Manufacturable Edgewise Winding Solutions Considering Parallel Slot and Parallel Tooth Stator Structures

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***Abstract*—Due to climate concerns, the push towards transportation electrification to deliver electric machines capable of high-power density performance is becoming increasingly critical. A key component of this is the structure and manufacture of the windings as these are the dominant source of machine loss. As current solutions are high loss, expensive or time consuming to manufacture, to accommodate the increasing demands for electric machine solutions, across the operating requirements, manufacturable winding solutions are necessary. This paper provides a multi-physics review of stranded and edgewise conductor performance. Stranded and edgewise winding structures are then simulated on a base machine, considering the impact of slot structures on winding geometry. The contribution of the paper is the development of a highly manufacturable edgewise winding structure without significant performance loss.**

***Keywords*— Manufacturing, windings, prefabricated, stranded, edgewise.**

I. Introduction

The demand for high power density machines is ever increasing to accommodate a diverse range of applications. Electrification of the automotive market is an important aspect to reduction of global greenhouse gas emissions, fueled by contributions such as increases in power density and energy storage, charging time and infrastructure, market competition and cost performance metrics [1, 2]. There is high interest in winding-specific manufacturing processes as windings are a dominant source of loss in the machine. The APC UK electrical machine roadmap outlines electrical machine operating regions, from cost effective and high-volume, up to ultra-high-power density and efficiency applications [3]. Technology demand forecasts predict that increasing volumes of production will be required across all operating regions and, as such, manufacturing innovations towards high-volume winding production is necessary [3]. The pushing of power density limitations is achieved by delivering high magnetic and electrical loading, whilst at high machine speeds. Typically, the limiting condition is the current loading, as high current loading leads to high loss densities, consequently operating at higher temperatures and making thermal management complex [1]. Considered here are stranded conductors, which are defined as having circular Cross-Sectional Area (CSA), and can be wound ortho cyclically, in layers, or randomly. Also considered are edgewise conductors, which are bar conductors with large CSA, but are rectangular with a large aspect ratio. Alternate manufacturable winding solutions such as hairpin and litz [4] are available. Hairpin conductors can achieve high fill factor but suffer from high AC losses, whereas litz wire has very good high frequency performance but are complex and expensive to manufacture, however these are not considered for the current research.

Section I introduces the background for the research. The main contribution of the paper is the development of a highly manufacturable edgewise winding solution with minimal performance impact. Section II introduces the performance characteristics for stranded and edgewise windings. Section III discusses simulation results. Finally, Section IV concludes the work and discusses plans for future work.

II. Stranded and Edgewise winding review

The electromagnetic, mechanical, thermal, and manufacturing characteristics are considered for the conductor types.

A. Electromagnetic characteristics

The main electromagnetic characteristics considered are slot fill factor, end winding length, and DC and AC resistance.

The fill factor for stranded conductors is inherently limited by using conductors with circular CSA in rectangular slots [5], typically achieving 0.4 fill factor in distributed windings and 0.5 to 0.6 in concentrated windings [6]. Conversely, edgewise windings can achieve higher fill factor, up to 0.7, as their rectangular CSAs are compatible with typical slot structures [7]. This results in the conductor volume in the machine being substantially higher when using prefabricated windings. This increases the amount of winding area over which the current is applied, hence reducing current density, and improving thermal performance.

DC loss performance is dependent on resistance, which increases with conductor length and decreases with CSA. Consequently, the DC characteristics of stranded conductors tend to be poor, owing to their small area and long lengths. Edgewise conductors benefit from low DC loss due to large CSA [7], as well as reduced end winding length which further reduces DC loss [8].

AC losses increases with frequency and conductor CSA, so stranded conductors tend to have good AC performance, however, they suffer from variation in AC performance due to manufacturing conditions, such as conductor position and bundle factor. Additionally, they tend to have larger numbers of conductors per slot which can increase susceptibility to AC losses, split into skin effect and proximity losses [5]. Bar conductors experience high AC loss due to their large CSA, as the large material area allows for eddy current circulation in the winding. For bar conductors, AC losses are generally dominant and limit the potential applications to those with lower frequency [9]. For edgewise conductors, the aspect ratio acts as an additional design parameter to minimize eddy current circulation and hence AC losses, so can be better suited to high frequency applications [7, 8]. A summary of these conclusions is shown in Table 1.

