Novel 3D Printed Coils for High Power Density Electrical Machine and Traction Applications

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***Abstract*— Nowadays, manufacturability challenges are limiting the performance of electrical machines. With the emergence of additive manufacturing (AM) technology, new design solutions are becoming applicable which were not possible to achieve using conventional production techniques. This work addresses unconventional design possibilities in the manufacturing of machine windings. Using 3D printing technology, a new coil is designed and prototyped for high power density electrical machines. Targeting traction applications, the proposed design combines higher performance and easier manufacturability. Moreover, a new thermal management approach is introduced using a novel AM shaped profile coil which allows for high electromagnetic as well as thermal performance.**

Keywords*— Electrical Machines, 3D printing, Traction Applications, Manufacturability.

I. Introduction

As the market of electric vehicles (EVs) expands, high reliability and ease of manufacturability are becoming important aspects during the early stage design process of electric traction motors. Therefore, original equipment manufacturers (OEMs) are trying to address manufacturability challenges using unconventional production techniques that allow for improved supply chain resiliency. In this context, additive manufacturing (AM) technology has gained a lot of interest recently [1], [2]. Thanks to its unlimited design freedom, complex and scalable parts can be easily printed for electrical machines saving a lot of time and cost. Additionally, with the high feedstock flexibility, advanced materials can be used with tuned chemical composition. To sum up, the development of electrical machines can be greatly accelerated using AM technologies, resulting in redesign of traditional manufacturing as well as rapid commercialization of new families of electrical machines [3]–[5].

Different research studies highlighted very promising outcomes of using AM technology for electrical machines. In [6], state of the art of additively manufactured electromagnetic materials is introduced for topology optimized electrical machines. It is found that printing of magnetically and electrically conductive materials show equivalent properties to high-grade commercial materials [7]–[12]. Moreover, It is also possible to print passive parts for electrical machines with high mechanical properties and optimized weight. An example is reported in [13] for a complete electrical drive housing produced by Porsche. This housing has double the mechanical strength and 40% lighter than the conventional design. In parallel, AM hard magnetic materials are introduced in [14], [15]. Roughly equivalent performance is obtained compared to commercial ferrite permanent magnets (PMs). Nevertheless, printed high quality PMs are still at early-stage research. To achieve that, an effective magnetization process is yet needed to impart complex 3D printed PMs. On the counterpart, the maturity of AM electrically conductive materials is superior in many ways. That is why 3D printed coils are employed in many applications, and even suitable for commercial applications. In [16], pure copper coils are printed with a relative electrical conductivity of 100% IACS. Yet, due to the relatively higher production costs, printing pure copper is still limited to nonconventional complex winding types [17]. Alternatively, aluminum alloys can be used for such windings due to their lower weight as well as cost [18]–[25].

Boosting the power density in electrical machines is essential as vehicle electrification advances. With this being said, this paper introduces unconventional design possibilities in the manufacturing of machine windings enabled by AM technology. Targeting traction applications, a new coil is designed and prototyped for high power density electrical machines combining between higher performance and easier manufacturability. Furthermore, a new direct cooling approach is proposed using a novel AM shaped profile coil and heat exchanger which allow for high electromagnetic performance as well as optimal thermal management.

II. New Design Concept for 3D Printed Coils

One of the common electrical machines that can benefit from AM technology is the switched reluctance machine (SRM). In such machine, multi-turn concentrated coils are typically used for the stator three phase windings. An example is shown in Fig. 1 for a 6.5 kW peak, 4 kW continuous 3-phase SRM with slot/pole combination of 6/4 slot. One of the main issues of SRMs is the lower copper utilization leading to lower efficiency and reduced power density. To tackle this issue, different cooling system can be used to dissipate the heat generated in the winding conductors. A naturally air-cooled jacket with fins has a simple and rugged structure. However, it is not as effective as the water cooling systems (whether direct or indirect). In the baseline machine (Fig. 1), the coils are typically wound first using a single strand round conductor and then placed in the slot. As a result, there is a triangular prism gap between adjacent windings. This space is used for direct cooling of the coil conductors and to push current limitations to higher levels. Nevertheless, the slot copper fill factor is minimally reduced by 25% due to this space [26].

