Electrical Machine Insulation: Traditional Insulating Materials, Nanocomposite Polymers and the Question of Electrical Trees

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Abstract

Electrical machine insulation consists basically of epoxy resin and mica foils. Both are good insulating materials and they proved to withstand large partial discharges and/or the combined attack from electrical, thermal and mechanical stresses. Nowadays alternatives to the traditional insulating materials exist, namely those of nanocomposite polymers, which present somehow improved performance regarding the aforementioned stresses. It is the aim of the present paper to investigate mechanisms of electrical treeing and/or breakdown in machine insulation as well as to study possible improvements with the aid of nanocomposite polymers.

Keywords

Machine insulation, nanocomposite polymers, breakdown, partial discharges, breakdown strength, pre-breakdown phenomena

Introduction

Machine insulation is generally characterized by hard materials, capable to withstand partial discharges of quite large magnitudes. An electrical insulation in high voltage machines must have a high breakdown strength, a good long term functioning without possible problems emanating from degradation effects (partial discharges (PD), treeing phenomena etc.) and certainly rather small – if any – leakage currents. Such insulation must also have a satisfactory thermal performance and must withstand relatively high temperatures. The electrical and thermal properties of such insulation must not be deteriorated because of some extreme conditions, i.e. the highest possible temperature to be tolerated should not provoke any alterations to the insulation itself. The electrical machine insulation should have good long term functioning and it should present only small changes (to be tolerated) after many thermal cycles. Moreover, electrical machine insulation should have a satisfactory mechanical behavior, i.e. high mechanical strength which should stay high even at higher temperatures.

Thermal stressing may cause some sort of breakdown on the surface of mica sheets, whereas mechanical stressing may cause also fissures in epoxy resin and in mica. Electrical stressing may cause partial discharging in possible existing imperfections of the insulation and thus lead to electrical failure [1]. Needless to say that all properties – electrical, mechanical and thermal – are vital for the reliable operation of rotating machines. The insulation should have satisfactory electrical properties, it should withstand the expansion and contraction during temperature cycles and it should respond in a good way to mechanical stresses.

Rotating machines can be divided into two categories: those with voltage ratings less than 6.6 kV and those with voltage ratings higher than 6.6 kV. Mica has been used for years in the electrical machine industry. Mica sheets with a backing of glass cloth and of binding material, like epoxy resin, have been the classical insulation systems for rotating machines. Generally speaking, such insulating systems have proved to be reliable [2]-[4].

Research on possible breakdown mechanisms in such systems revealed that PD and electrical treeing may lead to breakdown [5]. As is pointed out in published work, electrical trees propagate through the weaker material and they tend to reach the opposite electrode, resulting thus in total failure [2]-[5].

It is the aim of the present paper to explore mechanisms of failure both in conventional insulating materials used for rotating machines as well as to investigate alternative insulating systems based on a new series of insulating materials, namely, the nanocomposite polymers. Simulation data will be presented for conventional insulating materials and possible improvements will be suggested. It has to be noted that this review is by no means an exhaustive one. Rotating machine insulation is a complex insulating system and, in the context of the present paper, only some aspects of it will be treated. It should also be added that the present review does not deal with the subject of enameled wiring, which will possibly consist the topic of another review paper.

At this stage, it would be fitting to state that review papers are useful even today. Why? Because they give some insight to the newcomer as well as to the experienced scientist regarding a particular subject. Although we are flooded with much information from the Internet with practically thousands and thousands of references (books, papers, journals etc.), a review paper can always be a starting point for the interested person. The purpose of a review paper is not simply to collect information on a particular subject, it is rather to offer – besides a wealth of information and the relevant references – comments and interrelations between experimental data, criticism and approaches for possible new theoretical models, it is probably the right place to also propose some new insights from the reviewer, it is the place to offer some thoughts for possibly new developments. This is why we believe in the validity of such efforts, this is why we think that reviews will always be useful, despite the flood of new scientific and technical information, almost on an every second-basis.

