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# Survey of Insulation Systems in Electrical Machines

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## Abstract:

Insulating materials and insulation systems design have been gaining more attentions as more electrical machines tend to operate in harsher environments for various applications. Harsh environments include high temperature, humidity, erosion, low air pressure, etc. This paper discusses recent advances in insulation systems for electrical machines. Insulation tests as well as test standards that have been used to evaluate insulation systems and detect insulation failures will be discussed. Insulating materials used for a wide range of industrial applications such as wind turbine generators, aerospace hybrid/electric powertrain, and hydro generators have been summarized. For the emerging high-altitude, highvoltage aerospace applications, partial discharge and its

impact on insulation systems will be discussed. Finally, polymer nanocomposite materials with excellent thermal conductivity and dielectric strength are highlighted as an outlook.

## SECTION I. Introduction

Due to the continued growth of renewable energys, the number of electrical machines used worldwide has significantly increased. Insulation system is a very critical component of electrical machines. Insulation breakdown can lead to failures, which eventually result unpredicted downtime and negative financial impacts and in some applications can be a safety hazard. For some specific industries where uninterruptible operation is required, the unpredicted downtime is unacceptable. The unpredicted downtime for an offshore oil plant would be $25,000/h [1]. The dielectric strength of electrical insulation materials has been gradually improved over the years. By introducing new materials in the past 20 years for instance, the dielectric strength of ground-wall insulation nearly doubled [2]. Electrical, mechanical, thermal, and ambient stresses can cause insulation degradation which consequently leads to insulation failure [3], [4]. Insulation failure causes short circuits in the stator winding and consequently high currents could pass through the defected stator winding [5]. A survey on 1141 induction motors with power ratings above 200 hp shows that around 30% of motor failures are due to insulation failures [6]. With advances in sensors, digital signal processing, diagnosis methods and test standards, insulation failures can be detected [7], [8]. Through online estimation of material degradation and lifetime in early stages, insulation systems of electric machines can be protected from further aging while unpredicted downtime could be avoided through scheduled maintenance.

Even though insulation system is a passive component in an electrical machine which does not produce torque, insulation build/thickness (which represents the key thermal resistance in electrical machine)can have significant impact on the machine cooling and hence electrical loading and torque production. There have been several efforts to minimize insulation thickness for design compactness, low manufacturing cost and high efficiency [3]. The two main functions of insulation systems in electrical machines are (i)avoid short circuit between winding turns and winding turn to ground (iron core); (ii)prevent winding movement in the rotor and stator. Insulation system for different types of electrical machines like wound-field synchronous machines, permanent-magnet machines etc., can be divided in to two categories, i.e. stator winding insulation and rotor winding insulation. An overview of insulation system components in electrical machines is shown in Fig. 1. Both stator and rotor have different insulation components as shown in Fig. 1.
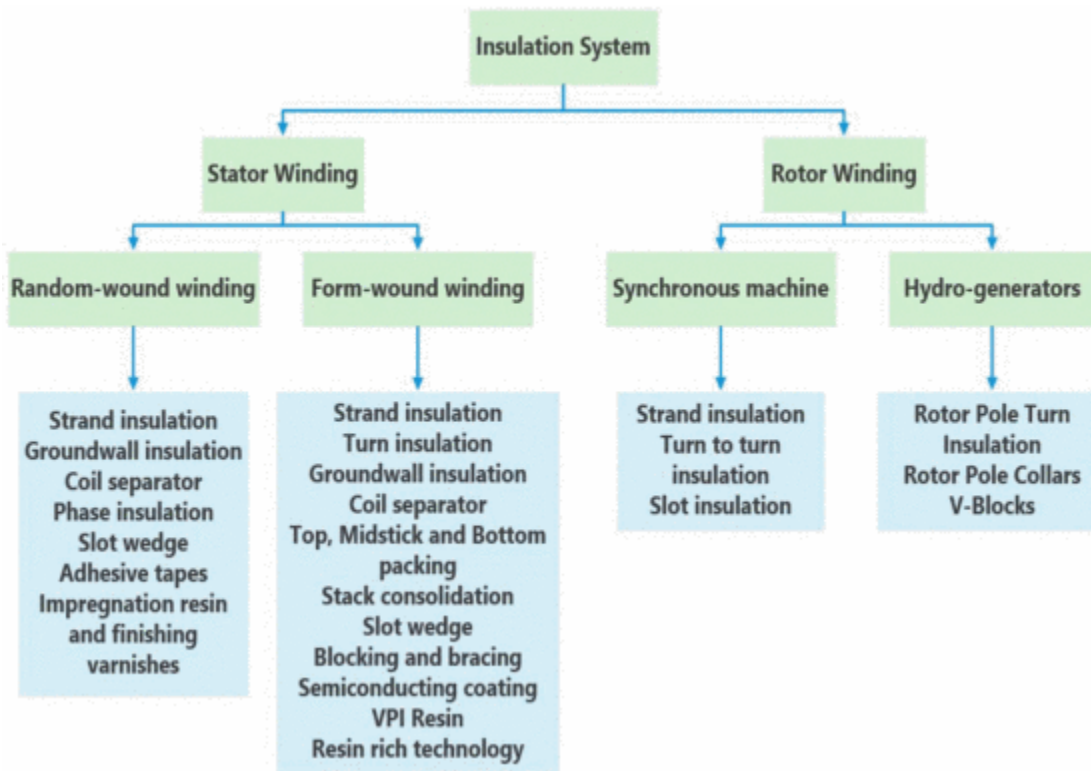
**Fig. 1.**

Overview of the insulation system in electrical machines [3]
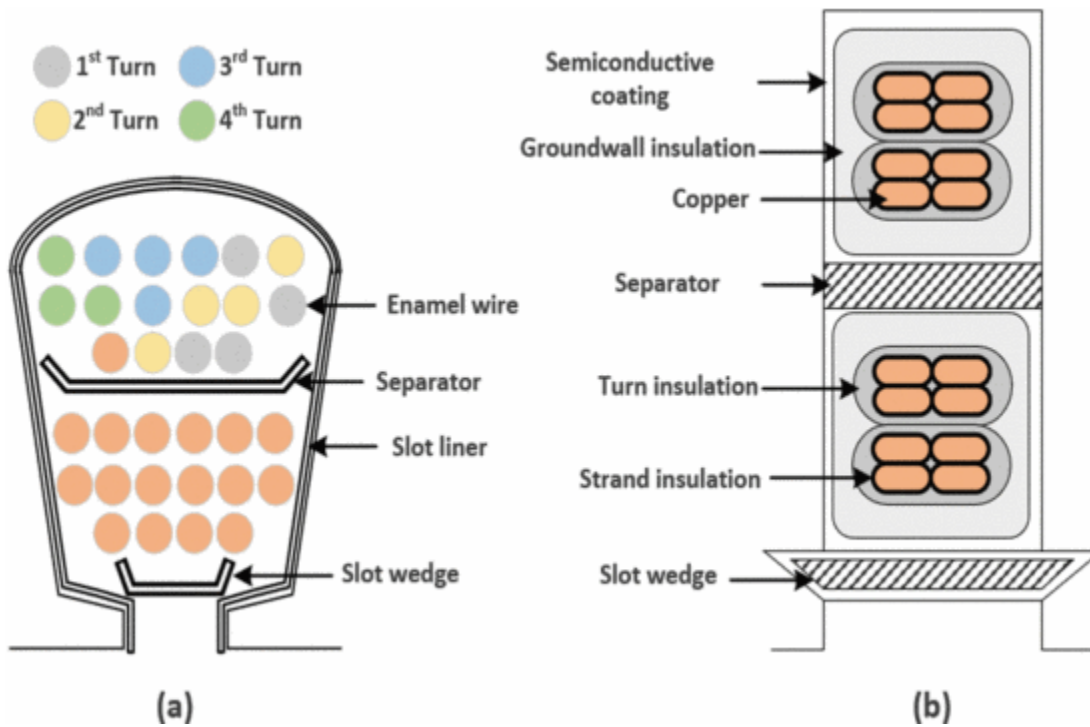


