High Voltage

Review Article

High power density technologies for large generators and motors for marine applications with focus on electrical insulation challenges

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Abstract: High power density generators and motors are envisaged in modern all-electric ships where electrical power for both propulsion and service loads is provided through a common electrical platform known as an integrated power system. Three recent high-power density technologies for generators and motors proposed for marine applications are reviewed, and the author focuses on their electrical insulation challenges. These technologies are high-frequency (high-speed) generators (200–400 Hz), superconducting generators, and novel insulation materials and systems. For high-speed generators, high loss in magnetic materials may shorten its insulation life. Thus, these generators should be designed to be cooled by water instead of air. For superconducting generators, the most significant concern is the integrity of the insulation system over the large thermal excursion whenever the system is cycled between room temperature and operating temperature. In novel insulation materials and systems section: (i) using mica paper tapes containing boron nitride filler in the binding resin of the glass backing insulation, developed by Toshiba and Von Roll, resulted in a 15% increase in the MVA of generators for the same slot dimensions and operating temperatures, (ii) GE developed an enhanced polyethylene glycol terephthalate-mica tape having superior voltage-endurance characteristics, (iii) Isovolta has introduced a mica paper tape using a flat glass fibre backing material, called Powerfab, rather than the more common woven structure, leading to a 15% reduced mica tape, and (iv) adding novel nanocomposites as fillers to ground wall insulation, introduced by Siemens, is a promising technique towards more high power density designs. Furthermore, accelerated aging of insulation systems especially those in electrical rotating machines exposed to voltage pluses with high slew rates up to hundreds of kV/μs and high-repetition rates ranging from hundreds of kHz to MHz is discussed. These voltage pulses are generated by wide bandgap-based converters envisaged in the medium voltage DC architecture for future U.S. naval ships.

1 Introduction

Maximising revenue for commercial ships and more space to carry mission-critical components for military ships are motivations for higher power density designs for electrification components. In this regard, the power generation subsystems must often be packaged in a limited space and within strict weight limits. At the same time, the demand for ships is increasing and anticipating as much as 100 MW for moderate-sized ships where its most substantial part is for propulsion and then for heating and cooling; navigation and communication; and in warships for weapon systems.

It should be noted that although the peak load in modern naval ships may approach 100 MW, a ship at anchor may require <5 MW [1]. Therefore, it would not be efficient to provide power for both of these situations with a single prime mover. Therefore, multiple generators are used for fuel economy as well as reliability concerns. Examples of existing large ships having electrical propulsion are (i) Queen Elizabeth 2 with nine 10.5 MW, 10 kV diesel generators feeding two 44 MW propulsion synchronous salient pole type motors where <7% of generated power is used for ship's service and its dominant sector is utilised for propulsion [2], (ii) Icebreaker ‘Shirase’ with four 7.4 MW, 6.6 kV generators provide the power required for four 5.516 MW induction motors (two per propeller shaft) [3, 4], and (iii) DDG-1000 U.S.S. Zumwalt is the U.S. Navy's biggest and most expensive destroyer ever built with two 35.4 MW generators to supply power to two advanced induction motors driving two propellers [5].

Chronologically the first electrical power system was installed on the USS Trenton in 1883 [6]. The system consisted of a single dynamo supplied power to 247 lamps under 110 V_{dc}. It was during World War I that 230 V, 60 Hz power systems were introduced into naval vessels.

Traditionally U.S. ships have had mechanical propulsion, and the electric generation and loads on ships were small only for meeting the requirements of the hotel functionality of ships. In the late 1990s, the U.S. Navy began pursuing additional research and development activities related to all-electric ship or integrated power system (IPS) by combining propulsion and service loads into a single supply.

According to the U.S. next-generation IPS roadmap [7], medium voltage power generation in 4–13.8 kV range operating at 60 Hz is required now while high-frequency (200–400 Hz) power in the same voltage range will be needed shortly in a 10–15-year timeframe and medium voltage DC (MVDC) power is a goal to be achieved ten years beyond that.

Conventional generators cannot provide the multimegawatt levels of power without paying a significant penalty in size, weight, and efficiency. Recent technical accomplishments and promising solutions to develop high-power density generators and motors for marine applications are reviewed, and our focus is on their electrical insulation challenges. These technologies are (i) high-frequency (high-speed) generators (200–400 Hz), (ii) superconducting generators, and (iii) novel insulation materials and systems. Moreover, electrical insulation challenges when using wide bandgap (WBG)-based converters are evaluated.

