Tiismus, Hans; Kallaste, Ants; Vaimann, Toomas; Rassõlkin, Anton; Belahcen, Anouar

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Oil Spray Cooling with Hairpin Windings in High-Performance Electric Vehicle Motors

Payam Shams Ghahfarokhi
Dep. Electrical machine and aparutus
Riga Technical University
Riga, Latvia
payam.shams@ttu.ee

Andrejs Podgornovs
Dep. Electrical machine and aparutus
Riga Technical University
Riga, Latvia

Ants Kallaste
Dep. Electrical Power Engineering and Mechatronics
Tallinn University of Technology
Tallinn, Estonia

Toomas Vaimann
Dep. Electrical Power Engineering and Mechatronics
Tallinn University of Technology
Tallinn, Estonia

Anouar Belahcen
Dept. of Electrical Engineering and Automation
Aalto University
Espoo, Finland

Antonio J. Marques Cardoso
Electromechatronic Systems Research Centre
University of Beira Interior
Covilhã, Portugal

***Abstract*—This paper presents a survey about implementing hairpin winding with an oil spray cooling system on the new generation of electrical vehicle (EV) motors as an option to produce high power density, high efficiency, cost-effectiveness, lightweight, reliable EV motors. It provides the advantages and drawbacks of this rectangular winding compared to random winding and considers the hairpin winding production aspects. According to the high AC losses of this configuration, the paper considers two conventional approaches for calculating these losses with their advantages and drawback. Then it proposes the novel hybrid FEA method for calculating the AC copper losses to overcome the weaknesses of analytical and numerical methods. Finally, it provides a holistic view related to the oil spray cooling of the electrical machine and points the future work associated with this cooling method**

Keywords—electrical motors, electric vehicle, hairpin winding, spray cooling, thermal management.

I. Introduction

The negative impact of combustion engines on global warming and greenhouse gas emissions enhances the demands for clean and green transportation systems and transport electrification at different levels, for an instant, electric vehicle (EV), electric aviation, and electric train [1]. The traction motors' demand metrics are mainly concentrated on high power density, high efficiency, cost-effectiveness, and lightweight [1], [2].

One of the options to achieve the high power and torque density for automotive traction motors is altering the traditional stranded winding with hairpin winding. Accordingly, in recent years this winding configuration is becoming a more popular and attractive solution to the electrical motor for traction applications [3], [4], and [5]. Different automotive companies have started implementing this winding configuration on their new generation of electrical engines, such as GM-Volt-Motor and Chevrolet-Volt [5].

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However, to achieve cost-effectiveness and lightweight demand metrics, the automotive company starts to manufacture EV motors with compact structures that generate a few dozen kilowatts. Therefore, the standard air-cooling method [6], [7], and [8] and cannot provide sufficient cooling conditions for the high-power density and compact motors; and, there is a need for novel cooling methods.

In the first generation of the EV motors, mainly indirect liquid cooling, was implemented. In this cooling approach, the liquid jackets surround machine housing. However, this cooling approach has a long conduction path from the slots as hot spots with low conductivity to active cooling. Also, it cannot provide the proper cooling for the end winding and the rotor. To improve the cooling condition for EV motors, direct liquid cooling (DLC) techniques such as semi-flooded cooling was introduced. In semi–flooded cooling, the segregated sleeve was used to generate the liquid fluid path and generate the wet chamber (stator) and dry chamber (rotor). But as the EV motors are still evolving based on the demand metrics, new types of machines with new cooling systems are needed. The best options for EV motors are the interior permanent magnet synchronous motors (IPSM), and permanent magnet assisted synchronous reluctance motors (PMASynRM). Increasing the price of rare earth materials and the negative environmental impacts of producing the magnet from rare earth material [9]; leading the automotive industries to develop reduced rare-earth or rear earth-free motor topologies [9]. For this purpose, reducing the size of the air gap is essential, and the semi-flooded method cannot help to reduce the size of the airgap.

To overcome the above problem, one solution is to implement the novel oil spray cooling on EV motors as the latest cooling method. For instance, Toyota Company unveiled the combination of the hairpin winding and direct oil spray cooling method in its latest Toyota Prius [10]. This cooling enables to cool the end winding and rotor directly.

This paper provides a comprehensive study on the hairpin configuration as a novel winding for the e-mobility motor. In the beginning, the hairpin winding structure and design principle are discussed in detail. Then, according to the high impact of AC copper losses on the EV motors' efficiency, the various calculation methods of these losses will consider their advantages and drawbacks. Finally, the paper provides a holistic view of the oil spray cooling as the proper thermal management method for this winding and gives the perspective to improve this cooling method.

