Academic Journal of Engineering and Technology Science
ISSN 2616-5767 Vol.7, Issue 1: 16-21, DOI: 10.25236/AJETS.2024.070103

Integrated Drive Module Design and Analysis

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Abstract: *This paper presents a comprehensive examination of an integrated drive module developed for electric vehicles, emphasizing the critical issue of effectively managing heat dissipation generated by the traction motor. The compact dimensions, weight restrictions, and high-power demands of the motor necessitate careful consideration of thermal management strategies. Excessive heat can cause deterioration of the motor winding insulation and rotor magnets, leading to suboptimal performance. To tackle this challenge, cooling mechanisms are essential for both the inner rotor and outer stator components. An efficient motor cooling system must be capable of accommodating varying temperature ranges, humidity levels, and dust conditions. To analyze the thermal performance of the WEG jacket cooling design, this study employs advanced automated meshing techniques in drivetrain simulations. By investigating these aspects, valuable insights can be gained for the advancement of electric vehicle drive modules.*

Keywords: *Integrated drive module, drivetrain unit, electric vehicle, WEG jacket, simulation*

1. Introduction

The growing popularity of electric vehicles (EVs) highlights the increasing importance of thermal management for high-power motors. The rear motor in EVs typically utilizes liquid cooling technology and is a permanent magnet synchronous motor, while the front motor is an induction motor with liquid cooling and frequency conversion drive. A prevailing design trend involves boosting motor output power while reducing its volume for easier integration, leading to a substantial increase in heat density and motor temperature. Elevated temperatures adversely affect motor lifespan, reliability, and electromagnetic performance. Consequently, effective thermal management strategies for high heat density electric motors have become a critical concern [1].

The success of Tesla electric cars in the market heavily relies on the high-performance motor, which is a complex, high-speed rotating machine. Understanding and measuring the internal heat flow field during motor operation is challenging experimentally, leading to the utilization of computer-based fluid dynamics (CFD) simulations. Mechanical CFD plays a crucial role in providing detailed physical data for internal phenomena, serving as an essential tool for motor thermal management analysis and design. During operation or charging, Tesla's motors and batteries generate heat, which, if not effectively managed, can result in reduced battery efficiency and instability, leading to performance degradation. To address this, dual-mode coolant loops are employed for efficient cooling [2].

Numerical simulation analysis of high-power and high-efficiency motors faces numerous challenges due to their intricate structures. Traditional approaches often simplify complex geometries, but such simplifications can lead to the loss or inaccuracy of crucial physical phenomena, potentially misleading design decisions. Moreover, the arduous and cumbersome simulation process can discourage designers from utilizing CFD. To enable the accurate and effective thermal management design of high-power motors, it is crucial to develop advanced numerical simulation techniques, particularly fast mesh generation methods capable of handling extremely complex geometries. Overcoming these challenges involves the development of efficient mesh generation techniques [3]. This article aims to explore the application of this technology in a comprehensive electric vehicle powertrain analysis, encompassing electric motors, interconnected output gearboxes, and a SiC-based MOSFET inverter. The study retains the authentic geometry without simplification, allowing for an analysis of achievable results.

In summary, the goal of this study was to analyze and design an integrated drive module for electric vehicles, with a focus on effective thermal management of high-power motors. The study addressed the challenges of increasing heat density and temperature rise in motors due to size and power output requirements. By utilizing advanced numerical simulation techniques, including fast mesh construction for complex geometries, the study aimed to accurately model the thermal performance of the motor cooling system. The results and analysis obtained from this study contribute to the understanding of efficient cooling strategies and provide valuable insights for the design and optimization of electric vehicle drivetrains. By considering the real geometry without simplifications, the study aimed to provide a comprehensive analysis of the electric vehicle power plant. Overall, this research highlights the importance of thermal management in achieving optimal performance and reliability of electric vehicle integrated drive modules. Additionally, the article examines and compares two new distinct liquid-cooled runner modules design and compared the original one.

2. Method

This study investigates the concept of an integrated drive module in electric vehicles. The research begins by examining the disassembled rear drive unit, which consists of the motor, inverter, and differential set (Figure 1). The internal structure of the integrated drive module comprises the inverter with PCB, the differential gear set, the motor body, and the integrated drive module with cooling pipes that encompass the motor and inverter. Notably, the analysis encompasses all components, including gears, shafts, and bearings, providing a comprehensive understanding of the thermal management of the entire drivetrain. Detailed specifications of integrated drive module HVH-250 are listed in Table 1.

Table 1: Integrated drive module (HVH-250) specifications.[4]

Integrated Drive Module Power Electronics	
Operating voltage range	240-450 VDC
Phase Current	200 ARMS continue/450 ARMS peak
Efficiency	>95%
Switching frequency	2 to 12kHz
Environmental	-40 to 85℃ operations
IP Level	IP6K9K
Communication interface	CAN
Cooling	Nominal operation 65℃
Electrical Machine -HVM 250 PMSM	
Number of Poles	10
Nominal Voltage	330VDC
Maximum current	450ARMS
Peak torque	310Nm
Peak Power	125kW @330VDC
Max Operating Speed	10600rpm
Cooling media	WEG Jacket
Coolant flowrate	8-15LPM
Velocity Streamline	<1.04m/s
Transmission	
Gear ratio	9.4:1
Efficiency	97%
Output Torque	2800Nm
Reduction gearbox	Two stages
Lubricant	Passive lubricant

Figure 1: Integrated drive module HVH-250 [4].

