Challenges and Future Opportunities of Hairpin Technologies

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Abstract— **Hairpin windings are seeing an ever-increasing application and development in electrical machines designed for high power and torque densities. In fact, due to their inherently high fill factor, they are very attractive in applications, such as transportation, where these characteristics are considered main design objectives. On the other hand, high operating frequencies also contribute to improve power density of electrical machines. However, at high fundamental frequencies, hairpin windings are characterised by increased Joule losses due to skin and proximity effects. Hence, while these technologies are introducing new opportunities, a number of challenges still need to be addressed. These include manufacturing aspects, contacting processes, thermal management, etc. This paper presents an overview of the current state-of-the-art of hairpin technologies and propose possible future opportunities. The authors' perspective is then finally provided, showing how innovative winding patterns can potentially overcome the above mentioned challenges.**

Keywords—fill factor, hairpin, contacting, modelling

I. INTRODUCTION

In the last years, there has been increased need and attention towards greener, lighter, more efficient and reliable technologies in all industrial fields [1]. Among these, the automotive, marine and aerospace industries are replacing their traditional hydraulic, pneumatic and mechanical systems with electrical ones, as this has allowed to achieve significant reductions in fuel use and/or emissions [2]. Therefore, electrical motors and generators are assuming an ever-increasing role in these sectors. The performance of vehicles is very sensitive to the components' power/torque and mass. Hence, nowadays, maximisation of power-to-weight and/or torque-to-weight ratios represents always a primary objective when designing electrical machines and, in general, electric drives for transportation applications.

A number of methods are available for increasing power density in electrical machines [3]-[4]. However, simplistically, two main knobs can be manipulated to maximise it: the output torque and the angular speed. According to the Lorentz force method, the maximum ratio of electromagnetic torque to rotor volume in an electrical machine can be expressed as the product between magnetic and electric loadings [5]-[6]. The electric loading deals with the conductors' current density and thus relies on the cooling system. Hence, today, there is an ever-increasing need of powerful computational tools to analyse complex thermo-fluid phenomena, innovative cooling systems to increase the current density and new insulation materials to withstand very high temperatures [7]-[8]. On the other hand, there is also interest in exploiting new materials [9] featuring excellent magnetic characteristics to increase the magnetic loading.

The angular speed represents the second knob for maximising the power density, and increasing it allows to achieve more compact and lighter designs [3]. Therefore, besides their magnetic properties, the materials employed in today's electrical machines must feature good mechanical properties to withstand the high speeds required today.

In addition to this researches at machine-level, a lot of improvements have been done at power electronic-level, where the arrival on the market of new power devices based on wide bandgap semiconductors are enabling higher fundamental frequencies [10], [11]. However, to fully exploit these new opportunities, a number of challenges need to be addressed. In fact, as higher operating frequencies contribute to improve power density of machines, they also reflect on increased power losses in cores and windings [12], as well as faster devices commutations are known to trigger partial discharges and faster degradation of coil insulation [13], [14].

Table 1 summarizes the key enablers for power density discussed above. The two main branches, i.e. torque and speed, are highlighted. In the table, it can be observed that a communal enabler for both parameters is represented by winding technologies. Windings are currently a main bottle-neck for improved performance. Whilst techniques such as hairpin windings have been developed, these are often limited to solid conductors resulting in high AC losses.

Table 1: Summary of the key enablers for power density maximization in electrical machines

<table>
<tr><th rowspan="3">Power density</th><th>Torque</th><th>Speed</th></tr>
<tr><td>Air gap flux density
E.g. improved electromagnetic properties of materials
Linear current density
E.g. new cooling systems and improved thermal management
Operating conditions
E.g. innovative tools of analysis, optimal control</td><td>Mechanical properties of materials
E.g. increased yield strength with no impact on magnetic properties
Optimal machine design
E.g. optimal pole pair number, interaction with converter design
Parasitic effects
E.g. compensation for skin effect, increased reliability</td></tr>
<tr><td colspan="2">Winding technologies
○ Decrease winding resistance, e.g. through larger wire diameters, reduced end winding lengths
○ Decrease AC parasitic effects, e.g. through multi-stranded and smaller wire diameters, reduced stray inductances via optimal end winding shape
○ Increase fill factor, e.g. through pre-formed profile wires</td></tr>
</table>

To cope with the desire of operating at high fundamental frequencies (>1kHz), coils are often required to be multi-stranded with small cross-sectional areas or Litz-wire to reduce losses and with appropriate insulation to withstand the fast switching edges. This in turn leads to poor overall fill factors, large end windings, higher coil thermal resistance, and higher likelihood of winding failure. New winding concepts and manufacturing techniques are thus required to mitigate these, as high reliable and power dense machines require high fill factors and low losses in automotive and aerospace environments. This paper reviews the methods for increasing the fill factor, focusing on the hairpin technologies, their challenges and future opportunities.