**Fig. 2.**

Crosse section of the stator slot: (a) Random-wound winding, (b) Form-wound winding [3]

In general, there are two types of stator windings: (i) Random-wound windings; (ii) Form-wound windings with multiple conductors or Roebel bars. A cross section of both stator winding structures are shown in Fig. 2. The Random-wound windings consist of enamel wire, separator, slot liner, slot wedge, etc. In Random-wound windings, round insulated coppers (magnet wire or enamel wire)are wrapped around the stator teeth randomly adjacent to each other.

Typically, random-wound windings are used for machines with a power level of several hundred kilo-watt and voltage level of less than 1000V [3]. Due to the use of random-wound winding, it is possible that a high voltage turn (the turn connected to input terminal)would be adjacent to a lower voltage turn (that is close to the low voltage neutral point). This means that there is a high voltage difference between the first turn and the last turn in random-wound stators, where thicker insulation is needed. As for form-wound windings, coils are pre-shaped before being inserted to slots. Conductors can be purposely placed in a way that minimum voltage difference between adjacent turns in the same coil is achieved.

This paper discusses recent advances in insulation system of electrical machines. The paper is arranged as follows, Section II covers common key insulation tests including latest standards. Section III discusses causes of Partial Discharge (PD)and its impacts on the electrical insulation system. Section IV covers main factors leading to insulation degradation as well as challenges for aerospace applications, wind turbine and hydro generators. Section V covers nanocomposite materials and their effectiveness in insulation systems of electrical machines.

## SECTION II. Insulation System Tests

There are two categories for electrical insulation tests, i.e. online tests and offline tests. Online testing is implemented when electrical machine is spinning. Real-time stresses on electric machines are extracted to monitor the degradation of insulating materials. However, it is hard to show all the failures inside an electrical machine through online testing/monitoring only. Hence, offline tests are required. In offline tests, shortly after an electrical machine shuts down and is disconnected from the supply, testing methods are applied. An estimated maintenance time would be acquired, which can avoid unpredicted downtime [3], [9].

The most common offline insulation tests include: 1)insulation resistance (IR), 2)polarization index (PI), 3)AC high potential test, 4)DC high potential test, 5)capacitance test, 6)dissipation (power)factor test, and 7)surge test and 8)offline partial discharge. The most common online insulation testing/monitoring include: 1)thermal monitoring, 2)condition monitors and tagging compounds, 3)ozone test, 4)online partial discharge test, 5)current signature analysis and 6)voltage surge monitor. The commonly-used offline insulation tests and standards are summarized in Table I.

Specifically, the IR test can measure resistance between the copper coil and rotor/stator core. The DC high potential test determines existing defects inside the ground-wall insulation. AC high potential test is more effective than DC high potential test because significant defects might be missed in DC high potential test but can be detected in AC high potential test. Capacitance test can measure winding capacitance with respect to the neutral point, showing the insulation deterioration due to overheating. Dissipation (power)factor test measures the dielectric losses inside an insulation system. PI test is an extension of the IR test. PI is equivalent to measured ratio of IR after 10 minutes and 1 minute. Offline and online partial discharge tests can measure PD activities within the insulation system. In surge test, a high voltage with short rise time surge is fed into the winding so that insulation weaknesses can be detected. Thermal monitoring uses sensors to monitor temperature inside the electrical machine. It can be used to diagnose the ongoing insulation failure. Condition monitors can detect hot spot locations of insulation system inside generators. Tagging compounds are special

paints. When they are exposed to high-temperature environments, chemical compounds are released. Thus, the overheated area can be traced by condition monitors. Ozone is by-product of PD in the air. Ozone test can measure ozone concentration in the electrical machine. Current signature analysis can detect cracked rings and broken rotor bars in the cage induction motor as well as winding failures. Voltage surge monitor can detect voltage surges that occur in the machine winding due to PWM inverter switching, lightning and so on.

**Table I:** Offline insulation tests for electrical machines

| Test | Standard | Test Description |
|---|---|---|
| Insulation resistance (IR) | IEEE 43 [10], NEMA MG1 [11] | Contaminations and defects between phase to ground can be found |
| Polarization index (PI) | IEEE 43 | Contaminations and defects between phase to ground can be found |
| DC high potential test | IEEE 95 [12] | Defects between phase to ground can be found |
| AC high potential test | NEMA MG1 or IEC 60034 | Defects between phase to ground can be found and more effective than DC high potential test |
| Offline partial discharge | IEC 60270 [13], IEC 62478 [14], IEEE 1434 [15], IEC 60034-27-1 [16], ASTM D1868 [17] | Defects between turn to turn and phase to ground can be found |
| Dissipation (power) factor | IEEE 286 [18] or IEC 60894 [19] | Contaminations and defects between phase to ground can be found |
| Surge test | IEEE 522 [20] and NEMA MG1 | Defects between turn to turn and phase to ground can be found |

# SECTION III. Partial Discharge

For high-voltage, low-air-pressure applications, PD is one of the major factors that can results in insulation failure. PD usually happens inside the void space inside/between insulating material like pores and delamination. Basically, there are four types of PD in electrical insulation systems [21]:

- *PD in short airgap*: They happen either in air-pockets between adjacent wires or embedded inside insulation system. These PDs are spark type pulses with slow or high rise time;
- *PD in long airgap*: the streamer discharge happens during a very short time due to ionizing radiation at the streamer tips;
- *Corona effect*: it happens when a metallic spike or sharp edge is at a high electric potential;
- *PD on the surface of the insulators*: these are surface corona or surface tracking type of PD. Contamination and moisture might increase these possibilities.

It has been known that, for low-voltage motors with organic magnet wire, PDs occur in short air-gap. Bubbles or voids occur between adjacent wires or between wires and stator core. Multi-megawatt generators may have PD in short air-gap and PD at the surface tracking of bar winding. When electric field inside the air becomes higher

than 3kV/mm, air breaks down (at one atmosphere and room temperature). This results in spark and heat. The insulation will be degraded by repeated sparks. If these sparks are not removed or stopped, ultimately a hole inside the insulation will be created. The void spaces are typically generated during manufacturing.

