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Smart Grids and Energy Markets

4.11.2010

WP 2.6: New materials and technologies

Task 2.6.1: Survey of possibilities of nanotechnology and functional materials in developing novel network equipment and solutions, and energy storage technologies

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Abstract

New insulation materials can be tailored by compounding nanofillers and polymer materials. The advantageous changes in properties of polymer nanocomposites can be explained by the large interface area of the nanofillers. Theoretical models developed in the field of nanodielectrics concentrate on the analysis of the interface volume. Dielectric breakdown strength (DBS) is one of the most important properties of an insulation material. The DBS of nanocomposites depends heavily on the nanofiller content and even small quantities can cause improvement. This is linked to the maximum interface volume achieved even at low nanofiller concentrations. Homogeneous nanodispersion is the key for DBS increase and reliable results. Often the most profitable nanofiller quantities are below 5 wt-%. A similar observation was made with relative permittivity and dielectric losses of nanocomposites. At low nanofiller concentrations the relative permittivity and dielectric losses stay at the reference level or are even lower. With increasing nanofiller content relative permittivity and dielectric losses start to increase. This is related to the overlapping of interfacial zones of nanoparticles. The overlapping of the interfacial zones also depends on the nanofiller size and dispersion. The treeing growth and partial discharge (PD) endurance of nanocomposites was found to have a partly different kind of behaviour. Surface PD endurance of nanocomposites is strongly a mass related phenomenon, but treeing growth is more complex. It is related to large interface volume of nanocomposites having similar behaviour as observed with short-time DBS.

With respect to the properties of nanodielectrics studied possible applications could be e.g. capacitors, cables, dry transformers, rotating machines, switchgear and outdoor insulations. Although the future of nanodielectrics is promising, there are many questions to be resolved. Manufacturing processes must be optimized and up-scaled to larger volumes. Promising results have mainly been achieved with short-term measurements and work has been done to understand mechanisms behind the functionality, which is important. Full scale models of applications should be produced and long-term measurements conducted in operating conditions. Long-term measurements for real components will finally reveal the actual benefits and possible drawbacks of nanocomposites compared to the insulation materials used at the moment. In addition to dielectric properties, the thermal, mechanical, chemical and ageing properties critical for each component must be verified. This means that the industry should be intensively linked to develop actual new products. In this survey the possibilities of nanotechnology and functional materials in developing novel network equipment and solutions and energy storage technologies are studied.



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List of abbreviations

ac	alternating current
Al ₂ O ₃	alumina
ATH	aluminatrichydrate (microfiller)
CIGRE	International Council on Large Electric Systems
DBS	dielectric breakdown strength
dc	direct current
EP	epoxy
EVA	ethylene vinyl acetate
IEEE	Institute of Electrical and Electronics Engineers
LDPE	low density polyethylene
LFS	liquid flame spray
LI	lightning impulse
LS	layered silicate
MgO	magnesia
MMT	montmorillonite
NMMC	nano- and microfiller mixture composite
PA	polyamide
PD	partial discharge
PE	polyethylene
PEI	polyetherimide
PI	polyimide
POSS	polyhedral oligomeric silsesquioxane
PP	polypropylene
RMS	root mean square
SiO ₂	silica
SR	silicone rubber
TiO ₂	titania
XLPE	cross-linked polyethylene



1 Introduction

Electricity and its distribution to customers are in a key role in ensuring human well-being. Insulation materials are a vital part of the components used in a electrical energy distribution network. In recent years interest in advanced materials e.g. nanodielectrics has been growing. The use of nanotechnology in insulation materials is a new way to develop dielectric materials. In the past, the target was to produce as pure as possible dielectric material, and thus ensure the optimal performance of the component. By contrast, nanodielectrics are dielectric materials mixed with inorganic particles size 1 to 100 nm. The idea of nanocomposites is to use small mass amounts of nanofillers to produce a large interfacial area between the matrix polymer and nanofillers. It is possible to tailor the properties of a dielectric. A homogeneous dispersion of nanoparticles is a prerequisite for improved dielectric properties.

2 Background

Nanofillers or nanoadditives are defined as material having one dimension less than 100 nm. In the field of insulation the word “nanofiller” is mostly used. Polymer nanocomposites are defined as polymers with a small amount (0.1 to 10 wt-%) of nanofillers. Fillers should be homogeneously dispersed in the polymer matrix to form a nanodielectric material [Tan05, Tan06]. The mostly used polymers in nanodielectrics research are polyamide (PA), polyethylene (PE), polypropylene (PP), ethylene vinyl acetate (EVA), epoxy resins (EP) and silicone rubbers (SR). Polymers are combined with inorganic nanofillers such as layered silicate (LS), silica (SiO₂), titania (TiO₂), alumina (Al₂O₃), magnesia (MgO).