2 High-speed generators

Gas turbines as prime movers have the characteristic shown in Fig. 1, where the output speed varies with power level [8]. The power ratings of gas turbines for electric ships range between 1 and 40 MW, and as seen in Fig. 1 this is a portion of the curve in which the turbine speed changes rapidly with a change in power. In order to address this issue, the conventional approach has been using a

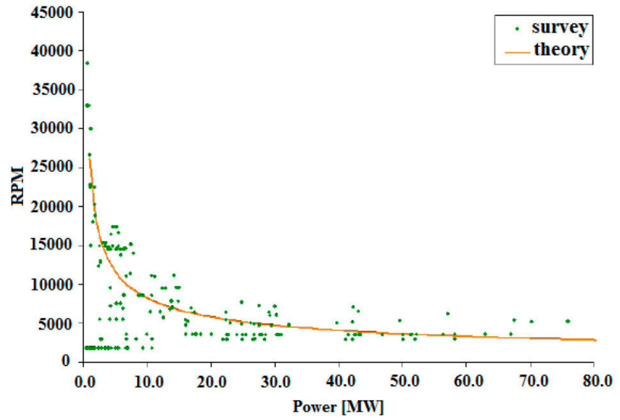

Fig. 1 *Solid line is the theoretical speed-power curve for gas turbines, and the points are manufacturers' published specifications [8]*

Table 1 Design specifications of high-speed and traditional generators [10]

	233.3 Hz air cooled	233.3 Hz water cooled	60 Hz air cooled
prime mover	LM1600	LM1600	LM1600
generator rating, MVA	11.1	11.1	10.0
generator power, MW	10	10	8
line-to-line voltage, kV	6.9	6.9	4.16
number of rotor poles	4	4	2
speed, rpm	7000	7000	3600
insulation type	F	F	F
overall machine width, m	3.75	1.55	3.68
overall machine length, m	3.47	2.21	4.06
overall machine height, m	3.02	1.68	2.79
machine weight, tons	23.00	9.75	57.15

gearbox on the output of gas turbines to reach an appropriate speed for generators to produce electricity at a conventional power frequency, i.e. 50/60 Hz. However, systems using gas turbines as prime movers can achieve significant size reduction and improve efficiency by directly coupling the gas turbines to the generators, i.e. without using gearboxes. This topology is more advantageous for low- to medium-power levels (1–15 MW) because gas turbine speed is higher at lower power, as seen in Fig. 1.

In this regard, the dynamic behaviour of a 240 Hz power system was studied in the MATLAB Simulink environment [9]. This system was proposed to reduce the size of the power generation system in future ships.

Since losses in magnetic materials scale as the square of the electrical frequency, then without aggressive cooling, the temperature is higher, and the insulation life is shortened in high-speed generators [1].

A high speed (7000 rpm), four poles, high frequency (233.3 Hz), mid-level generator (10 MW, 6.9 kV) was designed and manufactured by Curtiss-Wright Electro-Mechanical Corporation [10]. In order to meet the typical lifetime requirements of a marine electric generator and take into account the higher operating frequency, the generator was designed to be cooled by water instead of air. It was coupled directly to the output of a GE LM1600 Gas Turbine. Table 1 provides the details of the designed high-speed generator cooled by air or water compared to an existing similarly rated 60 Hz generator.

As seen in Table 1, significant size and weight reductions can be offered by the water-cooled high-frequency design. Using water cooling as well as thicker insulation was also mentioned in [11, 12]. To the best of our knowledge, no basic research about the influence of losses in magnetic materials on the insulation life in high-speed generators has been reported. However, for more high-power density designs, water cooling may not work alone and further research is needed to address the thermal issue on the insulation life in high-speed generators. In this regard, three methods mentioned in Section 4 to reduce the thermal impedance of the ground wall in combination with water cooling can be studied.

3 Superconducting motors and generators

While superconducting generators have strongly been considered for naval applications, superconducting motors for propulsion are under active development.