Organic insulating materials like polymers (polyimide (PI), polyamideimide (PAI), polyesterimide (PEI))used for low voltage machines (Type I), insulation fails easily under repetitive PDs [35]. In contrast, mixed organic/inorganic insulating materials used for high-voltage machines (Type II)can tolerate PDs during normal service. Different types of PDs result in different degradation level of "Type II" insulation system. For example, if two types of PD are detected in an electrical machine, priority to maintain is not directly and only related to amplitude of PDs. It is related to PD ranking in IEC 60034-27-1. In order to overcome this problem where a maintenance action is needed, [22] introduced a health index (HI)approach to monitor PD database history, type of PD, equipment history, etc. to predict maintenance schedule.

The common PD test and measuring process is explained in IEC 60270. A capacitor is used to detect PD pulses. This standard uses 50 kHz to 1 MHz range frequencies to detect PD pulse currents. But, recently a new complementary standard IEC 62478 [14]was published, and it increased the PD detector' bandwidth to 3000 MHz. Complete bandwidth ranges are defined as follows:

- Low frequency (LF): below 3 MHz
- High frequency (HF): 3–30 MHz
- Very high frequency (VHF): 30–300 MHz
- Ultra-high frequency (UHF): 300–3000 MHz

Among the four frequency ranges mentioned above, the UHF sensors have the highest noise suppression. Even though UHF sensors can suppress the disturbance noises outside the generators such as transmission-line corona and inverter switching noises, they need to be installed close enough to coils or bars. Attenuation effect would be increased when PD detection frequency is getting higher [16]. LF has the lowest attenuation and highest sensitivity to PD current pulses. The PD can be detected remotely from where the LF sensors are installed.

In order to identify PD signal from disturbance noises, high-pass filters with appropriate bandwidth are adopted in UHF sensors. However, there are two limitations for UHF sensors: (i)the sensitivity of UHF sensor is lower than that of conventional sensors; (ii)With fast-rising/falling voltage pulses, signal-to-noise ratio (SNR)may not be high enough to catch the PD signal. In order to address this issue, a novel UHF sensor adopts Archimedes spiral antenna was proposed in [23].

The early generators are usually driven by 50/60 Hz frequency which do not include high frequency harmonics. However, the prevalent PWM power converters introduce higher switching frequency and harmonic components compared to the fundamental electrical frequency. Moreover, the potential use of wide-bandgap (WBG)power switches like silicon carbide (SiC)and gallium nitride (GaN)can further increase the switching frequency as well as introduce higher dv/dt. Fast rise/fall time produces higher frequency harmonics, resulting in electrical stress on the winding insulation [24]. In addition, these higher frequency harmonics cause heating of the insulation system which makes PD even worse [25]. To eliminate the high frequency harmonics, employing filters is necessary. These harmonics are mainly produced by high frequency PWM switching of power converters. Depending on the requirements of an application, both active and passive filters can be employed [26]. However, these filters increase system cost and mass [27].

## SECTION IV. Challenges of High-Voltage Sysytems

In this section, challenges of insulation system design for different applications are discussed.

## A. Aerospace

The more electric aircraft (MEA) concept focuses on replacing hydraulic and pneumatic systems with electric systems. Like electrified vehicles, next generation MEA can significantly improve system efficiency and reduce fuel consumption. The power rating of a generator for large passenger aircraft is usually higher than 1 MW. In order to reduce the cables size, there are attempts to increase the system voltage/supply voltage of the electrical machines. However, the supply voltage level is limited by the PD phenomenon since the inception voltage is fairly low at higher altitudes and lower air pressure. In 1936, voltage supply in an aircraft was 14.25 VDC while in 1946 it increased to 28 VDC [28]. The need for high-voltage electrical systems resulted in a transition from 28 VDC to 115/200 VAC, 400 Hz system for commercial aircrafts like Airbus A380, A350 as well as Boeing 787. Still, 28 VDC system is used for low voltage system of an aircraft. Owing to the increase of system voltage from 28 DC to 115/200 VAC, the size and weight of a generator can be significantly reduced [29]. In addition, in order to achieve more weight reduction in military aircrafts, 270 VDC is adopted [30].

In recent years, Boeing company manufactured the B787 which uses hybrid voltage system which operates at 235VAC, 360–800 Hz and $\pm 270$ VDC [31]–[32][33]. With the increasingly higher voltages, the likelihood of PD phenomenon rises consequently. Also, PD and insulation breakdown bring concerns about safety and reliability in high voltage direct current (HVDC)systems in commercial aircrafts [34]. Recently, with the increased interest in hybrid/electric propulsion systems even higher voltages $(>1\text{kV})$are being considered which significantly increase the PD challenge.

PD is one of the main reasons for deterioration of insulation made from inorganic or mixed organic/inorganic materials. Organic enameled wire is a mature technology in industry for class H $(180\ \circ\text{C})$ and N $(200\ \circ\text{C})$. The maximum operating temperature for organic materials are 200°C but in some specific machines they can operate at higher than nominal temperature for a short time such as a fan motor for blowing off smoke when a fire happens or electric motor for electric torpedo [21].

Experimental results show that insulation deterioration is rapidly amplified as the magnitude and frequency of supply voltage increase [36]. The insulation system of an aircraft generator can experience different electric frequencies and air pressures during a flight cycle. This makes it complicated to implement a thorough evaluation. Typically, occasional PDs will accelerate insulation aging instead of resulting in complete immediate failure, so it is mainly a life issue.

However, there are couple of factors that can increase the possibility of PD phenomenon and significantly decrease the life of insulation system. These factors include low air pressure at high altitude [37], high dv/dt pulses at the machine terminals (which are a combination of PWM pulses and reflected waves due to cable and motor terminal impedance mismatch)[38]–[39][40], and high operating temperature [41]. In the IEC 600034-27-1 standard, different types of PDs such as slot discharge, surface discharge, etc. are categorized. Based on their insulation degradation level, they are sorted and showed in a table [42]. It has been shown that one single online or offline test can't monitor the condition of the insulation system and evaluate its lifetime comprehensively [43]. Among all aforementioned offline insulation tests, offline PD and surge test can observe turn-to-turn insulation defects.

For aerospace application, PD should be taken in to account in machine design. In [44]a tool to help machine designers or coil manufacturers to consider PD in low voltage machines was introduced. Literature reviews are available in [21,27,50-73]where wire insulation materials are identified for different applications such as aerospace, wind generator and so on. Table IV provides a summary of wire insulation materials, key dimensions as well as specific test conditions. The commonly-used insulation material is polyester-imide. There has been a

lot of work done to assess the impact of PWM switching on PD. In addition, some of the papers explore the influence of temperature, altitude, humidity and mechanical vibration on PD and insulation aging.

