Innovative Design of the Cooling Topologies for Electric Vehicle Motors

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Abstract. According to the different cooling medium, the electric motor cooling styles can be divided into liquid cooling and air cooling; the former involves water cooling and oil cooling while the latter comprises natural air cooling and forced air cooling. Whereas, the air cooling system is difficult to meet various performance requirements for the modern Electric Vehicle (EV). Therefore, approximately all EV motors are liquid cooled at present. Moreover with the trend of EV motors to Permanent Magnet (PM) and to high speed, for instance, the maximum working rotated speed from 10,000rpm to 20,000 rpm, the packaging of the motor is minimizated at same power while efficiency drops, lifetime shorten even cause demagnetization due to thermal effects without optimum design. Consequently, the improvement of the liquid cooling system is essential to enhance the efficiency of the EV motor in the future for higher power density. In this perspective, the innovative cooling topologies of electric machines based on the development results of the parts such as lubricating oil and motive seal of electric vehicles are presented in this paper. It solves some problems brought about by predecessors in view of the high efficiency and reliability of the motor with higher energy density.

1. Introduction

For sustainable and green future, it is crucial to reduce the use of an internal combustion engine from the transportation; electric motors ought to be used. Many researchers have been working on the cooling system of the EV motors in recent years. For the cooling of EV motors, investigators are using two basic methods: air cooling and liquid cooling. Air cooling further can be split into natural air cooling and forced air cooling. Since it’s relatively low heat transfer coefficient, the electric motors of EV are mostly cooled by a liquid cooling system nowadays that consists of water cooling and oil cooling. Usually, water used in cooling jackets for indirect cooling and oil enter in the internal part of the motor to cool the hot spot directly. The development of the electric motor, particulary PM motor leads to several improvements, for example, the maximum rotated speed rises from 10,000rpm to 20,000 rpm, power density becomes high, mass is reduced, and diameter and axial length become smaller. However, heat generated from the electric motor is increased. Therefore the performance and the lifetimes of these machines are easily affected by the thermal condition [1], and the flow structure has a significant impact on the overall thermal performance of the cooling design [2]. Optimum design of the motor cooling system will surely play the vital role in improving efficiency, prolonging service
life, and preventing demagnetization of the permanent magnet as well as the insulation of coils. Furthermore, thanks to the development of the motive seal, high speed bearing and new fluid for e-axle that the key attributes are durability at low viscosity, copper corrosion protection, excellent oxidative stability and thermal management, foam suppression and high speed operation, etc. in this way, we have immense possibilities and suitable conditions for the cooling topologies of the electric motor.

In 2014, Zhang Fengge proposed three cooling schemes combined with air cooling and water cooling for a 1.12MW PM motor[3]. Comparing and analyzing the temperature field, it is concluded that the temperature rise of the rotor is the key point in the design of the cooling system. In 2015, BAE Systems publishes a patent in which the stator is cooled by the oil from the rotated rotor with the cooling flange [4]. Its purpose is to effectively cool the motor and develop the motor performance. An IEEE paper mentions the evolution and cooling methods of electric motor [5]. Christian Paar concluded that specific thermal optimization of the electric motor considering its thermal environment and operating profile permits a better meeting of customer requirements such as packaging, weight, performance, and cost [6]. In the same year, Tesla Motor, Inc. reveals a liquid cooled motor based on pressure and gravity [7], which is characterized by the shape of the oil tray and the design of a drainage plate under the action of gravity to make the oil dispersed in contact with the expected components to avoid the blocking of the openings. It does not depend on the size and quantity of the openings commonly using in only pressure-based distribution. The difficulty is that the dispersal of gravity cannot guarantee the cooling effect of the lower part of the motor. So the lower part may overheat, which puts forward higher requirements for the thermal stability of the stator and rotor materials of the motor.