When analyzing the motor body, one of the most challenging aspects traditionally has been dealing with many intricately shaped coils [5]. In the case of this motor, there are a total of 96 sets of overlapping coils in the stator. Conventional approaches often simplify such complex geometries, which results in merging the independent coils. Unfortunately, this simplification tends to underestimate temperature predictions, yielding excessively uniform results that are overly optimistic and potentially increasing the design risk. In this study, the original geometry of all 96 high voltage hairpin type winding sets of coils is retained for mesh construction and heat flow analysis, ensuring a more accurate representation, as depicted in Figure 2.

To facilitate the numerical simulations, the following simplifications have been incorporated:

1) The thermal conductivities of motor materials are assumed to be isotropic.

2) The iron losses in the rotor and stator are considered constant, assuming uniform heat generation.

3) The rotor slot and stator slot material are assumed to be identical, and the windings are fully covered by insulating material.

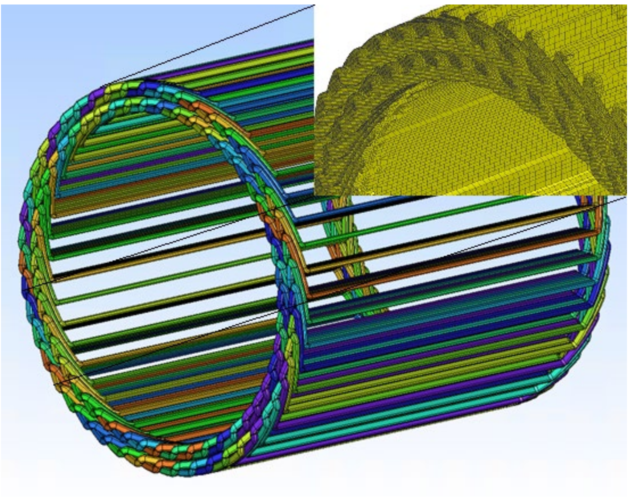

Figure 2: The stator contains 96 overlapping coil sets.

The integrated drive module has a system that cools down its important parts, called stators and rotors, using oil. In the oil-cooled version, oil is pumped into a special area and then flows over the ends of the module. This flow of oil helps to cool both the rotor and stator, allowing the module to produce more power for longer periods of time. On the other hand, in the water-cooled version, a system of water jackets is used to cool the stator, but the ends of the module and rotor do not have direct cooling. To improve cooling, a process called end turn potting can be applied. This system not only helps to exchange heat between the motor and the water more effectively but also reduces the temperature of the conducting materials and increases the power output compared to the weight of the module.

Figure 3 depicts the grid configuration of the liquid cooling pipeline, illustrating a comparison between two recently developed liquid-cooled runner modules. Geometric calculation grids are generated using the grid technique, followed by heat source analysis using electromagnetic analysis software. By specifying material properties, motor speed, and boundary conditions, the heat flow field within the motor can be analyzed. This analysis enables the evaluation of temperature distribution in components such as shafting, bearings, and gears, offering valuable insights into the internal temperature of the motor. It is important to note that analyzing the rotor results alone is inadequate due to the stator coil's elevated temperature.

Figure 3: The cooling jacket pipelines consist of six spiral passes.

In Figure 4 and 5, the schematic flow channel shows the liquid pressure drops of 10395 Pa and 5074 Pa, respectively. Other objects are represented by temperature values. The ambient temperature for both cases is set at 25℃.

When analyzing the flow channel of the bow-shaped spiral pass design, we observe minor pressure changes, resulting in insignificant pressure loss. However, this design leads to higher motor temperatures. On the other hand, the spiral 6 passes design experiences significant pressure loss in the flow channel but maintains lower motor temperatures.

To investigate the heat transfer between the motor and gearbox, we connect the motor with the output gear set. In both the spiral 6 passes design and the bow-shaped spiral pass design, the gear temperatures reach approximately 80℃.

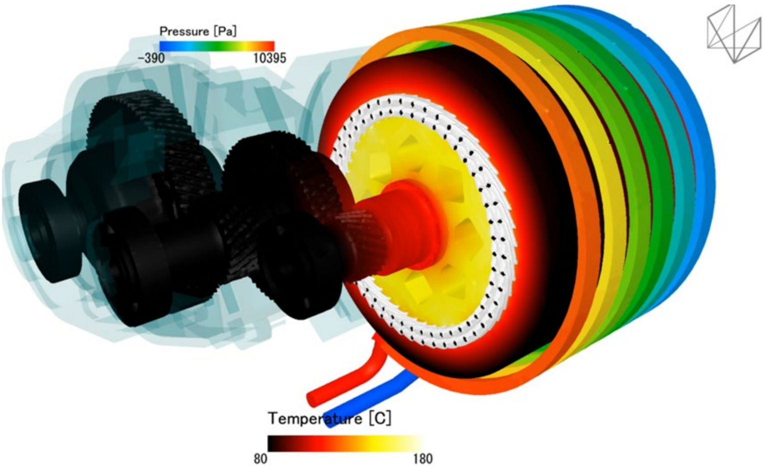

Figure 4: The temperature analysis of the cooling jacket with six spiral passes.