II. Hairpin Winding and Production Aspects

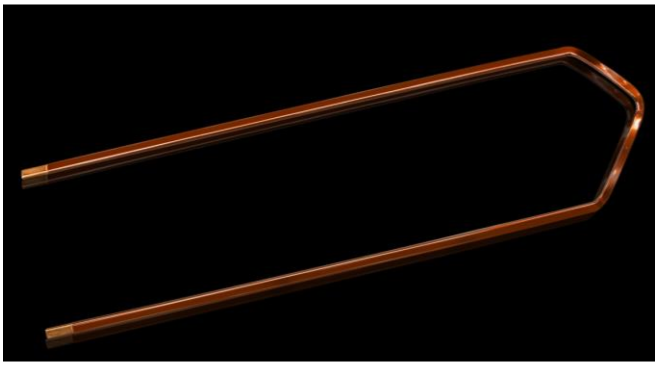

Fig. 1. Configuration of the rectangular hairpin.

The hairpin winding's name comes from its shape, which is formed in advanced [3]. As seen in Fig. 1, this type of winding has a rectangular cross-section inserted to the rectangular slots and bent. Finally, As illustrated in Fig .2, they are welded to the corresponded conductor to form the lapped winding configuration.

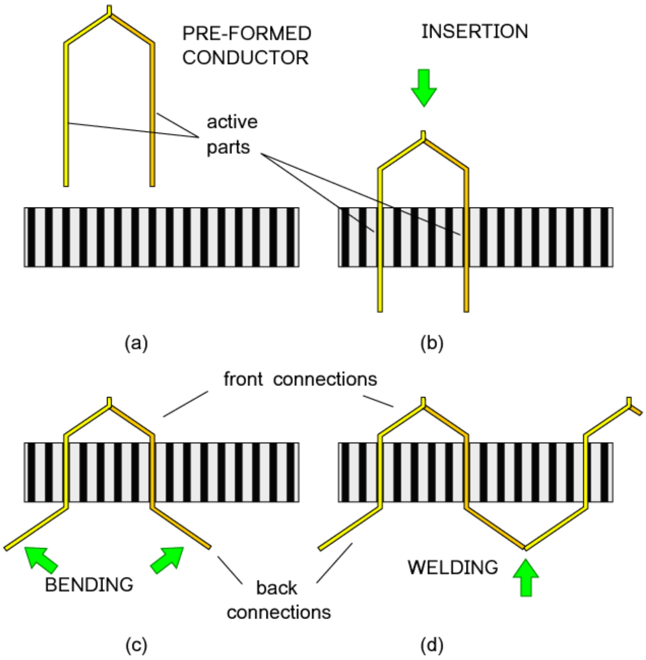

Fig. 2. Hairpin winding concept [3].

This winding configuration has numerous advantages compared to the conventional stranded winding, more straightforward manufacturing process, handle higher current density, higher slot filling factor, good thermal performance, shorter end winding, lower DC electrical resistance, and lower manufacturing time and cost [11], [12]. However, this winding configuration has low flexibility in the motor design, and it has a higher amount of AC losses. The higher AC copper losses are coming because from a manufacturing and practical perspective, the maximum number of conductors in the slot is restricted between 8 and 10 [13].

Several research studies are dealing with the design of the hairpin winding configuration for EV motors[3], [4], and [12]. In their research, it turns out defining the correct position of rectangular conductors in the slot. There are two basic rules- layer arrangement and slot per pole arrangement

The layer arrangement rule comes from the fact that the conductor resistance and impedance in slot layers of AC machine are not equal [3], [4]. Hence, the conductor layer closer to the air gap has a higher resistance and lower inductances [3], [4]. As equal impedances for the parallel path is essential, special attention must be on the correct connection and transposition of the conductors from slot to slot [3], [4]. Meaning, the wire belongs to the one winding path should be located in all the layers of a slot (according to the various values of the conductors' impedances in different layers) [3], [4].

Similarly, for the slot per pole arrangement, when the number of slots per pole and per phase is higher than unity ($q > 1$), the electromotive force (EMF) induced in the adjacent slots' conductors is different. The angular displacement corresponds to an electrical angle $\alpha^e = 360 \cdot p/Q$ (where p is the number of pole pairs, and Q is the total numbers of slots) [3], [4]. It follows that conductors of the same phase located in adjacent slots have to be series-connected. Accordingly, the law is described as follows: the wires that belong to the same winding path have to be placed in all the slots per pole per phase, no matter which layer. This is because the electromotive forces induced in one slot differ from the other when $q > 1$[3], [4].