In this regard, two subscale superconducting propulsion motors have been built [13–15]. One motor is a prototype 5 MW, 4.2 kV, 230 rpm, six-pole, 11.5 Hz synchronous type using high-temperature superconductor (HTS) coils in the rotor [14]. The rotor includes a field winding operating at 32K. The stator employs liquid-cooled coils made from Litz wire. Another one is a 3.7 MW, 500 rpm DC homopolar type with stationary NbTi LTS coils that operates at 4.7 K [15]. Size and weight reductions of >50% in the world's first highest HTS-AC ship propulsion motor rated at 36.5 MW, 120 rmp [16] saves close to $1 million annually on fuel [17]. Another manufactured synchronous generator with HTS field winding rated at 4 MVA, 6.6 kV, 3600 rpm operating at 60 Hz was reported in [18, 19]. The question here is whether insulating systems can work at cryogenic temperatures. Fortunately, many electrical insulating materials work better at lower temperatures. However, the concern is the integrity of insulation systems over large thermal excursions whenever the system is cycled between room temperature and operating temperature [1]. To the best of our knowledge, no research has been reported about this issue and further research is needed to address this concern.

Moreover, the world's first highest LTS DC homopolar propulsion motor at rated 36.5 MW, 120 rpm successfully passed the related tests [20]. Since homopolar machines have characteristics of low voltage and high current (for the 36.5 MW, 120 rpm motor: $I = 54$ kA, $V = 716$ V_{dc} [21]), the design of their electrical insulation systems was not a challenging task.

4 Novel insulation materials and systems

It is well known that the life of a stator winding is limited most often by its electrical insulation and the end-of-life failure causes of stator windings are mainly associated with their insulation failures as reported by CIGRE study committee SC11, EG11.02 where among 69 hydro generators failure incidents, insulation damage was main cause (56%). Other causes were mechanical damage (24%), thermal damage (17%), and bearing damage (3%) [22]. The causes of the insulation damage were also subdivided into aging (31%), contamination of winding (25%), internal partial discharges (PDs) (22%), loosening of bars in the slot or the overhang (10%), thermal cycling or overloading (7%), defective corona protection (3%), and overvoltage (2%) [22].

Therefore, winding insulation has been the main challenge to electrical machine designers for several decades, e.g. the ground wall insulation thickness has reduced from 15.1 mm in 1911 to only 2.5 mm 100 years later as shown in Fig. 2 [23], leading an increase in the power output per kilogram for motors and generators for the same operating voltage as shown in Fig. 3 [24, 25]. The trend mentioned above is desirable for naval applications where high-power density generators are needed.

The three main components in a stator are copper conductors, stator core, and insulation. Stator insulation system components shown in Fig. 4 are strand insulation, turn insulation, and ground wall insulation. Fig. 4 shows a form-wound multi-turn coils stator where it has typically two coils per slot. Ground wall insulation failure usually triggers a ground fault relay, and therefore stator ground wall insulation is critical to the proper operation of a motor or generator. Thus, our focus in this study is on stator ground wall insulation.