II. Round vs. Rectangular Conductors' Cross Sections

The electric fill factor is defined as the ratio of the amount of electric conductor material A_{copper} (with no insulation) to the available winding space A_{slot}. It has a significant impact on the power density, but also on thermal conductivity, manufacturability and overall costs [15]-[17]. The fill factor has a direct correlation with the current density limitations and thus on torque and power. In general, high fill factor means high conductor area with respect to the slot's one. This ensures higher thermal conductivity, as proven in [18], since the amount of copper is larger compared to dielectric material, that suffers from higher thermal resistance. Improvements in the insulation material thermal properties can reduce the thermal stresses, due to the higher capability of heat dissipation, allowing higher temperatures in the machine. For example, in [19], the 60% increase in the stator current density is predicted at the cost of a temperature rise by 70 °C (from 130 °C to 200 °C).

In simplistic terms, two main families of conductors can be defined according to their cross section: round and rectangular wires. While round conductors inherently feature low fill factors, rectangular wires match well with the slot shape and they are thus characterised by high fill factors. However, in high-frequency applications, round conductors are still preferred and several methods are used to increase the fill factor. These are discussed in the next sub-section.

A. Round Conductors

The insertion mechanism of round conductors within the slot affects the fill factor of such type of winding. As reported in [20], wires can be located in the slot with different patterns.

The winding mechanism can occur randomly and thus a random winding is achieved as shown in Fig. 1a. This is the most common solution for an automated process and big scale production, but achieves very low fill factors, usually lower than 55% [21], [22]. A second winding mechanism consists in placing tidily the wires in layers, as seen in Fig. 1.b This winding type, known as layer winding, can reach higher fill factors than random windings, but only when these layers are placed as in Fig. 1.c the fill-factor can rise up to 75% [23]. In this case, an orthocyclic winding is realised. Layer and orthocyclic windings can be achieved using special needle machineries. With this technology, each wire is precisely placed inside the slot in its desired position.

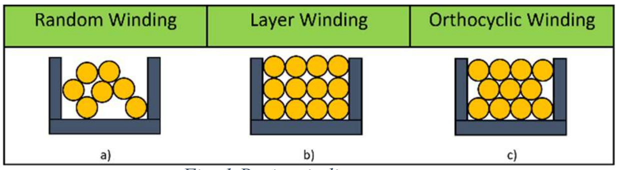
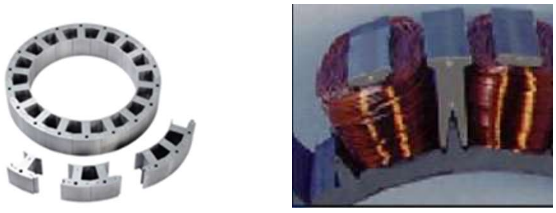


Fig. 1 Basic winding patterns

Another way to improve the fill factor of round wires is to use a segmented stator, as reported in Fig. 2.a [24]. Here fill factors up to 60% can be achieved, but the design is limited to only concentrated windings, since the winding is wound directly on the tooth. Concentrated windings have advantages like shorter end windings (reduced copper loss) and higher fill factor compared to distributed windings, but they come at the cost of a lower fundamental of flux linkage and induced voltages [25] and higher eddy current losses in permanent magnets (when present).

To achieve even higher fill factors, in some cases on-tooth coils can be pressed as shown in Fig. 2.b [26], [27]. With this technology, the fill factor is ≈80%, since the coils are wound directly on the tooth. Similar values of fill factors have been achieved by using soft magnetic composite structures and prepressed windings [28]. The purpose of this process is to lower the amount of voids in the windings, but the process is limited by the deformation and by the mechanical properties of the insulation layer [29]. In [30], a 75% slot fill factor is obtained by using a "joint-lapped core".



a) b)

Fig. 2: a) segmented stator [49] and b) laminated plug-in tooth

In [23], the round wires are squared by lamination, thus achieving a fill factor of ≈83%. Even in this case the insulation material was under investigation to ensure no electric faults in the coils.

