

Direct Coil Cooling of a High Performance Switched Reluctance Machine (SRM) for EV/HEV Applications

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ABSTRACT

This paper presents the development of a novel direct coil cooling approach which can enable high performance for electric traction motor, and in further significantly reduce motor losses. The proposed approach focuses on bypassing critical thermal resistances in motor by cooling coils directly in stator slots with oil flow. Firstly, the basic configuration and features are shown: sealed stator slots to air gap, pressure reservoirs on both side of the slots and slot channels for oil flow. The key to enhance thermal performance of the motor here is based on introducing fluid guiding structure in the slot channels. Next, heat transfer in the channel with guiding structure is investigated by CFD and compared with bare slot channel without guiding structure. For studying the effectiveness of proposed cooling concept, numerical analysis is conducted to compare it with HEV favored oil impingement cooling. Finally, thermal performance of the proposed cooling approach is verified and compared with water/glycol jacket cooling on a switched reluctance machine prototype for EV application inside a public funded project ODIN.

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INTRODUCTION

As vehicle electrification is becoming a key issue for automotive industry, the demand for electric machines with high performance and efficiency has been growing. By increasing power density, the thermal behavior becomes one of the most crucial limiting factors for electric traction machine. In this paper a direct coil cooling approach is proposed to improve cooling performance of electric machine, and in further increase its power capability.

The design study is conducted on an electric machine based on switched reluctance principle. A switched reluctance machine (SRM) can be applied widely in field of automotive, such as traction machine, electric supercharger and engine starter [1], [2], [3]. It is well known for its low manufacturing cost [4], high mechanical robustness and suitability for running at high speed, which could bring the machine additional power density [5]. However, this machine type has also known issues regarding acoustic and vibration, which can be undesired characteristics for automotive applications. Improvements can be done with different measures, such as control strategy and optimized machine design [6], [7], [8].

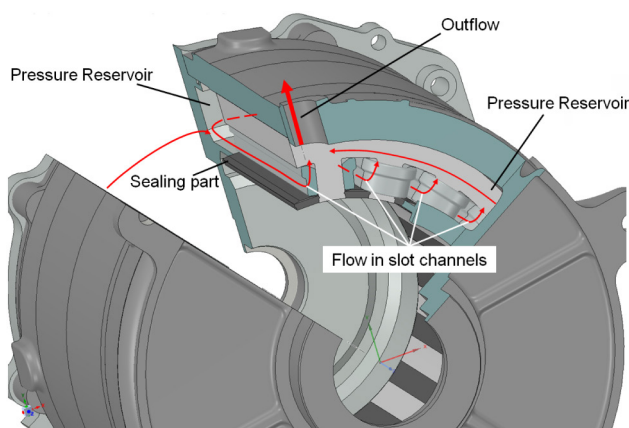
DIRECT COIL COOLING

Concept Description

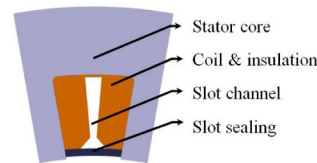
Conventional cooling solution for high performance electric machine is based on forced liquid jacket cooling. Different forms of ducts for conducting coolant flow are fabricated in the stator housing [9]-[10]. With this cooling approach the major heat generation in motor is conducted through stator core into the housing, and taken away by cooling fluid. Water is the most widespread fluid for liquid jacket cooling principle for its superior thermal conductivity and heat capacity. To adapt cold environment, antifreeze fluid is commonly added into water in vehicle applications. However, water jacket cooling has an obvious drawback. The coils and the insulation, which should be cooled intensively, have yet the longest thermal pass to the coolant. Coils in the machine can only dissipate heat all along through winding enamel, insulation phase paper, stator core, housing and finally into cooling fluid. The heat dissipation scheme causes the coil to build up the highest temperature in all involved components. Furthermore, the stator core involved also generates its own losses, which lead to additional temperature rise in the coils at high speed. In the end, when coil temperature reaches the thermal limit, power output of the machine must be throttled.