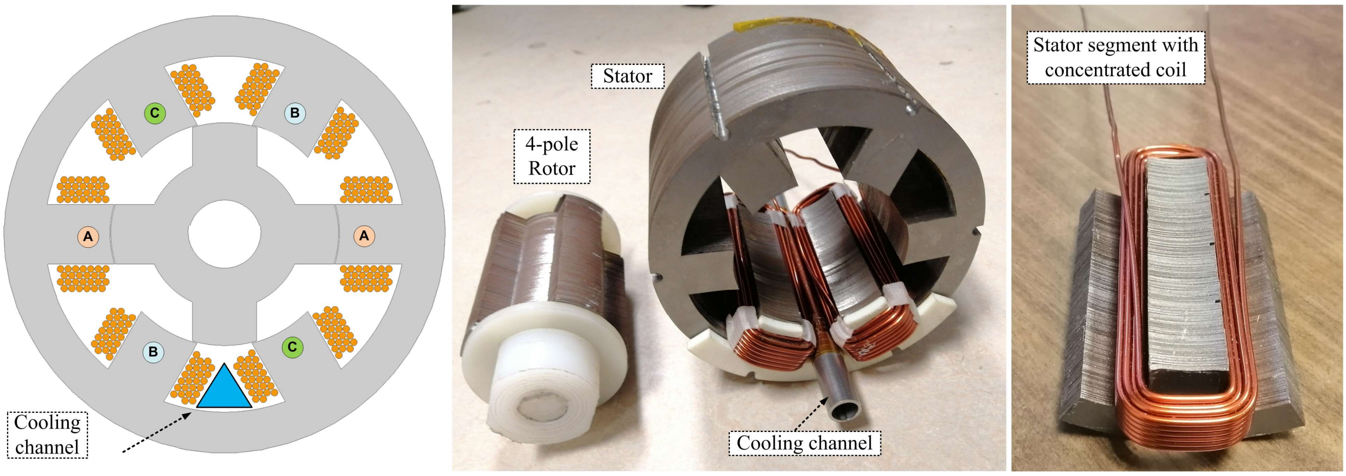
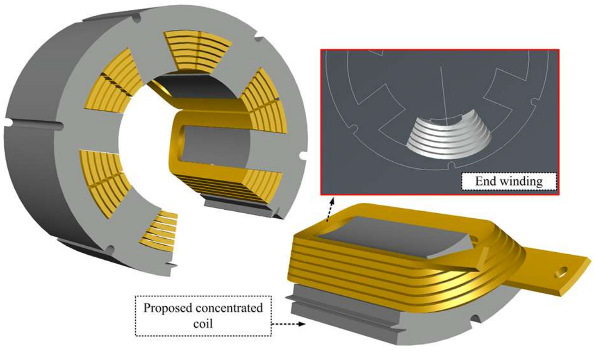
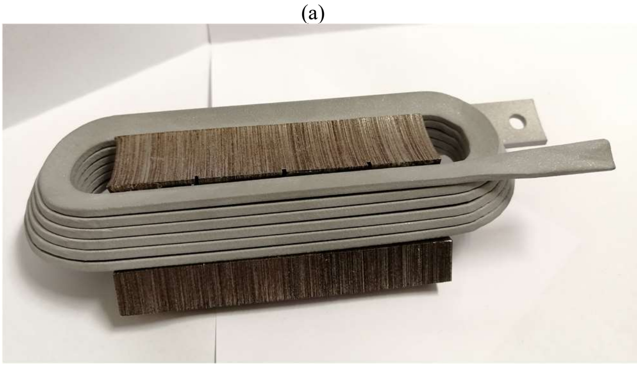


Fig. 1. Configuration of a typical three-phase switched reluctance machines with direct cooling channels.