Conventional Insulating Materials for Rotating Machines

Mica sheets are used in rotating machine insulation as traditional insulating material. Mica is a natural mineral. Its crystalline nature gives very strong bonds in one plane and very weak Van-der-Waals’s forces in the plane normal to this. The consequence of that is that mica can be split easily into flakes [2]. Mica has excellent tracking strength, high breakdown field strength, very good resistance to PD, high volume resistance as well as good thermal stability up to 6000 C [2]. For high voltage applications, mica sheets use as bonding material epoxy resin, a thermosetting material with very good electrical properties and good resistance to PD. Moreover, for a resin to be suitable for long-term operation, it requires high thermal stability with low electrical loss at service temperature and at power frequency, excellent adhesion to mica, high resistance to moisture, chemicals and other contaminants, high mechanical strength over a range of service temperatures, dimensional stability, ability to operate at higher temperatures and a short cure time at 1500 C to 1600 C [6]. In typical rotating machine insulations, mica sheets form a sort of sandwich with epoxy resin, thus rendering the electrical breakdown of such a combined system rather difficult [7].

One of the problems facing the mica/epoxy resin insulation is the one of electrical trees, which may grow and eventually bridge the gap between the electrodes causing thus ultimate failure. Elongation of electrical trees has been experimentally observed in [8], [9]. In such a case, the mica sheets consist the harder material and the electrical trees propagate via the epoxy resin, which is the weaker material. Electrical trees propagate, generally speaking, more easily in epoxy resin, a fact also confirmed in another paper [10].

Normally prior to electrical treeing, PD take place in defects in the machine insulation. Such defects may come about from construction or from the stressing of the insulation. As said, the stressing in machine insulation can be multi-factor stressing, i.e. the insulation may be stressed because of high voltage, thermal cycles as well as from mechanical loading [11]. Defects can come about as enclosed cavities, delaminations, problematic interfaces, possible enclosed foreign particles etc. The consequence of all these is local electric field enhancement, PD activity which subsequently may result to insulation damage. Such PD can be quite intense in the order of 1-10 nC [12], [13]. These phenomena can have a cumulative effect and cause aging and shortening of the lifetime of machine insulation [14], [15].

Rotating machine insulation systems suffer from what most of composite insulating systems suffer, i.e. the presence of interfaces. Mica sheets and epoxy resin consist of a system with multiple interfaces. Interfaces may encourage electric field intensifications in the weaker material and, thus, the cause of deteriorating phenomena. On the other hand, thinner (and consequently more) mica sheets may delay the discharge process in that discharges lose energy at the interfaces, i.e. a discharge having penetrated one layer could not enter the next layer of material until the spot on the interface, centred on the channel, had been charged to a potential which could produce a field comparable with that of the channel at the level in question [16].

Breakdown mechanisms inside the insulation may start from defects due to excessive electrical field. Previous work done on epoxy resin samples showed that it is possible that trees emanate from enclosed cavities, causing thus conditions for further propagation and eventual failure [17]. Although such emanating trees are still put into question from some researchers [18], experimental evidence can hardly be refuted. PD cause pits on the inner surface of such cavities possible and then electrical trees may ensue. One aspect that should be stressed is that of the applied voltage: for meaningful comparisons of data (perhaps with several years interval) and/ or comparison of data in the same laboratory or factory, it is essential to use identical wave shapes of voltages [19]. It is something that people tend to forget but something that comes out when PD measurements – comparisons of such measurements at different times – have to be performed.

Mica barriers delay tree propagation. Depending on the dielectric constants of mica sheets and of epoxy resin as well as on the threshold voltages, electrical trees may take different forms but, in general, they seem not to penetrate the mica barriers [20]. Mica barriers may result in a major increase in breakdown time, this increase being depended on both the tree growth time and the set-in of the failure time [21].

The interplay and interdependence between PD and electrical treeing has been shown before, where in narrow holes of short length small PD in a rather high number may be produced whereas in holes of larger diameter and longer length, fewer PD but with larger magnitudes will ensue [22]. In any case, trees tend to grow around the mica barriers [23].