Another widespread thermal solution is based on sending oil onto the e-motor's end winding area [11]. In this case, transmission oil is used as coolant for its dielectric characteristics [12]. The oil is guided and accelerated onto the end winding area either through fixed nozzles or through rotor movement. It has similar problem as water jacket cooling. A large sum of losses generated in stator is on the contrary hard to evacuate through the coils, which are only capable of delivering heat in axial direction effectively. Thus, the thermal critical area for end-turn winding cooled machine is its middle-section, especially critical for high speed machine with large axial length. This cooling is usually preferred in HEV applications and e-machine with short lamination stack.

In the direct coil cooling approach presented in this paper, the entire slot area of stator core takes over the main cooling function. By closing the air gap side of stator slots through sealing components, oil can be kept in and send through the so called slot channels. Figure 1 shows the basic structure of a direct coil cooled machine. In Figure 1(a) the red lines represent the direction of oil flow in the machine. Slot sealing shown in Figure 1(b) is realized by parts which are similar to slot wedges. The geometry of the parts is designed to reduce leakage flow. Coils with high losses density have direct contact with cooling oil along the entire slot in this concept. Heat generated in the coils can have direct dissipation path into fluid other than going through adjacent motor components. To sustain continuous oil flow in slots, the stator is sealed in axial direction from both sides through ring-shaped structures which are extended from housing and bearing shield. Thereby, pressure reservoirs on both sides of the machine are created. One reservoir is connected with oil inlet, and the other is connected with outlet. During operation the reservoirs are fulfilled and end windings of the coils are submerged in the cooling fluid. By sending fluid into the machine, pressure in the reservoir on the inlet side would be higher than its counterpart on the outlet side. The oil flow is generated in the parallel connected slot channels through this pressure difference.



(a)



(b)

Figure 1. (cont.) One implementation of the proposed cooling concept: (a) Flow distribution in direct coil cooled machine sealed with slot sealing parts (b) Sectional view of stator cross-section with slot sealing

In this implementation, minor oil leaking into air gap is allowed and can be guided to gearbox. During manufacturing most of the gaps in the stack are closed through resin impregnation. No further complicated sealing measures are necessary. Functional test under temperature variation shows that the leakage is fewer than 3% of the total flow rate. If leakage-free implementation is desired, alternative manufacturing methods, such as resin molding techniques, can be involved for creating slot sealing.

Evenness of flow distribution in slot channels can be adjusted through the relationship of flow resistances between pressure reservoirs and slot channels [13]. This part is out of the discussion of the paper.

For oil cooling applications, however, the thermal conductivity and heat capacity of oil is only around one half of that of water. Also, the viscosity is considerably higher, made the fluid only possible to go into turbulent regime at high velocity. To further enhance heat transfer effectiveness, special designed fluid guiding baffles are proposed in this paper. Figure 2 presents the sample geometry of one baffle. The structure is consisted of two zigzag geometry halves, which are shifted by half periodic in longitudinal direction. Through this geometry the fluid flow in the channel can be intensified through local pressure difference. A velocity component of flow which is normal to the heated coil surface can then be generated in this case to reduce local thermal boundary layer. This effect results in improved heat transfer between oil and targeted wall. Also, through enhanced mixing of fluid, the core flow picks up more heat from the fluid near wall.

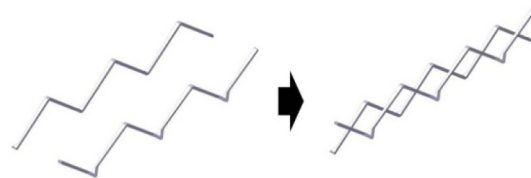


Figure 2. Basic geometry of the fluid guiding structure

Prototype Implementation

In this paper the OIDN prototype machine is used for study case. This machine is designed as an axle traction machine for electric vehicle. To reach high power density through high machine speed, switched reluctance machine is chosen. The key parameters of the machine are presented in Table 1.

Figure 1.

