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New materials in high voltage technology

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Assets in high voltage technology have to meet harsh service conditions over long lifetimes of 40 years or more. Due to environmental concerns, substitution of conventional insulating materials becomes a necessity. Because robustness and sustainability are serious requirements, only few new materials are really breaking through. At present some promising material technologies emerge with great potential applicability in high voltage engineering. This paper discusses especially nanocomposites and high temperature superconductors.

Keywords: high voltage technologies; nanocomposites; superconductors

Neue Materialien in der Hochspannungstechnik.

Anlagen in der Hochspannungstechnik haben raue Betriebsbedingungen während einer langen Lebenszeit von über 40 Jahren zu ertragen. Wegen ökologischer Bedenken wird der Ersatz von konventionellen Isolierstoffen durch ökologische Alternativen eine Notwendigkeit. Weil Robustheit und Nachhaltigkeit wichtige Anforderungen sind, schaffen nur wenige neue Materialien den Durchbruch. Zurzeit entstehen einige vielversprechende Materialien mit großem Potenzial für die Hochspannungstechnik. Dieser Beitrag diskutiert vor allem Nanokomposite und Hochtemperatur-Supraleitern.

Schlüsselwörter: Hochspannungstechnik; Nanokomposite; Supraleitern

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1. Introduction

In high voltage technology the assets have to meet harsh service conditions over long lifetimes of 40 years or more. Moreover, due to environmental concerns, substitution of conventional insulating materials becomes a necessity. For instance cross linked polymers, mineral oil and SF_6 are becoming considered non-sustainable solutions in the near future. Currently, these insulating materials are the cornerstone of many high voltage components. Because robustness and sustainability are serious requirements, only few new materials are breaking through. In general, in HV constructions new material inventions require interfacial matching with existing materials. For example for paper/oil insulation in submarine HVDC cables new polymeric insulation formulations are upcoming. However, interfaces with semiconducting layers influence the threshold field for space charge accumulation. This kind of complexity implies much longer development times than usual, notwithstanding the fact that at present some promising material technologies emerge with great potential applicability in high voltage engineering. To elucidate this some recent progress will be discussed. The topics are nanodielectrics, nanofluids, high temperature superconductors and electroactive polymers.

2. Polymer nanodielectrics

Nanodielectrics are a new class of insulation materials, utilizing the interfacial region between nanoparticles and a polymer host, in order to achieve improved dielectric properties (*Lewis 1994*). Figure 1 shows a slice of an epoxy nanocomposite with 2 wt.% of aluminum oxide nanoparticles. It has been shown that these materials exhibit unexpected dielectric behavior (*Frechette et al. 2010*). As illustrated in Fig. 2, the relative surface area of particles increases with decreasing filler size. This surface area seems to be the key to the potential of nanocomposites (*Lewis 2005; Rätzke and Kindersberger 2010;*

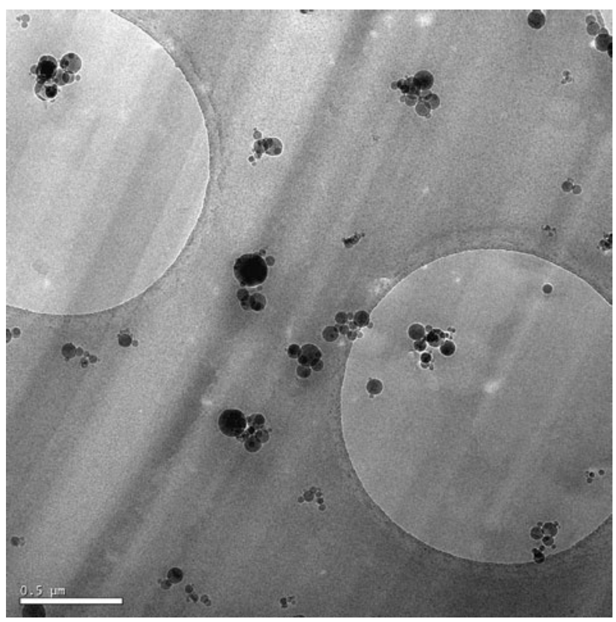

Fig. 1. Transmission electron microscopy of an epoxy nanocomposite with 2 wt.% of aluminum oxide filler with an average particle size of 50 nm