TABLE I. ELECTROMAGNETIC PERFORMANCE PARAMETERS FOR CONDUCTOR TYPES

Param.	Winding type		
	Stranded	***Edgewise***	***Ref***
Fill factor	0.45-0.55	0.7-0.75	[10]
DC losses	High	Low	[7, 8]
AC losses	Medium	Medium-High	[11]

B. Mechanical and thermal characteristics

The mechanical and thermal performance of the winding structures are considered. Manual stranded winding construction does not significantly deteriorate mechanical characteristics as the strain applied is lower than automated systems. Despite this, stranded winding design is influenced by mechanical strain restrictions, for example, the typical bend radius that can be used in the end windings is influenced directly by the mechanical strength of the wire used. End winding length and hence electrical losses are directly influenced by the mechanical limitations of stranded wires [12, 13]. Additionally, stranded windings require attention to impregnation to limit vibration in the machine.

Non-impregnated or insufficiently impregnated coils are adversely affected by Noise and Vibration Harshness (NVH). In extreme cases, the increased strain on the mechanical characteristics from excess NVH can result in insulation degradation, partial discharge, and vibration sparking, which can lead to complete failure [14, 15].

In general, prefabricated windings have improved mechanical performance due to lower variability in design and manufacturing procedures. The size of the conductors, hence mechanical strength, combined with winding structure limitations, leads to prefabricated windings being more robust with reduced position sensitivity [16]. Despite the potential mechanical improvements for using prefabricated windings as opposed to stranded, there are still notable consequences manufacturing. Mechanical strain, for example, from bending and welding, causes material changes, such as reduced conductivity [17]. Due to their aspect ratio, as shown in Figure. 1, edgewise conductors are highly affected by bending strain, and can experience performance degradation or failure if not adequately designed.

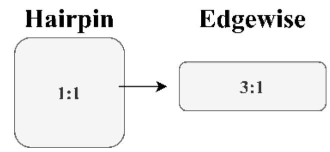


Fig. 1. Hairpin and edgewise winding aspect ratio difference

Additionally, harsh environments where windings will experience significant NVH can be problematic for bending failure in edgewise windings [18]. Deformation and mechanical stress negatively impacts other material properties such as breakdown voltage, thermal resistance, and expected lifetime [19]. Degradation of the insulation due to mechanical or thermal sources acts to reduce mean time to failure, as machine lifetime tends to be dictated by thermal performance.

Edgewise winding structures still suffer from manufacturing variability. A key factor in edgewise manufacture is ensuring manufacturing variability has minimal impact on turn-to-turn contact, which is critical to thermal conduction. Variation in turn-to-turn contact leads to lower heat transfer and can cause winding hotspots [19]. Prefabricated conductors tend to be structured such that good thermal contact is achieved between coils, and hence the thermal performance can be improved. Due to the increased ratio of surface area to volume, edgewise conductors experience the highest thermal contact of those considered. Due to high fill factor and improved thermal conduction, edgewise is a good choice for applications where volume and electrical losses should be kept low, and thermal conduction should be maximized [20]. Alternatively, the volumetric and thermal improvements can be utilised to implement cheaper (but less effective) conductor materials, reduce the insulation requirements, or extend the lifetime of the machine [8].

C. Manufacturing

The manufacturing characteristics for the conductor types are assessed, considering upfront and long-term costs, manufacturing tolerances, repeatability, and robustness. All manufacturing procedures are subject to tolerance; however, manual manufacturing has significantly higher tolerance, influencing factors such as AC losses and fault tolerance and increasing labour costs [21]. Despite this, manual manufacturing of stranded windings is often necessary for complex, high performance structures [5, 12], however, the processes are less robust, leading to lower reproducibility.