## B. Wind Generator

In this section, different materials for wind turbine insulation systems are summarized. Insulation materials are highly dependent on availability and cost. The first insulating material from the beginning of the 19th century was natural fiber materials like cotton, silk, cellulose, etc. Insulating materials used fiber with natural resins which are extracted from plants or petroleum. The advent of materials like epoxy resins, glass fibers, mica, etc. which are extracted from inorganic substances, have very high dielectric strength compared to organic materials. Hence, insulation life can be increased.

In [45], a research on 1200 repaired electrical wind generators has been conducted. This study shows that, for the insulation system for earlier designed wind generators less than 1 MW, most of the failures happen in rotor insulation due to either electrical and mechanical failures of conductors, or the failure of banding. This is because the rotor bandings were not designed properly. In addition, contamination and not properly designed bracing for stator winding cause insulation failures. For wind generators at a power level of $1\sim2$ MW, overheating leads to insulation failure. For wind generators higher than 2MW, magnetic wedges can cause stator failures. PWM-power-converter-driven wind generators with conventional winding insulation systems suffer from high magnitudes and high frequency repetitive voltage pulses on winding insulation, which might cause PD. An aging test of turn insulation shows that for wind generator under power frequency (60 Hz)and PWM frequency (14 kHz), mica has better resistibility to PD than enamel because of its high dielectric strength to resist to PD [49]. The insulating materials for low-voltage wind turbine generators used by Von Roll is shown in Table II. Depending on the machine power rating, voltage rating, size and winding type (random-or form-wound), either slot liner or ground-wall insulation is used. This comment is applicable for a wide range of applications and not only wind generators. A good example where ground-wall insulation (typically mica-based)is used is large turbo generators. In Table III, the thermal Conductivity and dielectric Strength of few available encapsulation materials for using in electrical machines are shown. Epoxy resin is one of the main encapsulation materials that has been used for electrical machines. Also, some of these materials as well as other resins can be used in the Vacuum Pressure Impregnation (VPI)process which can help eliminate/fill potential air voids in the machine/insulation system.

Fig. 3.

Semicon coating damaged by surface PD [75]

**Table II:** Insulating materials for low-voltage wind turbine generators [8]

| Component | Insulation Material |
|---|---|
| Winding wire | Enameled with modified Polyester-imide or Polyamide-imide and enameled with Polyesterimide base/Polyamide-imide overcoat/mica tape |
| End winding tape | Intertape® 4616/17/18 Glass cloth |
| Slot insulation | Impregnated PET felt/film/felt, Nomex/PET film/Nomex or PET film/mica/PET film |
| Impregnating resin | Polyester-imide, Polyester, Polyurethane |
| Wedges/closures | Glass mat with epoxy resin, glass fabric bonded with epoxy resin |
| Finishing varnish | Isophthalic acid Alkyd resin |

**Table III:** Encapsulation materials of insulation system [5]

| Encapsulation Material | Dielectric Strength(kV/mm) | Thermal Conductivity(W/m-K) |
|---|---|---|
| E88 epoxy C89 hardener | 30.7 | 1.049 (at 23°C) 1.069 (at 50°C) |
| Aradur CW 229-3 Hardener HW-229 | 20 | 0.75 |
| Altherm XB-2710 Aradur XB-2711 | 20 | 1.5 |
| Araldite XB-2252 Aradur XB-2253 | 20 | 0.7 |
| Araldite CW-1312 Aradur HY-1300 | 15 | 1.1 |
| Arathane CW-5631 Arathane HY-5610 | 20 | 0.6 |
| Aratherm CW-2731 | - | 3.0 |
| Catalyst-11 | 15 | 1.28 |
| Epoxy-234 | 16.3 | 3.77 |
| Epoxy-1121 | 17.3 | 0.14 |
| Epoxy-1282 | 17.3 | 0.14 |
| Epoxy-1285 | 14.4–15.7 | 1–1.27 |
| Thermoset SC 320 | - | 3.2 |
| Epoxylite® 6203 [46] | 22 | 0.25 |
| Epoxylite® 8628 [47] | 23.6 | 0.25 |
| Dolphon® CC-1105 [48] | - | 0.2–0.25 |

**Table IV:** Wire insulation materials with specified test conditions from the literature

| Application or reference | Test condition | Wire insulation/size |
|---|---|---|
| Aerospace [50] | Excitation: 540 VDC | Ceramic: $D^a$= 1 mm, $T^b$= 5 µm; Mica film: D= 1 mm; Mix of organic and inorganic material: D= 1.2 mm |
| Aerospace [51] | Excitation: 60 Hz, Thermal: 660°C | Class200 and Silox magnet wire, AWG 20 |
| Aerospace [52] | - | Litz wire: Heavy polyimide, AWG 27 |
| Aircraft [53]<br>Aircraft [54] | Excitation: 500 Vdc, 5 to 15 kHz, Thermal: -55 to 180 °C<br>Excitation: 5 to 200 kHz and 20 to 100 kPa | Polyester-imide<br>D = 625 µm ± 4 µm, T = 28 µm ± 2 µm |
| Aircraft [55] | Excitation: 280 and 400 Vdc, 5 kHz sinusoidal and square voltage waveforms, altitude= 2.5, 5, 10, 20 and 30 km | Polyamide-imide |
| Wind Generator [56] | Excitation: 800, 900 and 1000 V @ 10, 100 kHz, Thermal: 120 °C | Polyester-imide |
| Wind Generator [57] | Excitation: 4.5kV @ 10 kHz, rise rate= 2000 V/µs, Thermal: -30 to120 °C, $RH^c$= 20%-80%, Vibration: 100 Hz, 0.2mm | Stator insulation thickness= 0.8 mm |
| Wind Generator [58] | Excitation: 4-6 kV@5-20kHz, Thermal: -70 to 150 °C, RH= 20%-98% | Magnetic wire: polyimide film, T= 0.5 mm Main insulation: lapped glass-mica tapes impregnated with unsaturated Polyester-imide, T= 0.8 mm |
| Traction motor [59] | Excitation: 50 Hz | Polyimide film (100HN), T= 25 µm; Polyimide film (100CR), T= 25 µm |
| [60] | Excitation:12kV, Thermal: 25 and 80 °C, RH= 30, 60 and 70% | Epoxy-mica, groundwall thickness= 3.04 mm |
| [61] | Excitation: 2 to 10 kV peak-to-peak @3kHz | Kapton HN: T= 25.4, 50.8, 76.2 and 127 µm |
| [27] | - | Polyamide-imide, D= 1.5 mm, T= 40 µm; Mica (bar), D= 2mm×5mm, T= 0.2 mm |
| [62] | Excitation: 600V square wave @ 10 kHz, Thermal: 240 °C, RH=85%, Vibration: 50 Hz, 1.5 mm | Polyester inner coating and polyamide-imide overcoat |
| [63] | Excitation:1 kV@ 0.5-2 kHz, PWM duty cycles= 0.85 | Polyamide-imide, T= 40 µm, D= 1.5 mm |
| [21] | Excitation:10 kHz, Thermal: 20 °C | Ceramic coated wire: D= 0.8 mm, T= 10 µm; PEI-PAI coated wire: D= 0.8 mm, T= 28 µm |