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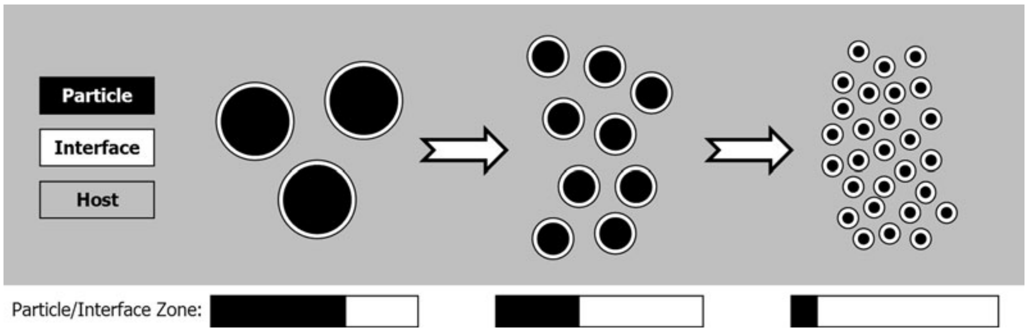

Fig. 2. Effect of decreased particle size on the relative surface area of the filler material

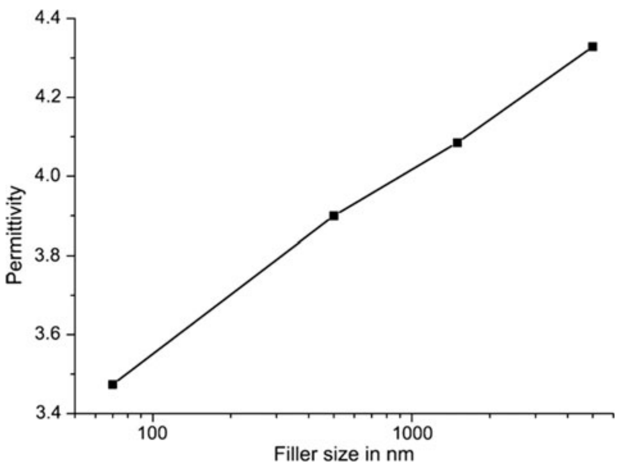

Fig. 3. The real part of the complex permittivity as function of filler size for BN-epoxy nanocomposites with a fillgrade of 10 wt.%

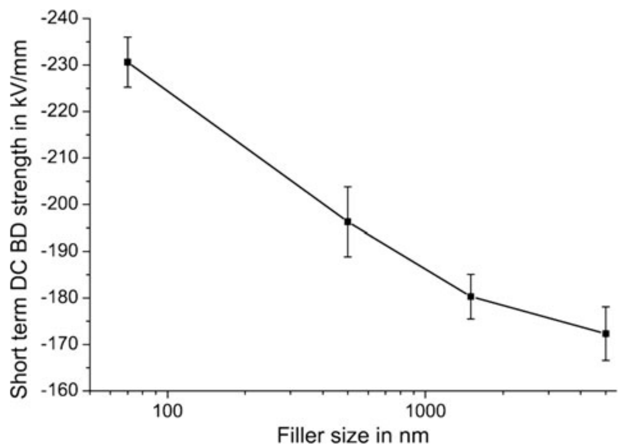

Fig. 4. DC breakdown strength results for BN-epoxy nanocomposites as function of filler size

Tanaka 2005). So far there is no direct measurement of the thickness of these interfacial layers. However, there is an indication that this layer extends about 20 nm for nanoclay in PMA (*Miwa et al.* 2006). For other material combinations this might differ. A strong indicator for the different properties of the nanoparticle surface compared to the host material and the particles itself comes from measurements of the permittivity. When a high-permittivity filler is introduced into a host material in form of nanoparticles, the permittivity of the resulting material is often lower than either host or particle (*Andritsch* 2010). Figure 3 shows how the real part of the complex permittivity can change as function of the filler size. The fillgrade in this case was at constant 10 wt.% of boron nitride (BN) with the same crystal structure and the same preparation procedure for all samples. The only variable was the filler size, which was 70, 500, 1500 and 5000 nm.