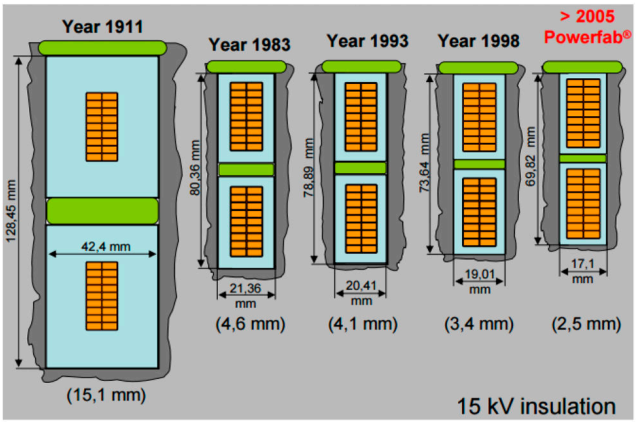

Fig. 2 *Historical reduction of stator groundwall thickness [23]*

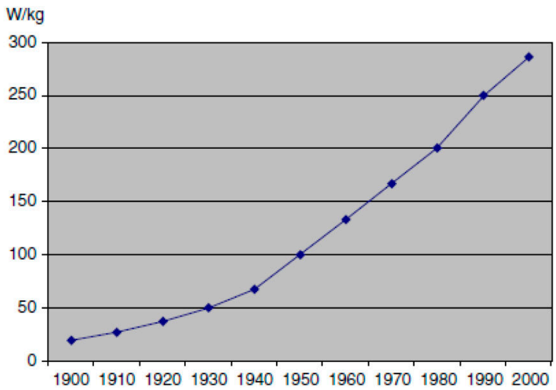

Fig. 3 *Evolution of power output per kilogram for rotating machines [24, 25]*

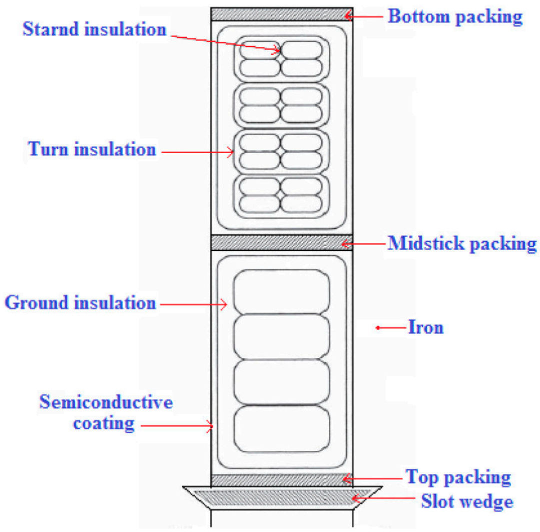

Fig. 4 *Cross-section of slots in form-wound multi-turn coils*

In this section, we review recent technologies and promising solutions for insulation materials and systems for ground wall insulation, which can lead to significant size and weight reductions.

In 2011, GE developed enhanced polyethylene glycol terephthalate (PET)-mica tape through using PET films as backing material for mica paper, processed in an optimised vacuum pressure impregnation (VPI) treatment [26]. PET is a linear, thermoplastic polymer which exhibits a high melting point (265°C) and excellent stability. The enhanced PET-mica system has superior voltage-endurance (VE) characteristics compared to traditional insulation systems with and without PET-mica, as shown in Fig. 5.

Reducing the thermal impedance of the ground wall is a powerful way to reduce the stator winding temperature (or increase the power rating) of the stator in indirect-cooled stator windings. There are three ways to reduce the thermal impedance [27]

(i) Reduce the ground wall thickness.
(ii) Use a ground wall with an inherently higher thermal conductivity.
(iii) Use a thinner ground wall based on what is called a 'flat glass' mica paper tape through increasing mica content.

For method 1, reducing ground wall thickness to improve thermal conductivity will increase the electric stress and the rate of electric aging regarding some small voids present in the ground wall insulation leading to PD.

For method 2, the polymer resin binders have the lowest thermal conductivity in the ground wall insulation system. In order to address this issue, Toshiba and Von Roll have introduced a new insulation system using mica paper tapes containing boron nitride filler in the binding resin of the glass backing. The resulting increase in thermal conductivity allows Toshiba to increase the MVA of its generators by as much as 15%, for the same slot dimensions and operating temperatures as conventional designs [28]. This newly developed high thermal conducting (HTC) insulation can improve the thermal conductivity of insulation while it maintains electrical stresses and coil temperatures at the same level as conventional insulation generators [28].

Fig. 6 shows temperature measurements conducted on a 350 MVA class hydrogen-cooled turbine generator with HTC insulation coils described in [28]. In comparison with a conventional insulation generator of the same frame size, the HTC insulation generator shows a remarkable reduction on both coil surface temperature and conductor temperature. Furthermore, the temperature difference between the internal and the external surfaces of HTC insulation was found to be smaller, as shown in Fig. 6 [28].

For method 3, Isovolta has introduced a mica paper tape using a flat glass fibre backing material rather than the more common woven structure used in high-voltage stator bars [29]. This glass cloth called Powerfab is thinner than the glass cloth currently used, although the total weight is the same. The reason for this comes out of a new production method for glass cloths where the glass filaments are not twisted, but they are just laid in parallel, as shown in Fig. 7. This method leads to a 15% reduced mica tape, as shown in Fig. 8. The resulting backing tape is thinner and allows for an increased amount of mica for the same overall tape thickness. The higher percentage of mica in the tape increases thermal conductivity and PD resistance. Experience with such tapes has been reported by Siemens [23].

The reduction in the ground wall insulation thickness increases the electric stress in the insulation and the risk of deterioration due to PD in voids. The reductions in ground wall thickness over the past decade have been made possible due to

- Better materials and processing to reduce the size and number of ground wall voids.
- Better taping machines are available that apply consistent tape tension and consistent overlap of tape layers.
- Increasing the percentage of mica within the ground wall to increase PD resistance.
- Development of other materials that increase the percentage of PD resistant materials in the ground wall to improve its voltage endurance.