To combine a high fill factor and good thermal performance, a 3D trapezoidal-shape coil is proposed as shown in Fig. 2(a). This 6-turn coil has conductors with different cross-sections to have a perfect fit in the trapezoidal slot. Also, the coil has a very high fill factor of 73% which is two times its value in the conventional coils. Moreover, the end turns are ingenuously designed to have a smooth and continuous transition between the different cross-sections. In order to apply this concept to a SRM, the stator must have a partitioned structure that can be assembled later after all coils are inserted. Additionally, the thermal management system will be using an outer cooling jacket with indirect water cooling.



(a)



(b)

Fig. 2. High fill factor trapezoidal-shape coil. (a) 3D design, (b) 3D printed prototype using aluminum.

Different materials and methods can be used to print the aforementioned coil design. Apart from copper, a cost-effective alternative will be using aluminum. Despite aluminum has lower electrical and thermal conductivity, it has nearly half weight and much lower cost compared to copper. Therefore, the trapezoidal-shape coil is 3D printed using aluminum using selective laser melting (SLM) technology as shown in Fig. 2(b). The printed part has a very accurate finishing with perfect fit with the core dimensions. Despite having a higher fill factor, the coil is 32% lighter than the conventional copper coil without taking the weight of cooling tube into account. Additionally, by comparing the thermal profile under the same cooling conditions, it is found the 3D high fill aluminum coils has remarkably lower temperature compared to the conventional coils as shown in Fig. 3.

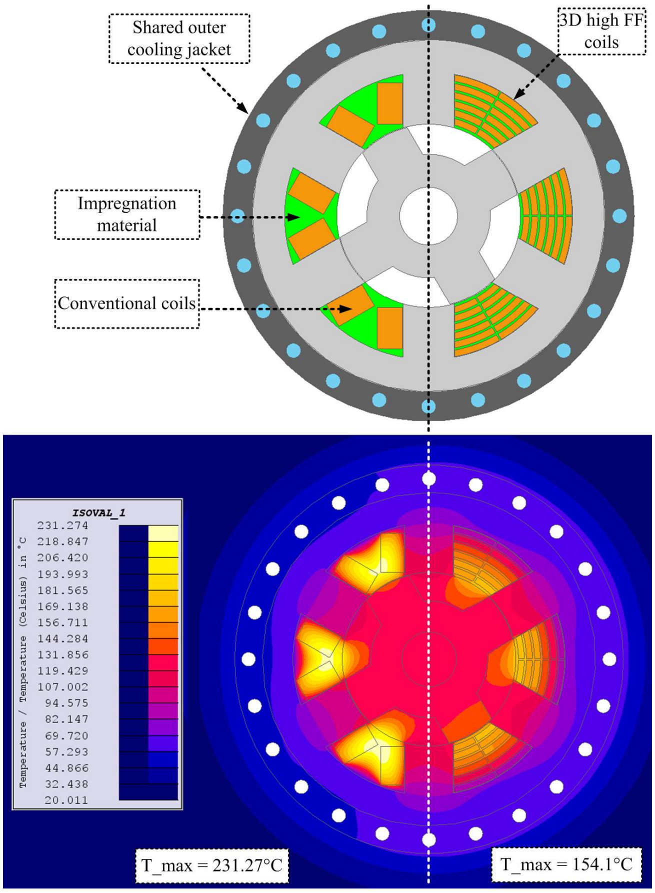


Fig. 3. Thermal profile of the 3D high fill factor coil compared conventional coils under the same cooling conditions.

Using finite element analysis (FEA), the power losses are calculated at different frequency levels for the conventional coil. The results are also compared with a trapezoidal-shape coil with two different materials (copper and aluminum) as shown in Fig. 4. It is found that at nominal frequency level, using aluminum coil reduces the losses by over 25%. Also, in case of copper, the losses decrease by over 50%. Therefore, it can be concluded that using a 3D printed trapezoidal-shape coil with high fill factor is a more effective replacement for the traditional copper coils.