| | | |
|---|---|---|
| [64] | Thermal: 20-25 °C, RH= 30-40% | Polyamide-imide: D= 0.822 mm, T= 21.5, 34.5 and 41 µm<br>Inner coating polyester-imide and outer coating polyamideimide: D=0.75, T=20 µm |
| [65] | Excitation: 50/60 Hz | Polyamide-imide, D= 0.67 and 2.24 mm, T=40 µm |
| [66] | Excitation: PWM duty cycles=10, 50 and 90%, 100 and 1000 Hz, Thermal: 20 °C, 1 atm, RH= 40%, | D= 1.25 mm |
| [67] | Excitation: 500 Hz, rise time= 0.2 µs, fall time= 20 µs | Polyamide-imide, D= 1.4 mm, T= 45 µm |
| [68] | Excitation: sine, triangular and square waveforms with 10, 20 and 30 kHz | Modified Polyester, A16 gauge, T= 40 µm |
| [69] | Excitation: 50/60 Hz, Thermal: 220-260 °C | with and without nano-modified polyester glass fiber, D= 0.5 and 1 mm |
| [70] | Excitation: 50 Hz sinusoidal, 500 Hz square wave, 25 kHz surge wave | Polyamide-imide, D= 0.71 mm, T= 26.5 µm; Polyamide-imide with ceramic nanoparticles: D= 0.38 mm, T= 20 µm; polyamide-imide with unspecified nanoparticles, D= 1 mm, T= 42.5 µm |
| [71] | Excitation: 500 Hz | Polyamide-imide cellular coating, D= 1 mm, T= 0.37 µm |
| [72] | Excitation: 3kV@1kHz, rise time= 10,30,80 and 100 ns | Polyamide-imide, D= 1.5, T= 0.37 µm |
| [73] | Thermal: 25°C, RH= 40% | Polyamide-imide, D= 1.7, T= 50 µm |

a. D represents wire diameter, b. T represents wire insulation thickness, c. RH represents relative humidity


## C. Hydro Generator

There are high demands on high-power-level generators as the heart of electrical power plants. Due to the high cost of replacing outdated generators, careful monitoring and management are of importance [74]. For winding voltage level of 6 kV or higher, the probability of surface PD occurrence are increasing due to winding imperfect manufacturing, operating under higher stresses/temperatures. It creates bright white powders on the surface of stator windings. The use of PWM in adjustable speed drives makes the situation even worse [75]. Fig. 3 shows that, at the bottom of the slot, the semicon coating (a stress relief coating material)is damaged by surface PD. White powders at the bottom of the slots are created due to PDs effect as well. Recently, the outer corona protection (OCP)of high-voltage electrical machines has received lots of attentions [76]. The OCPs can even out the unavoidable surface roughness and lead to uniform electric field distribution in the insulation system [77]. The impact of anisotropic OCP material is assessed by finite element method (FEM)in [78]. The impact of the parameters of OCP materials on electric field distribution is presented. In order to identify the ideal properties for OCP materials, a swarm optimization algorithm is adopted [77].

# SECTION V. Polymer Nanocomposite

Recent advances in polymer nanocomposite materials show their ability of improving the electrical, thermal, and mechanical properties compared to unfilled polymers [79]. These improvements are associated with types, shapes, sizes, distribution of nanofillers in the base resin [80]. Basically, polymer nanocomposite is referred to as a combination of two or more materials, which have physical and chemical property differences [81]. Polymer nanocomposite can be used in various applications such as aerospace, healthcare, automotive industry, etc. [82]. Also, Polymer nanocomposites have drawn attention by researchers and industry to be used in insulation system in electrical machines. For example, epoxy resins are widely used for low and high voltage electrical machines. The thermal conductivity of epoxy resins is very low, which prevents heat dissipation. This can cause insulation degradation [83].

There are various micro- or nano- fillers such as aluminum oxide $(Al_2O_3)$ [84]–[85][86], silicon dioxide $(SiO_2)$ [87], aluminum nitride (A1N), silicon nitride $(Si_3N_4)$ [88], boron nitride (BN)[89], [90] etc. Typically, epoxy resin has very low thermal conductivity between $0.1 \sim 0.3$ W/(m.K). In contrast, the micro- or nano-fillers have relatively higher thermal conductivity compared to epoxy resin (how much higher?). These micro- or nano-fillers can be added to the epoxy impregnation resins and the thermal conductivity of epoxy impregnation resins would be improved. This improvement results in temperature reduction in stator winding. Thus, thermal conductivity and machine efficiency can be improved as well [91]. By using the insulation nanocomposites materials, improvements in the insulation lifetime, breakdown voltage, thermal conductivity are expected. Consequently, winding current density as well as specific power can be improved.

A comparative study on a specific medium-voltage induction machine with conventional insulation material and proposed nanocomposite material is presented in [92]. It has been demonstrated in a case study that, with the same geometry, by increasing the thermal conductivity of insulating material from 0.25 W/m.K to 0.7 W/m.K, the torque and current density can be boosted by 14% and 26%, respectively. In [93], two types of epoxy nanocomposite resins with either hydrophilic or hydrophobic silica have been investigated. It has been shown that the base resin with hydrophobic silica has high treeing resistance and tougher mechanical strength compared to the base resin and epoxy resin with hydrophilic silica. In [94] it was proven that the critical size of voids inside polymers for PDIV are at micron order. A novel epoxy/clay nanocomposite for motors used for ship propulsion was developed in [95]. It has been shown that the lifetime of the novel nanocomposite has been increased more than 7 times compared to a neat epoxy resin. Moreover, erosion depth and volume of nanocomposite are less than half of a neat epoxy resin, when subjected to PD. The results show that the power density of the motor has been improved by 10~15% through adopting SiO$_2$nanocomposite. Also, the insulation lifetime can be increased since SiO$_2$ acts as a barrier to obstruct breakdown channels created by PD [96]. Simulation techniques can be used to effectively predict the distribution of nanofillers as well as the mechanical strength of nanocomposite resin base on stress-strain curve (S-S curve). In order to calculate the distribution of nanofillers in resin and S-S curve, coarse-grained molecular dynamics model is utilized. It can be used for simulating new nanocomposite materials [80].

# SECTION VI. Conclusions

This paper focuses on insulation system for electrical machines. Design challenges for various applications are discussed, including aerospace, wind generators and hydrogenerators. PD is one the main factors of insulation aging and degradation and ultimately, failure. The impact of high dv/dt in PWM power converters, low air pressure, humidity and high temperature on PD has been discussed. Wire insulation materials and test conditions are summarized. Advanced polymer nanocomposites with good dielectric strength and thermal conductivities could be promising candidates for insulation system design in electrical machines. The incremental improvements of insulation materials in terms of their dielectric properties are gradually enhancing

the specific power of electrical machines. These improvements can be leveraged to deal with the well-known tradeoffbetween size/weight and insulation reliability for electrical machines especially those used in harsh environments with high temperature, low air pressure, erosion and humidity.