A crucial factor determining tree propagation along a mica barrier is the type of chemical bonding between mica and epoxy resin. The stronger the bonding, the higher the resistance to the tree propagation [24]. Imperfections may result from imperfect mica sheet overlapping, from the creation of cavities in parts which are at the edges of windings, from not so smooth mica sheets or from abrupt interruptions of mica sheets (because of constructional faults) [25]. Furthermore, the layered mica can delaminate under thermo-mechanical stresses and thus cause cavities, which in turn will lead to PD [25]. Examples of imperfections are given below. In Fig. 1, a winding insulation is shown and the different radii of mica sheets are noted. In Fig. 2, imperfections in winding insulation are noted.

Experimental evidence that a mica barrier may withstand electrical treeing much better than epoxy resin was given in [10], where it was also noted that the breakdown strength of such a combination depends on the thickness of mica sheets, on the thickness of epoxy resin, the temperature, the type of epoxy resin as well as the cleanliness of both materials.

Generally speaking, the time to breakdown is the sum of the time from the initial PD activity and the creation of initial tree channels and the growth time of trees to the final breakdown. For some authors, there is an incubation period during which PD activity is barely detectable and trees grow only slightly, then a period of tree expansion follows and finally a widening of the smaller tree channels which eventually leads to bridging of the electrodes and the breakdown [9]. For others, two stages of treeing are observed: first, the inception period which may be for very many cycles, followed by a relatively short period of tree growth. PD detection reveals that a transition is accompanied by big increase in the PD magnitude, which persists until breakdown [26]. A good account of PD measurements and the effect of PD in rotating machines were given in [27], where examples of "good" (i.e. relatively free of PD) and "bad" (with delaminations) windings were presented. In [27], it was emphasized that for any comparison between PD measurements, the experimental conditions play a predominant role, a statement that echoes reference [19]. Certainly, a condition assessment of windings can be done by continuously monitoring the PD activity, taking into account that an increase in discharge activity occurs when the insulation is eroded and also that a PD activity can manifest itself both as internal PD activity and as surface discharges [28]. A good account of the relation between PD and tree structures was given in [29], where it was emphasized that electron avalanches, field fluctuations arising from the discharges themselves, local variations in permittivity and resistance of the insulation can play a decisive role for the electrical tree propagation. Minor variations of trapped space charges may lead to preferred directions for new tree channel formations and, thus, may also affect the tree propagation.

Fig. 1: Winding insulation. Note the different radii which cause the different bending of mica sheets (after [10])

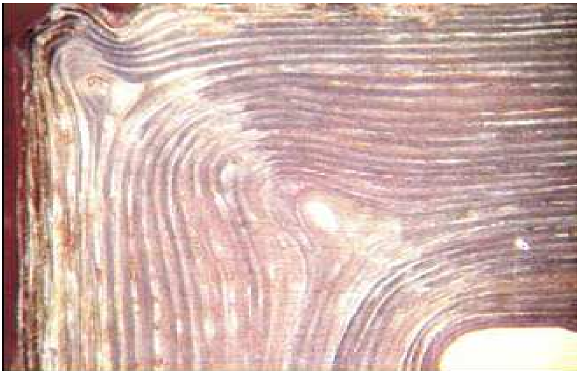

Fig. 2: Imperfections of winding insulation at the edges (after [10])

It is not to underestimate that several years ago, problems with very small PD – not to say with phenomena below the inception voltage – were noticed in turbine generator armature winding insulations, namely that although such windings withstood standard testing, they failed short after the beginning of their service. Why was that? Possibly because extremely small PD, not easily detected by conventional methods, are at work and little by little could deteriorate the insulation of such windings [30].

