Insulation Technologies for State-of-the-Art Electrical Machines Used in Transport Electrification

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Insulation technologies for state-of-the-art electrical machines used in transport electrification

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***Abstract*—This paper aims at presenting the technologies used in the electrical insulation of rotating machines dedicated to transport electrification. An analysis of the materials used in various insulation subsystems, the evaluations required for achieving a partial discharge-free design of hairpin machines, and the impact of cooling fluids will be discussed. The result presented here show that the most critical part is the phase-to-phase insulation in the end-winding. The insulation thickness depends on the tolerances in conductor spacing. Cooling oil spayed on the end-windings can decrease the partial discharge inception voltage by about 10-15%. This factor should be considered in the design phase.**

Keywords—Transport Electrification, Electrical Machine, Electrical Insulation

I. INTRODUCTION

The electrification of transportation systems (e.g. cars, buses, trucks, aircrafts, motorcycles), presents significant challenges for electric motor designers as high power, torque densities and exceptional reliability are required to stay on the market. Over the past one or two decades, various technologies have been developed for manufacturing advanced motors designed to operate under the unique conditions required by transport electrification. These systems have reached a certain level of maturity in some sectors (EVs), while in other sectors (notably, aviation) still face hurdles in design, manufacturing, and quality control. Achieving high power density is a complex task involving several aspects, e.g., the selection of adequate bandaging of high-speed rotors, the use of high-performance permanent magnets and low losses high saturation magnetic steels and designing low-loss windings with a high slot fill factor. The insulation system is also crucial, as it ensures reliable operation under electrical and thermal stresses. This overview focuses on the insulation technologies employed in EV motors. Technologies specific to aviation are not detailed, as their maturity level has not yet reached that of electric vehicles (EVs), and companies often keep advancements in this area confidential. However, it is reasonable to assume that these developments build incrementally upon EV technologies.

II. TARGETS AND TECHNOLOGIES

Expectations for modern electrical machines used in transport electrification demand continuous power densities exceeding 7 kW/kg (42 kW/l), as well as torque densities surpassing 20 Nm/kg (50 Nm/l) [1]. To meet these requirements, the industry has shifted from the standard random wound motors (circular conductors) to the hairpin winding technology (rectangular conductors). The form wound structure of hairpin windings results in a significantly higher slot fill factor (greater than 0.7), which supports the use of thicker conductor insulation [2]. Whereas insulation thickness in random-wound machines is typically 30–50 µm, hairpin machines can accommodate insulation thicknesses exceeding 100 µm. Hence, hairpin machines can be designed with higher voltage and current ratings, if compared with random wound machines.

Another critical issue in random wound machines powered by converters is the turn-to-turn voltage, which can reach over 90% of the phase's applied jump voltage. This depends on factors such as the winding design, the inverter's rise time, and chance. The worst-case scenario for turn-to-turn voltage stress occurs when the first and last turns of a single coil are adjacent. This occurs randomly, with a probability determined by the number of turns in the coil. High turn-to-turn voltages can incept partial discharges (PDs), leading to insulation failure. Thanks to its form-wound structure, the hairpin winding limits the turn-to-turn voltage to a small fraction of the jump voltage. This feature reduces the risk of PD inception and enables the use of higher DC bus voltages while maintaining excellent reliability, even if modern drives tend to increase the risk of double pulses [3].

Currently, a common choice for DC bus voltage is 800V, with some applications reaching 1000V. Exploration is also underway for systems operating at 1200V, which appears to be the upper limit for achieving desired power and torque densities. Raising the voltage beyond 1200V would likely necessitate a bulkier stator, as the maximum magnetic induction is limited by the properties of the steel, typically ranging between 1.5 and 1.7 T [4], [5]. To reduce stator mass while maintaining performance, one would need to increase the rotor's mechanical speed. However, due to centrifugal forces, achieving rotor tip speeds of 367 m/s seems a significant challenge [6]. Considering the rated power of EV machines, mechanical stresses become extremely challenging above 20,000 RPM.

To further improve power and torque densities, industry is focusing on innovative solutions for thermal management. Oil spraying ensures a uniform distribution of cooling medium over critical components like the stator and rotor. Direct oil contact provides better thermal conductivity compared to air cooling or indirect liquid cooling methods, reducing the need for additional heat sinks or radiators, allowing for smaller and lighter motors.