Stranded windings can be automatically manufactured with relatively low initial cost and good scalability using needle winding machines [22]. However, even when using automatic manufacturing techniques, stranded windings are prone to long end winding length and high tolerances, reducing design robustness [17]. Alternatively, prefabricated windings benefit from being highly manufacturable, with reasonable upfront and long-term costs and good design scalability, and the coils manufactured are highly robust. There are issues associated with these structures, however, such as high initial investment cost, and manufacturing limitations such as number of turns, layers or parallel paths [18]. Additionally, prefabricated windings are limited by

other manufacturing factors such as stator structures and slot opening. Typically, it is required to compromise electromagnetic performance to practically be able to manufacture the winding, for example, the slot opening must be wide enough to fit the coil, as shown in Figure 2.
For edgewise, there are larger upfront costs as they are less readily available and tooling must be formed, however, they are becoming a more widely adopted and available solution [23].

End-winding variation is a limiting factor in stranded winding manufacturing due to placement sensitivity. The lack of robustness in manufacturing techniques leads to irregular placement which can lead to insufficient separation between phases or coils, which can lead to partial discharge and ultimately insulation failure and short-circuit. This can be improved by using packing to essentially restrain the winding, which can improve lifetime and maintenance requirements but can considerably sacrifice performance due to the already limited slot fill [14].

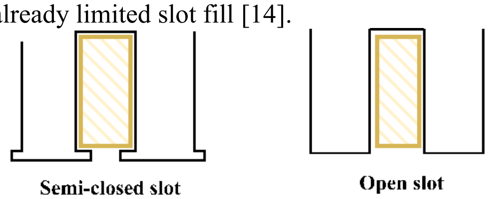


Fig. 2. Semi-closed slot structure and open slot structure

D. Parallel slot and parallel tooth structures

Manufacturing factors such as robustness and ease of assembly are becoming more important to design procedures, which means that compromises must be made to the performance in aid of manufacturability. A further manufacturing consideration, especially for edgewise winding structures, is the slot-tooth relationship. The Parallel Slot (PS) structure ensures that the whole depth of the slot has the same slot width, resulting in a trapezoidal tooth. Alternatively, the tooth can have a fixed width and the slot can be trapezoidal, giving a Parallel Tooth (PT) structure. The PS structure is shown in Fig. 3.

Using a PS structure can be intuitive as using conductors with rectangular aspect ratio in rectangular slots has the potential to achieve high fill factors. It has been shown that thermal performance can be a limiting factor, however, overall electromagnetic performance is advantageous. It allows for higher torque production, and hence higher power delivery with minimal weight increase. Despite the potential electromagnetic advantages, there are manufacturing complications when using PS structures due to the irregular winding shapes. As shown in Fig. 4 when using PS structures, the end winding is trapezoidal as the tooth width varies depending on slot depth. On a single, concentrated coil, the dimensions are different from turn-to-turn, resulting in the tapered winding. When using multiple layers, each layer of coils will have different dimensions depending on slot placement. Using the PT structure gives coils that are identical from turn-to-turn and at different slot depths. This reduces manufacturing complexity, and hence probability of issues arising. This also means that the coil and end winding volumes are even at different points in the machine, as shown in Table II.