The short history of nanodielectrics dates back to 1994. The first paper using nanodielectrics was published by John Lewis in the Transactions on Dielectrics and Electrical Insulation (Institute of Electrical and Electronics Engineers, IEEE). The paper is entitled “Nanometric Dielectrics” and discusses the future of insulation materials [Lew94]. After a fairly slow start in the 1990’s nanodielectrics research has increased rapidly in this millennium, which can be seen in the increasing number of publications and group activities in the International Council on Large Electric Systems (CIGRE) and IEEE. The history and development of nanodielectrics have been described more closely in [Dan09, Dis04, Fré01, Fré06a, Fré09, Nel02, Nel06, Nel07, Phi04, Tan05, Tan06].



3 Dielectric breakdown strength

Dielectric breakdown strength (DBS) is one of the most important properties of an insulation material. The properties of polymer nanocomposites are mainly explained by a large interfacial area of nanofillers. This interfacial area is responsible for the interaction of the electrical field between the matrix polymer and nanofiller [Gua06, Nel04, Nel06, Vau05]. The DBS of the nanocomposites depends heavily on the nanofiller content and even small quantities can cause improvement. Often the most profitable nanofiller quantities are below 5 wt-%, as has been noted in [Tak08a, Tak08b, Tak09, Tak10a, Tak10b]. Figure 1 presents third order polynomial fittings for the DBS results of nanocomposites as a function of nanofiller content. It shows that the same kind of behaviour with different voltage shapes can be achieved with nanocomposites, but with dc voltage the increase is bigger. The difference between the dc vs. ac DBS values is in the order of $\sqrt{2}$, because ac DBS is given as root mean square (RMS) value. The peaks of the fittings are approximately in the same position with respect to nanofiller content. DBS has a maximum value with respect to nanofiller amount and decreases thereafter. Filler quantities around 5 wt-% and even lower are the most attractive considering DBS of nanocomposites. This kind of behaviour is similar to the interphase volume model presented by Raetzke [Rae09]. In Table 1 the DBS results of nanocomposites are presented.

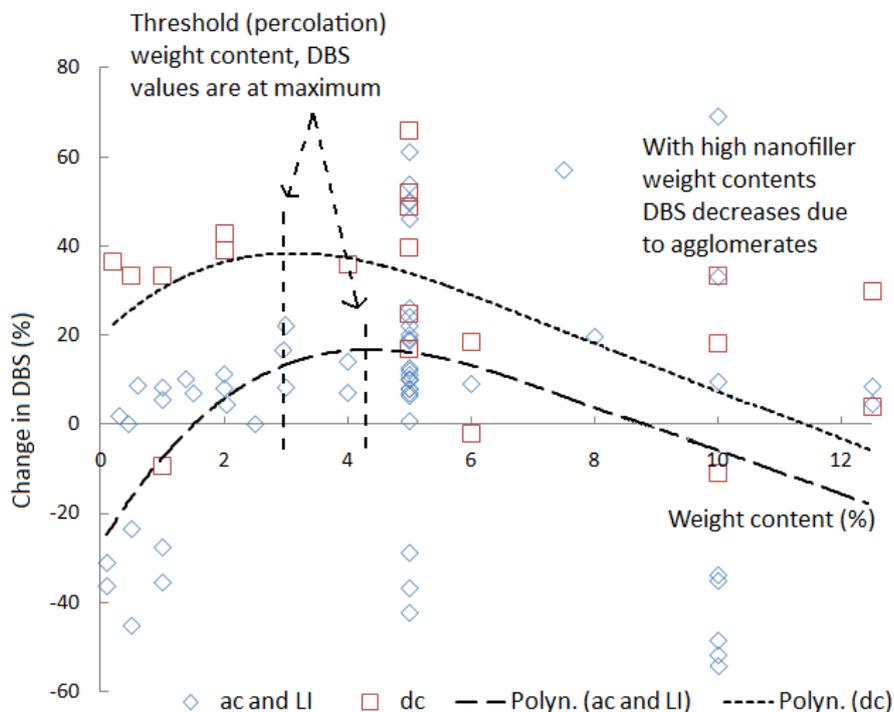


Figure 1. DBS of the nanocomposites as a function of filler content. Diamonds are the measurement results for ac and LI voltages and squares for dc voltage. Third order polynomial fittings are presented with broken lines [Bam05, Gre08, Gua06, Gua08, Gua09, Hoy08, Hu06, Ima04, Ima06a, Ima06b, Ima08, Kur06, Mon04, Mon05, Mur08, Nel04, Pél06, Roy07, Shi04, Sin06, Sin08a, Smi08, Tun09, Vau05, Tak07, Tak08a, Tak08b, Tak09, Tak10a, Tak10b].