Another solution that does not require concentrated windings or deformation of the coil insulations is presented in [31]. In that work, a new segmented stator geometry allowing for a distributed winding to be implemented is proposed: the windings are mounted on a flat band-shaped stator that is bent and welded in a second moment.

B. Rectangular Conductors

As anticipated above, using conductors with a rectangular cross section can enhance the fill factor. As observed in Fig. 3 [22], [32], this technology ensures the complete filling of the slot obviously excluding the percentage of dielectric materials. Conductors with rectangular cross sections are extensively used in high-voltage, high-power synchronous generators featuring open slot structures and double layer windings [33]. More recently, bar-wound layouts obtained from preformed elements made of enamelled wires have been also implemented for stator windings. These are known as hairpin windings and the aspects relative to their manufacturing and contacting processes are detailed in the next section, where the main challenges associated to them are also discussed.

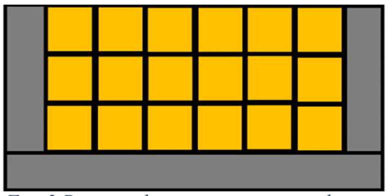


Fig. 3 Rectangular cross section conductors

III. Hairpin Windings: Current Technologies and Challenges

A typical "hairpin" is reported in Fig. 4. Since they are characterised by a rectangular cross section, the electric fill factor can achieve values of 80-85% in machines where they are employed [21].

Fig. 4 Bended conductor with a rectangular cross section: the hairpin

A. Manufacturing process

The manufacturing process of hairpin windings equipping electrical machines' stators can be divided in 4 main phases: shaping, assembly, twisting and contacting. These 4 steps can be schematically observed in Fig. 5. First, the rectangular conductors are bent to achieve the hairpin shape (phase 1) [35]. Here, different shapes of hairpins can be realised depending on specific design envisioned. The shaping phase can be very complex if performed "manually", i.e. with no automation of the process [21], [36]. Therefore, in order to reduce the production times, an automatized mechanism is usually utilised. The insertion mechanism (phase 2) is obtained introducing each hairpin in the slots. The complete pattern of hairpin windings defined during the machine design is achieved by using a gear element which twists (phase 3) the free ends of all of the hairpins, placing these ends in the most appropriate position for the contacting step (phase 4), obviously considering the coil pitch selected during the design stage. Finally, to ensure electric continuity between hairpins, the contacting process (phase 4) is performed [22]. The transposition mechanism is performed after phase 4 to reduce the Joule losses within the conductors. When *n* parallel paths are considered, transposition of conductors must be performed *n*-1 times forcing current to experiment same deviation along a single path [37].

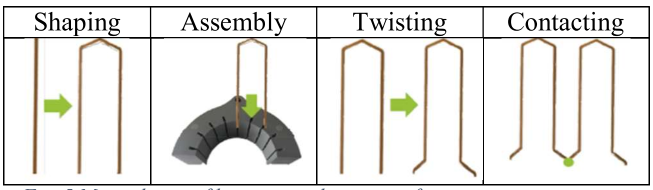


Fig. 5 Main phases of hairpin windings manufacturing

B. Contacting techniques

Contacting between two terminals of different hairpins is considered a crucial point by electrical machines' manufacturers in defining the efficiency of the whole technology, as it involves the qualification of the contact resistance and the characteristics of the manufacturing process. The choice between welding or soldering techniques is influenced by both these aspects [21]. According to [22], the "*resistance welding"* pros are mainly related to the ease of mass production due to the process' low costs. Automation of the process is possible and the associated cycle time is low. A limited flexibility and accessibility are observed in this process due to complexity of the plant structure. It lacks of process stability due to electrode wear.

In "*ultrasonic welding"* the contacting process is obtained by high frequency vibrations of the materials involved. This solution is cheaper than "*laser welding"*. Additional benefits include the short cycle time and the possibility of automation. However, the high frequency vibrations are a potential source of damage of the material structure, so quality and reliability may be compromised [21].

"*Laser welding*" represents another welding technique applied in the electric motors' production chain involving hairpins. The contacting resistance reaches values much lower than that considered as reference for hairpins, i.e. the hairpin active part resistance [21], [22], [39], [40]. It allows high accessibility in the process, the materials involved during welding experience low damage during the process so the wear of components is acceptable. Most importantly, from a mass production point of view, laser welding ensures a low cycle time, i.e. high number of contacts per time unit, and the automation of the process is easily obtainable [16]. With the advent of machine learning, laser welding performance is improved as the contacting surfaces between two terminals are opportunely controlled to perform the best welding [41]. "*Wobble beam*" represents a particular laser appliance used to reduce damage in the contacting frame. A spot smaller than the surface is obtained by moving rapidly the focused beam in such a way to describe a helix [42]. This solution allows high contacting quality. Laser technology is also exploited in stripping for insulator removal. This process allows for improvements in contacting as the insulation material must be totally out of welding area, in particular with the complementary actions of CO_2 and fibre laser [43]. Costs represent the main drawback of laser welding.