The amount of publications regarding the dielectric properties of nanocomposites is still increasing. Not all results are conclusive, but there are trends regarding an improvement of the DC breakdown strength, improved resistance to partial discharges and space charge reduction that shall be explored here.

2.1 Improved DC breakdown strength

While the AC breakdown behavior of nanocomposites doesn't seem to differ much from conventional material or unfilled polymers, there is large potential for DC applications (*Murata et al.* 2005; *Okuzumi et al.* 2008). It has been found that very small amounts of various nanoparticles can increase the DC breakdown strength of epoxy by up to 80 % (*Andritsch et al.* 2009a). What is truly remarkable is that this increase in breakdown strength happens at fillgrades as low as 0.5 wt.%. That this increase of breakdown strength is by virtue of the filler size can be seen in Fig. 4, which shows breakdown results for epoxy with 10 wt.% of boron nitride (BN) filler (*Andritsch* 2010). The unfilled epoxy has in this case a DC breakdown strength of 163 kV/mm, while BN-filled composites range between 172 kV/mm for 5 µm particles and 231 kV/mm for particles of 70 nm. What exactly causes this remarkable behavior is still subject of research, but the combination of bisphenol-A epoxy resin and boron nitride seems to be beneficial.

2.2 Reduction of space charges

Space charge accumulation is a limiting factor for HVDC applications (*Bodega* 2006). Several filler materials have been found to reduce space charges in polymers when introduced in the nanophase (*Andritsch et al.* 2009b; *Maezawa et al.* 2007). Magnesium oxide (MgO) seems to be the most effective and is a commonly investigated nanofiller regarding space charge reduction. Even small amounts of MgO reduce the amount of charges that are trapped in the material. In epoxy with 0.5 to 2 wt.% magnesium oxide filler, the amount of space charges is only about a third to a half of the amount that can be measured in unfilled epoxy (*Andritsch* 2010). Figure 5 shows a comparison of the charge build-up in unfilled epoxy and a MgO-epoxy nanocomposite with a fillgrade of 2 wt.% of 20 nm particles.

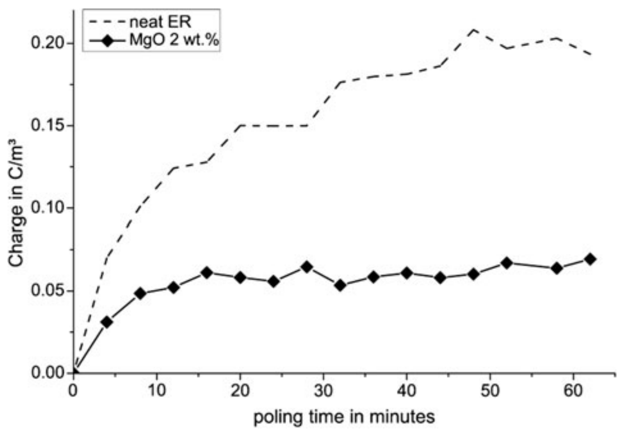

Fig. 5. Space charge accumulation within 60 minutes in epoxy compared to a MgO-epoxy nanocomposite with a fillgrade of 2 wt.%

2.3 Improved resistance to partial discharges

The electrical tree phenomenon is a common insulation mechanism failure mode. It can be initiated directly in regions of high electric stress or caused by defects, such as protrusions, in insulation systems. Polymers are very susceptible to insulation failure due to treeing, and also less resistant to partial discharges than e.g. ceramic insulators. There is a generally agreement on the fact that nanoparticles significantly slow down the rate of electrical tree propagation in the polymeric insulation. There are a multitude of reports about improved PD and treeing resistance of polymer nanocomposites. (*Henk et al.* 1999*; Kozako et al.* 2003*; Weiner et al.* 2011).