Table 1. Relative change of ac, dc and LI DBS of nanocomposites with respect to the reference material in various experimental studies.

DBS	Matrix	Nanofiller	Weight content (%)	Change (%)	Publication
ac	PP	SiO ₂	5	20	Tak09, Tak10b
	PP	octamethyl-POSS	3	22	Tak08a
	PP	isooctyl-POSS	5	11	Tak08a
	PE	MMT	2, 4, 8	11, 14, 20	Gre08
	LDPE	SiO ₂	5	8	Gua06
	LDPE	MMT	5	24	Gua09
	LDPE	MgO	1, 5, 10 (phr)	5, 13, 28	Kur06
	LDPE	MMT	5	54	Hoy08
	LDPE	MMT (washed)	5	61	Hoy08
	EP	glycidyl-POSS	1, 3	8, 8	Tak08b
	EP	LS	5	10	Ima06a
	EP	SiO ₂	5	22	Ima06a
	EP	TiO ₂	5	50	Ima06a
	EP	LS	5	12	Ima08
	EP	SiO ₂	5	26	Ima08
EP	TiO ₂	5, 7.5, 10	46, 57, 69	Ima08	
dc	PP	SiO ₂	5	52	Tak09, Tak10b
	PP	organosilicate	2, 4	39, 36	Bam05
	XLPE	SiO ₂	5	17	Roy07
	XLPE	silane treated SiO ₂	5	49	Roy07
	XLPE	silazane treated SiO ₂	5	25	Roy07
	XLPE	silane treated SiO ₂	5	66	Roy07
	XLPE	SiO ₂	12,5	4	Smi08
	XLPE	silane treated SiO ₂	12,5	30	Smi08
	LDPE	MgO	0.2, 0.5, 1, 2, 5, 10	37, 33, 33, 43, 40, 33	Mur08
LI	PP	octamethyl-POSS	10	13	Tak08a
	XLPE	SiO ₂	12,5	22	Smi08
	XLPE	silane treated SiO ₂	12,5	31	Smi08
	EP	octaglycidyl dimethylsilyl-POSS	1	26	Tak08b
	EP	TiO ₂	10	2	Hu06



4 Relative permittivity and dielectric losses

Relative permittivity and dielectric losses are connected to polarization mechanisms. Polarization mechanisms can be divided into electronic, ionic, dipolar, interfacial (space charge) and hopping charge polarization [Lu08a]. Each polarization mechanism has a characteristic relaxation frequency. With increasing frequency the slower mechanisms are neglected and relative permittivity decreases. In microcomposites (filler content 50-60 wt-%), relative permittivity usually increases with increasing filler content due to the strong presence of Maxwell-Wagner interfacial polarization [Tan05]. On the other hand, in nanocomposites relative permittivity also tends to increase with increasing nanofiller content, but lower relative permittivity values than with reference are also possible, especially with low nanofiller content. Actually lower relative permittivity values than with reference can be considered as a sign of a good nanocomposite, but increase in relative permittivity is also possible, especially at higher nanofiller loadings [Tak08b, Nag08]. In Figure 2 a schematic drawing of the relative permittivity and dielectric losses of nanocomposites as a function of nanofiller content is presented. With increasing nanofiller content, the relative permittivity and dielectric losses have a threshold nanofiller content. Both relative permittivity and dielectric losses start to increase after that level. Behaviour is the same as with microcomposites. However, at low filler contents the relative permittivity of nanocomposites tend to decrease and dielectric losses remain at the reference level or even decrease. Table 2 presents the threshold of the nanofiller content in relative permittivity and dielectric losses of nanocomposites.