## References

1. S. Grubic, J. M. Aller, B. Lu, T. G. Habetler, "A survey on testing and monitoring methods for stator insulation systems of low-voltage induction machines focusing on turn insulation problems", *IEEE Trans. Ind. Electron.*, vol. 55, no. 12, pp. 4127-4136, Dec. 2008.
2. M. Leijon, M. Dahlgren, L. Walfridsson, L. Ming, A. Jaksts, "A recent development in the electrical insulation systems of generators and transformers", *IEEE Electr. Insul. Mag.*, vol. 17, no. 3, pp. 10-15, 2001.
3. G. C. Stone, I. Culbert, E. A. Boulter, H. Dhirani, Electrical insulation for rotating machines: design evaluation aging testing and repair, John Wiley & Sons, vol. 21, 2014.
4. A. Siddique, G. S. Yadava, B. Singh, "A review of stator fault monitoring techniques of induction motors", *IEEE Trans. Energy Convers.*, vol. 20, no. 1, pp. 106-114, 2005.
5. J. Faiz, H. Nejadi-Koti, Z. Valipour, "Comprehensive review on inter-turn fault indexes in permanent magnet motors", *IET Electr. Power Appl.*, vol. 11, no. 1, pp. 142-156, 2017.
6. M. R. W. Group, "Report of large motor reliability survey of industrial and commercial installations Part I", *IEEE Trans Ind. Appl.*, vol. 1, no. 4, pp. 865-872, 1985.
7. F. Wu, A. El-Refaie, "Diagnosis and remediation of single-tum short circuit in a multiphase FSCW PM machine based on T-type equivalent circuit", *Proc. 2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 3228-3235, 2018.
8. F. Wu, P. Zheng, T. M. Jahns, "Analytical modeling of interturn short circuit for multiphase fault-tolerant pm machines with fractional slot concentrated windings", *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 1994-2006, May 2017.
9. G. J. Paoletti, A. Golubev, "Partial discharge theory and technologies related to medium-voltage electrical equipment", *IEEE Trans. Ind. Appl.*, vol. 37, no. 1, pp. 90-103, Jan. 2001.
10. "IEEE 43-2013" in IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery, IEEE Press, 2013.
11. N. E. M. Association, "MG 1: Motors and Generators", *ANSINEMA MG*, pp. 1-2009, 1998.
12. "IEEE Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and above)With High Direct Voltage", *IEEE Std 95–2002 Revis. IEEE Std 95–1977*, pp. 1-56, Apr. 2002.
13. "High-voltage test techniques: partial discharge measurements", *IEC 60270*, 2015.
14. "62478: 2016 High Voltage Test Techniques-Measurement of Partial Discharges by Electromagnetic and Acoustic Methods", *BSI Lond. UK*, 2016.
15. *IEEE 1434–2014 - IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery*, [online] Available: https://standards.ieee.org/standard/1434-2014.html.
16. "IEC 60034–27-1 Rotating electrical machines - Part 27-1: Off-line partial discharge measurements on the winding insulation", *International electrotechnical Commission*, 2017.
17. "ASTM D1868–07 Standard Test Method for Detection and Measurement of Partial Discharge (Corona)Pulses in Evaluation of Insulation Systems", *West Conshohocken PA USA ASTM*.
18. "IEEE Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation", *IEEE Std 286–2000*, pp. 1-29, 2001.
19. "Guide for the Test Procedure for the Measurement of Loss Tangent on Coils and Bars for Machine Windings", *IEC Standard 60894*.
20. "IEEE Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines", *IEEE Std 522–2004 Revis. IEEE Std 522–1992*, pp. 1-18, 2004.

21. V. Iosif, D. Roger, S. Duchesne, D. Malec, "Assessment and improvements of inorganic insulation for high temperature low voltage motors", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2534-2542, Oct. 2016.

22. G. C. Montanari, P. Seri, A. Contin, "How to deal with the severity of different partial discharge sources in rotating machines: the definition of a new health index", *2018 IEEE Electrical Insulation Conference (EIC)*, pp. 469-472, 2018.

23. P. Wang, W. Zhou, Z. Zhao, A. Cavallini, "the limitation of partial discharge inception voltage tests at repetitive impulsive voltages using ultra-high frequency antenna and possible solutions", *IEEE Electrical Insulation Conference (EIC)*, pp. 192-195, 2018.

24. B. Florkowska, M. Florkowski, A. Rybak, P. Zydroń, "Comparison of PWM and SIN aging of insulating material subjected to surface discharges", *Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 44-47, 2012.

25. D. E. Moghadam, J. Speck, S. Grossmann, J. Stahl, "Parameters affecting the turn insulation lifetime and durability", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 2, pp. 516-523, Apr. 2018.

26. S. Vahid, H. Rastegar, S. H. Fathi, M. Jedari, "A comprehensive comparison between three different control strategies for four-leg active power filters", *4th International Symposium on Environmental Friendly Energies and Applications (EFEA)*, pp. 1-7, 2016.

27. T. J. A. Hammarström, "Partial discharge characteristics within motor insulatioi exposed to multi-level PWM waveforms", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 2, pp. 559-567, Apr. 2018.

28. J. Weimer, "Past present and future of aircraft electrical power systems", *39th Aerospace Sciences Meeting and Exhibit*, no. 1147, pp. 1-9, Jan 2001.

29. B. Sarlioglu, C. T. Morris, "More Electric Aircraft: Review Challenges and Opportunities for Commercial Transport Aircraft", *IEEE Trans. Transp. Electrification*, vol. 1, no. 1, pp. 54-64, Jun. 2015.

30. I. Moir, A. Seabridge, Aircraft Systems: Mechanical electrical and avionics subsystems integration, John Wiley & Sons, vol. 52, 2011.

31. M. Sinnett, "787 no-bleed systems: saving fuel and enhancing operational efficiencies", *Aero Q.*, vol. 18, pp. 6-11, 2007.

32. L. Tarisciotti, A. Costabeber, C. Linglin, A. Walker, M. Galea, "Evaluation of isolated DC/DC converter topologies for future HVDC aerospace microgrids", *IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 2238-2245, 2017.

33. G. Buticchi, S. Bozhko, M. Liserre, P. Wheeler, K. Al-Haddad, "On-board microgrids for the more electric aircraft-technology review", *IEEE Trans. Ind. Electron.*, vol. 66, no. 7, pp. 5588-5599, Jul. 2019.

34. V. Madonna, P. Giangrande, M. Galea, "Electrical power generation in aircraft: review challenges and opportunities", *IEEE Trans. Transp. Electrification*, vol. 4, no. 3, pp. 646-659, Sep. 2018.

35. "Part 18–41: Qualification and Type Tests for Type I-Electrical Insulation Systems Used in Rotating Electrical Machines Fed from Voltage Converters", *IEC International Standard 60034-18-41*, 2014.