Oil spraying onto the end windings of electric machines is gaining popularity as an effective cooling method. This approach requires oil to be delivered via dedicated channels or nozzles, supplied by an oil pump often integrated into the vehicle's existing lubrication system. As a result, automatic transmission fluids (ATFs) are commonly employed in this thermal management solution due to their compatibility and dual-purpose functionality.

This type of oil-cooled motor, where ATF is used for both cooling and lubrication, introduces additional challenges for the motor's electrical insulation system, as the oil becomes an integral part of the overall insulation system.

Contrarily to insulating oils, those fluids have a relatively large viscosity, and their conductivity is normally relatively high if compared with that of air (e.g. 10^{-9} S/m). As a result, the insulation resistance of a healthy insulation systems can be unexpectedly low if compared with air-cooled machines, especially at operating temperatures. Other issues can arise as chemical compatibility of the ATF with the solid insulation, and the impact of ATF on the PD inception of the winding.

ATFs dielectric properties and interaction with other insulating materials must be carefully considered to ensure reliable performance and long-term durability.

III. Thermal Challenges

The intended lifetime of electrical motors in EVs is typically 8,000-10,000 hours—equivalent to approximately 400,000 km under urban driving conditions. In urban scenarios, EVs tend to operate at relatively low temperatures (low speeds, frequent stops at traffic lights). Both requirements seem to indicate relatively easy management of thermal stress for the insulation. However, concerns arise when EVs are subjected to demanding conditions that cause prolonged spikes in operating temperature. Interestingly, the primary temperature limitation in such scenarios is not the insulation material but the risk of permanent magnet (PM) demagnetization. A common design guideline is to use PMs with a thermal class one grade below that of the insulation . Rotor temperature limitations are enforced through EV inverter controls to protect the magnets, often resulting in hot spot temperatures of 180°C depending on the cooling system's efficiency. In the slots, 200-220°C hotspots can be reached.

Dealing with turn insulation, the hot spot range (200–220°C) seems to rule out the use of conventional insulation systems, such as those with a THEIC-reinforced polyester (PET) or polyester-imide (PEI) basecoat and polyamide-imide (PAI) overcoat. While these systems might still meet certain lifetime targets, industry favors higher temperature coatings like 220°C PAI and 240°C polyimide (PI), with PAI preferred due to its lower cost and ease of processing. Indeed, recent findings have shown that the PAI-copper interface can have adhesion problems, especially if exposed to coolants as ATFs [7]. Some manufacturers are also exploring polyether-ether-ketone (PEEK), which offers several advantages: it can withstand temperatures up to 260°C, has a lower relative permittivity than PAI and PI (increasing partial discharge inception voltage, PDIV), can be extruded onto conductors without volatile organic compounds (VOCs), and is recyclable [8]. Nevertheless, PEEK is not without its drawbacks. It has poor adhesion to impregnation resins, a sharp increase in permittivity and conductivity above 160°C (which contributes to the reduction of PDIV), and a tendency to soften under overload conditions.

One point that could be interesting to explore in the future is whether the use of high temperature materials as PI and PEEK can be considered an overdesign. As mentioned above, most EVs, if designed correctly, do operate at moderate temperatures during a large fraction of time. Thermosetting materials are well suited to operate at overtemperatures for moderate amounts of type (as an example, some machines insulated with PI can be exposed to temperatures up to 400°C for brief amounts of time). The same is not true for PEEK, which tend to soften and could allow the conductors to move under electrodynamic forces. Investigating whether a PEI basecoat with a PAI overcoat could suffice, despite its lower thermal performance, may provide a cost-effective alternative.

IV. Electrical Challenges

The most critical phenomenon in EV motors is partial discharges (PD). When using wide-bandgap inverters with switching frequencies above 20 kHz, PD inception can lead to dielectric failure, as the endurance of insulation systems under PD conditions is often negligible once the Partial Discharge Inception Voltage (PDIV) falls below the applied voltage stress. Before delving deeper, it is useful to evaluate typical voltage stress levels in an EV to identify which insulation systems are most critical.