In 2016, a paper said that the high temperature of rotor produced by losses is one of the important issues for the high-speed electric motor, and it has great significance for the cooling design topologies to enhance the motor’s efficiency [8]. Shanghai Dajun Technologies Inc. introduces a new type of oil cooling motor characterized by spraying the wire bag and iron core to overcome the defects of the water cooling motor and improve the power density [9]. Daniel publishes a patent of the liquid cooling motor with the motive seal to set an injector that moves relatively towards the stator winding [10]. The target is to eliminate the coil erosion and the adverse effects of the oil-air mixture on the performance of the oil pump after the spray of cooling fluid. LASSILA shows a liquid cooling motor through the eccentric setting of the injector nozzle and some former ways to make the relative motion between the oil injector and coil [11]. The goal is to avoid corrosion as well as local overheating. In 2017, Zhang Shixiang introduced a utility model of an oil cooling motor [12], which has the slot in the rotor’s circumferential direction. Some of the oil enter in the jacket slot to cool the rotor, and the others are injected from the jacket openings onto the stator winding. But the oil is difficult to enter the slot for the pressure of the air gap. The results from Pia Lindh confirm that the proposed direct cooling method is practical also in small machines. Moreover, it offers significant improvements in the thermal management of the machine [13]. BYD develop a utility model of the oil cooling motor [14]. Its characteristic is that the stator shell has a stator oil way and has a shell injection port towards the stator winding. The rotor has a rotor oil path connected with the stator oil way via the endbell oil way. The magnetic isolating plate has an oil channel in a radial direction towards the winding. Its purpose is to optimize the heat dissipation and improve the efficiency of the design. The shortcoming is that the cooling capacity still needs to be optimized and the shaft is likely to have a dynamic imbalance, leading to NVH problem. In 2018, a review on state-of-art modern cooling systems employed for thermal cooling of electric motors provided[15].In summary, the cooling of the electric motor needs to be improved to increase its efficiency by enhancing its cooling mechanism.
2. Analysis of typical patents

2.1. BYD oil cooling system

The utility model is an oil cooling motor. The housing has shell oil cooling channels which connect to external oil supply pipeline through the inlet and communicate with the external oil pipeline through the outlet. The rotor that is provided with the rotor injection ports facing to the stator has a shaft oil way connected with the shell oil channel in which the injection ports are facing to the stator.

![BYD oil cooling system](image1)

The cooling topologies can cool both rotor and stator, especially the end parts of the stator which is easy to be overheated. The stator core is cooled through cooling jackets. And direct inner oil cooling is also applied in terms of the stator winding via fixed-point injection of the cooling jacket and the rotating injection of the magnetic isolating plates, which means the stator winding is cooled by forced convection heat transfer with oil. As the rotor with the permanent magnets is sensitive to temperature, two ways are supported. One is the heat conduction to the cooling shaft; another is the heat transfer by cooling channels in the magnetic isolating plates. However, the limited position of the injection openings and channels cause unsatisfactory heat transfer area. It leads to an inadequate cooling on the stator winding as well as on the end parts of the rotor. For further high-speed motors, the heat generated in the air gap tend to be even larger. This cooling contracture will not work very well. Besides, two isolating magnet plates are placed at both ends of the rotor under certain conditions of oil pressure and the motor speed. It is unavoidable that the flow rate of oil in the channel is not uniform, thereby generating vibration of the dynamic imbalance. So the NVH problem brought by the rotated injection rotor should also be taken into consideration.

2.2. Tesla liquid cooling system

The liquid cooling system includes a manifold is extending above the stator (S) which is receiving the liquid under pressure and having the openings that direct the liquid jets onto the stator and the end parts of the rotor (R). Meanwhile, the trays acquire fluid from the manifold injectors and distribute gravity-fed liquid onto the end parts.
In this cooling topology, both rotor and stator are directly cooled by liquid. In detail, liquid manifold injection dissipates the heat of the stator core by means of the forced convection heat transfer with the coolant, and heat transfer via gravity-fed liquid distribution of the trays and the rotated rotor makes the stator winding cool. The rotor is cooled by heat transfer with the fluid via liquid manifold injection and gravity-fed liquid distribution of the trays. The cooling effect at the end parts of the rotor is relatively good, but the coolant cannot contact with the outer and inner surface of the rotor and thereby reduce the heat dissipation of the rotor. It causes insufficient cooling capacity under heavy load conditions. What is more critical is that despite the good cooling effect at the upper part of the stator winding due to the gravity-fed liquid distribution of the trays that slope downward with flow directors, a similar cooling effect cannot be obtained in the lower part of the stator. It will lead to disequilibrium temperature field then require higher thermal stability of silicon steel sheets, end up with shortening the motor service life.

Tesla believes that a system that uses only pressure-based distribution, with ten or more openings, the openings would need to be relatively small and therefore prone to clogging. However, if such openings were made larger, at low oil flow rates, the coolant may not fill the distribution channel (e.g., a manifold) and the coolant would not reach some parts of the motor. The gravity-fed liquid distribution has its advantages as compared to pressure-based distribution, while along with the development of the special fluid for e-axle, it will partly remove the concerns about the lower limit of the opening size. Consequently, to obtain the most adequate and balanced cooling scheme, various methods of the pressure-based distribution are still not negligible.