36. "Managing Higher Voltages in Aerospace Electrical Systems", *AIR-6127 SAE Int.*, 2017.

37. A. N. Esfahani, S. Shahabi, G. Stone, B. Kordi, "Investigation of corona partial discharge characteristics under variable frequency and air pressure", *2018 IEEE Electrical Insulation Conference (EIC)*, pp. 31-34.

38. A. Cavallini, D. Fabiani, G. C. Montanari, "Power electronics and electrical insulation systems; Part 1: Phenomenology overview", *IEEE Electr. Insul. Mag.*, vol. 26, no. 3, pp. 7-15, May 2010.

39. C. Hudon, N. Amyot, T. Lebey, P. Castelan, N. Kandev, "Testing of low-voltage motor turn insulation intended for pulse-width modulated applications", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 7, no. 6, pp. 783-789, Dec. 2000.

40. "Failure mechanism of winding insulations in inverter-fed motors", *IEEE Electr. Insul. Mag.*, vol. 13, no. 6, pp. 18-23, Nov. 1997.

41. P. H. F. Morshuis, "Degradation of solid dielectrics due to internal partial discharge: some thoughts on progress made and where to go now", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 12, no. 5, pp. 905-913, Oct. 2005.

42. "Part 27: Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines", *IEC 60034*, vol. 27, 2006.

43. G. C. Stone, I. Culbert, "Prediction of stator winding remaining life from diagnostic measurements", *2010 IEEE International Symposium on Electrical Insulation*, pp. 1-4, 2010.

44. C. Philippe, M. David, L. Yvan, "Tool to Design the Primary Electrical Insulation System of Low Voltage Rotating Machines Fed by Inverters", *2018 IEEE Electrical Insulation Conference (EIC)*, pp. 8-13, 2018.

45. K. Alewine, W. Chen, "A review of electrical winding failures in wind turbine generators", *IEEE Electr. Insul. Mag.*, vol. 28, no. 4, pp. 8-13, Jul. 2012.

46. *Epoxylite®E 6203 Hi Temp*, [online] Available: https://www.eis-inc.com/medias/sys_master/h6d/h40/8835217588254.pdf.

47. *Epoxylite® E8628 Hi Temp*, [online] Available: https://www.eis-inc.com/medias/sys_master/h6d/h40/8835217588255.pdf.

48. *Dolphon® CC-1105*, [online] Available: http://www.dolphs.com/wp-content/uploads/DataSheets/CC1105HTC-ds.pdf.

49. G. Gao, W. Chen, "Design challenges of wind turbine generators", *Proc. IEEE Electrical Insulation Conference*, pp. 146-152, 2009.

50. L. Fang, I. Cotton, Z. J. Wang, R. Freer, "Insulation performance evaluation of high temperature wire candidates for aerospace electrical machine winding application", *2013 IEEE Electrical Insulation Conference (EIC)*, pp. 253-256, 2013.

51. F. Arastu, X. Yi, M. Garg, K. Haran, J. Lyding, "Magnet Wire for Venus Exploration", *AIAA Scitech 2019 Forum*, 2019.

52. A. M. El-Refaie, M. R. Shah, K. Huh, "High-power-density fault-tolerant pm generator for safety-critical applications", *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 1717-1728, May 2014.

53. N. Lahoud, J. Faucher, D. Malec, P. Maussion, "electrical aging of the insulation of low-voltage machines: model definition and test with the design of experiments", *IEEE Trans. Ind. Electron.*, vol. 60, no. 9, pp. 4147-4155, Sep. 2013.

54. D. R. Meyer, A. Cavallini, L. Lusuardi, D. Barater, G. Pietrini, A. Soldati, "Influence of impulse voltage repetition frequency on RPDIV in partial vacuum", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 3, pp. 873-882, Jun. 2018.

55. A. Cavallini, L. Versari, L. Fornasari, "Feasibility of partial discharge detection in inverter-fed actuators used in aircrafts", *2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 1250-1253, 2013.

56. P. Werynski, D. Roger, R. Corton, J. F. Bmdny, "Proposition of a new method for in-service monitoring of the aging of stator winding insulation in AC motors", *IEEE Trans. Energy Convers.*, vol. 21, no. 3, pp. 673-681, Sep. 2006.

57. X. Z. Liu, Y. G. Bai, X. M. Wang, X. X. Ding, J. J. Zhang, T. L. Zhang, K. Zhang, "Evaluation method of insulation system for wind turbine generator based on accelerated multi-factor ageing test", *2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 56-59, 2013.

58. X. Liu, T. Zhang, Y. Bai, X. Ding, Y. Wang, "Effects of accelerated repetitive impulse voltage aging on performance of model stator insulation of wind turbine generator", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 4, pp. 1506-1515, Aug. 2014.

59. M. Katz, R. J. Theis, "New high temperature polyimide insulation for partial discharge resistance in harsh environments", *IEEE Electr. Insul. Mag.*, vol. 13, no. 4, pp. 24-30, Jul. 1997.
60. L. Lin, A. Kang, J. Song, Z. Lei, Y. Zhao, C. Feng, "Influences of humidity and temperature on oil contamination discharge of HV motor stator windings", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2695-2703, Oct. 2016.
61. A. Mirza, W. Chen, H. Nguyen, Y. Cao, A. M. Bazzi, "High-voltage high-frequency testing for medium-voltage motor insulation degradation", *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 2444-2447, 2018.
62. S. J. Williamson, R. Wrobel, J. Yon, J. D. Booker, P. H. Mellor, "Investigation of equivalent stator-winding thermal resistance during insulation system ageing", *2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines Power Electronics and Drives (SDEMPED)*, pp. 550-556, 2017.
63. M. Florkowski, P. Blaszczyk, P. Klimczak, "Partial discharges in twisted-pair magnet wires subject to multilevel PWM pulses", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 4, pp. 2203-2210, 2017.
64. N. Hayakawa, Y. Daicho, T. Kaji, H. Kojima, "Estimation of partial discharge inception voltage under repetitive inverter surge voltage by volume-time theory", *2018 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, pp. 550-553, 2018.
65. M. Florkowski, B. Florkowska, P. Zydron, "Partial discharges in insulating systems of low voltage electric motors fed by power electronics-twisted-pair samples evaluation", *Energies*, vol. 12, no. 5, pp. 1-19, Jan. 2019.
66. L. Benmamas, P. Teste, E. Odic, G. Krebs, T. Hamiti, "Contribution to the analysis of PWM inverter parameters influence on the partial discharge inception voltage", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 26, no. 1, pp. 146-152, Feb. 2019.
67. M. Hikita, H. Mizoguchi, T. Kubo, T. Uchimura, M. Kozako, J. Sun, A. Izumi, K. Karasawa, T. Ueno, T. Hirose, S. Hiroshima, "Influence of electromagnetic sensor location on repetitive partial discharge inception voltage in actual stator core of inverter fed motor", *2018 IEEE Electrical Insulation Conference (EIC)*, pp. 435-438, 2018.
68. S. Narasimha Rao, K. Elanseralathan, "Influence of switching frequency of the voltage waveforms on breakdown in twisted pairs", *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, pp. 545-548, 2016.
69. W. Brithinee, M. Winkeler, S. Tuckwell, "Impact of nanoparticles on primary and secondary motor insulation in stators", *2016 IEEE Electrical Insulation Conference (EIC)*, pp. 596-600, 2016.
70. L. Lusuardi, A. Cavallini, A. Caprara, F. Bardelli, A. Cattazzo, "The impact of test voltage waveform in determining the repetitive partial discharge inception voltage of type i turn/turn insulation used in inverter-fed induction motors", *2018 IEEE Electrical Insulation Conference (EIC)*, pp. 478-481, 2018.
71. M. Hikita, N. Yanaze, T. Uchimura, M. Kozako, K. Tomizawa, M. Ohya, "Partial discharge and breakdown characteristics of inverter-fed motor winding with micro cellular coating", *2016 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, pp. 482-485, 2016.
72. P. Wang, C. Zheng, Y. Li, Y. Lei, A. Cavallini, "The PD and endurance features of enameled wires at short repetitive impulsive voltages", *2018 IEEE Electrical Insulation Conference (EIC)*, pp. 572-576, 2018.
73. P. Wang, A. Cavallini, G. C. Montanari, "The influence of repetitive square wave voltage parameters on enameled wire endurance", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 3, pp. 1276-1284, Jun. 2014.
74. A. Jaber, P. Lazaridis, Y. Zhang, D. Upton, H. Ahmed, U. Khan, B. Saeed, P. Mather, M. F. Q. Vieira, R. Atkinson, M. Judd, I. A. Glover, "Comparison of contact measurement and free-space radiation measurement of partial discharge signals", *2015 21st International Conference on Automation and Computing (ICAC)*, pp. 1-4, 2015.