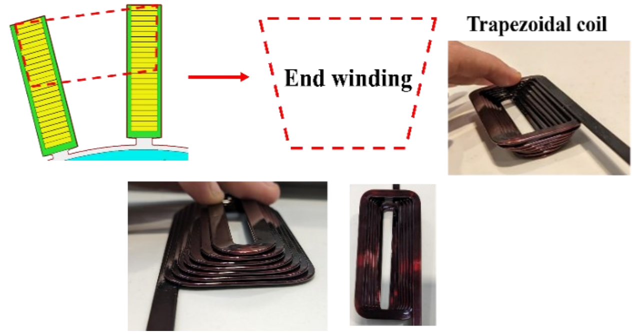


Fig. 3. Coil and end winding structures when using parallel slot structure

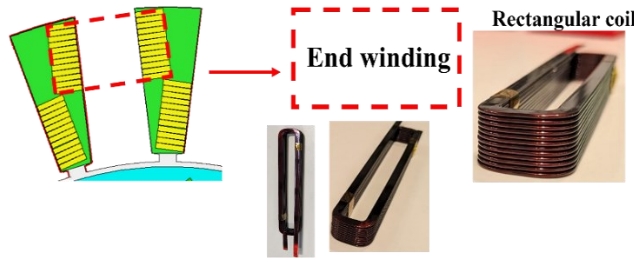


Fig. 4. Coil and end winding structures when using parallel tooth structure

TABLE II. MANUFACTURABLE EDGEWISE WINDING GEOMETRIC CHARACTERISTICS

Parameter	**Winding type**	
	Edgewise – PS	***Edgewise – PT***
Conductor CSA (mm²)	6.71	6.71
Slot fill factor	0.7062	0.5178
Analytical end-winding length per turn (mm)	74.68	64.24
Upper coil end winding profile (mm²)	336.408	252.12
Lower coil end winding profile (mm²)	283.615	252.12

III. CASE STUDY

A. Base machine

The base machine parameters used for simulation is shown in Table III, and the winding structures considered are given in Table IV.

TABLE III. SIMULATED MACHINE GEOMETRIC PARAMETERS

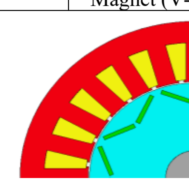
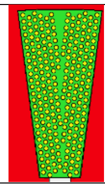
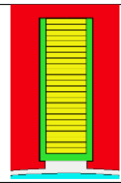
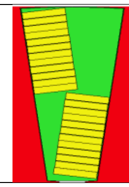
Machine parameters			
Geometry		***Machine type:***	V-shaped Interior Permanent Magnet (V-IPM)
Outer diameter (mm)	245		
Active length (mm)	110		
Slots/Poles	24/8		
Operating speed (RPM)	4000		
Winding temperature limit (°C)	180		
Cooling: Spiral Water Jacket			
Flow CSA (mm²)	210	Coolant	Water
Length (mm)	1532	Flow rate (L/min)	3

TABLE IV. SIMULATED MACHINE WINDING PARAMETERS

Winding parameters			
Parameter	***Stranded***	***Edgewise – PS***	***Edgewise – PT***
Structure			
Turns per coil	12	12	12
Parallel paths	2	2	2
Layers	2	2	2
Strands in hand	10	1	1
Fill factor	0.4224	0.7062	0.5178
Available slot area (mm²)	317.8	234.9	317.8
Slot conductor area (mm²)	99.22	165.89	121.63
Conductor CSA (mm²)	0.5451	6.71	6.71
Conductors per slot	240	24	24

The base machine and the winding structures are designed such that, the narrowest part of the slot where the flux density is highest, is kept constant. As the difference in end winding structure leads to substantial difference in manufacturing, it is chosen to apply manufacturing factors to the simulated winding lengths, calculated using [24] to more accurately reflect winding length. The difference is shown diagrammatically in Figure. 5, and the resultant end winding lengths are shown in Table V. Simulation assessment is given for electromagnetic and thermal characteristics, with a focus throughout on manufacture practicalities, and mechanical limits enforced.

TABLE V. ANALYTICAL END WINDING LENGTH DETERMINATION

Analytical end-winding length per turn (mm)		
Stranded	***Edgewise – PS***	***Edgewise – PT***
77.93	74.68	64.24