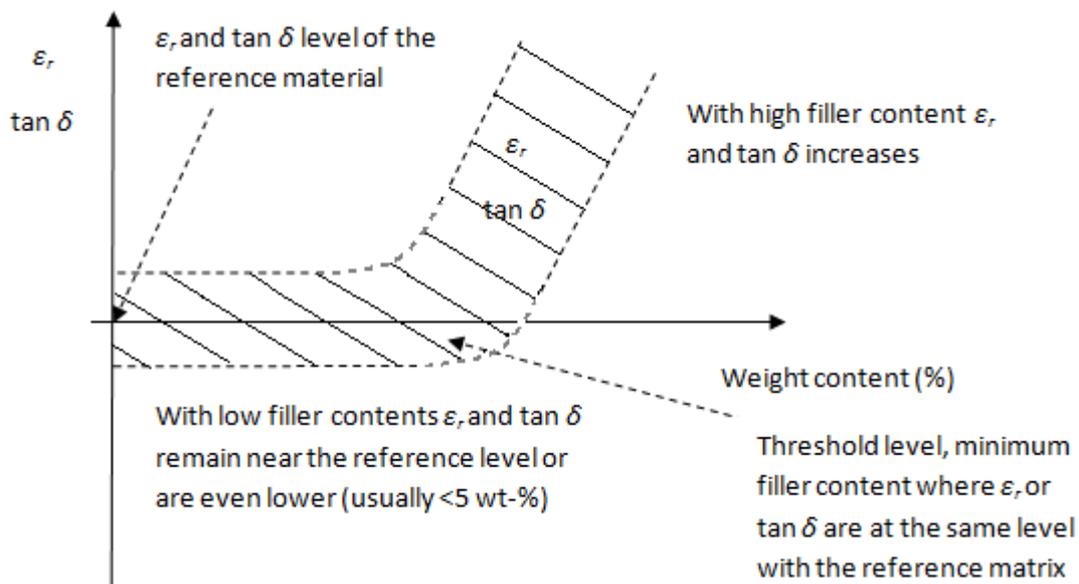


Figure 2. Relative permittivity and dielectric losses of nanocomposites as a function of filler content [Che08, Fus04, Fus08, Ima02, Jia07, Koc09a, Koc09b, Nag08, Roy05, Shi04, Sin08a, Tak08a, Tak08b, Tak09, Tak10a, Tak10b].



Table 2. Threshold of the nanofiller content in nanocomposites, where relative permittivity and dielectric losses are at the same level as the reference matrix.

	Matrix	Nanofiller	Weight content (%)	Effect compared to reference	Threshold weight content (%)	Publication
ϵ_r	PP	octamethyl-POSS	1, 2, 3, 5, 10	increase		Tak08a
	PP	SiO ₂	5	no difference		Tak09, Tak10b
	LDPE	MgO	1, 5, 10 (phr)	decrease and increase	between 1 and 5	Nag08
	LDPE	MgO	1, 2, 5, 10 (phr)	decrease and increase	between 1 and 2	Hin06
	XLPE	SiO ₂	5	decrease		Roy05
	XLPE	vinylsilane-treated SiO ₂	5	no difference		Roy05
	PEI	SiO ₂	5, 10, 15	decrease		Che08
	PA	mica (silicate)	2, 4, 5	decrease		Fus08
	EP	glycidyl-POSS	1, 3, 4.8	decrease and increase	between 1 and 3	Tak08b
	EP	octaglycidyl dimethylsilyl-POSS	1, 3, 4.8	no difference		Tak08b
	EP	SiO ₂	3	increase		Jia07
	EP	LS	6	decrease		Ima02
	EP	aluminum nitride (AlN)	0.5, 2, 5, 10	decrease and increase	between 0.5 and 2	Koc09a
	EP	boron nitride (BN)	0.5, 2, 5	decrease and increase	between 2 and 5	Koc09a
	EP	Al ₂ O ₃	0.5, 2, 5, 10	decrease and increase	between 5 and 10	Koc09b
	EP	LS	6	decrease		Shi04
	EP	TiO ₂	0.1, 0.5, 1, 5, 10	decrease and increase	between 0.5 and 1	Sin08
	EP	ZnO	0.1, 0.5, 1, 5	decrease and increase	between 1 and 5	Sin08
	SR	LS	5	no difference		Tan04
	$\tan \delta$	PP	octamethyl-POSS	1, 2, 3, 5, 10	decrease and increase	between 2 and 3
PP		SiO ₂	1, 2	decrease or no difference		Tak10a
PP		SiO ₂	5	no difference		Tak09, Tak10b
XLPE		SiO ₂	5	decrease		Roy05
XLPE		vinylsilane-treated SiO ₂	5	decrease		Roy05
PA		mica (silicate)	2, 4, 5	no difference		Fus08
EP		glycidyl-POSS	1, 3, 4.8	decrease and increase	between 1 and 3	Tak08b
EP		octaglycidyl dimethylsilyl-POSS	1, 3, 4.8	no difference		Tak08b
EP		LS	6	decrease		Ima02
EP		SiO ₂	3	decrease		Jia07
EP		aluminum nitride (AlN)	0.5, 2, 5, 10	increase		Koc09a
EP		boron nitride (BN)	0.5, 2, 5	no difference		Koc09a
EP		Al ₂ O ₃	0.5, 2, 5, 10	no difference		Koc09b
EP		LS	6	decrease		Shi04
EP		TiO ₂	0.1, 0.5, 1, 5, 10	decrease and increase	between 1 and 5	Sin08
EP		ZnO	0.1, 0.5, 1, 5	decrease	over 5	Sin08
SR		LS	5	no difference		Tan04