III. AC Copper Losses

The challenging parameter in the hairpin configuration is the high value of AC copper losses. Fig. 3 shows the ratio of AC to DC winding losses at various frequencies for different conductor numbers in the slot with constant current density. The ratio increases by enhancing the frequency and became more severe in high-speed operation. By increasing the number of conductors and reducing the rectangular conductor area, we can minimize these losses. However, it is still a significant value during high-frequency operation. Therefore, the accurate calculation of the AC copper loss in the early stage of design is of particular importance and directly impacts thermal modeling accuracy.

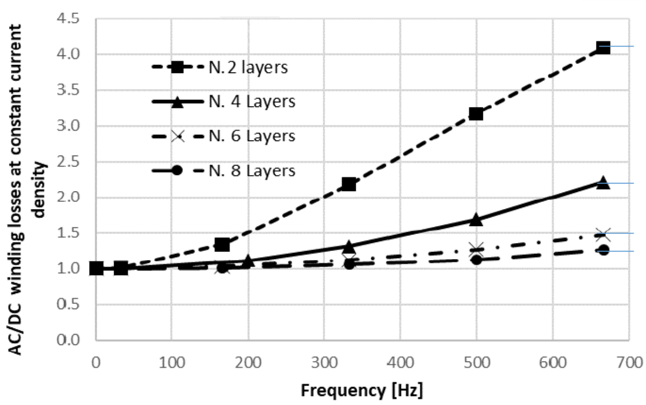

Fig. 3. The ratio of AC /DC copper losses in various frequencies [14].

The AC copper losses are calculated mainly using an analytical approach and finite element analysis (FEA). There are several different papers considering the calculation of the AC copper losses using analytical calculation [15], [16], and [17]. This method has some benefits, such as easy setup and computational efficiency. However, this method's drawbacks are the possibility of inaccurate results and the inability to consider complex winding distributions, higher-order harmonics, and non-linear behavior. Furthermore, in certain hairpin-winding configuration, the skin effect starts to dominate by increasing the frequency, and it is a big challenge to calculate it by using an analytical approach.

The most accurate method that can be applied to compute the AC copper loss is the FEA method. There are different research papers considering how to calculate the AC copper losses by the FEA method [18], [19], and [20]. In this method, the Maxwell equations are solved and integrated into mesh subdomains. For example, to calculate the eddy current, each wire is subdivided into fine elements with an element size smaller than the skin depth. Accordingly, it has a very long set up and computational time for multi-turn winding. Thus, it is mostly used for complex geometry with complex winding distributions. As mentioned, we face two approaches: fast but inaccurate, and the other is exact but with high computation time. The researchers start developing the new strategy by the title of the hybrid FEA to overcome the drawbacks of these two methods and utilize the advantage of two previous ways. It means the technique with appropriate accuracy and fast computation time

The hybrid FEA is composed of analytical and FEA methods. In this new method, analytical formulations are used. Instead of utilizing the analytical calculations regarding flux density values in the slot, flux density values are determined by the FEA approach [21]. For this purpose, The flux density distribution in the slot cross-section is evaluated at different layers in the slot [21]. Most of the mentioned papers consider calculating the AC copper losses for the conventional stranded winding, such as Litz winding, round conductor, etc. Simultaneously, only a few papers, such as Volpe et al., [5] considered the AC copper loss for hairpin winding. They implemented this method for hairpin winding and compared the results with the FEA method. Based on their observation, the hybrid FEA method is ten times faster than pure FEA, and the model can be solved in a few seconds. Besides, the maximum error of this method is smaller than 15%

IV. Oil Spray Cooling Method

Choosing the correct thermal management system has numerous effects on the amount of heat evacuation of the EV motors that directly impact the machine's power rating and temperature-sensitive components' reliability. The oil spray cooling method is one of the latest cooling trends implemented on electrical motors. This method reduces the conduction path from the windings to active cooling, creating enormous heat energy and reducing surface temperature. Another advantage of the method is the temperature uniformity, which protected the machine end windings from a hotspot.

This cooling method consists of the closed-loop system, including coolant, tank, pump, nozzles, and cooling temperature unit. In this system, the pump enhances fluid pressure from the tank to the nozzle. Then the nozzle alters the liquid into small droplets and spread them to the hot surfaces. In the end, the excess coolant liquid is gathered and send to the temperature control unit to remove the heat and prepare for recirculating.

Nozzle and coolant are the most challenging parameters in this system. Several research studies investigated to select the alternative coolant and nozzle for spray cooling of the current-carrying components [11], [22], [23], [24]. Proper coolant for spraying electrical components must follow the below requirements [23],[25]:

- Good environmental adaption,
- Hight safety,
- High dielectric strength,
- Good material compatibility.

The appropriated nozzle must have the following conditions:

- Working with high viscosity coolant material
- Working with high pressure
- Having the proper spray pattern.

