Interfaces at DC – electrical and thermal barriers

Peter **Morshuis,** Roman **Kochetov,** Ioannis **Tsekmes;** Delft University of Technology, (The Netherlands),
p.h.f.morshuis@tudelft.nl, r.kochetov@tudelft.nl, i.a.tsekmes@tudelft.nl

ABSTRACT

In the field of electrical insulation, the interfaces between different materials are generally considered the weakest parts of the equipment and we are challenged in the design process to take proper care of them. At dc stresses, the situation becomes even more complex due to the charge dynamics at the interface. Indeed, the design of UHVDC accessories has become a challenge if not a problem.

This paper focuses on some of the important electrical and thermal aspects of interfaces. It is discussed where we lack knowledge and where we may benefit from other scientific fields.

KEYWORDS

HVDC; interfaces; accessories; thermal conductivity; space charge.

INTRODUCTION

Interfaces in high voltage cable systems are unavoidable and they pose a serious challenge for the designer of cable accessories such as cable joints and cable terminations. In HVDC cable systems, the situation is even more precarious because of the charge dynamics at interfaces. To some extent we are now able to predict how electric field, temperature and material properties determine these dynamics. The first part of the paper will be devoted to this topic.

For the second part of the paper we move to the less frequented field of thermal household in dielectric systems containing interfaces.

The trend towards higher voltages is evident, 800 kV has become common, albeit far away in China. At the same time, we witness a movement towards dry-type accessories in which mass and oil are gradually being replaced by solid polymeric dielectrics. One of the important implications of these developments is that we are forced to consider in even more detail the thermal properties of accessories. It will become increasingly more difficult to transport conductor losses through the bulky insulation of the accessory to the ambient. One of the reasons for this is again the interface. In general, a thermal mismatch exists between the two materials that comprise an interface, i.e. conductor - dielectric or dielectric – dielectric.

While it is evident that a proper design of the interfaces in high voltage cable systems is a difficult task, we may have benefit from an unexpected area. In recent years, we have learned that interfaces do not necessarily affect insulation properties in an adverse way. In fact, at the nanometric scale the introduction of a large number of interfaces may even be beneficial. Where up to this moment we were forced to deal with interfaces, in the near future there may be a strong wish for creating beneficial nanometric interfaces in the new generations of HVDC components.

Some twenty years ago, in 1994, John Lewis published his visionary paper on nanometric dielectrics [1]. In fact, from that moment on our perception of interfaces changed drastically. Up to that moment interfaces were considered unavoidable weak spots, but now the scientific community started designing interfaces to create better properties in nanodielectrics. In fact, all new or changed properties in a nanodielectric are attributed to the interface between nano particle and host dielectric, or more precisely to the interfacial zone around the nano particles.

Some of the opportunities will be reviewed of nanometric interfaces. The potential of new techniques (in our field) will be stipulated such as molecular dynamics as a tool to design improved thermal interfaces. It will be shown that the way we need to look at interfaces changes drastically when we go down in size.

DIELECTRIC MODEL OF THE INTERFACE

Since the classic publications on polarization at dielectric interfaces by Maxwell, Wagner and Sillars (MWS) [2], [3], the dynamic charging processes at interfaces were modeled based on knowledge of macroscopic parameters. This is a straightforward and simple approach that can be followed if one has access to the conductivity and the permittivity of the dielectrics at both sides of the interface.

The MWS model provides an expression in closed mathematical form for the calculation of the time dependent surface charge $\kappa(t)$ at the interface between two dielectrics. When a step voltage U_0 is applied across the dielectrics, the interface is charged as follows:

$$\kappa(t) = \frac{\varepsilon_A \sigma_B - \varepsilon_B \sigma_A}{\sigma_A d_B + \sigma_B d_A} U_0 \left(1 - \exp\left(-\frac{t}{\tau_{MWS}} \right) \right) \quad (1)$$

with d_A and d_B the thickness of the dielectrics, σ_A and σ_B the respective conductivities and ε_A and ε_B the permittivities as shown in (1).

The polarization time constant is given by

$$\tau_{MWS} = \frac{d_A \varepsilon_B + d_B \varepsilon_A}{d_A \sigma_B + d_B \sigma_A} \quad (2)$$

This approach is attractive for its simplicity. We can extend the model by introducing the temperature and electric field dependence of the conductivity. This dependence can be taken into account, for instance as [4]:

$$\sigma(T,E) = \sigma_0 \left(\frac{E}{E_0} \right)^\nu \exp\left[\alpha(T - T_0) \right] \quad (3)$$

It is important to note that in this approach the possible

accumulation of space charge is neglected, except for the introduction of a field dependent conductivity. The latter leads to a deviation from ohmic behavior, which is exactly what we witness when we cross the threshold for space charge accumulation [5].