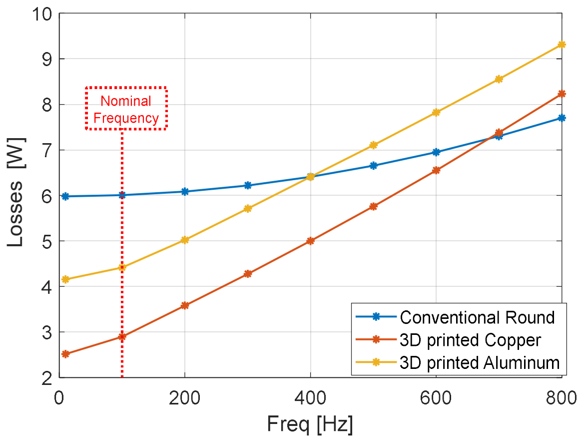


Fig. 4. Winding losses at different frequency levels: a comparison between conventional coils and 3D printed ones with high fill factor.

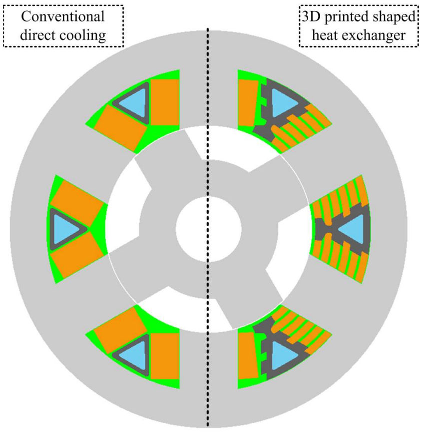
III. Thermal Management and Direct Cooling

In order to push current limitations to higher levels, direct cooling channels are usually used to effectively extract the heat generated by the windings and core losses. In [27], using direct in-winding cooling allows for a significant increase of current density limit by 30% compared to the naturally air-cooled SRM. Yet, the conventional triangular-shape cooling channel is not the optimal design for direct cooling. The main reason is that it has a very limited contact surface especially if the multi-turn windings has traditional round conductor. So, the contact surface between the turn and the channel is a line rather than an area. As a result, they are not as effective as expected in removing losses from windings.

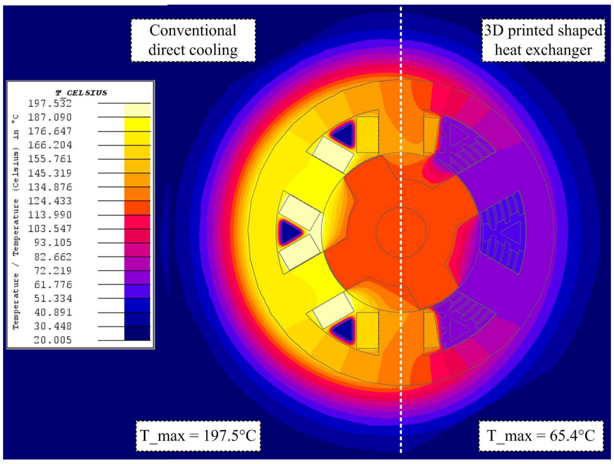
For an optimal heat dissipation, the contact surface needs to be increased. To this aim, a novel shaped profile coil is introduced in Fig. 5(a). In such design, the individual turns have unequal widths allowing for a zigzag-surface heat exchanger. The proposed design has twice the contact surface area of the conventional triangle shape cooling channel.