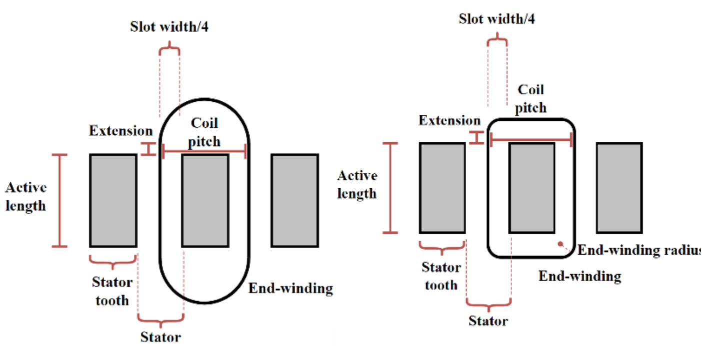


Fig. 5. Physical perspectives on manufactured coils

B. Torque performance

To compare the options under fixed thermal limit, the torque is assessed at constant current density of 6A/mm². Then to compare torque per amp, torque is assessed at constant current of 85A. These thresholds are chosen such that no winding structures are exceeding the thermal limit. Figure 6 shows that both edgewise solutions provide more torque for fixed current density. The edgewise PT solution delivers the most, followed by edgewise PS, then stranded. The stranded structure has significantly lower fill, and hence lower conductor area. This means that the current required to achieve the requested current density is 31.1% lower, resulting in lower torque production in comparison to both edgewise structures. For fixed current density, the edgewise PT solution delivers more torque than the parallel slot solution despite having a 26.7% reduction in fill factor. The reason for this is that the PS solution has higher loss density, and hence has the lowest current threshold before reaching the thermal limit, as shown in Table VI.

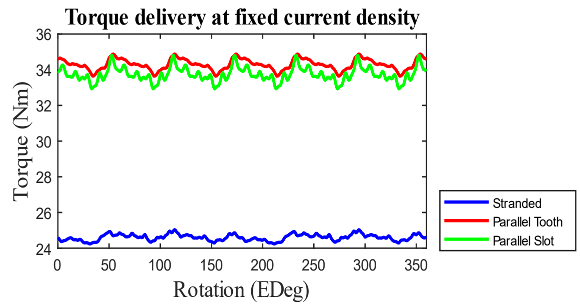


Fig. 6. Torque delivery per winding structure when operating at fixed current density 6A/mm²

When fixing the supply current, as in Figure 7 it is shown that the torque delivery is highest for the stranded winding. As the current loading is fixed, the reason for this is magnetic loading. When moving from stranded to PS, the mean air gap flux density is reduced by 6.50% and the reduction in average torque is 6.47%, this indicates that the difference in air gap flux distribution due to stator structure is influencing the torque production, with small deviations due to the difference in efficiency between windings, as shown in Table VII and Table VIII.

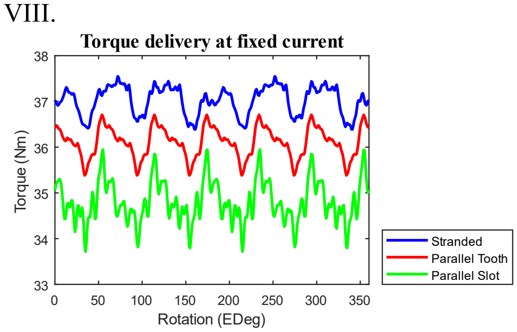


Fig. 7. Torque for fixed current of 85A

TABLE VI. CURRENT DELIVERED AND CORRESPONDING EFFICIENCY

	Stranded – PT	***Edgewise – PS***	***Edgewise – PT***
Current (A) to reach thermal limit	85	50	106
Current density (A/mm²)	9.2	3.73	7.9
Machine efficiency (%)	93.61	96.83	94.17

However, by enforcing a realistic thermal limit, the PS solution reaches the thermal limit with much lower current and current loading, meaning that the thermal dissipation is insufficient to accommodate the increase in conductor area, and hence increase in loss density. Additionally, the stranded solution can accommodate the highest current density without overheating, however, due to the increased slot fill in the edgewise PT solution, the RMS current that can be accommodated is higher, and the torque production remains highest under these conditions. When operating at the thermal limit, it is shown that the machine efficiency is related to applied current density, as shown in Table VI. Edgewise PS has the highest efficiency, due to having the lowest current. The edgewise PT structure then is the next most efficient when operating at the thermal limit, this reflects the improvement in DC loss performance when using edgewise conductors.