Mica sheets offer a good protection to breakdown paths and/or to electrical treeing. This certainly depends on the applied voltage. Simulations in epoxy resin/mica sheets show that there is a voltage limit beyond which breakdown even of mica sheets is possible. From a certain voltage value upwards, mica sheets are also prone to treeing, as the following figures show. In Fig. 3, the applied voltage is 28 kV, which creates a rather distinguished form of treeing in the epoxy resin but which cannot penetrate the mica sheet. On the contrary, in Fig. 4, with another higher applied voltage, the mica sheet is penetrated by the electrical trees and in Fig. 5, there is a complete failure of the system epoxy resin/mica sheet. It is to be noted that in Fig. 4 as well as in Fig. 5, the trees in the epoxy resin are of bush-type and in the mica sheet of branch-type. This is because trees in the weaker material are far more numerous and thus they are interconnected much more densely than in the stronger material. The simulations shown in Figs. 3, 4 and 5 were performed with the method of Cellular Automat [31]-[33]. The different types of electrical trees in epoxy resin (bush-type) and in mica sheet (branch- type) depend on the applied voltage as well as on the type of the insulating material [34]. In Figs. 4 and 5, the progression of treeing towards the opposite electrode can well be seen. It is indeed a question of time before the treeing structure reaches the opposite electrode.

All in all we observe that conventional insulating materials functioned more or less satisfactorily. Both experiments and simulations indicated that breakdown paths follow the easiest way to the other electrode, i.e. through the epoxy resin, which is the weaker of the two materials. Breakdown of the mica sheets may be possible but this depends on their thickness as well as on the voltage applied.

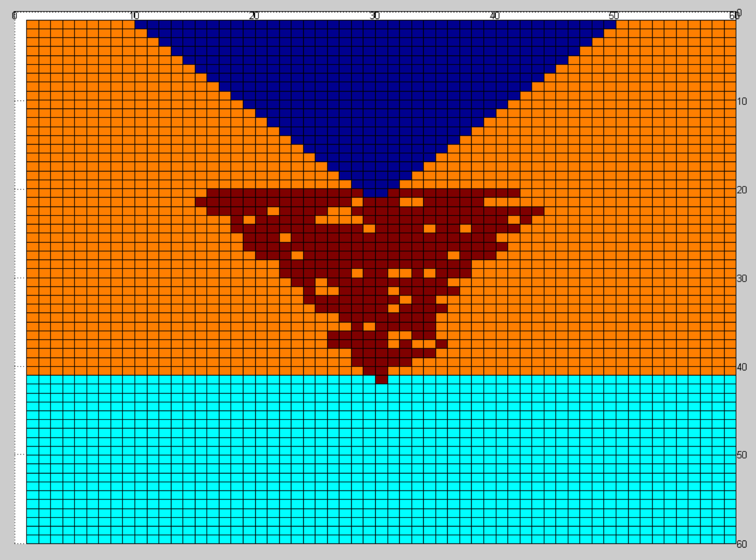

Fig. 3: Propagation of electrical tree in epoxy resin and mica sheet. Applied voltage 28 kV, breakdown strength of epoxy resin is 26 kV/mm, breakdown strength of mica sheet is 35 kV/mm

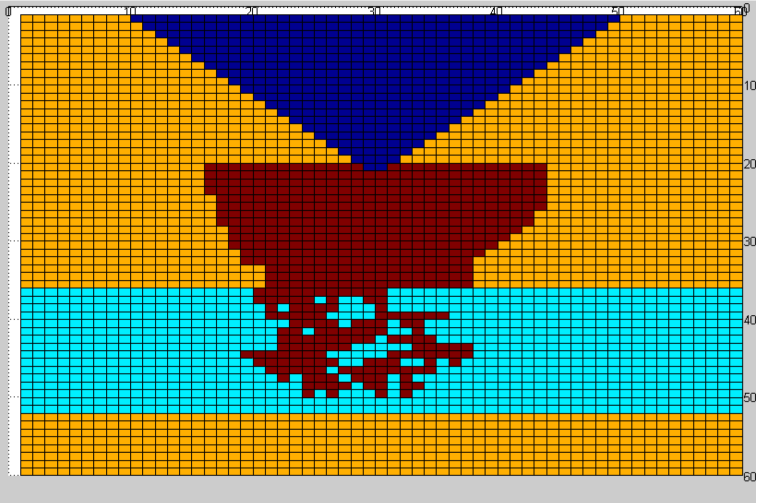

Fig. 4: Propagation of electrical tree in epoxy resin and mica sheet. Applied voltage 34 kV, breakdown strength of epoxy resin is 26 kV/mm, breakdown strength of mica sheet is 35 kV/mm

