacements

The desire to replace sulphur hexafluoride, SF_6, remains driven by its environmental impact. The unique excellence of SF_6 to suppress and extinguish discharges and arcs [51], has led to reduction in plant size and reduced substation sizes. Therefore replacing this with a gas which does not perform as well technically has become economically prohibitive.

The most likely replacements are mixtures of gases (such as tri-fluoro iodide methane, CF_3ICO_2 [52], SF_6 and nitrogen, N_2 [53]) which are already used commercially for insulation (rather than arc extinguishing).

e. Oils

The UK leads oil insulation research [17]–[19] . Biodegradable oils are working their way into high voltage application [54]. Nano-filled oils appear to provide improved dielectric performance and are being studied alongside solid equivalents [55], [56].

f. <u>Superhydrophobicity</u>

High hydrophobicity (contact angles of >90°) [57] is normally obtained through creating a surface chemistry which repels the dipolar water modules [58]. This is most readily and sustainably achieved with silicone rubber for example. Superhydrophobicity (contact angles of >150°) [59] is obtained by controlling the surface roughness on a nano-scale: this not only keeps a surface dry but also self-cleans, as water droplets pick up and remove detritus from the surface [60]. This is known as the lotus effect [10] as the lotus flower leaf is a naturally occurring example of self-cleaning through superhydrophobicity. Biomimicry has led to surface coatings which can give this effect. The longevity [61] of those coatings in a natural environment is an issue for power systems.

Two key applications of such materials are, firstly, to overhead line insulators, which may allow for a reduction in creepage distance and so smaller structures [62]. A second application considers the way in which superhydrophobicity reduces ice accretion on surfaces [63]. This, in turn, can reduce worst case loading on conductors and overhead line towers: increasing flexibility in design, and reducing tower sizes and cost.

3. APPLICATION CONCEPTS

Here the discussion is limited to primary equipment and plant. Clearly the opportunities presented by communication and sensor technologies are myriad, but are very different from bulk power application.

In general, benefits from new materials can be listed as:

→ Compaction,	reduced visual impact or footprint
→ Increased ratings	increased voltage and/or current; AC and DC
→ Reduced maintenance	increased reliability or self-repair
→ Reduced cost	capital / whole life
→ Environmental sustainability	reduced pollution or better recyclability
→ Power quality immunity	enables relaxed power quality limits

a. <u>Tower Structures</u>

Superhydrophobic surfaces may reduce ice loading [62], which is a critical design constraint. Long term efficacy of any solution is critical however [63].

Corrosion resistant paints and surface treatments [64], [65] many of which are driven by the petrochemical industry, would provide a major benefit in reducing maintenance costs.

b. <u>Conductors</u>

Composite conductors using metallic composites, and non-metallic composites as strength member structures are now commercially available for overhead line application [6]. These are known as high temperature low sag (HTLS) conductors [66], and allow higher currents on existing tower structures without infringing line clearances.

Superhydrophobic surfaces may reduce ice loading on conductors [67], which is a critical design constraint to overhead line systems. Long term efficacy of any solution is critical however.

Superhydrophobicity and very low hydrophobicity are both solutions to acoustic noise from high voltage conductors in the wet allowing higher voltage ratings [68]-[71]. However, longevity of any solution is critical. Such coatings [72] are close to market.

It is a moot point whether copper and aluminium will be replaced as the principal conductive media in power networks. It is possible that the first place these would be replaced is where alternatives have additional benefits. Carbon based (graphene/carbon nanotube) composites or coatings may first seen in overhead lines.

c. HV insulators/bushings

The main developments in this area are around design and fabrication. Non-linear dielectrics are beginning to emerge as practical ways to manage field stress grading [36], [38]. This may allow smaller insulation lengths and less metal-work in designs.

Hydrophobic materials are beneficial for polluted environments, and silicone based systems are well established. Superhydrophobic coatings may yield additional benefits of ice shedding [73-74] and self-cleaning [75], as with towers and conductors.

d. Transformers (asset management) Wide participation

As discussed previously a key development concerns improved liquid insulation systems. Transformer materials provide an excellent example of the need to have detailed design and materials engineering working together to optimise the system [75].

e. Substations

Generally power electronics is outside the scope of this work-theme within HubNet. However it is clear that few in the dielectrics community are working on high voltage power electronics insulation or packing (an exception si found in [76].

As noted for transformers, the complexity of, for example a converter station [77], requires optimal design and utilisation of materials for electrical thermal and mechanical operation.

New gases for switchgear have been researched for some time [5], [20], [21], [51]–[53]. However new approaches to molecular engineering may provide solutions to the need for highly electronegative and thermal conductive gases.

Superconductive fault-current limiters [40]–[42] may migrate from specialist applications to more general use.

4. DIRECTIONS FOR FUTURE RESEARCH

New developments which are in the right timeline for academic work in the scope of materials for power network plant appear to be:

→ Use of 2-D materials in coatings and composites (including graphene and its derivatives)

→ Consideration of HV power converter insulation structures and systems

- → Compaction of equipment through use of high temperature materials
- → Non-linear insulation
- → Optimising overhead line structures

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