Table 1. ODIN prototype specification

ODIN Switched Reluctance Machine	Value (Unit)
Diameter	220 mm
Stack length	120 mm
Number of Phase	3
Pole Pair	3
Number of Stator/Rotor Poles	18/12
Peak Torque	110 Nm
Max. Speed	> 18000 rpm
Peak Power	60 kW

The topology of the machine is presented in Figure 3. The NVH issue of SRM is supposed to be suppressed through previously developed control algorithm [13].

The prototype machine is designed also with a redundant water jacket cooling system, so that the performance comparison with the novel direct coil cooling can be directly conducted on a single machine.

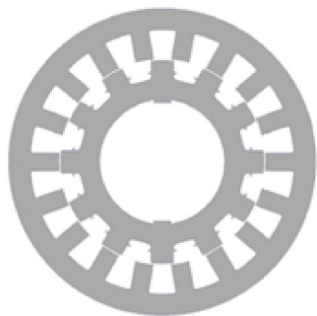


Figure 3. Topology of the prototype machine in consideration

NUMERICAL STUDY

Flow Channel Optimization

Due to the use of fluid guiding structures in motor slot channels the oil flow motion becomes highly complex. It is difficult to utilize analytical approach on the case to conduct precise thermal investigations. Therefore, in this paper the study is mainly carried out based on CFD analysis. In order to have reduced calculation time, the study case is simplified into a normalized slot channel model without solid components. The coils are represented by the side walls of the slot channel. Figure 4(a) illustrates the thermal boundary definition of the model. For the study case these main heated surfaces are applied with 51 kW/m^2 constant heat flux. This means in total 3240 W losses to be dissipated for all 18 stator slots in motor. The geometry of the fluid guiding structures can be considered as several serial connected double "V" segments. Hence, a parameter v is given here to the guiding structure to define its periodicity in longitudinal direction along the entire channel. Figure 4(b) demonstrate a sample structure with 3 double "V" elements in the given channel ($v=3$). A 0.2 mm minimal distance is kept between the baffles and the both heated

walls, so that, the wall surface can be fully used for forced convection and also secondary flow can be generated in gaps between to further enhance heat transfer.

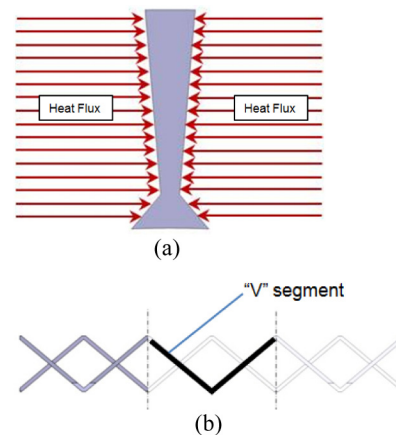


Figure 4. CFD model definition: (a) Coil contact surface with homogeneously applied heat from channel inlet view, (b) Guiding structure with 3 double "V" ($v=3$)

Temperature dependent data from transmission oil TYPE-I is implemented in CFD model. Its characteristics at 40°C are presented in Table 2.

Table 2. Characteristics of oil TYPE-I @ 40°C

	Value (Unit)
Density	$\sim 900 \text{ kg/m}^3$
Kinematic Viscosity	$< 15 \text{ mm}^2/\text{s}$
Heat Capacity	$2140 \text{ J/kg}\cdot\text{K}$
Thermal Conductivity	$0.15 \text{ W/m}\cdot\text{K}$

For CFD analysis Reynolds-averaged Navier-Stokes (RANS) governing equations is chosen based on commercial solver of FLUENT®. The RANS equations averages the Reynolds stress term in Navier-Stokes equations in time domain, so that the fluctuation in flow which is excited by guiding structure can be given approximated time-averaged solutions. The study cases for comparison are outline in Table 3.

Table 3. Definition of CFD study cases

Model Definition	
Baseline	Bare slot channel without baffles
Case 1	Slot channel with baffle $v=3$
Case 2	Slot channel with baffle $v=7$
Boundary Definition	
Fluid	TYPE-I
Inlet Temperature	50°C
Inlet Flow Rate in one Channel	1 l/min
Heat Flux on Heated Wall	51 kW/m^2