In the next section, the extent to which we can use the MWS approach is further discussed.

ELECTRICAL INTERFACES

If we have access to the values of the permittivities and conductivities at both sides of the interface we can obtain an indication of the polarization at the interface through the MWS model for axis-symmetric geometries [4].

Let us now take the simple configuration of a model of a medium voltage size joint consisting of two concentric dielectric layers with different properties, see Fig. 1. Resorting to PEA space charge measurements [6] we have a means of comparing measured and calculated charge dynamics.

First, the earth screen and the outer semicon of an XLPE insulated cable were scraped off for a length of 80 mm. Then, part of the exposed insulation was removed using a glass blade. The insulation surface was smoothened using successive grades of abrasive cloth. After these operations the remaining XLPE had a thickness of 2 mm. Then a special tool was used to apply a 2 mm thick EPR tube over the exposed insulation. Some silicone oil was applied to facilitate this action. Finally, an outer semicon layer was taped around the EPR tube. Before any testing the model was thermally treated at 80 $^{\circ}$C for 20 days.

A schematic representation of the thus obtained joint model is shown in Fig. 1.
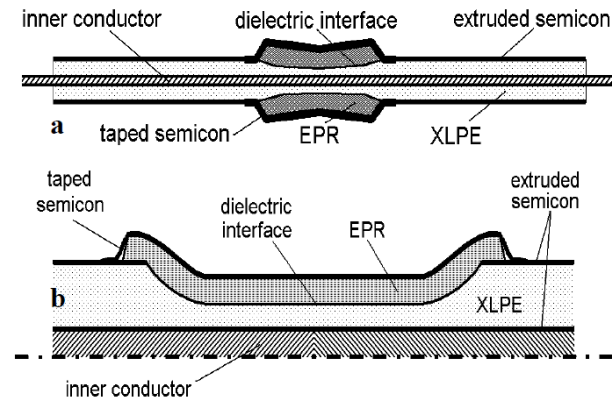
Fig. 1: Schematic representation of a model of a medium voltage size XLPE-EPR joint [4].

In the following, the results are shown of measurement and calculation of space charge profiles obtained on the XLPE-EPR joint. The following parameters were used:

Applied voltage: 80 kV; conductor temperature: 65 $^{\circ}$C; outer semicon temperature: 45 $^{\circ}$C; total poling time: 20.000 seconds (about 6 hours).

All space charge measurement tests and calculations were started only when the test specimen was in thermal equilibrium. In Fig. 2a-b, the calculated and measured space charge distributions are shown as a function of the poling time.
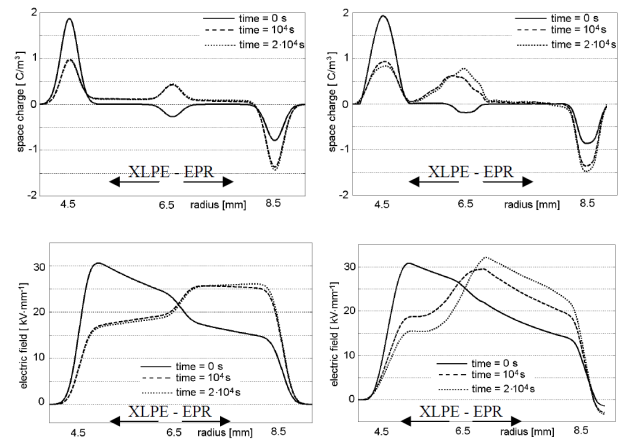
Fig. 2: a) calculated space charge distributions; b) measured space charge distributions; c) calculated electric field; d) measured electric field [4].

In Fig. 2a-b, it is shown how charge builds up at the interface after the application of a dc voltage. Both the results of calculation based on MWS and the results of PEA space charge measurements are plotted. We notice that the –macroscopic– MWS model predicts the interface charge and its development in time reasonably well. According to the model however, positive space charge should accumulate from the high voltage electrode into the bulk of the insulation because of the temperature drop across the insulation. This positive space charge is not visible in the measured space charge distribution although it seems that there is some positive charge visible at the right side of the interface in Fig. 2b. From other measurements there is evidence of negative hetero charge in front of the inner semicon. This hetero charge could very well compensate for the predicted positive charge. Here in fact we see the limits of the MWS approach: as long as the conduction mechanism is ohmic the approach works well but injection and accumulation of space charge cannot be predicted. Even so, a good indication of the electric field distribution is obtained; compare Fig. 2c and Fig. 2d.