To save time during the transient thermal simulation, the proposed design is solved with the conventional on the same stator core. A comparison between the thermal performances is also shown in Fig. 5(b) under the same ampere turns and coolant flow rate values. Also, the corresponding instantaneous temperature rise is shown in Fig. 6. As can be seen, the proposed shaped profile coil along with the zigzag-surface direct cooling channel have remarkably reduced the maximum temperature from 197.5°C to only 65.4°C. Further, the maximum temperature is also compared at different ampere turns and convective heat transfer coefficients as shown in Fig. 7. Obviously, the proposed cooling approach has a much better thermal profile compared to the traditional one under the same operating conditions. This allows for a significant increase of current density. Eventually, the torque and power density are improved.

The shaped profile coil along with the zigzag-surface heat exchanger are designed in 3D, and the assembly with the stator are shown in Fig. 8. Different materials can be used for the heat exchanger. The simulation is initially performed using a non-magnetic stainless steel which has good thermal conductivity. These will be printed using a single material AM, and the coil insulation will be added in a post process using varnish.



(a)



(b)

Fig. 5. Shaped profile coil with the zigzag-surface heat exchanger compared to conventional direct cooling. (a) Design concept, (b) Thermal profile under the same operating conditions.

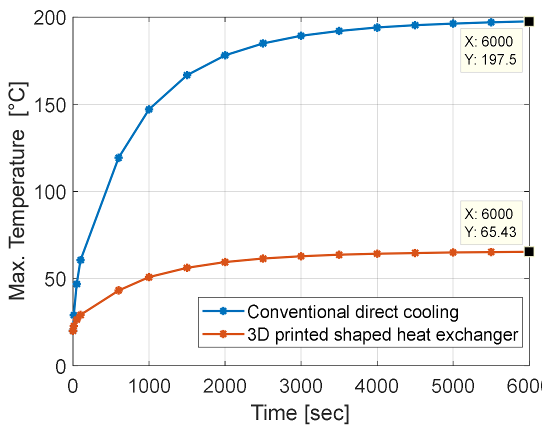


Fig. 6. Comparison between the instantaneous temperature rise at a fixed convective heat transfer coefficient (h=1000 W/m^2.°C), and Ampere turns = 1080AT.

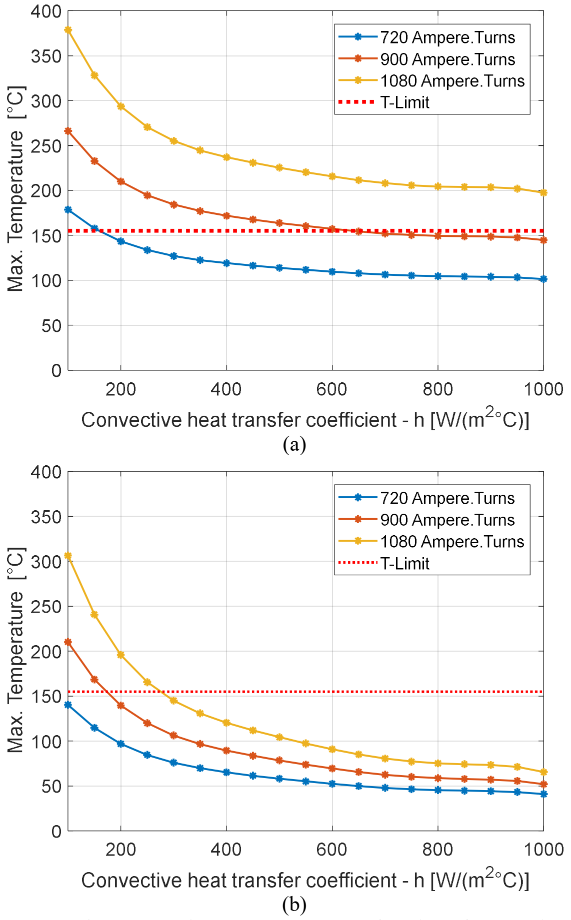


Fig. 7. Steady state maximum temperature as function of convective heat transfer coefficient at different ampere turns levels. (a) Conventional direct cooling. (b) 3D shaped profile coil with the zigzag-surface heat exchanger.