One way to increase the amount of mica in the ground wall other than the use of flat glass is to replace the glass cloth backings in mica paper tapes with thermoplastic films with a one-quarter thickness of the glass cloth (down to about 0.0065 mm). In this regard, PET films have been widely used [26]. Newer polyester films made by polyethylene naphthalate having better thermal stability are replacing PET films. For example, the DuPont product named Kaladex™ has a glass transition temperature that is 42°C higher than PET film. The film has a higher modulus, which gives it a 25% greater stiffness. It also has an average electric strength of 25% higher than PET film.

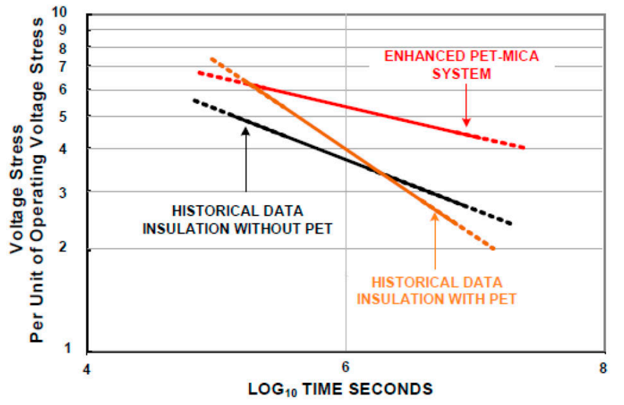

Fig. 5 *VE life curve for the enhanced PET-mica system compared to other systems [26]*

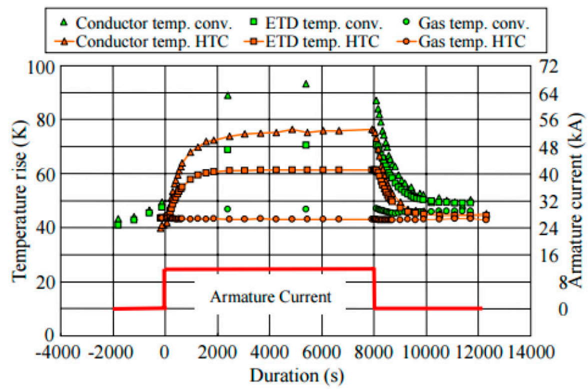

Fig. 6 *Temperature tests at rated stator current [28]*

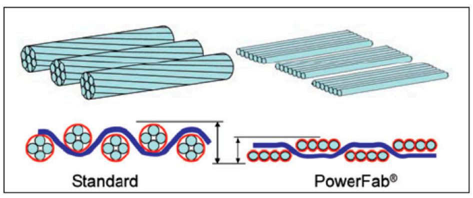

Fig. 7 *Glass filaments in the standard method and Powerfab's method [29]*

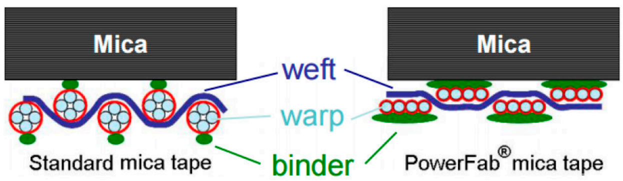

Fig. 8 *Thickness of the standard tape and Powerfab's tape [29]*

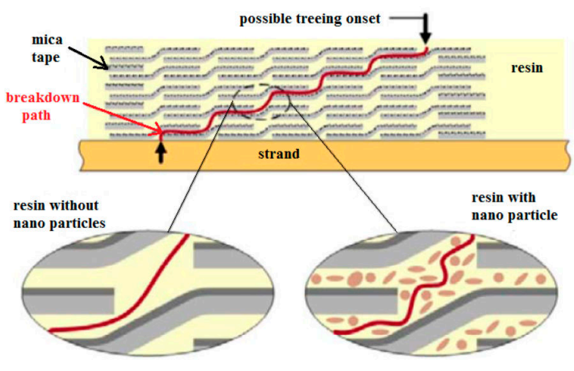

Fig. 9 *Prolongation of the treeing propagation path in the groundwall insulation when adding nanoparticles to the resin [31]*

As discussed, the film-backed mica paper tapes yield a higher percentage of mica in the insulation and thus yield better thermal conductivity in addition to enhanced PD resistance. Films may also be filled with thermally conductive and partial-discharge-resistant fillers. Metallic oxides, such as submicron aluminium oxide, given good results in films and combination with epoxy resin and mica paper [30], may lead to improved ground wall insulation.