On increasing the electric field above the threshold for space charge accumulation, charge injected from the electrodes and accumulating at the interface affects the net charge which is measured at the interface. This asks for a model which can take into account charge injection processes at the electrode-dielectric interfaces. Understanding the injection and extraction of charge at the interface between electrode and dielectric has indeed been the topic of many studies. In [7], a first attempt was made of modeling the charge dynamics above the threshold for space charge accumulation. In this dynamic model, electronic charge injection, an exponential distribution of charge traps and hopping charge transport improved in a bipolar model [8]. It was assumed that in the interfacial region a higher density of exponentially distributed trapping sites is present than in the bulk. Although this model is able to predict some of the space charge profiles measured at higher fields there is still work to be done on obtaining the thickness of the interfacial region because the parameters of the model are directly linked to it.

THERMAL INTERFACES

The thermal household in bulky interface constructions such as in dry-type accessories requires careful attention. It may be argued that in such cases the organization of a proper thermal household may become even more difficult than the electrical household.

There are several parameters that affect the thermal household, i.e. the thermal conductivity of the insulation and the thermal resistance at the different interfaces. Indeed, at any interface a thermal interface resistance is experienced and for that reason alone the number of interfaces should be minimized.

To improve the thermal properties of the bulk insulation, often large amounts of filler are introduced, for instance in epoxy resin (up to 60% of filler). These filler particles have a size in the range of micrometers. The thermal conductivity of the thus obtained (micro)composite is calculated by using the common rules of mixture [9]. Due to the high thermal conductivity of the filler, the thermal conductivity of the epoxy resin increases from around 0.1 to 1.

Improving the thermal properties while not affecting too much the electrical properties is a balancing act. The addition of micron sized filler often has negative side effects such as a decrease in breakdown strength.

A considerable amount of papers have been published showing the advantageous effect of nano particles on the breakdown properties of polymeric insulation. From the field of nanofluids we know that small volume fractions of nano particles may also have a positive effect on the thermal conductivity.

Recently, a number of studies were published on the effect on thermal conductivity of adding nanoparticles to a base resin [9], [10]. In principle, interfaces perpendicular to a heat flow pose a thermal barrier, resulting in a temperature drop. Phonons, the "carriers" of heat, are scattered at interfaces. One would think that the introduction of manifold interfaces in a nanocomposite would decrease the thermal conductivity rather than increase it. From the literature we learn that it is not that straightforward. In [9], three types of Boron Nitride nanocomposites were tested, spherical BN particles with a diameter of 70 nm and 1.5 micron and platelet-shaped BN particles with a length of 0.5 micron. All nanocomposites were produced at equal weight percentages with and without surface modification of the nanoparticles. In Table 1, the results are shown of the thermal conductivity measurements. From Table 1, it appears that for the same weight percentage, the nanocomposite with spherical particles has the same thermal conductivity as the microcomposite with spherical particles. This is surprising because of the expected increase in phonon scattering in the nanocomposite. The nanocomposite containing the platelets has the highest thermal conductivity. For this specimen, the average distance between particles is smaller than for the spherical particles. Because the thermal conductivity in the polymer is much lower than in the nanoparticles the reduced distance between particles may explain the more efficient heat transfer. The question remains why boron nitride nanocomposites perform as well as the microcomposites. The properties of the interfacial zone also here may play a crucial role.

Table 1: Thermal conductivity of BN (boron nitride) nanocomposites for different particle size and shape

Epoxy resin – BN nanocomposites, 10 wt% BN			
Particle size	Particle shape	Thermal conductivity ($Wm^{-1}K^{-1}$) No surface treatment	Thermal conductivity ($Wm^{-1}K^{-1}$) Surface treatment
70 nm	spherical	0.234	0.240
0.5 µm	spherical	0.264	0.274
1.5 µm	platelet	0.236	0.242

Here, we may learn from the research efforts in other scientific domains. Recently, interesting results were obtained using molecular modeling simulations of the heat transport at interfaces between different materials. Starting from a basic treatment of how heat is transferred between different materials, i.e. between materials with different phonon vibrational spectra, strategies were developed for improving the heat transfer.

As a result of the mass difference of the materials at both sides of the interface and affected by the strength of bonding, a mismatch in phonon vibrational spectra is observed [11], [12]. One of the ideas is to "bridge" the vibrational spectra by interposing a layer with mediating vibrational properties in between both materials [12]. Another approach [11] starts from the idea that the chemical bonding between the two materials is improved by a mediating layer that "anchors" to the materials at both sides of the interface.