C. Operating point analysis

Two fixed operating point conditions are considered, firstly at rated operation at 4000rpm and 35Nm, and then at 12000rpm and 11Nm, shown in Table VII and Table VIII respectively. Two fixed operating point conditions are considered, firstly at rated operation at 4000rpm and 35Nm, and then at 12000rpm and 11Nm (?), shown in Table VII and Table VIII respectively.

During rated operation, the stranded topology needs the lowest current, as shown previously, this is due to the magnetic loading and is further investigated in III.D. Slot opening considerations. Despite this, the stranded design has higher DC losses than edgewise, as expected from literature. Edgewise PT has the lowest DC losses, partially due to slightly lower current, but mainly due to the reduction in operating temperature which reduces effective winding resistance. Edgewise PT also experiences higher AC copper losses and iron losses than the PS, as the PT geometry has higher average flux density, but the overall efficiency is improved due to DC copper loss dominance at this operating point. The stranded design experiences high AC copper losses, the system is operating at 266.67Hz, which gives substantial headroom to avoid issues with skin depth.

However, the stranded design is experiencing higher average air gap flux density, as shown by the iron losses. Additionally, stranded topologies are more prone to proximity losses. Proximity losses are generated when strands are exposed to external magnetic fields generated by parallel strands. The variation in leakage flux at different points in the slot results in variation of flux linkages between parallel strands, resulting in induced fields [25]. Due to the combination of high flux density and ten times increase in number of conductors per slot in stranded configurations, the AC losses are high and is also very susceptible to manufacturing position, so can be difficult to predict following manufacture.

TABLE VII. FIXED OPERATING POINT AT 4000RPM AND 35NM

	Stranded – PT	***Edgewise – PS***	***Edgewise – PT***
Current (A)	77.5	79.7	79
Efficiency (%)	95.381	96.775	97.107
Copper losses (DC (W) / AC (W))	489 / 106	388 / 12.63	307 / 23.1
Stator and rotor iron losses (W)	108	82.8	101.8

The simulation is repeated at 3x rated speed to observe impacts when moving into field-weakening (FW) operation. The stranded design needs the largest amount of FW as it has higher air gap flux density, which requires more negative d-axis current to counteract [26]. When increasing the speed, the efficiency trend changes, as edgewise PS is most efficient. This is because the DC copper loss trend is the same but, due to the increased speed, AC copper and iron loss are now dominant. In particular, the stranded winding has dominant AC losses due to amplified impacts from proximity effects discussed previously.

TABLE VIII. HIGH SPEED OPERATING POINT AT 12000RPM AND 11NM

	Stranded – PT	***Edgewise – PS***	***Edgewise – PT***
Current (A)	77.5	79.7	79
Current phase advance (°)	76.7	76.5	76.6
Efficiency (%)	91.082	95.656	95.407
Copper losses (DC (W) / AC (W))	559 / 649	398 / 92	320 / 177
Stator and rotor iron losses (W)	131	115	131

D. Slot opening considerations

Stranded windings can be constructed with partially closed slot openings due to smaller CSA. This results in smaller effective air gap and decreased air gap flux variation, so the torque ripple characteristic is also improved when using semi-closed slot structures, as shown in Table IX. However, this improvement in electromagnetic performance is insufficient to compete with the prefabricated conductors.

TABLE IX. TORQUE RIPPLE PERCENTAGE WHEN USING MANUFACTURABLE SLOT OPENINGS AT 6A/MM²

Torque ripple (%)		
Stranded – PT	***Edgewise – PS***	***Edgewise – PT***
2.667	3.451	3.998

Conversely, the edgewise windings require that the slot width is sufficient to fit the coil, meaning the slot opening must be increased, typically to larger than is ideal. For the stranded topology, the optimum slot opening ratio was determined to be 0.53. To fit the edgewise winding, it needs to be increased to 0.88. The impact of this increase on torque ripple is shown in Table IX. It is found by directly increasing the slot opening of the parallel tooth structure by 66.5%, the increase in torque ripple is 54.1%.