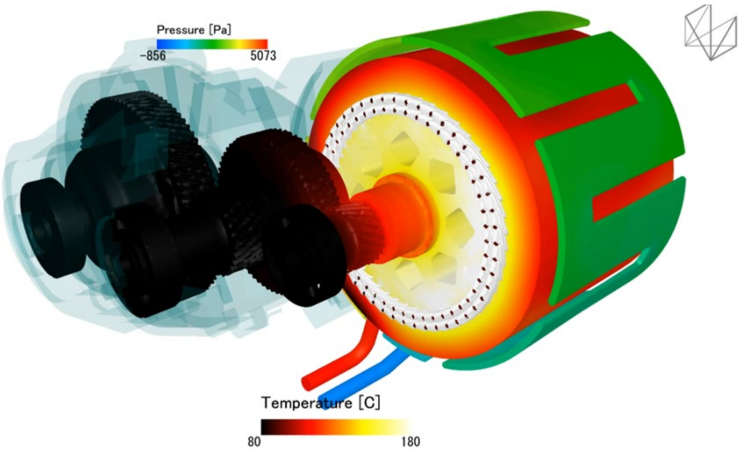

Figure 5: The temperature analysis of the cooling jacket with a bow-shaped spiral pass.

Thermal analysis helps us understand temperature distribution in the stator winding coils, providing accurate information about temperature changes. Instead of assuming a constant temperature, this analysis reveals the actual temperature variations in specific areas, allowing for precise evaluations during design.

In Figure 4 and Figure 5, the highest temperature inside the integrated drive module is 180 °C. This temperature is measured at the stator for the WEG jacket cooling with six spiral passes and a flow rate of 10 LPM. It's worth noting that this temperature falls within the safe range established in the original design, which was set at 200°C. The stator core, which is in direct contact with the cooling fluid, remains at lower temperatures.

The integrated drive module also powers electronic components such as IGBT, GaN, SiC, and Si MOSFETs. To ensure their cooling, the coolant circulates through the inverter and exits through the cooling jacket module system. The transmission of the reduction gear and differential also requires cooling, although it receives some heat from the lubricant oils as it is located between the warmer motor and the PCB controller.

A heat exchanger is positioned between the motor and the controller, raising the temperature of the motor oil. This slight increase in temperature contributes to a small improvement in vehicle efficiency. It is important to note that the stator can reach a maximum temperature of 200°C, and demagnetization starts to occur at 180°C [6]. The analysis provides valuable information about the temperature of both the stator and rotor.

3. Result and Discussion

In this study, we provide a concise summary of the simulation and analysis conducted on integrated drive modules. By comparing the simulation results with actual motor measurements, the previous analysis performed using computational fluid dynamics (CFD) software demonstrates the remarkable efficacy of our study. The utilization of a CFD honeycomb control volume grid in this article brings notable advantages in terms of robust grid generation technology and efficient computational performance. This approach allows for direct grid generation for solid computer-aided design (CAD) models, eliminating the need for traditional fluid area calculations, manual surface registration, or complex grid generation processes. This grid generation technique is particularly well-suited for addressing challenges posed by intricate geometric components such as electric motors.

The analysis presented in this paper places specific emphasis on a real electric vehicle power motor, considering both the motor body and the associated gear set responsible for power transmission. The operational conditions considered in the study incorporate the temperature of the gearbox set to assess the impact of lubrication conditions and potential thermal deformation on gear engagement. As a result, the study incorporates dynamic rotating discontinuous meshes and employs multi-fluid analysis techniques in addition to mesh generation methods. By integrating these techniques, we gain a more comprehensive understanding of the thermal behavior and fluid dynamics within the integrated drive module.

4. Conclusions

In conclusion, the integrated drive module encompasses an integrated drivetrain comprising an electric motor, power inverter assembly, and gearbox, all housed within a single enclosure. This consolidation brings about a range of advantages, including reduced weight, complexity, volume, assembly integration, and manufacturing costs. Furthermore, this integration enables the use of short, low-loss, rigid bus bars instead of long, flexible cables, leading to improved cooling efficiency.

The electric motor, power inverter assembly, and gearbox are interconnected within a mutual thermal management system, ensuring optimal heat dissipation. To address the design challenges associated with the WEG Jacket system, the study utilizes automated meshing techniques to analyze temperature fields and flow paths within windings, slots, gaps, and the jacket itself. These advancements facilitate a comprehensive understanding and effective management of thermal performance in the integrated drive module system. By employing the WEG Jacket system and leveraging advanced analysis techniques, the integrated drive module achieves enhanced cooling and overall system efficiency.

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