75. G. C. Stone, H. Sedding, "Detection of stator winding stress relief coating deterioration in conventional and inverter fed motors and generators", *2016 International Conference on Condition Monitoring and Diagnosis (CMD)*, pp. 270-273, 2016.
76. A. Litinsky, G. Schmidt, F. Pohlmann, H. Hirsch, "Ageing of corona protection material on rotating machines", *2017 IEEE Electrical Insulation Conference (EIC)*, pp. 356-359, 2017.

77. A. Staubach, G. Schmidt, F. Pohlmann, H. Hirsch, "Investigation of ideal anisotropic material properties for outer corona protection systems in large rotating machines", *2018 IEEE Electrical Insulation Conference (EIC)*, pp. 365-368, 2018.
78. A. Staubach, H. Hirsch, G. Schmidt, F. Pohlmann, "Examination of anisotropic material characteristics in Outer Corona Protection (OCP)systems in large rotating machines", *2016 IEEE International Conference on Dielectrics (ICD)*, vol. 1, pp. 422-425, 2016.
79. T. Tanaka, "Polymer nanocomposites as HV insulators: Superiority and expectation", *2007 Proceedings of the XVth international symposium on high voltage engineering. (ISH)*, pp. 16-19, 2007.
80. K. Kobayashi, A. Ohtake, A. Sano, T. Kato, "Multi-scale simulation techniques of mechanical strength of nanocomposite insulating materials", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 6, pp. 3500-3504, Dec. 2017.
81. T. Tomášková, P. Trnka, "The influence of thermal properties of aluminum oxide on electrical insulating materials", *Proc. the 2014 15th International Scientific Conference on Electric Power Engineering (EPE)*, pp. 421-425, 2014.
82. Y.-W. Mai, Z.-Z. Yu, Polymer nanocomposites, Woodhead publishing, 2006.
83. J. Samek, C. Ondrusek, J. Kurfurst, "A review of thermal conductivity of epoxy composites filled with Al 2 O 3 or SiO 2", *2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*, 2017.
84. X. Lyu, H. Wang, "Dielectric properties of epoxy-A12O3 nanocomposites", *2016 IEEE International Conference on Dielectrics (ICD)*, vol. 2, pp. 1081-1084, 2016.
85. S. Zhao, H. Hillborg, E. Mårtensson, G. Paulsson, "Evaluation of epoxy nanocomposites for electrical insulation systems", *2011 Electrical Insulation Conference (EIC).*, pp. 489-492, 2011.
86. Q. Wang, G. Chen, A. S. Alghamdi, "Influence of nanofillers on electrical characteristics of epoxy resins insulation", *2010 10th IEEE International Conference on Solid Dielectrics*, pp. 1-4, 2010.
87. S. Sprenger, "Epoxy resin composites with surface-modified silicon dioxide nanoparticles: A review", *J. Appl. Polym. Sci.*, vol. 130, no. 3, pp. 1421-1428, 2013.
88. I. L. Hosier, M. Praeger, A. S. Vaughan, S. G. Swingler, "The effects of water on the dielectric properties of silicon-based nanocomposites", *IEEE Trans. Nanotechnol.*, vol. 16, no. 2, pp. 169-179, Mar. 2017.
89. M. Reading, A. S. Vaughan, P. L. Lewin, "An investigation into improving the breakdown strength and thermal conduction of an epoxy system using boron nitride", *2011 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 636-639, 2011.
90. W. Zhou, J. Zuo, X. Zhang, A. Zhou, "Thermal electrical and mechanical properties of hexagonal boron nitride-reinforced epoxy composites", *J. Compos. Mater.*, vol. 48, no. 20, pp. 2517-2526, 2014.
91. J. Samek, C. Ondrusek, J. Kurfurst, "A review of thermal conductivity of epoxy composites filled with AIN or BN", *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/ICPS Europe)*, pp. 1-6, 2017.
92. Y. Liu, H. Nguyen, A. M. Bazzi, Y. Cao, "Torque enhancement and re-rating of medium-voltage induction machines using nanostructured stator winding insulation", *2017 IEEE Electric Ship Technologies Symposium (ESTS)*, pp. 232-237, 2017.

93. H. Matsumoto, A. Ohtake, A. Sano, "Comparison studies on mechanical and electrical properties of epoxy/silica nanocomposites using Hydrophilic and Hydrophobic Silica", *IEEJ Trans. Fundam. Mater.*, vol. 133, no. 2, pp. 57-63, 2013.

94. L. Zhao, J. C. Su, Y. F. Pan, R. Li, L. Zheng, Y. Zhang, X. L. Wu, P. C. Gao, "Calculation on heating effect due to void discharge in polymers in cumulative breakdown process", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 5, pp. 3113-3121, Oct. 2017.

95. H. Nguyen, A. Y. Mirza, W. Chen, J. Ronzello, S. Nasreen, J. Chapman, A. Bazzi, Y. Cao, "Discharge resistant epoxy/clay nanocomposite for high torque density electrical propulsion", *2018 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, pp. 171-174, 2018.

96. T. Hildinger, J. R. Weidner, "Progress in development of a nanocomposite stator winding insulation system for improved generator performance", *2017 IEEE Electrical Insulation Conference (EIC)*, pp. 139-142, 2017.