For single prototyping processes, i.e. no mass production, the suggested technique is manual soldering: it ensures high contacting quality between hairpins' terminals, high accessibility and the materials involved in the process experience low damage. The drawbacks of soldering are the long cycle time and the impossibility of automation [21]. Table 2 summarizes the main properties of welding and soldering techniques.

Table 2 Contacting technologies

Technologies	Automation	Flexibility	Tool Wear	Process Reliability	Accessibility	Cycle Time
Resistance Welding	+	o	--	o	o	+
Ultrasonic Welding	+	o	+	+	-	++
Soldering	--	++	++	-	++	o
Laser Welding	++	+	++	++	++	++

C. Recommended cross sections – technological limits

The dimensions of width and thickness of a hairpin are standardized by IEC 60317-0-2 [34]. In particular, the ratio between width and thickness is the most important parameter, i.e. recommended ratios are taken from the Rénard series R 20 and R 40 according to ISO 3, for mass production. Besides the actual dimension of the hairpin, the reference tables provide the most suitable insulation grade according to the considered application. When this standard is followed for the definition of a conductor, the related info is the reference to IEC specification, the nominal conductor dimensions in *mm* and the grade (defining the wire insulation thickness). The minimum suggested dimensions are 2*mm* for the width and 1.12*mm* for the thickness, while the maximum dimensions are 16*mm* and 3.15*mm*.

D. AC losses

Although hairpin windings ensure a higher fill factor than random windings with round cross section, their major limit of application is the high copper loss at high-frequency. At relatively high frequencies, in fact, skin and proximity effects cannot be neglected even when the minimum dimensions indicated in Section III:C are adopted.

When an alternating current flows in a solid conductor located in a slot and thus surrounded by ferromagnetic material, an alternating flux in the conductor material is produced. This alternating flux induces voltages and eddy currents trying to oppose the flux penetrating through the conductor. As a result, there will be internal "circulating" currents in the conductor summing to the conductor current. Therefore, the total current distribution becomes uneven, meaning that most of the current tends to flow through the area farthest from the centre of the round conductor. This phenomenon is called skin effect. The effective cross-sectional area through which the current passes is a fraction of the conductor's whole cross-sectional area. To differentiate from the value of the conductor resistance calculated on the actual value of the conductor cross section, i.e. the DC resistance, an AC resistance is defined.

The proximity effect, on the other hand, occurs when eddy currents are induced in a conductor due to the changing magnetic flux produced by the neighbouring conductors. This also causes a non-uniform current distribution within a conductor causing a higher copper loss. In addition, being the non-uniform current density within the conductors caused by the leakage flux, the conductors close to the slot opening have a higher variance in the current density distribution. All the above phenomena can be observed in Fig. 6, where an example with 4 conductors per slots is considered.

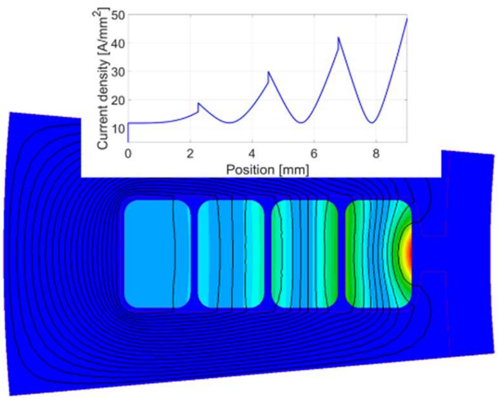


Fig. 6 AC losses: current displacement (f=1kHz)

In literature, several analytical methods have been used to predict AC losses [36]. In [37] the basic rules to design hairpin windings are provided. To reduce the AC losses, the transposition of the conductors is a key point [43]. Another method consists in reducing the dimension of each conductor and leave a free space near the slot opening [44]. A recent study has shown that it is possible to reduce the current density near the slot opening with an asymmetric bar layout, without increasing the manufacturing complexity [45].