It is shown that following this first approach the vibrational spectra are indeed matched. In this case, in addition to the interposition of a matching layer with an atomic mass in between those of both materials, the interface between the layer and both materials is treated as well. Various degrees of disorder are used to calculate the thermal profile. Compositional disorder creates a more gradual temperature change across the interface as opposed to the situation with a "sharp" interface. This is realized by allowing for a certain degree of mixing of atoms in the direct vicinity of the interface. For the case studied in [12], it is shown that the interfacial conductivity can be increased by 53% for an optimal amount of disorder when the optimal atomic mass is chosen for the layer.

The second approach focuses on a stronger bonding between the two materials, albeit using a similar approach. The authors considered an interface between copper (Cu) and silica (SiO_2) and focused on a strong bonding between the two by interposing a nanometric layer of organic molecules. Organosilane molecules ensured a good bonding with the copper and with the silica.

A more precise model for molecular modeling was used and Fig. 4 shows how the interposition of the mediating layer leads to a gradual temperature change across the interface. In Fig. 5, the spectra of the occupied vibrational states are shown of copper, silica and the nanometric layer (NML).
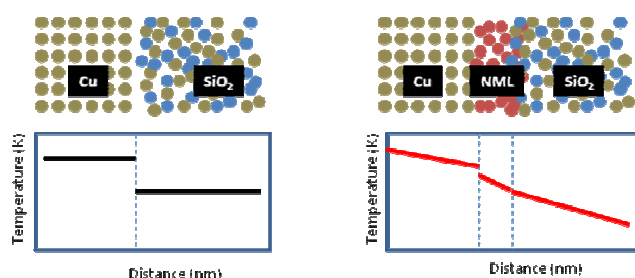
Fig. 3: Temperature profiles obtained by molecular dynamics simulations. Left: Cu/SiO$_2$ interface without interface layer. Right: Cu/SiO$_2$ interface with an SH-terminated organosilane NML. After [11].
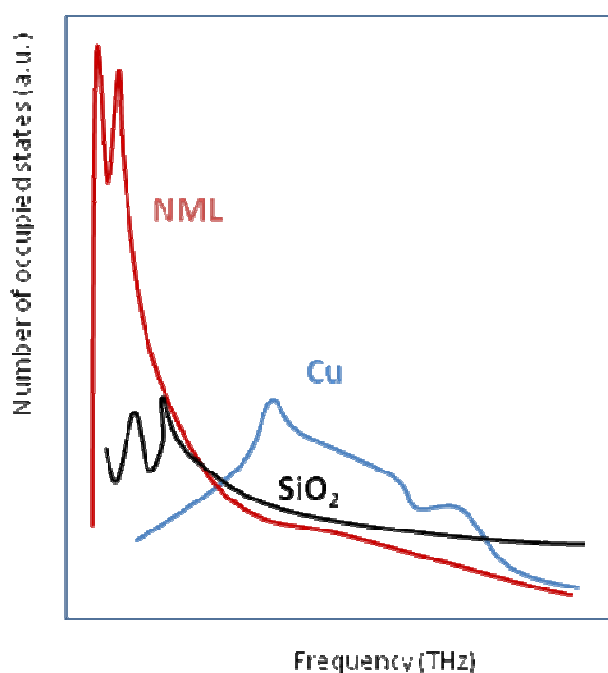

Fig. 4: Occupied vibrational states of the Cu, SiO$_2$ and the SH-NML layers in Cu–NML–SiO$_2$ structures. After [11].

Obviously, the NML and silica spectra overlap to a large degree and a strong coupling between the two is expected. In contrast, there is only little overlap between the NML and copper. Nevertheless, the authors succeeded in obtaining a fivefold increase of the thermal conductance of the interface. What has changed due to the NML is the coupling between copper and silica. The authors of this paper show that the operating mechanism behind the increase of the thermal conductance of the interface is the strength of coupling (or stiffness) rather than the matching of vibrational spectra.

Whatever the exact mechanism, it appears that the interposition of a mediating layer between two "mismatched" materials can lead to a significant increase of the interfacial conductance.

Let us zoom out again to the macroscopic interfaces that we need to deal with in cable accessories. Can we perhaps benefit from the findings at the nanometric scale? I would say potentially, without a doubt we learn more about the parameters that affect the thermal barriers in

our systems. Nanotechnology has already entered high voltage dc polymeric cables, i.e. in minute fractions in the bulk of the insulation. We may further improve especially the thermal household by tailoring the interfaces between nanoparticles and insulation and, more in particular the interfaces between cable conductor, semicon and insulation. We need to consider the fact that the highest thermal resistance is to be expected at weakly bonded interfaces and between materials with a large difference in atomic mass. Therefore, little improvement is to be expected at the interface between co-extruded layers. More benefit could be obtained at mechanically bonded interfaces or at the interface between conductor and semicon. If nanoparticles are used to improve bulk insulation properties it could be appropriate to loom for a kind of surface treatment that minimizes the thermal resistance.