IV. CONCLUSION

It is shown that there are manufacturing-specific concerns for utilisation of prefabricated winding types. While edgewise windings in PS structures have electromagnetic advantages, when considering mechanical, thermal, and manufacturing limitations, the simulated study has shown that highly manufacturable edgewise windings with PT structure have a number of advantages, such as accommodating 24.7% more current before overheating, has 38.6% lower losses at rated speed and 45.5% lower losses at three times rated speed than the stranded topology, while being easily manufacturable compared to other solutions considered due to structural symmetry and repeatable processes. Future work aims to investigate the potential for cooling techniques to achieve enhanced heat dissipation for higher levels of power density.

V. References

[1] T. Zou *et al.*, "A Comprehensive Design Guideline of Hairpin Windings for High Power Density Electric Vehicle Traction Motors," *IEEE Transactions on Transportation Electrification,* pp. 1, 2022, doi: 10.1109/TTE.2022.3149786.

[2] E. Agamloh, A. von Jouanne, and A. Yokochi, "An Overview of Electric Machine Trends in Modern Electric Vehicles," *Machines,* vol. 8, no. 2, p. 20, 2020. [Online]. Available: https://www.mdpi.com/2075-1702/8/2/20.

[3] A. UK, "Electrical Machines," in "Technology Roadmap," 2020.

[4] L. George, A. Walker, F. Zhang, G. Vakil, and C. Gerada, "Comparison of V-shaped IPM Machines Winding Topologies for Heavy-duty EV Applications," in *2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, 29-31 March 2023 2023, pp. 1-7, doi: 10.1109/ESARS-ITEC57127.2023.10114821.

[5] A. Selema, M. N. Ibrahim, and P. Sergeant, "Development of Novel Semi-Stranded Windings for High Speed Electrical Machines Enabled by Additive Manufacturing," *Applied Sciences*, vol. 13, no. 3, doi: 10.3390/app13031653.

[6] M. Schiefer and M. Doppelbauer, "Indirect slot cooling for high-power-density machines with concentrated winding," in *2015 IEEE International Electric Machines & Drives Conference (IEMDC)*, 10-13 May 2015 2015, pp. 1820-1825, doi: 10.1109/IEMDC.2015.7409311.

[7] T. Okada, H. Matsumori, T. Kosaka, and N. Matsui, "Hybrid excitation flux switching motor with permanent magnet placed at middle of field coil slots and high filling factor windings," *CES Transactions on Electrical Machines and Systems,* vol. 3, no. 3, pp. 248-258, 2019, doi: 10.30941/CESTEMS.2019.00033.

[8] REO. "REO EDGE-WINDING." (accessed 25/05/2022, 2022).

[9] A. L. Rocca, T. Zou, M. Moslemin, D. Gerada, C. Gerada, and A. Cairns, "Thermal Modelling of a Liquid Cooled Traction Machine with 8-layer Hairpin Windings," in *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, 13-16 Oct. 2021, pp. 1-6, doi: 10.1109/IECON48115.2021.9589672.

[10] R. Wrobel, S. Ayat, and J. L. Baker, "Analytical methods for estimating equivalent thermal conductivity in impregnated electrical windings formed using Litz wire," in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, 21-24 May 2017 2017, pp. 1-8, doi: 10.1109/IEMDC.2017.8002003.

[11] V. Väisänen, J. Hiltunen, J. Nerg, and P. Silventoinen, "AC resistance calculation methods and practical design considerations when using litz wire," in *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, 10-13 Nov. 2013, pp. 368-375, doi: 10.1109/IECON.2013.6699164.

[12] P. Arumugam, T. Hamiti, and C. Gerada, "Fault tolerant winding design — A compromise between losses and fault tolerant capability," in *2012 XXth International Conference on Electrical Machines*, 2-5 Sept. 2012, pp. 2559-2565, doi: 10.1109/ICElMach.2012.6350245.

[13] P. Arumugam, E. Amankwah, A. Walker, and C. Gerada, "Design Optimization of a Short-Term Duty Electrical Machine for Extreme Environment," *IEEE Transactions on Industrial Electronics,* vol. 64, no. 12, pp. 9784-9794, 2017, doi: 10.1109/TIE.2017.2711555.