IV. Future Opportunities

This section provides possible future developments in the field of hairpin windings, mainly aimed at overcoming their current limitations highlighted above.

A. Manufacturing challenges

1) Automation of the shaping process

As mentioned in Section III.A, shaping a hairpin is a crucial process. Machine learning is going to be very important since guarantees the possibility to modify the process parameters and finally to achieve the geometry targets required. This new technology can be implemented even in the already existing manufacturing chains.

Continuous hairpin windings, may allow improvements in reducing the number of welding points and cycle time too. The single conductor is formed by two continuous α-shaped coils. The winding process is easier compared to conventional, elementary hairpins and the process is still automatized [46]. However, open slot structures or novel stator layouts are necessary to allow their continuous insertion inside then slots.

2) Automation of the welding process

The welding process is one of the most critical aspects in hairpin production. As already introduced, laser welding seems to be the best solution in terms of productivity and feasibility. However, contacting is still a bottle neck and the process needs to be optimized. It is already possible to find in literature solutions that reduce significantly the number of welding spots [47], but these constrain the winding layout. For this reason, it is perceived that the research and industry worlds will focus on this aspect, especially with a view to mass production of hairpin motors, thus allowing the use of such technology also in aerospace applications.

B. AC losses challenges – innovative layouts

As mentioned above, AC losses represent one of the key limit for the widespread of hairpin windings at high rotational speeds / high frequencies, e.g. in the automotive field this limit is at ≈30krpm today. It is expected that alternative winding techniques will be introduced in the next coming years to reduce the AC losses and thus to increase this limit. Some examples are provided below.

1) Variable cross section conductors

Since the most loaded conductors are those closer to the slot opening (see Fig. 6), the basic idea consists of placing conductors with increasing cross sections along the radial direction, i.e. increasing thickness from the slot opening to the slot bottom, as schematised in Fig. 7. This solution is already under investigation [45] and the relevant results in terms of loss reduction seem to be promising.

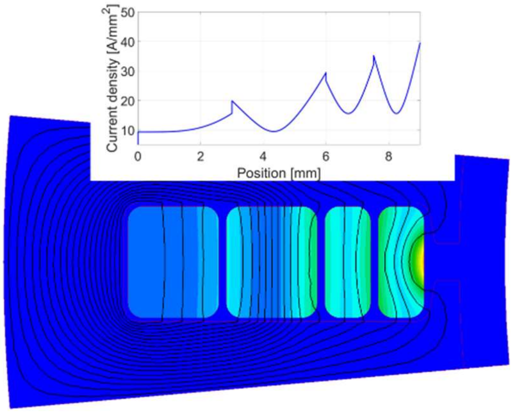


Fig. 7 Variable cross section conductors

2) Parallel paths

Another way to possibly reduce AC losses in hairpin windings is to consider parallel paths, as shown in Fig. 8. This method consists of dividing the hairpins near the slot opening (the last 2 in the example of Fig. 8) in sub-conductors, conceptually similarly to subdividing the round conductors in strands (or Litz). However, this solution entails the adoption of a suitable transposition, otherwise the parallel conductors act as a unique equivalent one, thus making basically useless this method. This solution seems to be particularly promising since the losses drop significantly, as noticed in the current density graph of Fig. 8.

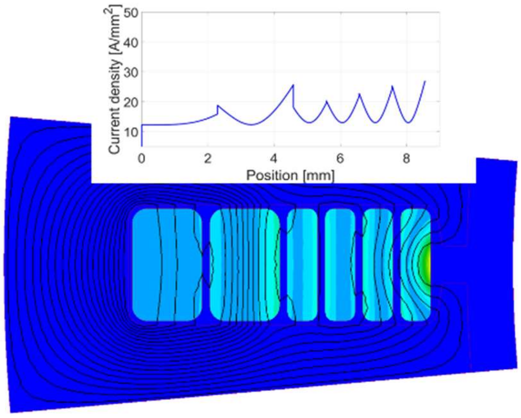


Fig. 8 Parallel conductors

3) Hybrid solutions

Theoretically, even a solution that is a mid-way trade-off between the variable cross sections and the parallel conductors can be implemented. This hybrid layout is also currently under investigation.

4) Impact on manufacturing process

Although the above techniques might effectively lead to improved scenarios of AC losses, their impact on the manufacturing should be carefully evaluated. Designing the conductors with variable cross section is challenging since this implies that the two "legs" of an elementary hairpin would be different, i.e. a different production method must be used for production (e.g. 3D printing). Another way is to maintain the size of the conductors equal for two layers, as described in [45], with no added manufacturing complexity. In the case of parallel paths, it is important to notice that the number of welding spots increase. Therefore, ways to mitigate this challenge should be investigated in future.