5 Treeing growth and partial discharge endurance

The time scale of the treeing growth and PD endurance measurements is clearly longer than the short-time DBS measurements discussed in Chapter 3. The correlation between the results from short-term DBS and treeing growth and PD endurance measurements of nanocomposites has been found to be good [Hor05, Hor06, Ima04, Ima06a, Ima06b, Ima08, Kur06, Mon05, Tak10b]. In general, this means that the materials with increased short-time DBS also have better resistance to treeing growth or PD endurance. In some cases these properties even correlate with the filler amount [Ima06a, Ima06b, Ima08, Kur06]. These properties are connected because the affecting mechanisms are partly the same. Figure 3 presents a schematic drawing of the treeing growth and PD endurance of nanocomposites as a function of nanofiller content. The surface PD endurance of nanocomposites is strongly a mass related phenomenon, but treeing growth is a more complex phenomenon. It is related to large interface volume of nanocomposites and has similar behaviour as that observed in short-time DBS (Figure 1). In the context of treeing this is called the crossover phenomenon. Table 3 shows the treeing growth, PD endurance, tracking and arcing of nano- and microcomposites.

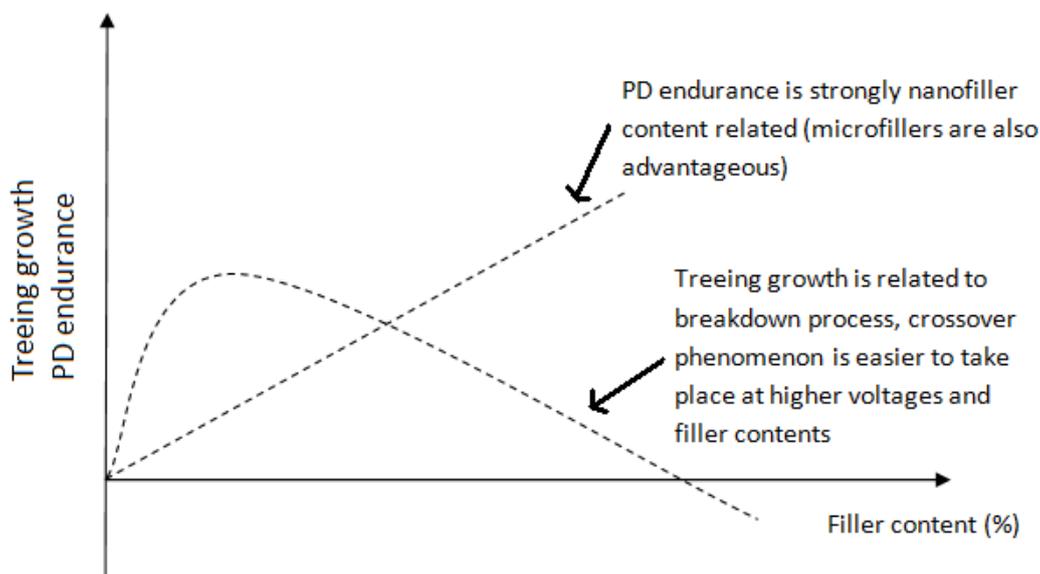


Figure 3. Treeing growth and PD endurance of nanocomposites as a function of filler content [Fus08, Hen99, Ima06b, Kur06, Min04, Nag08, Pre09, Rae09, Tan04, Tan07a, Tak10b].



Table 3. Treeing growth, PD endurance, tracking and arcing of nano- and microcomposites with respect to the reference material.