The average discharge magnitude for neat polymers usually shows two distinct categories: one of small discharges and the other of big discharges. However, in nanocomposites only small discharges were dominant. This observations are consistent with treeing models proposed by the likes of *Tanaka* (2011). While the tree can easily propagate in neat polymer, it's path is obstructed in nanocomposites. Reason for this is that even for fillgrades of 2 to 5 wt.% of nanoscale filler the average distance between nanoparticles is in the range of 100 nm or less (*Tanaka et al.* 2008).

In unfilled polymer insulation tree channels of various sizes are equally prominent. Trees in nanocomposites tend to consist only of very small treeing channels, giving the overall tree a distinctive, bush-like appearance.

2.4 Applications

There are no large-scale applications of polymer nanocomposites in high voltage engineering yet. It is only in certain cases feasible to just introduce a novel technology into existing products and expect radical improvement. As an example: replacing the conventional silica filled epoxy in cast resin transformers with nanocomposites would increase the price drastically. This is due to microscale silica being used in large quantities and being cheaper than the base resin. Simply replacing micro with nano would correspond to a decrease in fillgrade, increasing cost twofold: more costly epoxy is needed to replace the silica and nanoscale filler material is more expensive as well. Thus, the use of nanodielectrics has to be considered already at the design stage, to make the most of their properties (*Andritsch* 2010). The immediate benefit of nanodielectrics in HV components would be compact build size and for very low fillgrades transparency. Transparent insulating materials would enable easier monitoring and the use of optical sensing techniques to judge the condition of a particular device. Compact build is of course important for urban areas.

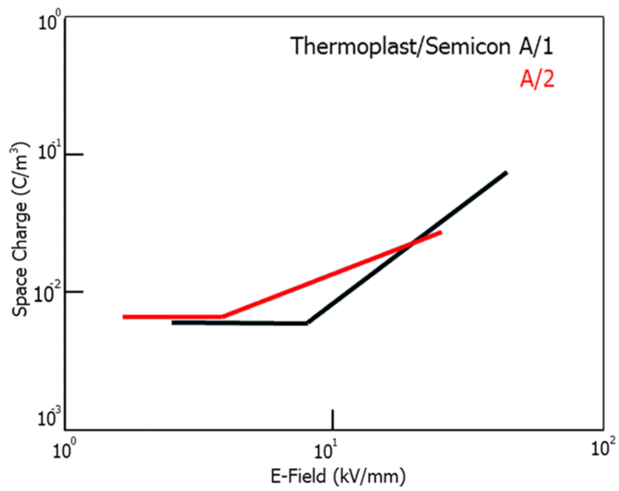

Fig. 6. Changes to the threshold for space charge accumulation due to changes in the material combination at 20 °C

The use of low-permittivity dielectric coating with nanoscale filler in gas insulated switchgear can help reducing the size of GIS installations. Together with replacement or dilution of SF_6 in GIS this can serve to reduce the environmental impact of such HV installations.

Advances in this field benefit our general understanding of insulation systems, since dealing with nanocomposites means dealing with interfaces. Interfaces between dielectrics are generally the weakest parts of insulation systems, especially under DC stress. For example, changing the material composition in high voltage DC cable systems changes the threshold for space charge accumulation at the interface. Using a different combination of thermoplastic isolator and semiconducting material in HV bushings can lead to a reduction of the threshold for charge accumulation, as illustrated in Fig. 6. This leads to faster ageing processes, hence reduced reliability.