It is well known that the use of erosion-resistant nanoparticulate fillers such as silica and alumina in epoxy resin prevents erosion of the polymeric matrix exposing to PD and leads to significant improvements in the insulation regarding the electrical longevity. The later can be explained due to the prolongation of the treeing propagation path in resin with nanoparticle compared to the case without nanoparticle, as shown in Fig. 9 [31]. The first merit can be explained as follows. As the duration of erosion increases, a firmly adhering, sheet-like layer is gradually formed on the surface of the test element consisting of exposed nanoparticulate filler. Therefore, the surface is passivated, and the polymer beneath the passivation coat is effectively protected from further erosion under PD exposure [32]. We reported preliminary results of the development of a novel nanocomposite insulation based on 2D-nanostructured platelet fillers in [33].

To date, only one preliminary application of nanomaterials to real ground wall insulation in form-wound coils has been reported where Siemens has developed a VPI epoxy resin filled with treated silicon dioxide nanoparticles that are used to impregnate mica paper tapes [31, 32]. It was also reported that the use of adhesion promoters in the impregnating resin inhibits erosion. Adhesion promoters are attached chemically to the surface of nanoparticles, leading to an improved attachment of the particles to the polymer matrix and an improved erosion resistance [33]. Three organosilicon compounds including 3-glycidyloxy-propyltrimethoxysilane, octamethyltrisiloxane, and polyhedral oligomeric silsesquioxanes were examined in [32]. Fig. 10 shows the lifetime curves for the unfilled and nanoparticulate-filled high-voltage insulating system (Micalastic and Micalastic with nanoparticles with 10wt% (diameter about 20 nm) + organic silane (3-glycidyloxy-propyltrimethoxysilane with 5wt%)) [32].

Micalastic has a fraction of about 50wt% for mica and 50wt% for resin. The stated fraction of nanoparticles reduces the fraction of resin. The fraction of mica remains constant in each case. The test results for two other organosilicon compounds were also reported in [32] where improvements in the lifetime in the factor of 20–30 were achieved.

To the best of our knowledge, none of the novel insulation materials and systems, discussed in this section to achieve high-power density designs for rotating machines, has been proposed and studied for marine applications. It is the author's point of view that these materials and systems can be envisaged for marine applications. In this regard, specific aspects and conditions discussed in Section 5 for marine applications should also be taken into account when developing the novel insulation materials and systems discussed in this section. This is also the case for high-speed generators and superconducting motors discussed in Sections 2 and 3, respectively.

5 Other electrical insulation challenges in a marine application

The electrical, mechanical, and thermal environment on a ship is far from a land-based environment. That causes the following challenges for insulation system designers.

- The land-based power grid is an antenna for lightning pulses, and critical components are tested to ensure that they can withstand standard lightning impulse. Being in an imperfect Faraday cage, ship power systems are expected to have different lightning exposure than land-based systems.
- Land-based components are also typically tested for immunity to standard switching surges. The ship has a tightly coupled power system, so a very different type of switching surge is expected.

- The demand for increased power and energy density for ships encourages the use of high speed or superconducting solutions for rotating machines. That leads to mechanical and thermal stresses that are not common in land-based systems.
- Different system impedances lead to different relationships between voltage and current harmonics in land-based and shipboard systems.
- MIL-E-917E [34] is the only military standard dealing with electrical insulation for electrical equipment. However, MIL-E-917E has not been revised since 1993, and it only covers operating voltages up to 5 kV at 60 Hz applications as well as it does not offer specifics on the evaluation of complete insulation systems for rotating electrical machines.
- The effects of the marine environment, such as large temperature variations, high humidity, and heavy salt mist on the stator insulation system of offshore wind turbine generators were investigated [35–40]. This situation is similar to that for marine applications. An accelerated multi-stress test, including electrical, thermal, salt mist, and humidity stresses was designed and used to study the aging of specimens simulating insulation systems used in wind turbine generator (WGT). The test voltage was a bipolar repetitive impulse voltage at only one frequency (15 kHz) and one slew rate (12.5 kV/μs). Also, one percentage of humidity (93%) and one concentration of salt mist was used for the tests [35–40]. The variable parameter was the number of cycles of the test. Their test results show that with an increasing number of cycles, the polarisation index and PD inception voltage decrease, while the dissipation factor increases. However, the level of degradation is not significant, and all mentioned dielectric properties show partial recovery after drying, meaning that for the test cycle designed in [35–40] environmental stress does not cause significant degradation of the insulating material. However, some cruise ship operators have already experienced premature failures in high-voltage rotating machinery, which would normally be expected to have a working life in the order of 20 years. However, they are failing after as little as only five years [41].
- As mentioned, the MVDC architecture has been targeted for future U.S. naval ships where all generators, loads, and storages are connected to a DC bus via power electronics converters. In this regard, using wind bandgap (WBG)-based converters has been targeted instead of Si-based converters. Since WBG power modules made from materials such as SiC and GaN (and soon Ga_2O_3 and diamond), which can tolerate higher voltages and currents than Si-based modules, are the most promising solution to reducing the size and weight of power electronics systems. One of the merits of WBG devices is that their slew rates and switching frequencies are much higher than Si-based devices. However, from the insulation side, frequency and slew rate are two of the most critical factors of a voltage pulse, influencing the level of degradation of the insulation systems that are exposed to such voltage pulses. The shorter the rise time, the larger the PD magnitude; thus, the shorter the lifetime [42–49] as shown in Fig. 11. Furthermore, it can be seen in Fig. 11 that lifetime decreases with increasing frequency.