CONCLUSIONS

In this paper, some thoughts are presented on interfaces in dielectrics and electrical insulation. Size proves to be of major importance, going down in size our appreciation of interfaces changes. The birth of nanodielectrics has led to a quest to create the optimal interface and thus create new or improved properties.

The extent to which the polarization and charging processes at interfaces can be explained by the classic Maxwell-Sillars-Wagner model is limited. To obtain a first impression of the charge dynamics this approach is fine, but at electric fields above the threshold for space charge accumulation we will have to resort to high field modeling of charge injection/extraction and conduction processes.

The thermal household of some insulating materials is improved by adding large volume fractions of micron size particles with a high thermal conductivity. Phonon scattering at the interfaces between particles and host material impedes heat transport. For the same volume fraction, nano particles introduce a multitude of interfaces. The interposition of a mediating layer between two "incompatible" materials can strongly promote the heat transport through the interface. The results obtained in other scientific fields on molecular modeling of the heat transport across an interface are promising. Although there may still be some dispute on the exact mechanism, a significant increase of the thermal interface conductivity can be obtained. These results may provide guidelines for further improving the thermal design of cable accessories.

REFERENCES

[1] T.J. Lewis, "Nanometric Dielectrics".IEEE Trans DEI, Vol 1, No 5, pp 812-825, 1994.

[2] K.W. Wagner, "Erklärung der dielektrischen Nachwirkungsvorgänge auf Grund Maxwellscher Vorstellungen". Archiv für Elektrotechniek, Vol. 2, No. 9, pp. 371-387, 1914.

[3] R.W. Sillars, "The properties of a dielectric containing semiconducting particles of various shapes". Jrnl IEE, Vol. 80, No. 484, pp. 378-394, 1937.

[4] R. Bodega, Space charge accumulation in polymeric high voltage dc cable systems. PhD thesis Delft University of Technology, ISBN 90-8559-228-3, 2006.

[5] L.A. Dissado, C. Laurent, G.C. Montanari, P.H.F. Morshuis, "Demonstrating a threshold for trapped

space charge accumulation in solid dielectrics under dc fields". IEEE Trans DEI, Vol. 12, No. 3, pp. 612-620, 2005.

[6] R. Bodega, P.H.F. Morshuis, J.J. Smit, "Space charge measurements on multi-dielectrics by means of the pulsed electroacoustic method". IEEE Trans DEI, Vol. 13, No. 2, pp. 272-281, 2006.

[7] S. Le Roy, F. Boufayed, G. Teyssedre, C. Laurent, P. Segur, R. Bodega, P. H. F. Morshuis, G. C. Montanari, and L. A. Dissado, "Computer simulation of space charge distribution in an XLPE-EPR sandwich". Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 661-664, 2005.

[8] M. Taleb, G. Teyssedre, S. Le Roy, C. Laurent, "Modelling of charge injection and extraction in a metal/polymer interface through an exponential distribution of surface states". IEEE Trans DEI, Vol. 20, No. 1, pp. 311-320, 2013.

[9] R. Kochetov, A.V. Korobko, T. Andritsch, P.H.F. Morshuis, S.J. Picken, J.J. Smit, "Modelling of the thermal conductivity in polymer nanocomposites and the impact of the interface between filler and matrix". J. Phys. D: Appl. Phys., Vol. 44, pp. 395-401, 2011.

[10] T. Tanaka, M. Kozako, K. Okamoto, "Toward high thermal conductivity nano micro epoxy composites with sufficient endurance voltage". Jrnl. Int. Council on Electr. Eng., Vol. 2, No. 1, pp. 90-98, 2012.

[11] P.J. O'Brien et al, 2013, "Bonding-induced thermal conductance enhancement at inorganic hetero-interfaces using nanomolecular monolayers", Nature Materials, Vol. 12, 118-122.

[12] T.S. English et al, 2012, "Enhancing and tuning phonon transport at vibrationally mismatched solid-solid interfaces", Phys. Rev. B, Vol. 85, 035438-1-14.

GLOSSARY

UHVDC: ultra high voltage dc

MWS : Maxwell-Sillars-Wagner

PEA : pulsed electro-acoustic

BN : boron nitride

NML : nanometric layer