3. Nanofluids

Tailored insulating material is possible in the near future due to nanostructuring. Furthermore, nanofluids are promising nanotechnology-based heat transfer fluids. Nanofluids consist of a traditional heat transfer fluid like water, mineral oil or ester liquids, in which a small amount of particles is stably suspended. The particle sizes are smaller than 100 nm but the effects are profound. It has been shown that the introduction of TiO_2 nanoparticles into mineral oil can improve the breakdown strength by up to 34 % (*Yuefan et al.* 2010). Conductive nanoparticles seem to suppress streamer propagation in mineral oil, by this increasing the breakdown strength of nanofluids (*Hwang et al.* 2008). Introduction of urchin-like nanostructures can increase the thermal conductivity of PAO oil by 20 % for 0.2 wt.% fillgrade (*Han* 2008). These urchin-like structures are formed by attaching carbon nanotubes on to aluminum-iron oxide nanospheres. Nanofluids on basis of vegetable oils could replace mineral oil in a variety of applications, with the advantage of being easier degradable.

4. High temperature superconductors

Also current carrying capabilities of HV equipment can be improved by new materials. Nowadays, a long length commercial High Temperature Superconductor of the latest generation YBCO can carry 300 A/mm^2 when cooled to 77 Kelvin. The potential advantages of application in HV technology are increased power density, intrinsic ability to limit fault currents, increased lifetime of the electrical insulation, increased grid stability, higher efficiency, better control of

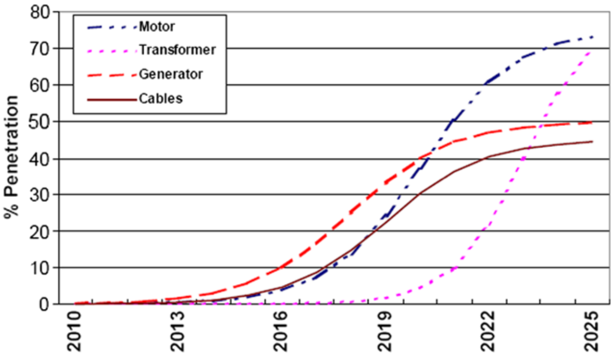

Fig. 7. Expected market penetration of HTS devices until 2025 (Mulholland 2003)

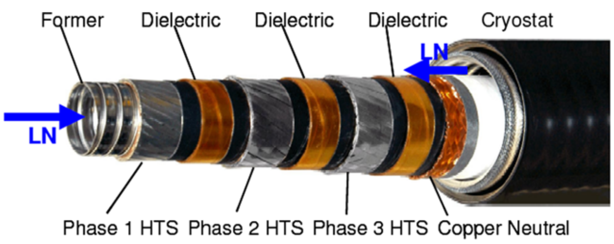

Fig. 8. Triax HTS cable (image: NKT)

power flow and improved environmental impact: less electromagnetic emissions, no soil heating.

Due to increasing power demand, the electricity grid is changing. The future transmission and distribution grid will obtain electrical power generated by decentralized renewable sources, together with large scale generation units located at the coastal region. In this way electrical power has to be distributed and transmitted over longer distances from generation to end user. Potential grid issues like: amount of distributed power, grid stability and electrical loss dissipation merit particular attention. High temperature superconductors (HTS) can play an important role in solving these grid problems. Advantages to integrate HTS components at transmission voltages are numerous: more transmittable power together with less emissions, intrinsic fault current limiting capability, lower AC loss, better control of power flow, reduced footprint, less magnetic field emissions, etc. The main obstacle at present is the relatively high price of HTS conductor. However, as the price goes down, initial market penetration of several HTS components (e.g.: cables, fault current limiters) is expected by the year 2015, Fig. 7 (*Zuijderduin et al. 2012*). The increasing and intermittent load flows in future grid scenarios supersede even more the possibilities of many existing designs.

On the other hand, relatively long length power connections using HTS may soon become feasible as explained below.