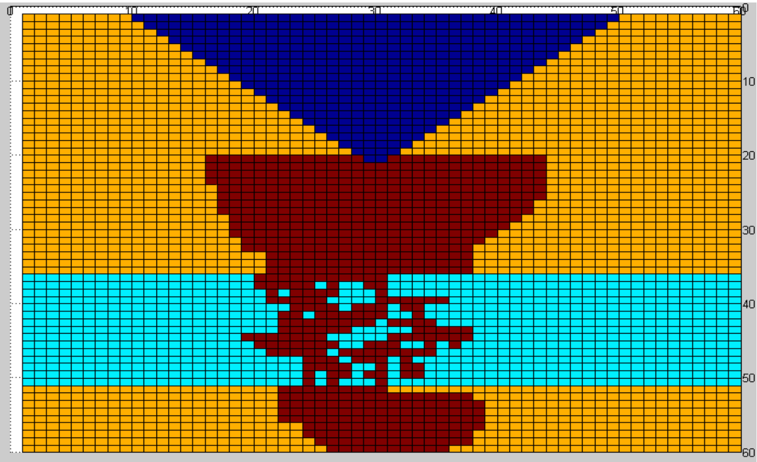

Fig. 5: Propagation of electrical tree in epoxy resin and mica sheet. Applied voltage 34 kV, breakdown strength of epoxy resin is 26 kV/mm, breakdown strength of mica sheet is 35 kV/mm

Is there a way to improve even more the electrical performance of such a composite system? The following section will concentrate on some of the modern materials proposed for machine insulation.

(As an explanatory note to this paper: It is evident from the present review that here we are not interested in an estimation of lifetime expectancies of the insulation in connection with the quality of the insulation itself. Models of lifetime expectancies have been developed and commented upon elsewhere [35]. It should also be emphasized that, the present paper is not concerned with the technicalities of the measurements of PD in rotating machine insulation either [36]).

Nanocomposite Polymers for Rotating Machine Insulation

A recent paper on nanodielectrics applications has pointed out that "three types of insulations have been developed with great improvements in the resistance to partial discharges: first in random-wound wire enamel; second in form-wound strand enamel; and third in form-wound stator bar insulation or ground wall insulation" [37]. Of these aforementioned applications, the one that interests us most for the time being is the third one, i.e. that of stator bar insulation. The other two types of insulation may constitute the subject of yet another review paper. In the context of the present paper, we will concentrate on some off the novel insulating materials concerning the stator bar insulation.

Results reported on 13.8 kV form-wound hydro generator bars made of epoxy resin with a high percentage of nanoparticles of silica, indicated a very optimum performance regarding their thermal and mechanical properties. The electrical performance of such an insulation w.r.t. the PD and electrical treeing resistance was also noted [37], [38]. Better resistance to PD and electrical treeing implies less insulation thickness.

Before starting an evaluation of nanocomposite materials for machine applications, let us be clear on a certain point: the novel materials may offer some new insights regarding the endurance of the insulation of electrical machines, but the condition -based maintenance treatment is not expected to change that dramatically. In other words, we are still far from new aging models and/or accelerated laboratory testing [40]. In yet other words, synergy effects may occur also with the new materials and, when two or more aging mechanisms are at work simultaneously, the total degradation may not be a single algebraic sum of the separate degradation outcomes [39], [40].