Thus, although WBG devices can lead to high-power density designs, their generated voltage pulses pose a severe threat to insulation systems: the risk of component failure can occur within hours or even minutes. For example, a failure time of around 50 working hours was reported for induction motors fed by a pulse width modulation inverter with a switching frequency of 10 kHz [50].

The insulation systems mentioned above are those used in different apparatuses from WBG devices and WBG-based converters that generate the fast, repetitive voltage pulses to those used in electrical motors, cable terminations, and transformers exposed to such voltages. The life of an electrical component is determined by the life of its insulation, and an electrical component failure may lead to blackouts. Also, such failures in electrical components used in electric vehicles or aircraft that can impact the safety of the passengers are unacceptable. A critical review of the accelerated insulation aging issue under fast, repetitive voltage pulses, identifying technical gaps, and future research needs, has recently been carried out [51] and with a focus on power electronics modules in [52, 53].

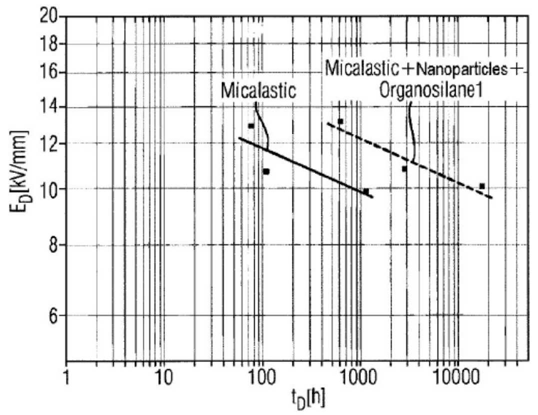

Fig. 10 *Lifetime curves for 'Micalastic', and 'Micalastic + SiO_2 with 10wt % + 3-glycidyloxy-propyltrimethoxysilane with 5wt%' [32]*

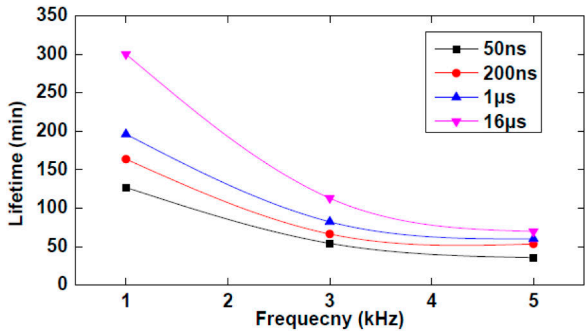

Fig. 11 *Average lifetime of single-contact point crossed enameled wire pairs as a function of frequency and rise time [44]*

Although the degradation effects of using power electronics on insulation systems have been studied, they are limited to low slew rates and low repetitions. For example, the slew rate and frequency of test voltages are limited to 70 kV/μs and 5 kHz, respectively, in [42–49]. There are no published experimental data for insulation degradation under voltage pulses with high-slew rates up to hundreds of kV/μs and high-repetition rates ranging from hundreds of kHz to MHz, which are the conditions generated and envisaged by WBG-based converters in the MVDC architecture for future U.S. naval ships.