4.1 Project demonstrating long HTS cables with integrated FCL property

To demonstrate high performances of the HTS cables technology in a real network a consortium of the Dutch DSO Alliander, Ultera™ (Southwire/nkt cables Joint Venture) and the Delft University of Technology (TUD) has formulated a R&D program with the aim to develop and install in Alliander's grid a 6 km FCL Triax HTS® cable, Fig. 8. At present the length of the HTS cables is limited up to 1–2 km due to inefficient cable cooling technology. Integrated fault current limiting (FCL) capability adds even more requirements

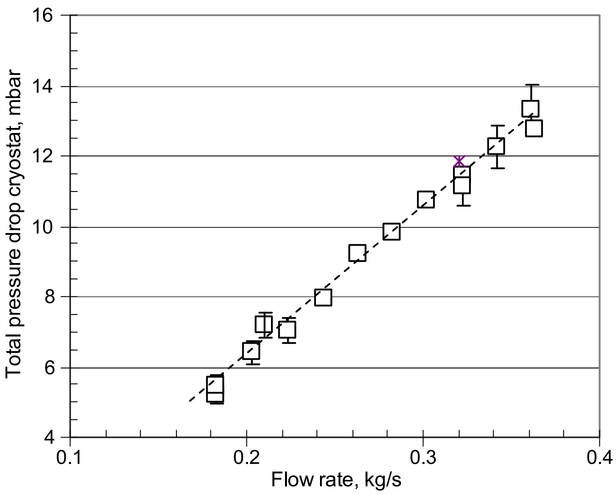

Fig. 9. Total pressure drop accross cryostat length versus coolant flow rate (at 68–82 K and 0.8–1.5 bar)

to cooling systems due to extra heat development. Therefore an advanced heat management is needed. To achieve project targets the consortium works on the heat management during and after fault in the next main directions: optimization of cooling channels of the HTS cable system for more efficient flow of the coolant, substantial improving of thermal insulation of the cryostat and considerable reduction of AC loss. The already attained results lead to breakthroughs in development of a long length FCL Triax HTS® cable. Calculations support a possibility of significant improvement of the thermal behaviour of the cryostat. The developed FCL modelling confirms that the stated targets for fault current limiting capability will be achieved in the project. The latest cable tests have demonstrated considerable reduction of AC loss and low flow friction of the cryostat. The results of modelling and performed tests are presented in *Melnik et al.* (*2012*).

4.2 Reduction of thermal losses

In order to solve the problem of possible excessively high coolant pressure drop in the cable, a model cryostat was developed consisting of alternating rigid and flexible sections and hydraulic tests were conducted using sub-cooled liquid nitrogen. In the 47 m-long cryostat, containing a full-size HTS cable model, measured pressure drop amounts 11 mbar at the mass flow rate of 0.3 kg/s and temperature 65 K, see Fig. 9. For a 6 km-long HTS cable this gives a pressure drop below 2 bar, which is acceptable. In order to achieve this result, the cryostat was manufactured from alternating straight rigid sections and corrugated flexible sections. A flexible dummy HTS cable was inserted into this cryostat and sub-cooled liquid nitrogen was circulated in the annulus between the dummy cable surface and the inner cryostat surface. In this paper details are presented of the cryostat, of the measurement setup, of the experiment and of the results (*Chevtchenko et al. 2012*).