It is rather clear that from the two basic components that constitute the rotating machine insulation, the one that is expected to be prone for the addition of nanoparticles, is the epoxy resin. Inorganic nitrides and oxides (such as, AlN, BN, SiO_2, ZnO, Al_2O_3 and TiO_2 among others) may be added in small amounts, and if homogeneously dispersed, they may show potentially better electrical and thermal properties than the conventional epoxy resin [41]. The need for good dispersion of the nanoparticles as well as the important role of interfaces in the nanocomposite polymers has been discussed elsewhere and there is no need for any repetition here [42]. Boron Nitride (BN) has been used to enhance the dielectric properties of the groundwall insulation system for generators because it has a reasonably high resistivity (10^{15} ohm.cm) and breakdown strength (53 kV/mm) as well as a rather small relative permittivity (around 4). Such inherent properties render BN a good nanoparticle material to be added to epoxy resin [41]. Moreover, the addition of BN nanoparticles improved the thermal conductivity of epoxy resin. In another publication, epoxy resin was mixed with Al_2O_3 nanoparticles [43]. The breakdown strength of such a nanocomposite was comparable to the breakdown strength of conventional epoxy resin but with a lower scatter in values. In [43], particular attention was paid to the fact that nanoparticle agglomerations were dependent on the method of preparation of the nanocomposite. As is well known, nanoparticle agglomerations affect the PD, the electrical tree propagation and the breakdown strength of nanocomposites [44]. Zirconia nanoparticles added to epoxy resin offer an improvement of the breakdown strength as well as of the thermal and dielectric properties. Addition of zirconia nanoparticles to about 5 wt% gives a higher breakdown strength compared to conventional epoxy resin [45]. It must, however, be noted that in [45], there are in certain parts of the paper discrepancies between the text and the experimental data.

Fillers in insulation systems for rotating machines are investigated in [46], a most thorough review publication. Without going into many details about the application of nanocomposites for machine insulation and the role of nanoparticles, that paper points out several vital aspects of insulation engineering, namely, the effect of electrical, mechanical and thermal stresses, which leads to delaminations and/or void formation. Nanoparticles are deemed to restrain the charge transport processes. As a consequence, nanocomposites exhibit less space charge formation than conventional polymers or their microparticle counterparts. The novel approach of [46] is that it insists on a concept for void formation that is based on a micro-mechanical approach, i. e. void formation can be considered as a process by which the insulating material accommodates mechanical energy, no matter whether this energy is purely mechanical, electro-mechanical or thermo-mechanical in nature. In the case of nanocomposites, crack initiation may be considered as having a critical nucleation size. Crack initiation sites may well come from nanoparticles aggregates, as was noted in [47]. In [47], the breakdown strength of epoxy resin/clay nanocomposites was investigated, the clays being Cloisite 20A (C20A) and Cloisite 30B (C30B) with different levels of loading. It was reported that the breakdown strength depends on the level of loading (around 5wt% being the optimum) and also on the type of nanocomposite structure (intercalated nanocomposite or exfoliated nanocomposite), with the exfoliated type giving the higher breakdown strength. Clay C30B gave the better results since it is more hydrophilic than clay C20B and, consequently, it has a greater affinity for epoxy resin. Epoxy pre-polymers can more easily intercalate into C30B clay galleries, increasing thus the interlayer spacing (more details on intercalated and exfoliated structures in [48], [49]). In yet another paper, it was reported that appropriate nanoparticles, if suitably added, may enhance the breakdown time of conventional epoxy resin by a factor of ten [50].

Nanosized particles were also discussed in [51], where excellent voltage endurance results seemed to be very promising. Large percentages of silica nanoparticles (up to 25 wt%) were reported for making practical coils in VPI (vacuum pressure impregnation) epoxy resin successfully [52]. The reported percentage seems to be excessive in view of previous publications. Nevertheless, for nanocomposite materials in high voltage machinery, the problems remain much the same as with the more traditional insulations, namely that the heat transfer must be satisfactory also for the new materials, the mechanical strength must be high enough and the risk from PD must be minimized [51]. Recent work on mechanical properties showed that, with epoxy resin and montmorillonite (MMT) clay mineral, natural frequency of vibration and damping factor of the said material increase by adding up to 5 wt% of nano clay [53]. Recent work also indicated that epoxy resin with 10 wt% TiO_2 nanoparticles improved greatly the ac breakdown strength and the time to breakdown [54].