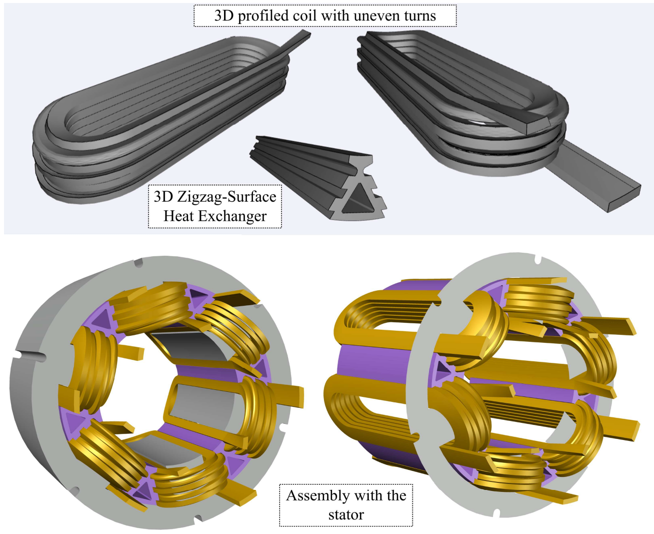


Fig. 8. Assembly of the shaped profile coil along with the 3D zigzag-surface heat exchanger.

To sum up, a comparison between different coil cases are listed in Table I. The conventional coils (coil1) and direct cooling system are not as effective as expected in removing losses from windings. Instead, using a 3D coil with high fill factor (coil2 or coil3) will provide a much better thermal performance and even lower weight (if Aluminum is used; coil3). Finally, the shaped profile coil (coil 4) along with the zigzag-surface direct cooling channel have the optimal thermal performance, and it can push current limitations to significantly higher levels.

TABLE I. COMPARISON BETWEEN DIFFERENT COIL TOPOLOGIES

Coil	**Coil1: Conventional**	**Coil2: 3D high fill Cu.**	**Coil3: 3D high fill Alu.**	**Coil4: 3D Shaped Alu.**
Number of Turns	26	6	6	6
Method	AWG 16 tradtional wire	3D printed	3D printed	3D printed
Material	Copper	Copper	Aluminum	Aluminum
Fill factor	36.7%	73%	73%	48.6%
Weight	158.6 g (1.00 p.u.)	356.6 g (2.25 p.u.)	107 g (0.67 p.u.)	80.3 g (0.51 p.u.)
Losses at Nominal speed *1	1.00 p.u.	0.48 p.u.	0.73 p.u.	0.72 p.u.
Cooling Method	Direct cooling using conventional triangle tube	Outer water cooling Jacket	Outer water cooling Jacket	Direct cooling using 3D zigzag-surface heat exchanger
Max. Temp. @ same conditions*2	197.5°C	141.7°C	154.1°C	65.4°C
Ampere turn upper limit *3	910	1179	1085	2570
Maximun Current density	10.47 A/mm^2	12.79 A/mm^2	11.04 A/mm^2	25.84 A/mm^2

*1 1 p.u.=6 W *2 At the same ampere turns (1080 ATs) and highest cooling rate h=1000 W/(m2.°C). *3 At the max. temperature limit (155°C) and highest cooling rate h=1000 W/(m2.°C).

IV. CONCLUSION

This paper introduces new winding designs for traction motors enabled by 3D printing technology. Targeting high power density, the proposed designs combine between high electromagnetic and thermal performances. First, a coil with high fill factor is proposed using different materials (copper and aluminum). Both coils have better electrothermal performance without the need for direct cooling channels. Secondly, a novel shaped profile coil is proposed along with the zigzag-surface heat exchanger. With the increased contact surface area, this approach has the optimal thermal profile with 67% temperature drop which allows for higher current density levels. Using additive manufacturing technology, the proposed designs will be printed and tested to verify its validity.