Also, neither an in-depth (physical-based) explanation nor a model is presented for the test results [42, 49]. In this regard, theoretical-based multiphysics models can be developed to help us understand the reasons and mechanisms behind the accelerated aging issue, most of which have not been discovered yet. Such models, developed e.g. for liquid dielectrics [54–58] or gases [59–63], can be envisaged for internal PD in solid dielectrics used in rotating machines under fast, repetitive WBG-based voltage pulses. In addition to developing the theoretical-based multiphysics models described above, finite element analysis (FEA) models for internal PDs under fast, repetitive voltage pulses can be developed. Although such models are much simpler than theoretically-based multiphysics models, they may not be able to elucidate the influence of different mechanisms and phenomena. However, these models can provide an initial approximation, and their accuracy can be improved through adjusting and modifying the assumptions and factors considered for the partial breakdown in air-filled voids and generated space and surface charges. FEA models for internal PD have been developed for an applied 50 Hz sinusoidal voltage [64–68] and fast, repetitive voltage pulses in a solid dielectric [69, 70] and silicone gel [71].

Besides insulation issues in the turn/turn, phase/ground, and phase/phase sections of rotating machines under fast, repetitive voltage pulses originating from converter-fed drives, the stress grading (SG) system in a form-wound machine is another part that

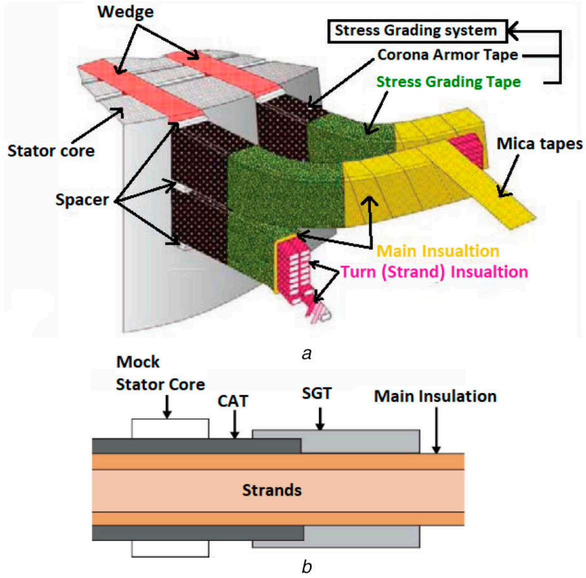

Fig. 12 *SG system*
(a) Insulation system of a slot end, ***(b)*** Cross-section of end-winding of stator

is adversely affected from such surges [72–79]. As shown in Figs. 12*a* and *b*, the SG system consists of a corona armour tape (CAT) and SG tape (SGT).

This grading system works efficiently at power (50/60 Hz) frequency to relieve the very high field, which would occur at the edge of the CAT [74]. PDs occur at the interface of the CAT and the SGT because the potential gradient becomes large in this area. Even if the SG coating is designed to keep the electric field below the surface discharge level, this capability will necessarily be accompanied by increased heat generation in the SGT. Degradation [75] and loss of resistivity and non-linearity of the SG material [76] can have increased temperature that in some cases can reach 55°C above that observed under sinusoidal 60/50 Hz frequency [77]. Consequently, not only the electric field but also the ohmic heat generation for inverter-fed motors must be controlled [78–81]. However, all these studies are limited to up to a few kV/µs and a few kHz. Studies show that both switching frequency and slew rate are critical parameters for the heat level generated in an SG system.

Some mitigation techniques are filters to decrease dv/dt at motor terminals [80, 81]; multilayer tapes; different materials, dimensions, and geometrical situations of tapes for SG systems of rotating machines. Electric stress reduction using non-linear field-dependent conductivity coatings can also be considered. Characterising non-linear field dependent conductivity (FDC) material for use in WBG power modules to address high-electric field issue within the modules has been carried out in [82–88] and can be envisaged for SG systems for rotating machines under WBG-based voltage pulses.

6 Conclusion

The study reviews electrical insulation novelties and challenges when manufacturing large generators and motors for marine applications in three categories containing high-frequency generators (200–400 Hz), superconducting generators, and novel insulation materials and systems. A water-cooled design was proposed for high-frequency generators to address the stator core loss. Although many insulation materials work better at lower temperatures, the performance of the insulation system over the large thermal excursion whenever the system is cycled between room temperature and operating temperature needs to take into account. Siemens reported improvements in the lifetime in the factor of 20–30 through developing VPI epoxy resin filled with treated silicon dioxide nanoparticles, showing nanoparticles as a promising technique for high-power density generators and motors. Using flat glass fibre backing material can lead to a 15% reduction in mica tape thickness. Developing HTC insulation for ground wall is another method to realise high-power density rotating machines. Technical gaps to address accelerated aging of insulation systems under WBG-based voltage pulses were also identified and discussed.

7 References

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