The percentage of nanoparticles to be included in a base polymer matrix depends on the type of nanoparticles as well as on the base polymer. It has been reported, for example, that with epoxy resin and layered silicate, just small amounts of nanoparticles are enough for the improvement of partial discharge resistance, whereas in other publications, it was confirmed that only 2 wt% of nanoparticles is sufficient to improve the partial discharge resistance of polyamide/layered silicate nanocomposites [55]-[57]. Small amounts of nanoparticles (3 wt% of SiO_2 nanoparticles) were also reported to improve the glass transition temperature of epoxy resin in comparison with the neat epoxy resin. This is due to the reduction of polymer chains mobility. On the other hand, in the same paper, the resistivity of epoxy resin with 3 wt % of TiO_2 nanoparticles was lower by one order of magnitude with respect to pure epoxy resin [58]. Paper [58] is a good example of the dependence of the nanocomposite properties on the nature of the added nanoparticles to epoxy resin. Further evidence as to the effect of the percentage wt% of nanoparticles in epoxy resin is offered in [59], where POSS (polyhedral oligomeric silsesquioxane) nanoparticles were added to the base material. Tanδ measurements as well as thermogravimetric analysis showed that moderate percentages in wt% (between 1% and 4%) offered the best results. The importance of nanoparticle percentage and functionalization was also emphasized in [60], where poly (butylene te-rephthalate) based polymers containing alumina nanoparticles were investigated, as alternative to epoxy resin. It was reported that an optimum nanoparticle percentage exists for giving a lowering of the permittivity of the resulting nanocomposite as well as a lowering of tanδ. The lowering of the aforementioned parameters can probably be ascribed to the restriction of polymer chain movement by nanoparticles due to the modified molecular structure and chain dynamics, which cause a strong surface interaction between the nanoparticle and the polymer matrix [61].

Treeing effects in nanocomposite epoxy resin propagate through the base material and do not go through the nanoparticles [44], [62]. Erosion depth was found to be minimal for a combination of micro- and nano- particles [62]. The desirable result of having good thermal conductivity and low dielectric constant is more difficult to obtain. In [60], it was shown that epoxy resin with h- or c- boron nitride nanoparticles presents higher thermal conductivity at the expense of a higher dielectric constant, whereas epoxy resin with silica nanoparticles has a much lower dielectric constant but with a far lower thermal conductivity. The reported lower thermal conductivity of epoxy resin with silica nanoparticles, however, was contradicted in [52], [63]. In [52], it was mentioned that nanosized SiO_2 particles act as barriers to the treeing phenomena and hinder propagation. Moreover, the mechanical and thermal properties are improved significantly, thus giving a promising new insulation system with less thickness and better heat transfer. The disagreement between [62] and [52] may be due to the different processing methods as well as to the different size and/or shape of the nanoparticles.

Differentiation between short-time breakdown and long-term failure in nanocomposites was reported in [64]. As the authors pointed out, short-term breakdown properties depend on the applied voltage waveforms as well as the bonded region of the nanoparticles, whereas for long-term aging and failure, the transitional region and the cohesive energy density (CED) of the polymer matrix play the dominant role. They remarked that the percentage weight of nanoparticles to be included in a polymer matrix depends on the matrix itself, the chemical nature of the nanoparticles, their functionalization, their size and their bonding to the polymer matrix. For example, Ag nanoparticles of about 20 nm in size mixed with epoxy resin at about only 0.05 wt% may improve the short-term breakdown strength by about 30% w.r.t. the pure epoxy resin. Regarding nanoparticle content and the polymer matrix, it was shown that with 1 wt%, epoxy resin nanocomposite has a better long-term electrical aging resistance than its polyethylene counterpart. The authors of [64] also remarked that PD resistance improves as the size of nanoparticles decreases because the probability of electron collision with nanoparticles increases leading the electron transport to become harder. The latter statement agrees with simulation results presented in [42].