C. Thermal management

A better thermal management is achieved when adopting hairpin windings, as opposed to round conductors. However, due to the inherently high copper losses at high frequencies, in [48] hollow and u-profile conductors, i.e. cooled conductors, are proposed. This allows for an axial coolant to flow through the machine, but comes at the cost of decreasing the fill factor within the slot. Nevertheless, thanks to a better cooling and thermal management, a higher current density is achieved. Always referring to [48], a comparison between oil-cooled hollow hairpins and solid ones is performed, proving that the former allows for higher torque capability, however coming at the cost of a lower efficiency.

It is perceived that future researches will focus on the cooling of the end regions of hairpin windings.

V. Conclusion

In this paper, the hairpin technologies and their inherently high fill factor were presented as potential enablers for power density enhancements in electrical machines mainly intended for transportation applications.

The importance of achieving high fill factors was first highlighted. Then, a review of the methods used to enhance it in electrical machines equipped with round conductors was performed. The focus was then moved to pre-formed conductors featuring a rectangular cross section, i.e. hairpins, showing that a significant increase in power density can be achieved just thanks to the higher fill factor than windings made of round and random wires.

The hairpin technology was then described in detail, highlighting the relevant manufacturing processes, the contacting techniques currently in use, the dimensional limits recommended by the standards and the challenges related to the AC losses. Finally, future opportunities are proposed.

The main objective of this paper was to describe the current state-of-the-art of hairpin technologies, taking into account the recent research and industry trends in the field. In this context, the final section of the paper represents the authors' vision to possible innovative scenarios and developments for hairpin windings.

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References

[1] M. Lukic, P. Giangrande, A. Hebala, S. Nuzzo and M. Galea, "Review, Challenges, and Future Developments of Electric Taxiing Systems," in *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, pp. 1441-1457, Dec. 2019.

[2] Dr J. Goss, CEO of Motor Design Ltd, Motor Design Limited, "Performance Analysis of Electric Motor Technologies for an Electric Vehicle Powertrain",2019

[3] M. Van der Geest et al., "Power Density Limits and Design Trends of High-Speed Permanent Magnet Synchronous Machines", IEEE Trans. Transport. Electrific, vol. 1, no. 3, pp- 266-276, 2015.

[4] Y. Wang, G. Vakil, S. Nuzzo, M. Degano, M. Galea, C. Gerada, H. Zhang, N. Brown "Sensitivity analysis for performance and power density improvements in salient-pole synchronous generators", IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), pp. 33-38, 2017.

[5] A. Tenconi, S. Vaschetto, and A. Vigliani, "Electrical machines for highspeed applications: Design considerations and tradeoffs," *IEEE Trans. Ind. Electron*., vol. 61, no. 6, pp. 3022–3029, Jun. 2014.

[6] Scitech Europa,"Ultra lightweight motors for the next electric vehicles", 25th March 2019

[7] A. Boglietti ; M. Cossale ; M. Popescu ; D. Staton, "Calibration Techniques of Electrical Machines Thermal Models", *2018 XIII International Conference on Electrical Machines (ICEM)*, pp. 1108-1115, 2018.

[8] K. Bersch, S. Nuzzo, P. H. Connor, C. N. Eastwick, M. Galea, R. Rolston, and G. Vakil, "Combined Thermofluid and Electromagnetic Optimisation of Stator Vent Cooling," in *23rd International Conference on Electrical Machines (ICEM 2018)*, pp. 1116–1122. 2018.

[9] A. Krings, M. Cossale, A. Tenconi, J. Soulard, A. Cavagnino, A. Boglietti,"Magnetic Materials Used in Electrical Machines: A Comparison and Selection Guide for Early Machine Design", IEEE, Nov.-Dec. 2017

[10] D. Barater, C. Concari, G. Buticchi, E. Gurpinar, D. De and A. Castellazzi, "Performance Evaluation of a Three-Level ANPC Photovoltaic Grid-Connected Inverter With 650-V SiC Devices and

Optimized PWM," IEEE Trans. Ind. Appl, vol. 52, no. 3, pp. 2475-2485, May-June 2016.

[11] D. Barater, E. Gurpinar, G. Buticchi, D. De, C. Concari, A. Castellazzi, and G. Franceschini, "Performance analysis of unitl-h6 inverter with sic mosfets," IEEE International Power Electronics Conference (IPEC), pp. 1-7, 2014.