Phase-to-ground insulation is the least critical insulation because it is manufactured with thick liners to separate the conductor insulation from the stator laminated core preventing abrasion. To be able to insert the liners in the slot, liners with thickness in the range 200-300 μm are used. Traditional liners, often made from aramid-polyimide-aramid composites, are effective but reduce the slot fill factor and thermal exchange properties due to their thickness. Alternatives, such as aramid-polyether sulfone-aramid liners, have also been proposed. Recently, an innovative approach involves injecting epoxy resin loaded with micrometric ceramics fillers directly into the slot. This technique has been used extensively in power electronics packaging and offers high endurance to electrical stress while enhancing thermal conductivity to 4–5 $W \cdot K^{-1} \cdot m^{-1}$ compared to the typical 0.1–0.2 $W \cdot K^{-1} \cdot m^{-1}$ of conventional liners [7]. While promising from a thermal point of view, the long-term mechanical and thermal performance of this solution remains to be fully validated.

On the other hand, PD inception is more critical in phase to phase and turn to turn insulations, due to typically thinner insulation layers and tighter tolerances. These areas are more susceptible to electrical stress, making effective insulation design critical for ensuring long-term motor reliability and preventing premature failures.

Corona-resistant (CR) enamels have been studied for use in high-temperature applications. With sufficiently durable materials, it might be possible to design machines that operate above PDIV, at least during part of their lifetime. Depending on the nanofiller content and functionalization, CR enamels can be designed to pursue different objectives: (a) reduction of PDIV and a "moderate" increase of endurance to PD, or (b) larger increase of the endurance to PD at the expenses of a lower PDIV. The weight percentage of nanofillers and their surface functionalization define which target is pursued. Being far easier to achieve from a technological point of view, commercial CR enamels tend to pursue target (b) using larger amounts of non-functionalized nanofillers, [9].

However, most OEMs currently prefer a PD-free design, a strategy which is consistent with long-standing industry standards [10]. This preference reflects over two decades of success in designing PD-free machines, while experience with CR insulation systems operating above PDIV has not been demonstrated, at least publicly. Unlike mica-based insulation used in medium-voltage systems, CR enamels lack comprehensive qualification frameworks based on [11] and operational data, reinforcing the preference for PD-free designs.

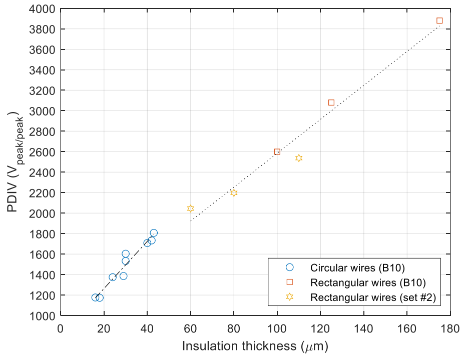

Figure 1: PDIV of round and rectangular wires having different insulation thicknesses.

V. Partial Discharge-Free Design

Consider a drive system with an 800V DC bus voltage and an overvoltage of 20% due to reflections at the motor terminals. Assuming double pulse transitions are avoided, and that the motor uses a hairpin winding with a voltage drop across the first two turns of the winding being 30% of the jump voltage in one phase (the jump voltage is defined in [10]), the peak-to-peak voltage stress on various insulation components can be estimated as described in [10].

Overvoltage:

$$U_b = 0.2 \times 800 = 160\ V_{pk} \quad (1)$$

Phase-to-phase:

$$U_{P-P} = 2 \times (800 + 160) = 1920\ V_{pk-pk} \quad (2)$$

Phase-to-ground:

$$U_{P-G} = 2 \times \left(\frac{800}{2} + 160\right) = 1120\ V_{pk-pk} \quad (3)$$

Turn-to-turn:

$$U_{T-T} = 0.3 \times 2 \times \frac{2}{3} \times \left(\frac{800}{2} + 160\right) = 224\ V_{pk-pk} \quad (4)$$

From these calculations, it becomes evident that turn-to-turn insulation is not a significant concern if the layout of the turns follows a sequential distribution and if the insulation thickness is chosen to meet phase-to-phase and phase-to-ground requirements. Figure 1 illustrates the PDIV of various insulated conductors, both circular and rectangular. The data reported in Fig. 1 can be compared with the intended PDIV of the insulation and can thus be used as a reference during the design phase.