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REFERENCES

[1] N. Simpson and P. H. Mellor, “Additive manufacturing of shaped profile windings for minimal AC loss in gapped inductors,” in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, May 2017, pp. 1–7, doi: 10.1109/IEMDC.2017.8002337.

[2] A. Selema, M. N. Ibrahim, and P. Sergeant, “Metal Additive Manufacturing for Electrical Machines: Technology Review and Latest Advancements,” *Energies*, vol. 15, no. 3, p. 1076, Jan. 2022,

doi: 10.3390/en15031076.

[3] S. Ayat, N. Simpson, B. Daguse, J. Rudolph, F. Lorenz, and D. Drury, "Design of Shaped-Profile Electrical Machine Windings for Multi-Material Additive Manufacture," in *2020 International Conference on Electrical Machines (ICEM)*, Aug. 2020, pp. 1554–1559.

[4] A. Selema *et al.*, "Evaluation of 3d-Printed Magnetic Materials for Additively-Manufactured Electrical Machines," *J. Magn. Magn. Mater.*, 2023, doi: 10.1016/j.jmmm.2023.170426.

[5] F. Wu and A. M. EL-Refaie, "Investigation of an Addtively-Manufactured Modular Permanent Magnet Machine for High Specific Power Design," in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2019, pp. 777–784.

[6] H. Tiismus, A. Kallaste, T. Vaimann, and A. Rassõlkin, "State of the art of additively manufactured electromagnetic materials for topology optimized electrical machines," *Addit. Manuf.*, vol. 55, p. 102778, Jul. 2022, doi: 10.1016/j.addma.2022.102778.

[7] A. Selema, M. Van Coppenolle, M. N. Ibrahim, and P. Sergeant, "Multi-physic design of ultra-efficient smart motor enabled by additive manufacturing," *Proc. Fac. Eng. Archit. Res. Symp.*, 2022, doi: 10.5281/zenodo.7405841.

[8] H. Chen, A. M. EL-Refaie, and N. A. O. Demerdash, "Flux-Switching Permanent Magnet Machines: A Review of Opportunities and Challenges—Part I: Fundamentals and Topologies," *IEEE Trans. Energy Convers.*, vol. 35, no. 2, pp. 684–698, Jun. 2020.

[9] A. Selema, M. N. Ibrahim, and P. Sergeant, "Additive Manufacturing for Electrical Machines: Opportunities and Challenges," in *Flanders Make: CMVPT Conference on Machines, Vehicles and Production Technology*, 2022, p. 1, doi: 10.13140/RG.2.2.13028.65920.

[10] F. Wu and A. M. EL-Refaie, "Toward Additively Manufactured Electrical Machines: Opportunities and Challenges," *IEEE Trans. Ind. Appl.*, vol. 56, no. 2, pp. 1306–1320, Mar. 2020.

[11] A. Selema, M. N. Ibrahim, and P. Sergeant, "Non-Destructive Electromagnetic Evaluation of Material Degradation Due to Steel Cutting in a Fully Stacked Electrical Machine," *Energies*, vol. 15, no. 21, p. 7862, Oct. 2022, doi: 10.3390/en15217862.

[12] R. Hemmati, F. Wu, and A. El-Refaie, "Survey of Insulation Systems in Electrical Machines," in *2019 IEEE International Electric Machines & Drives Conference (IEMDC)*, May 2019, pp. 2069–2076, doi: 10.1109/IEMDC.2019.8785099.

[13] Porsche AG; Amelia H., "Porsche Present 40% Lighter 3D Printed Electric Drive Housing," 2020. https://www.3dnatives.com/en/porsche-present-3d-printed-electric-drive-housing-261220204/ (accessed Dec. 18, 2022).

[14] J. Jaćimović *et al.*, "Net Shape 3D Printed NdFeB Permanent Magnet," *Adv. Eng. Mater.*, vol. 19, no. 8, p. 1700098, Aug. 2017.