[14] G. C. Stone and R. Wu, "Examples of stator winding insulation deterioration in new generators," in *2009 IEEE 9th International Conference on the Properties and Applications of Dielectric Materials*, 19-23 July 2009, pp. 180-185, doi: 10.1109/ICPADM.2009.5252475.

[15] H. G. Sedding, C. Chan, M. Sasic, and G. C. Stone, "Assessment of Stator Winding Insulation Condition Based on Absolute Partial Discharge Magnitude," in *2023 INSUCON - 14th International Electrical Insulation Conference (INSUCON)*, 18-20 April 2023 2023, pp. 19-23.

[16] A. Al-Timimy, P. Giangrande, M. Degano, M. Galea, and C. Gerada, "Investigation of AC Copper and Iron Losses in High-Speed High-Power Density PMSM," in *2018 XIII International Conference on Electrical Machines (ICEM)*, 3-6 Sept. 2018, pp. 263-269, doi: 10.1109/ICELMACH.2018.8507166.

[17] A. Selema, M. N. Ibrahim, and P. Sergeant, "Electrical Machines Winding Technology: Latest Advancements for Transportation Electrification," *Machines*, vol. 10, no. 7, doi: 10.3390/machines10070563.

[18] H. Naderiallaf, M. Degano, and C. Gerada, "Assessment of Edgewise Insulated Wire Bend Radius Impact on Dielectric Properties of Turn-to-Turn Insulation through Thermal Ageing," *IEEE Transactions on Dielectrics and Electrical Insulation,* pp. 1, 2023, doi: 10.1109/TDEI.2023.3309780.

[19] M. Linnemann, M. Bach, V. Psyk, M. Werner, M. Gerlach, and N. Schubert, "Resource-efficient, innovative coil production for increased filling factor," in *2019 9th International Electric Drives Production Conference (EDPC)*, 3-4 Dec. 2019, pp. 1-5, doi: 10.1109/EDPC48408.2019.9012063.

[20] D. Kampen, *Future Winding for Next Power Electronic Generation*. 2018.

[21] P. Herrmann, M. Gerngroß, C. Endisch, P. Stenzel, and P. Uhlmann, "Automated contacting technology for needle winding applications with distributed windings," in *2017 7th International Electric Drives Production Conference (EDPC)*, 5-6 Dec. 2017, pp. 1-8, doi: 10.1109/EDPC.2017.8328169.

[22] T. Grosse, J. Hagedorn, and K. Hameyer, "Needle winding technology for symmetric distributed windings," 2014.

[23] K. Kajita, T. Takao, H. Maeda, and Y. Yanagisawa, "Degradation of a REBCO conductor due to an axial tensile stress under edgewise bending: a major stress mode of deterioration in a high field REBCO coil's performance," *Superconductor Science and Technology,* vol. 30, no. 7, p. 074002, 2017/05/25, doi: 10.1088/1361-6668/aa6c38.

[24] Z. Q. Zhu *et al.*, "Effect of End-Winding on Electromagnetic Performance of Fractional Slot and Vernier PM Machines With Different Slot/Pole Number Combinations and Winding Configurations," *IEEE Access,* vol. 10, pp. 49934-49955, 2022, doi: 10.1109/ACCESS.2022.3172323.

[25] A. Bardalai *et al.*, "Reduction of Winding AC Losses by Accurate Conductor Placement in High Frequency Electrical Machines," *IEEE Transactions on Industry Applications,* vol. 56, no. 1, pp. 183-193, 2020, doi: 10.1109/TIA.2019.2947552.

[26] T. Gundogdu and G. Komurgoz, "Influence of design parameters on flux-weakening performance of interior permanent magnet machines with novel semi-overlapping windings," *IET Electric Power Applications,* vol. 14, no. 13, pp. 2547-2563, 2020, doi: https://doi.org/10.1049/iet-epa.2020.0390.