[12] F. Savi et al., "High-speed Electric Drives: a step towards system design," in IEEE Open Journal of the Industrial Electronics Society. doi: 10.1109/OJIES.2020.2973883.

[13] D. R. Meyer, A. Cavallini, L. Lusuardi, D. Barater, G. Pietrini and A. Soldati, "Influence of impulse voltage repetition frequency on RPDIV in partial vacuum," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 3, pp. 873-882, June 2018. doi: 10.1109/TDEI.2018.006722

[14] P. Giangrande, V. Madonna, S. Nuzzo and M. Galea, "Moving Towards a Reliability-Oriented Design Approach of Low-Voltage Electrical Machines by Including Insulation Thermal Aging Considerations," *in IEEE Transactions on Transportation Electrification.* doi: 10.1109/TTE.2020.2971191

[15] J. Hagedorn, F. Sell-Le-Blanc, J. Fleisher, Handbook of Coil Winding – Technologies for efficient electrical wound products and their automated production. Springer-Verlag GmbH Germany, 2018.

[16] M. Popescu, J. Goss, D. A. Staton, D. Hawkins, A. Boglietti, Y. C. Chong; "Electrical Vehicles - Practical Solutions for Power Traction Motor Systems," in IEEE Transactions on Industry Applications 2018

[17] K. Hee Nam, "AC Motor Control and Electrical Vehicle Applications", CRC Press, 3rd September 2018

[18] M. Stöck, Q. Lohmeyer, M. Meboldt,"Increasing the power density of e-motors by innovative winding design",Product Development Group Zurich, Eidgenössische Technische Hochschule ETH Zürich, Switzerland, CIRP 25th Design Conference Innovative Product Creation, December 2015

[19] R. Ranjan, J. Tangudu,"Thermal Design of High Power-Density Additively Manufactured Induction Motors", United Technologies Research Center, East Hartford, CT 06118, 13 November 2014

[20] N. Raabe, "An algorithm for the Filling Factor calculation of electrical machines standard slots", 2014

[21] T. Glaessel, J. Seefried, J. Franke, "Challenges in the Manufacturing of Hairpin Windings and Application Opportunities of Infrared Lasers for the Contacting Process", Institute for Factory Automation and Production Systems, Friedrich-Alexander-University, Erlangen-Nuremberg, Germany, Tobias.Glaessel@faps.fau.de, 02 April 2018

[22] A. Riedel, M. Masuch, M.Weigelt, T.Gläßel, A. Kühl, S. Reinstein, J. Franke, "Challenges of the hairpin technology for production techniques", 2018 21st International Conference on Electrical Machines and Systems (ICEMS) October 7-10, 2018Jeju, Korea

[23] M. Venturini, A. Zorzi and M. Mazzucchelli, "Torque/volume increase in Permanent Magnet Synchronous Motors by fill factor enhancement," International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2018.

[24] T Albrecht, W Konig and B Bickel, "Proceedings for wiring integrated winding of segmented stators of electric machines," 2011.

[25] D. Fallows, S. Nuzzo, A. Costabeber and M. Galea, "Harmonic reduction methods for electrical generation: a review," in *IET Generation, Transmission & Distribution*, vol. 12, no. 13, pp. 3107-3113, 31 7 2018.

[26] M. C. Kulan, N. J. Baker and J. D. Widmer, "Design of a High Fill Factor Permanent Magnet Integrated Starter Generator with Compressed Stator Windings," 2016.

[27] M C. Kulan, N J. Baker and J D. Widmer, "Design and Analysis of Compressed Windings for a Permanent Magnet Integrated Starter Generator," IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, 2017.

[28] A. G. Jack, B. C. Mecrow, P. G. Dickinson, D. Stephenson, J. S. Burdess, N. Fawcett, and J. T. Evans, "Permanent magnet machines with powdered iron cores and pressed windings" *IEEE Trans. Ind. Appl.*, vol. 36, no. 4, pp. 1077–1084, Jul./Aug. 2000.

[29] M. C. Kulan, N. J. Baker and J. D. Widmer, S. M. Lambert,"Modeling the Mechanical and Thermal Properties of Compressed Stator Windings", 2016

[30] H. Akita, Y. Nakahara, N. Miyake, and T. Oikawa, "New core structure and manufacturing method for high efficiency of permanent magnet motors," *in Conf. Rec. IEEE IAS Annual Meeting*, vol. 2, pp. 367–372, 2003.