[15] F. Bittner, J. Thielsch, and W.-G. Drossel, "Laser powder bed fusion of Nd–Fe–B permanent magnets," *Prog. Addit. Manuf.*, vol. 5, no. 1, pp. 3–9, Mar. 2020, doi: 10.1007/s40964-020-00117-7.

[16] A. Selema, M. N. Ibrahim, and P. Sergeant, "Additively Manufactured Ultralight Shaped-Profile Windings for HF Electrical Machines and Weight-Sensitive Applications," *IEEE Trans. Transp. Electrif.*, vol. 8, no. 4, pp. 4313–4324, Dec. 2022, doi: 10.1109/TTE.2022.3173126.

[17] F. Wu, A. EL-Refaie, and A. Al-Qarni, "Additively Manufactured Hollow Conductors Integrated With Heat Pipes: Design Tradeoffs and Hardware Demonstration," *IEEE Trans. Ind. Appl.*, vol. 57, no. 4, pp. 3632–3642, Jul. 2021, doi: 10.1109/TIA.2021.3076423.

[18] A. Selema, M. N. Ibrahim, and P. Sergeant, "Mitigation of High-Frequency Eddy Current Losses in Hairpin Winding Machines," *Machines*, vol. 10, no. 5, p. 328, Apr. 2022, doi: 10.3390/machines10050328.

[19] F. Wu, A. M. EL-Refaie, and A. Al-Qarni, "Additively Manufactured Hollow Conductors for High Specific Power Electrical Machines: Aluminum vs Copper," in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct. 2021, pp. 4397–4404, doi: 10.1109/ECCE47101.2021.9595470.

[20] A. Selema, M. N. Ibrahim, and P. Sergeant, "Electrical Machines Winding Technology: Latest Advancements For Transportation Electrification," *Machines*, vol. 10, no. 5, 2022.

[21] N. Simpson, D. J. North, S. M. Collins, and P. H. Mellor, "Additive Manufacturing of Shaped Profile Windings for Minimal AC Loss in Electrical Machines," *IEEE Trans. Ind. Appl.*, vol. 56, no. 3, pp. 2510–2519, May 2020, doi: 10.1109/TIA.2020.2975763.

[22] A. Selema, M. Gulec, M. N. Ibrahim, R. Sprangers, and P. Sergeant, "Selection of Magnet Wire Topologies With Reduced AC Losses for the Windings of Electric Drivetrains," *IEEE Access*, vol. 10, pp. 121531–121546, 2022, doi: 10.1109/ACCESS.2022.3222773.

[23] N. Simpson, S. P. Munagala, A. Catania, F. Derguti, and P. H. Mellor, "Functionally Graded Electrical Windings Enabled by Additive Manufacturing," in *2022 International Conference on Electrical Machines (ICEM)*, Sep. 2022, pp. 1477–1483.

[24] A. Selema, M. N. Ibrahim, R. Sprangers, and P. Sergeant, "Effect of Using Different Types of Magnet Wires on the AC Losses of Electrical Machine Windings," in *2021 IEEE International Electric Machines & Drives Conference (IEMDC)*, May 2021, pp. 1–5, doi: 10.1109/IEMDC47953.2021.9449507.

[25] P. Mellor, J. Hoole, and N. Simpson, "Computationally efficient prediction of statistical variance in the AC losses of multi-stranded windings," in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct. 2021, pp. 3887–3894, doi: 10.1109/ECCE47101.2021.9595867.

[26] M. N. Ibrahim *et al.*, "Directly Cooled Windings in Switched Reluctance Machines," in *2020 International Conference on Electrical Machines (ICEM)*, Aug. 2020, pp. 819–825.

[27] N. A. Rahman, E. Bostanci, and B. Fahimi, "Thermal analysis of switched reluctance motor with direct in-winding cooling system," in *2016 IEEE Conference on Electromagnetic Field Computation (CEFC)*, Nov. 2016, pp. 1–1, doi: 10.1109/CEFC.2016.7816110.

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