3. New cooling topologies

3.1 Brief description
As shown in fig.3, the fluid enter into the shaft cooling chamber from the shaft oil supply chamber formed by the inlet dynamic sealing device placed between the housing inlet and the shaft inlet. Then, the oil enters into the air gap cooling cavity or the stator winding rotary cooler low-pressure cavity to do the next cooling process. Optimum design of cooler and cooling chamber can effectively cool the motor and further enhances the service life of the driving motor.
Figure 3. innovative liquid cooling system

Fig.3, (a) provides a schematic diagram of the cooling system. (b) is a schematic diagram of the sectional structure. (c) is the local enlargement structure of the stator core. (d) is a stator winding fixed cooler, (e) is the stator winding rotary cooler 58a and the profile structure of the stator winding rotary cooler 58a.

In fig.3 (a), 10 is the stator core cooling cavity. 2 is the stator core cooling jacket. 20 is the jet of the cooling jacket. 21, 22, 23 are the inlets of the cooling jacket. 30 is the stator core oil channel. 31 is the inlet of the stator core. 32 is the air gap cooling cavity. 33 is the silicon steel sheet. 4 is the stator winding. 40 is the stator winding fixed cooler. 41 is the cooler cavity of the stator winding fixed cooler. 411-418 are the stator winding cooler guide openings. 51 is the inlet dynamic sealing device. 52 is the shaft oil supply chamber. 53 is the shaft inlet. 54 is the shaft cooling chamber. 55a and 55b are the stators winding rotary cooler inlet. 56a and 56b are the stators winding rotary cooler dynamic sealing device. 570a, 570b is the stator winding rotary cooler low-pressure cavity. 571a, 571b is the stator winding rotary cooler high-pressure cavity. 58a, 58b are the stator winding rotary cooler. 59a, 59b are the fluid injection port. 60 is the air gap cooling cavity inlet. 61 is the partition bearing dynamic sealing device. 62 is the partition board bearing. 7 is the partition board. 8 is the magnetic isolating plate.

3.2 Cooling principle

The rotor provided in this creative topology takes the heat transfer method via air gap cooling cavity and the means of heat conduction with the shaft cooling chamber. Specifically, two partition boards are mounted on the shaft through the partition bearings integrated with moving seals, and the circumferential surface of which are sealed with the stator forming the air gap cooling cavity, which can enhance the cooling effect of the air gap as well as the end parts of the rotor. Finally, we can get little drag loss but the improvement of overall efficiency and better electromagnetic stability that is the priority for PM motor. In addition, the stator core is made of a plurality of silicon steel sheets, and the sectional shape of the stator core oil channel can be rectangular. The length of the stator core oil
channel rectangular section is an integral multiple of the thickness of the silicon steel sheet, for example, it can be 10–20 times the silicon steel sheet thickness. By this approach, not only the cooling loop is optimized but also benefit to reduce torque ripple excitation thereby improving acoustic quality of the electric motor.

Under the action of the centrifugal force of the rotor, the fluid in the air gap cooling cavity can get into the stator core cooling jacket by the stator core oil channels. There are openings of the jacket onto the stator winding fixed coolers. Furthermore, the stator winding fixed cooler is invented by considering that the cooling effect is as equal as possible for the up and down circumference of the stator winding in order to prolong service life. In detailed, the stator winding fixed coolers, sealed with the jacket and stator, have guide openings of different design in the upper and lower circumference to play gravity-fed distribution and pressure based injection respectively, solving the problem of the inhomogeneous cooling intensity of the end parts of the rotor occurred in Tesla motor. Moreover, in order to strengthen the heat transfer of the stator winding further, the stator winding rotary coolers are provided. The stator winding rotary coolers are dynamic seal with the shaft, forming the stator winding rotary cooler cavity. The design of the coolers make the oil inlet cavity large in volume and small pressure, and the oil outlet cavity has a small volume and high pressure. Some fluid in the shaft cooling chamber will enter into the stator winding rotary cooler low-pressure cavity under the action of centrifugal force and be injected from the stator winding rotary cooler high-pressure cavity. In this way, the cooling chamber or cavity will always be filled with fluid, thus avoiding the NVH problems in BYD motor.

Besides, all the cooler such as the stator winding rotary cooler and the air gap cooling cavity are easy for modularized development of the electric motor cooling system. It is the innovative design of the cooling topologies for EV electric machine that can maintain the efficiency in high speed and heavy load.