Looking at the phase-to-phase insulation, one should consider that, to minimize electrical stress, machine designers generally adopt full pitch windings to avoid placing conductors of different phases in the same slot. Otherwise, thick liners are used to separate the phases. However, in end-windings, conductors of different phases can be positioned close to each other, separated by an air gap of a few tens of micrometers (typically ≥100 µm).

Figures 2 and 3 compare the PDIV of polyamide-imide (PAI) and corona-resistant polyamide-imide (CR-PAI) enameled rectangular conductors with thicknesses of 80 µm and 110 µm, separated by spacers at predefined distances. Results were obtained both at room temperature and 180°C [7] using AC voltage waveforms.

CR-PAI tends to exhibit slightly lower PDIV. It is suspected that this behavior is associated with the use of large weight fractions of ceramic nanofillers which increases the enamel permittivity. As mentioned above, this solution is the simplest one from a technological point of view as there is no need for nanoparticle functionalization and dispersion is not a concern [9].

Inspecting Figs. 2 and 3, it can be concluded that an insulation thickness of 80 µm is barely sufficient for a DC bus voltage of 800V, while 110 µm exceeds the requirements for 800V systems and is suitable for voltages up to 1000V if gaps are larger than 150 µm. For voltages above 1200V, additional spacing or thicker insulation would be required. The 110 µm insulation thickness also performs adequately for phase-to-ground insulation, even under worst-case conditions, such as direct contact with a metal plane. This is seen on the black blue and red lines representing the phase-to-phase voltages in operation corresponding to DC bus voltages of 800V, 1000V and 1200, respectively V.

After confirming that 110 µm insulation is adequate for phase-to-ground and phase-to-phase insulation up to 1000V, it is useful to compare the PDIV of turn-to-turn insulation with the corresponding voltage stress.

Figure 4 presents a comparison between the PDIV of turn-to-turn insulation models (measured at 180°C using AC voltages) and estimated voltage stresses. The voltage stresses were determined using Finite Element Analysis (FEA) and dynamic simulation to model the time-domain voltage evolution within the winding, as detailed in [12]. The results show that the PDIV of the turn-to-turn insulation is significantly higher than the applied voltage stress, ensuring that PD inception in turn-to-turn insulation will not occur during the motor's operational life.

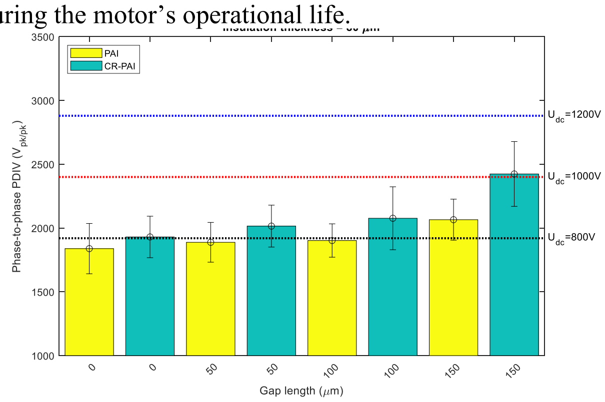

Figure 2: PDIV of PAI and CR-PAI rectangular conductors. Insulation thickness 80 µm. Results reported as a function of the gap between the conductors. Temperature 180°C. Gap length is 0 µm: a back-to-back model is used (turn-to-turn insulation test).

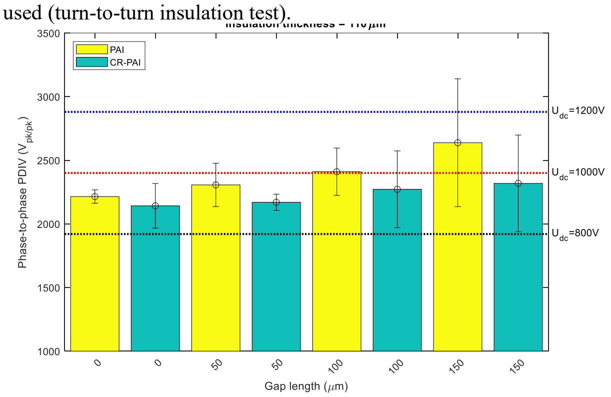

Figure 3: PDIV of PAI and CR-PAI rectangular conductors. Insulation thickness 110 µm. Results reported as a function of the gap between the conductors. Temperature 180°C. Gap length is 0 µm: a back-to-back model is used (turn-to-turn insulation test).