	Matrix	Nanofiller	Filler content (%)	Effect	Variable vs. nanofiller content behaviour	Publication
Treeing growth	LDPE	MgO	1, 5, 10 (phr)	2.8 times longer time to breakdown	increase with filler content (best result 10)	Kur06, Nag08
	XLPE	SiO ₂	5	100 times longer time to breakdown		Roy07
	EP	TiO ₂	10	33 times longer time to breakdown		Ima08
	EP	nanofiller	5, 10	length of electrical tree reduced to 1/15 (5 wt-%)	increase with filler content (best result 10)	Tan07b
	EP	LS	0.5, 2.5	24 times longer time to breakdown	2.5 wt-% gives best result	Ima06b
PD endurance	PP	SiO ₂	5	9 times longer time to breakdown		Tak10b
	PA	LS	2, 4, 5	erosion depth decreases to 1/4	4 and 5 wt-% give best results	Fus08
	PA	LS	2, 4, 5	surface roughness decreases to 1/8	4 and 5 wt-% give best results	Tan04
	PI	SiO ₂	5, 6, 7, 8	5.5 times longer time to breakdown between 8 and 5 wt-% samples	increase with filler content (best result 8)	Tan04
	PI	SiO ₂	8	12 times longer time to breakdown		Tan04
	PI	SiO ₂	3, 5, 6, 8, 10	3.5 times longer time to breakdown between 10 and 3 wt-% samples	increase with filler content (coupling agent better)	Min04
	LDPE	MgO	1, 5, 10 (phr)	erosion depth decreases to 1/3	increase with filler content (best result 10 phr)	Nag08
	EP	nano-SiO ₂ vs. micro-SiO ₂	5	erosion depth decreases to 1/5		Tan04
	EP	SiO ₂	1.8, 3.6, 4.8, 7.2, 8.5, 9	13 times longer time to breakdown	increase with filler content (best results 8.5 and 9)	Hen99
	EP	Al ₂ O ₃	0.1, 1, 5	surface roughness decreases to 3/5	increase with filler content (best result 5)	Pre09
Tracking	SR	LS	5	endurance time 2 times longer		Tan04
	SR	ATH (microfiller)	40	endurance time 2 times longer		Tan04
	SR	LS	5	erosion depth decreases to 1/3		Tan04
	SR	ATH (microfiller)	40	erosion depth increases by 1/4		Tan04
Arcing	SR	SiO ₂ precipitated	0.1, 0.2, 0.5, 1, 2, 5, 10, 15	arcing time 3 times longer (5 wt-% sample)	after 5 wt-% decrease in arcing time	Rae09
	SR	SiO ₂ fumed	2, 5, 10	arcing time 1.5 times longer	increase with filler content (best result 10)	Rae09



6 Discussion

The future of nanodielectrics is bright, but there are evident challenges in using this technology in electrical applications. The future of nanodielectrics has been discussed in [Cao04, Dan09, Fré06b, Nel07, Nel08, Tan04, Tan05, Tan07a]. As shown in the earlier chapters, the dielectric properties of polymers can be tailored with nanofillers. Tailoring of dielectric properties of nanocomposites is a reasonable research target in the future. The mechanisms and phenomena behind the properties of nanodielectrics must be thoroughly known. Even small nanofiller content creates large interfacial areas between the nanofillers and polymer matrix. This is one foreseen advantage in applying nanotechnology in dielectric materials, which can lead to lower costs after up-scaling of processes [An06, Ima06b, Zou06].

The insulation technology needs efficient, reliable and compact products. Improvement of dielectric properties leads to cost savings and superior products. On the other hand improved energy quality and energy savings are also wanted. Reliability would result in lower maintenance costs. There is a need for insulation for higher voltages as the transmission voltages are increasing. The use of dc voltage in power transmission is becoming more important. Environmental and health aspects also have to be taken into account. The whole life-cycle of materials used and applications has to be considered, including ultimate recycling. One environmental option is to get rid of SF₆ gas (a greenhouse gas) in switchgear [Ima08, Tag08]. One application is to develop more heat resistant thermoplastic nanocomposites and replace thermoset resins, which cannot be recycled. The price of nanoparticles is decreasing and availability is becoming easier, especially because the processing of nanoparticles is advancing rapidly.

6.1 Future trends and challenges

With increasing interest in the functionalization of nanofillers the target in future is to manufacture self-assembled nanodielectrics with controlled filler dispersion [Nel04, Nel06, Ima08]. This target is achievable if the matrix can be made chemically so attractive to the nanofiller (chemical hooks) that agglomerates are minimized and nanofillers are located at even distances in the matrix. Improved dispersion leads to small number of agglomerates with higher nanofiller contents. Thus, even lower threshold levels are possible as the dispersion of nanofillers is a key factor affecting dielectric properties. Possible ways of functionalization are nanocoating of insulation with flame spraying (LFS, liquid flame spray) or solution [Wu07, Wu08]. Superhydrophobic nanocoatings would increase resistance to tracking and erosion on SR and EP, although the effect on the self-recovery of hydrophobicity of SR needs to be studied further. Highly ordered layer structures could also be designed. One future trend could also be nanostructured layers with different functionalities e.g. a layer of high permittivity combined with a layer of high DBS [Tak06, Sal06]. Saha has concluded that a nanocapacitor with giant capacitance can be manufactured from metal filaments or conducting polymer chain segments [Sah08]. High capacitance capacitors would be useful for energy storage purposes. Water treeing resistance of nanocomposites has not been studied. This is an important property, especially considering high voltage cables. The crossover phenomenon has to be thoroughly studied.