The spray cooling approach itself is not a novel method, and there are numerous research studies in this field [26], [27]. However, these studies are mostly related to thermal engineering devices such as computers, power electronics, and satellite rather than the motors windings; as a result, they are less suitable for electrical machines.

The earliest study on implementing this cooling technique for electrical machines was presented by Li Zhenguo et al. [22], [28], where they utilized it for a large electrical machine. Based on their result, the spray cooling provided better cooling in comparison to the immersion coolant system. However, they used the fluorocarbon family as a coolant, which knows as a refrigerant family. This type of coolant increases the cooling system's complexity and mainly focuses on the system's phase changeability. One of the first research on implementing this system on the EV motors was provided by Davin et al. [29], [30]. They considered the effect of this cooling approach on the motor's end winding and tried to determine the heat transfer coefficients by the inverse method. However, they used only one nozzle in their research with a fixed location.

In recent years, some researchers such as Lim et al. [31], [32] and Park and Kim [46] studied the possibility of the spray system from the rotor shaft for in-wheel motor using numerical and analytical methods. The drawbacks of the oil spray cooling system on the rotor shaft are that it could not provide good oil atomization, and its performance depends on the rotor speed.

Liu et al. in [11], [33] provided the latest and comprehensive study about oil spray cooling systems. They implemented this cooling system on the motor with a hairpin winding configuration. They proposed the correlation using the reduced-parameter model to estimate the heat transfer coefficient (HTC) of spray cooling on hairpin winding. For this purpose, they developed the test rig (Fig. 4) to consider the effect of different parameters (flow rate, pressure) and various types and numbers of nozzles (full cone, hollow cone) on the cooling performance. However, they did not consider the effect of the rotational rotor speed and its impacts on spray cooling.

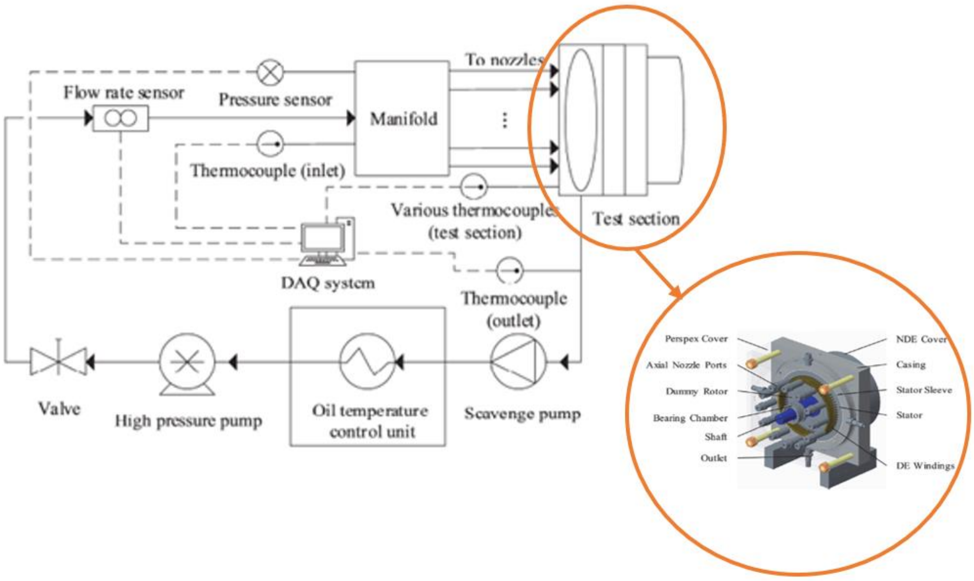

Fig. 4. Test rig [8].

The oil spray cooling for electrical machine seams promising solution. But it still needs more development and research work. It is necessary to deal with both the cooling method and also the system development. There is a need to develop the analytical correlation to calculate the HTC from the machine end winding. Further, it needs to improve and increase the numerical method's role to predict the thermal and fluid flow behavior during the design process. Besides, the best solution for the system components like nozzle, lubricant oil has to be found.

V. Conclusion

The paper provided an overview of the hairpin winding technology with oil spray cooling as the latest cooling technology as an excellent option for EV motors to achieve high power density, high efficiency, cost-effectiveness, lightweight, reliable operation. In the first part, the hairpin winding and its advantages, drawbacks, and production aspects were considered. According to this configuration's high AC losses, the paper investigated two conventional methods for calculating these losses with their advantages and drawback. Then it proposed the novel hybrid FEA method for calculating the AC copper losses to dominate the disadvantages of analytical and numerical methods. Finally, it provided a holistic view of the electrical machine's oil spray cooling and reviewed all the papers.

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