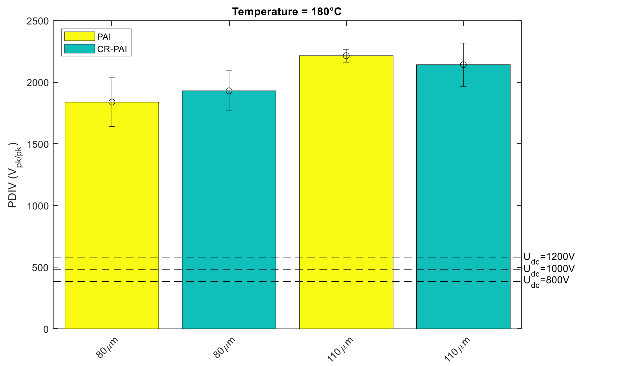

Figure 4: PDIV of PAI and CR-PAI rectangular conductors in a back-to-back configuration (turn-to-turn insulation test). Temperature 180°C.

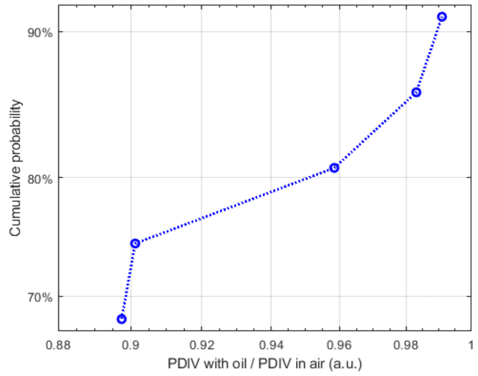

Figure 5: PDIV of rectangular conductors separated by a gap of 50 µm and sprayed with ATF. Conductor temperature 180°C. The PDIV is reported in per-unit of the average PDIV achieved without spraying the oil.

Indeed, as shown in [3], high switching frequencies combined with short interval times increase the risk of double-pulse superposition, which can result in overvoltage between the first and last turn coils in traditional interlayer transposition hairpin windings. While the partial discharge inception voltage (PDIV) of the insulation may still be sufficient to ensure machine reliability, [3] proposes a solution utilizing a novel interlayer transposition hairpin winding structure to mitigate this issue.

Lastly, the use of mineral or ester automatic transmission fluids (ATF) for cooling is becoming state-of-the-art. However, their interaction with insulation raises concerns. On one hand, chemical incompatibility between ATF and insulation could lead to cracks, delaminations, or other defects, significantly reducing the PDIV. Testing with one ester-based and one mineral oil ATF revealed some possible signs of delamination for PAI after two weeks at the maximum operating temperature of 160°C.

The effects of spraying ATF at 60°C on hot (180°C) conductors was also investigated. The results, reported in Fig. 5, show a reduction down to 10% of the PDIV when the oil spray is turned on. As some vapors could be visually observed during the test, it was preliminary assumed that hydrocarbons entering the gaseous phase could increase the Townsend first ionization coefficient of the gas around the conductors, leading to a reduction of PDIV.

VI. Conclusions

The insulation systems of electrical motors used in EVs are reaching a high level of maturity and are generally based on the "PD free" concept. Concerns have been raised concerning the possibility of double pulse superposition using high frequency SiC MOSFET inverters [3]. The same paper, however, presents a solution based on a modification of the winding topology. Corona-resistant materials, apparently, are not yet considered as a feasible turn insulation, despite their potential to improve the lifetime once PD have been incepted. The impact of cooling oil on the phase-to-phase insulation has been overlooked so far, but a reduction of the PDIV down to 10% could be observed when spraying the oil on hot conductors. This point should be investigated further and considered carefully in the design phase. Another point worth considerations concerns the expected lifetime and thermal stress profiles of EV machines. It can be speculated that the use of PI or PEEK amounts to overengineering. To investigate this point it would be interesting to test the PDIV of machines that have reached their intended lifetime and evaluate the residual margin.

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