Even though the future of nanodielectrics is promising, there are many questions to be resolved. Manufacturing systems must be optimized and up-scaled to larger volumes. Promising results (Tables 1-3) have mainly been achieved with short-term measurements and work has been done to understand the mechanisms behind the functionality, which is important. Full-scale models of applications should be produced and long-term measurements conducted in operating conditions. Long-term measurements for real components will finally reveal the actual benefits and possible drawbacks of nanocomposites compared to the insulation materials currently in use. In addition to dielectric properties, the thermal, mechanical, chemical and ageing properties critical for each component must be ascertained. This means that industry should be more intensively linked to the research activities and actual new products should be developed. This step has been taken in Japan by Maekawa et al. with XLPE dc cable [Nag08] and by Imai et al. with EP connecting conductor and vacuum interrupter [Ima08].

6.2 Applicability of nanocomposites

There is a wide range of possible applications for polymer nanocomposites in the high voltage technology area. For PP capacitors, dc DBS especially has been seen to increase with the addition of nanofillers. This has been noticed especially in case of SiO₂-PP nanocomposite [Tak09, Tak10b]. A general result related to DBS of nanocomposites is that homogeneous material leads to smaller deviation of the variable. Reduced deviation in DBS values leads to advantage in insulation design. By increasing nanofiller content over threshold level the dielectric losses increase and DBS increase is saturated or decreased. Higher relative permittivity would be advantageous in capacitors but it seems that larger nanofiller loadings or microparticles are needed to achieve this. This is basically also a typical engineering challenge to find out the material performance optimal for all these properties. The PD endurance measurement also revealed that SiO₂-PP nanocomposite withstands surface PDs better than the reference PP [Tak10b].

From the results of 5 wt-% SiO₂-PP nanocomposite [Tak09, Tak10b], it can be calculated that an increase of 47 % could be achieved in the reactive power of an ac capacitor. This result should be utilized in high voltage capacitor development by using higher electric field gradient or thinner insulation. There is also a growing need for further development of dc capacitors in industry. A larger increase of 52 % is observed with dc DBS of 5 wt-% SiO₂-PP nanocomposite leading to a 231 % increase in the energy density of the capacitor [Tak10b]. It should be noted that in real applications there are always transients affecting insulation materials. The withstand for transients must also be high. The next steps should be to up-scale things towards manufacturing. Larger areas of PP film should be tested and longer measurement times should be used for results comparable with industrial measurements. The accumulation of space charges at dc voltage should also be studied. Nanocomposite capacitors for electronics have been studied in [Li04, Jia07, Lu08a, Lu08b] and nanocomposite materials could be useful, also at lower voltages.

PE based XLPE for cable insulation is being actively researched. The lower relative permittivity values in nanocomposites than in the reference material may be important in decreasing the reactive current in cables [Nel06, Nel07]. Decay in space charge accumulation is important to decrease local electric field enhancement regarding dc cable application. Dc power transmission is growing rapidly and there is a need for cables rated for higher voltages with reduced insulation thickness.



Actually the first 500 kV dc cable has been manufactured in Japan with inorganic fillers added to XLPE [Nag08].

EP insulations are used in rotating machines, dry type and measurement transformers and switchgear casings. Using nanocomposites the size of mold transformers can be more compact and thus they can be installed in smaller spaces. In switchgear and transformers the idea is to replace the use of SF₆ and oil insulation by nanocomposites and thus decrease greenhouse effect and respectively reduce fire risk. In LI DBS measurements of 1 wt-% octaglycidyl dimethylsilyl POSS-EP nanocomposite DBS was 26 % higher than in the reference EP [Tak08b]. Compact switchgear with vacuum switches has been developed for 24 kV by using EP nanocomposites [Tan06a]. Connecting conductor and vacuum interrupters have also been molded by NMMCs [Ima08]. Nano- and microfillers are used together in NMMCs to achieve corresponding thermal expansion coefficient with aluminum. Thus, exfoliation of conductor and EP interfaces due to heat-cycling is weaker. The PD resistance of NMMCs is better than with single nanocomposite or microcomposite [Tan08]. It could be an auspicious way of research to compare the filler size effect in nano- and microcomposites, especially with EP.

SRs are used in high voltage outdoor insulations (surge arresters, post insulators, bushings). Resistance to tracking and erosion can be improved with LS-SR nanocomposites [Den04]. The addition of 5 wt-% of LS nanofillers to SR provided better resistance to tracking and erosion compared to 40 wt-% ATH filled SR [Tan04]. The erosion depth was smaller for nanocomposite than for reference SR and ATH-SR microcomposite. Dielectric losses were slightly higher with LS-SR nanocomposite. The effect of nanoparticles on hydrophobicity recovery of SR needs to be studied with long-term measurements.