4.3 AC loss reduction

Specifics of a 6 km long HTS AC power cable for the Dutch project are: a cable has to fit in an annulus of 160 mm, with two cooling stations at the cable ends only. Existing solutions for HTS cables would lead to excessively high coolant pressure drop in the cable, affecting public acceptance of the project. A way out would be to substantially reduce AC losses from 1 down to about 0.1 W/m per phase at rated current of 3 kA_{rms}, frequency of 50 Hz and temperature of

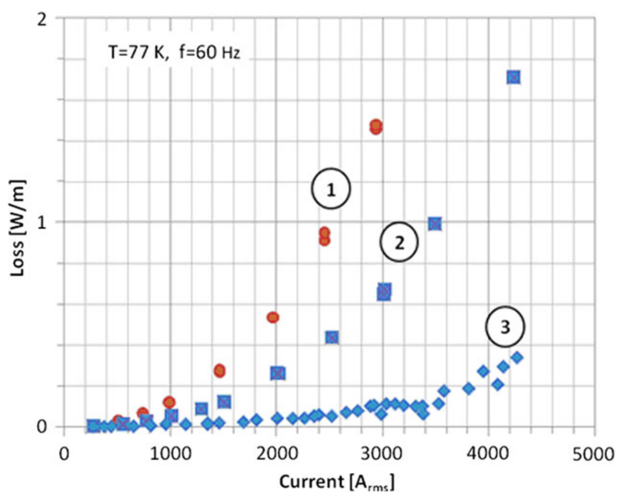

Fig. 10. Comparison of losses for 3 different YBCO samples

77 K. A strategy towards this ambitious goal is formulated, a concept design of the (single phase) cable conductor made of YBCO tapes is completed and corresponding simulation and experimental data are presented in Fig. 10. In an effort to reduce AC loss in YBCO cable conductor, several full-size single-phase cable models were prepared and tested. The HTS cable model sample was made of commercial YBCO tapes SCS3050 from Superpower. Each tape was 3 mm wide and 0.1 mm thick and had 1 μm thick (RE)BCO layer; 2 μm thick silver over-layer; 20 μm thick surround copper stabilizer and 50 micron Hastelloy substrate. Since the tape width is in fact fixed, special care was taken to match the diameter of the cable former to it. The tapes were arranged in two layers around the plastic cable former of relatively large diameter of 42 mm. Care was taken to diminish gaps between adjacent tapes. In order to reduce the loss, pitch angles in each layer of the cable conductor were properly selected, the layers were sufficiently insulated from each other, and the gaps between adjacent HTS tapes in the same layer were minimized.

The measured AC loss amounts 0.115 W/m at the transport current of 3 kA_{rms}, frequency of 60.2 Hz and temperature 77.3 K and critical current of 7.5 kA. This gives a value for the AC loss of 0.096 W/m at the frequency of 50 Hz and the same temperature. Similar result: 0.124 W/m at 60 Hz, 73.7 K and critical current of 9 kA was recently obtained by Furukawa, which indirectly confirms our measurement.

5. Electroactive polymers

Electroactive polymers (EAP) are a class of materials that exhibit a change in shape when under the influence of an external electric field. They are most commonly used in form of artificial muscles (*Ashley* 2003). However, it can also be used for energy generation. A small-scale prototype power generator for utilizing wave energy has been build already and work is done in terms of building simple EAP modules that can produce clean energy (*Chiba et al.* 2008). One of the issues with EAP is the electrode surface, which needs to be flexible, yet conductive (*Jones et al.* 2010).

6. Conclusion

Nanocomposites show great potential for high voltage engineering. With the right material combination, significant improvements of DC breakdown strength, PD resistance and space charge behavior are possible. The higher time to breakdown and increased resistance to electrical ageing that can be observed in nanocomposites also means more reliable systems. However, the properties of nanostructured insulation material have to be considered at the design of high voltage components, in order to get the most out of this novel material.

The increasing and intermittent load flows in future grid scenarios supersede the possibilities of many existing designs. To accommodate all high level requirements we arrive at the design limits of HV equipment. Nano and micro meter particles and layers help to expand the limits. Moreover, adding high temperature superconductors to the HV design makes possible higher power capacity, lower AC losses, intrinsic fault current limitation, better power flow control, smaller footprint and less emissions.

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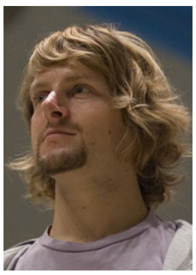

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