[31] S Makita, Y Ito, T Aoyama and S Doki, "The Proposal of a New Motor Which Has a High Winding Factor and a High Slot Fill Factor," 2014.

[32] Y. Zhao, "Overview of the Rectangular Wire Windings AC Electrical Machine" , Student Member, IEEE, Dawei Li, Member, IEEE, Tonghao Pei, Student Member, IEEE, Ronghai Qu, Fellow, IEEE, 2019

[33] S. Nuzzo, M. Degano, M. Galea, C. Gerada, D. Gerada, and N. Brown, "Improved Damper Cage Design for Salient-Pole Synchronous Generators," *IEEE Trans. Ind. Electron.,* vol. 64, no. 3, pp. 1958-1970, 2017.

[34] IEC 60317-0-2 Specifications for particular types of winding wires - Part 0-2: General requirements - Enamelled rectangular copper wire,IECwebstore, 2013-10-07, [Online]. https://webstore.iec.ch/publication/1347

[35] F. Wirth, T. Kirgör, J. Felischer,"FE-based Simulation of Hairpin Shaping Processes for Traction Drives",Institute of Production Science Karlsruhe Institute of Technology (KIT), IEEE, 2018

[36] T. Ishigami, Y. Tanaka, H. Homma, "Development of Motor Stator with Rectangular-Wire Lap Winding and an Automatic Process for Its Production", June 2014,Electrical Engineering in Japan 187(4)

[37] G. Berardi and N. Bianchi, "Design Guideline of an AC Hairpin Winding," 2018 XIII International Conference on Electrical Machines (ICEM), Alexandroupoli, 2018, pp. 2444-2450.

[38] N. Bianchi and G. Berardi, "Analytical Approach to Design Hairpin Windings in High Performance Electric Vehicle Motors," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 4398-4405.

[39] A. Kampker, K.D. Kreisköther, M. Kleine Büning, P. Treichel, M. Krebs, "EX-ANTE PROCESS-FMEA FOR HAIRPIN STATOR PRODUCTION BY EARLY PROTOTYPICAL PRODUCTION CONCEPTS",a.kampker@pem.rwth-aachen.de, 7 march 2019

[40] T. Glaessel, J. Seefried, M. Masuch, A. Riedel, A. Mayr, A. Kuehl and J. Franke,"Process Reliable Laser Welding of Hairpin Windings for Automotive Traction Drives", 10 October 2019

[41] A. Mayr, B. Lutz, M. Weigelt, T. Gläßel, D. Kißkalt, M. Masuch, A. Riedel, J. Franke"Evaluation of Machine Learning for Quality Monitoring of Laser Welding Using the Example of the Contacting of Hairpin Windings", 7 march 2019

[42] Coherent ROFIN, "Laser methods to support e-mobility", september-october 2018, AMS

[43] T. Glaessel, J. Seefried, A. Kuehl,J. Franke, "Skinning of Insulated Copper Wires within the Production Chain of Hairpin Windings for Electric Traction Drives", Institute for Factory Automation and Production Systems, Friedrich-Alexander-University of Erlangen-Nuremberg, Nuremberg, Germany, Email: Tobias.Glaessel@faps.fau.de, International Journal of Mechanical Engineering and Robotics Research Vol. 9, No. 2, March 2020

[44] C. Du-Bar, A. Mann, O. Wallmark and M. Werke, "Comparison of Performance and Manufacturing Aspects of an Insert Winding and a Hairpin Winding for an Automotive Machine Application", 2018

[45] S. Islam, I. Husain, A. Ahmed e A. Sathyan, «Asymmetric Bar Winding for High Speed Traction Electric Machines,» 2019.

[46] T. Ishigami, Y. Tanaka, H. Homma, "Development of Motor Stator with Rectangular-Wire Lap Winding and an Automatic Process for Its Production", Electrical Engineering in Japan, Vol.187 No.4 2014

[47] T. Ishigami, Y. Tanaka, H. Homma, "Motor Stator with Thick Rectangular Wire Lap Winding for HEV s", 2014

[48] A. Reinap, M. Andersson, F.J. Márquez-Fernández, P.Abrahamsson, M. Alaküla, "Performance Estimation of a Traction Machine with Drirect Cooled Hairpin Winding", Lund University, Sweden, 2019

[49] Segmented stator stack, PPM, [Online]. http://www.ppm.co.in/segmented-stator-stacks