Table 4 presents a summary of the analysis of possible applications and future on nanocomposite research.



Table 4. Possible applications of nanocomposites and status and future of the research.

Application	Current status of the research	Current status	Next steps	1. application and timeframe to market
PP Capacitor	Only few publications on PP nanocomposites	5 wt-% SiO ₂ -PP (ac 20 %, dc 52 %, $\epsilon_r/\tan \delta$ no effect, 9 times longer time to breakdown under PD stress) 3 wt-% octamethyl-POSS PP (ac 22 %, $\epsilon_r/\tan \delta$ increase) [Tak08a, Tak09, Tak10b]	Up-scaling of research activities, measurements for trial capacitors, long-term measurements, temperature and humidity measurements	DC capacitor, over 5 years
XLPE Cable	Active field and more publications than on PP or SR nanocomposites	5 wt-% SiO ₂ -XLPE (dc 66 %, $\epsilon_r/\tan \delta$ no effect/decrease, 100 times longer time to breakdown) 12.5 wt-% SiO ₂ -XLPE (LI 31 %) [Roy05, Roy07, Smi08]	Long-term measurements of full cables, space charge accumulation, thermal conductivity	DC cable, trial cable [Nag08], under 5 years
EP Insulation	Active field and many publications on EP nanocomposites	10 wt-% TiO ₂ -EP (ac 69 %, 33 times longer time to breakdown) 1 wt-% octaglycidyl dimethylsilyl-POSS EP (LI 26 %, $\epsilon_r/\tan \delta$ no effect) [Ima08, Tak08b]	Long-term measurements of full components, measurements for thermal conductivity	Rotating machines and switchgear, trial components [Ima08, Tan06a], under 5 years
SR Outdoor Insulation	Only few publications on SR nanocomposites	5 wt-% SiO ₂ -SR (arcing time 3 times longer) 5 wt-% LS-SR ($\epsilon_r/\tan \delta$ no effect, tracking test 2 times longer) [Rae09, Tan04]	Up-scaling of research activities, measurements for trial components, long-term measurements in outdoor circumstances	Post insulator, over 5 years



7 Conclusion

In this survey it has been shown that new insulation materials can be tailored by compounding nanofillers and polymer materials. The advantageous changes in the properties of polymer nanocomposites can be explained by the large interface volume of the nanofillers. Theoretical models developed in the field of nanodielectrics concentrate on the analysis of the interface volume. Dielectric breakdown strength (DBS) is one of the most important properties of an insulation material. The DBS of nanocomposites depends heavily on the nanofiller content and even small quantities can achieve improvement. This is linked to the maximum interfacial area already achieved at low nanofiller concentrations. Homogeneous nanodispersion is the key to DBS increase and reliable results. Often the most beneficial nanofiller quantities are below 5 wt-%. A similar observation was made with relative permittivity and dielectric losses of nanocomposites. A threshold nanofiller content can also be found for these properties. At low nanofiller concentrations the relative permittivity and dielectric losses stay at reference level or are even lower. With increasing nanofiller content relative permittivity and dielectric losses start to increase. This is related to overlapping of interfacial zones of nanoparticles. The overlapping of the interfacial zones also depends on the nanofiller size and dispersion. Moreover, the treeing growth and PD endurance of nanocomposites were found to be partly different phenomena. The surface PD endurance of nanocomposites is a decidedly mass related phenomenon, but treeing growth is more complex. It is related to the large interface volume of nanocomposites and similar behaviour as seen with short-time DBS.

With respect to the properties of nanodielectrics studied the possible applications could be capacitors, cables, dry transformers, rotating machines, switchgears and outdoor insulations. Even though the future of nanodielectrics is promising, there are many questions to be resolved. Manufacturing systems of nanocomposite materials must be optimized and up-scaled to larger volumes. Special effort has to be directed to ensure homogeneous dispersion, also in up-scaled manufacturing systems. Promising results have mainly been achieved with short-term measurements and work has been done to understand the mechanisms behind the functionality, which is important. Full scale models of applications should be produced and long-term measurements conducted in operating conditions. Long-term measurements for real components will finally reveal the actual benefits and possible drawbacks of nanocomposites compared to the insulation materials currently in use. In addition to dielectric properties, the thermal, mechanical, chemical and ageing properties critical for each component must be ascertained. This means that the industry should be more intensively linked to research activities to develop actual new products.



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