Rotating machine insulation will be better served with nanomaterials, if such materials include nanometric layered silica nanoparticles, since the latter offer better PD resistance and improved mechanical properties. As the design field nowadays for conventional machine insulation is limited to only about 3 kV/mm [65], silica nanoparticles may help to increase the design field [66]. Such layered silica nanoparticles present a barrier behavior, rendering them interesting for applications.

Possible Charging Phenomena Below Inception Voltage

The present paper did not deal with either the technicalities of PD measurements in rotating machine insulation or the modeling of lifetime of such insulation under a variety of simultaneous stresses (electrical, thermal and mechanical) [67]-[69]. The literature on such topics is very rich to be dealt with in the present work. This paper did not deal either with the possibility of charging phenomena below the so-called inception voltage. Relevant work done in the past revealed that it is possible to have sudden failures in insulation systems (including those of rotating machines), even though the equipment passed the relevant specification tests [30], [70]-[76]. More recent research on the topic of charging phenomena below inception voltage indicated that in both base epoxy resin [77], and in epoxy resin with TiO_2 nanoparticles and microparticles, charging phenomena were observed [78]. It has, however, to be noted that in the case of epoxy resin with nanoparticles and microparticles, charging phenomena below inception were rather sporadic. This may be due to the bonding strength between fillers and matrices, the interfiller space or matrix volume surrounded by neighboring fillers and to the morphology in the interfiller space [79]. The whole subject of possible charging effects below the so-called inception voltage cannot be dealt with in the present paper. It is, however, a subject which unjustly does not attract much attention from the insulation community. The authors intend to come back to this subject, possibly with another review paper concentrated on this subject only. Certainly, for the treatment of this question, important publications such as [80]-[83], must be taken into account.

Further Developments

It is understandable that there may be alternatives to the epoxy resin as insulating material for rotating machines. Such alternatives may be silicone based, resin rich insulation materials due to their thermal stability, flexibility, anti-vibration and very good electrical properties. It would be interesting to see admixtures of such materials with nanoparticles, as a further exploration for possible applications [84]. Furthermore, more fundamental research has to be performed regarding the combined stresses on nanocomposite polymers. Since the various stresses (electrical, thermal, mechanical etc.) are applied not sequentially but combined [85]-[88], experimental work has to be done in this respect. In [63], detailed steps for future work have been proposed, such as thermal aging and classification tests at different temperatures, electrical aging – voltage endurance tests at various levels resulting in lifetime curves, multifactor aging as well as thermo-mechanical bending endurance in parallel with electrical stress tests. On a more general basis, optimization of nanocomposite material fabrication methods, a better understanding of interfaces and possible combinations of micro- and nanocomposites may be research fields in the future. The need for nanocomposites having high breakdown strength, low thermal expansion coefficient, high thermal conductivity, satisfactory long-term aging and good withstanding capability to multistressing, will be even more pronounced in the coming years [89]. The variety of nanoparticle sizes and types, the variety of polymer matrices as well as the variety of processing methods, leaves us with the hope that optimal combinations w.r.t. the electrical, mechanical and thermal properties, may be found for the benefit of the electrical machines industry.

Conclusion

In this paper a review was performed for both traditional and modern insulating materials for rotating machine insulation. Traditional insulation mainly consists of mica sheets and epoxy resin, with the former being the stronger of the two materials. Electrical trees tend to propagate through the epoxy resin and have greater difficulty in breaking through the mica sheets. Nanocomposites on the other hand offer generally better insulating properties. The nanoparticles that are dispersed in the polymer matrix tend to act as extremely small barriers, preventing thus the propagation and growth of electrical trees. The performance of the nanocomposite polymers depends on a variety of parameters, such as, for example, the type of polymer matrix, the type of nanoparticles, their functionalization and their size.

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