4. Conclusion

It is realized that for a sustainable green future, the inevitable trend of automobile electrification has been shown worldwide. To satisfy the need for a lightweight and highly integrated EV, the required motor is to be high speed. Meanwhile, the pursuit of high efficiency makes the PM motor become more and more mainstream. High-speed PM motors need new and more stringent requirements on the cooling and lubrication system. The design of the cooling topologies of the motor is complex. It is perceived that in the past few years, due to heat management of the high speed and high energy density motor, the cooling system is from the indirect water cooling to the direct oil cooling. The new design proposed in this paper is based on the new development results of the parts such as fluid and bearing of electric vehicles. It solves some problems brought about by predecessors in view of the high efficiency and reliability of the motor with higher energy density in the future. However, the calculation of the cooling mass flow rate, the size of the openings and the matching of different working conditions are still under study. For future research, it would be more interesting to perform the analysis of the highly integrated motor and its experimental test for the electric vehicle.

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References

[1] Han-Kyeol Yeo, Hyeon-Jeong Park, Jung-Moo Seo, Sang-Yong Jung, Jong-Suk Ro, Hyun-Kyo Jung. Electromagnetic and Thermal Analysis of a Surface-Mounted Permanent-Magnet Motor with Overhang Structure [J]. IEEE Transactions on Magnetics, 2017 (6): Article Sequence Number 8203304.

[2] Aurélie Fasquelle, Daniel Laloy. Water Cold Plates Cooling in a Permanent Magnet Synchronous Motor [J]. IEEE Transactions on Industry Applications, 2017 (5): 4406 - 4413.
[3] Zhang Fengge, Du Guanghui. Temperature Field Analysis of 1.12MW High-Speed Permanent Magnet Machine with Different Cooling Schemes [J]. Transactions of China Electrotechnical Society, 2014, 29 (1): 66-71.

[4] Lassila, Viktor. Method and Device for Liquid Cooling of an Electric Motor: CN 201380056661.X [P]. 2015-07-22.

[5] Chuck Yung. Cool Facts about Cooling Electric Motors: Improvements in Applications That Fall Outside the Normal Operating Conditions [J]. IEEE Industry Applications Magazine, 2015 (6): 47-56.

[6] Christian Paar, Annette Muetze, Hendrik Kolbe. Influence of Machine Integration on the Thermal Behavior of a PM Drive for Hybrid Electric Traction [J]. IEEE Industry Applications Society, 2015 (5): 3914 - 3922.

[7] Gary A. Pinkley, David F. Nelson, William R. Fong, Scott Heines, Edwin M Pearce. Pressurized and Gravity-fed Liquid Cooling of an electric motor: US 20150222162A1 [P]. 2015-08-06.

[8] Ziyuan Huang, Jiancheng Fang, Xiquan Liu, Bangcheng Han. Loss Calculation and Thermal Analysis of Rotors Supported by Active Magnetic Bearings for High-Speed Permanent-Magnet Electrical Machines [J]. IEEE Transactions on Industrial Electronics, 2016 (4): 2027 - 2035.

[9] Zhou Ming, Zhu Lingyu, Zhang Gongming. Oil Cooling Structure for Driving Motor of New Energy Vehicle: CN 201521109578.7 [P]. 2016-06-01.

[10] Engblom, Daniel. Method and Device for Liquid Cooling of Electric Motor: WO 2016159860A1 [P]. 2016-10-06.

[11] Lassila, Viktor. Method and Device for Liquid Cooling of Electric Motor: WO 2016159862A1 [P]. 2016-10-06.

[12] Zhang Shixiang, Zhang Shengchuan, Xia Ji. Motor Rotor Oil Cooling Structure and Motor with the Oil Cooling Structure: CN 206313565 U [P]. 2017-07-07.

[13] Pia Lindh, Ilya Petrov, Ahti Jaatinen-Värrä, Aki Grönman; Miguel Martinez-Iturralde, Marco Sržustegui, Juha Pyrhönen. Direct Liquid Cooling Method Verified With an Axial-Flux Permanent-Magnet Traction Machine Prototype [J]. IEEE Transactions on Industrial Electronics, 2017 (8): 6086 - 6095.

[14] Li Huanwei. Oil Cooling Motor and Vehicle: CN 206149098 U [P]. 2017-05-03.

[15] Alberto Carriero, Matteo Locatelli, Kesavan Ramakrishnan, Gianpiero Mastinu, Massimiliano Gobbi. A Review of the State of the Art of Electric Traction Motors Cooling Techniques [J]. SAE Technical Paper, 2018-01-0057.