Integrated motor drive: A multidisciplinary approach

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Abstract: integrated drives are becoming a target for manufacturers aiming at addressing the increasing market of electrical embedded systems, such as e-transportation systems. Anyway, the integration of the power converter inside the electrical machine induces challenges if compactness is required. Additionally to the research of the best choices for the power electronics, electromagnetic, and thermal components, interconnection issues also arise, leading to cope simultaneously with several physical challenges. This paper gives an example of a multidisciplinary approach to propose smart integrated drive solution dedicated to middle power embedded systems.

I. Introduction

Integrated drives with only two DC cables are quite attractive and have been developed for transportation systems since 20 years by academics and manufacturers with Si components [1-4]. The integration of the inverter in the electrical machine avoids long AC cables and therefore EMI (Electromagnetic Interference). A common cooling for the inverter and motor can thus be considered. Nevertheless, maximum temperature (around 150°C) of Si semi-conductors prevents from high compactness and efficiency in harsh thermal environment of transportation with transient operations. Up to now, many current industrial solutions consist in putting an existing inverter packaging close to an existing machine [5-7].

In order to propose optimized solutions in terms of both carbon cost and economical cost for the electrified transportation mass-market up to 50-150kW, new topologies, with a more intimate integration of semi-conductor components in the machine, have been developed [8-10]: for a given compactness criterion, such as robustness and functional reliability, recyclability, efficiency should be considered simultaneously for the choice of a topology. But it is with GaN and SiC semi-conductors that a strong evolution can be expected since the maximum temperatures of the motor and the components are now close to each other [11], which is favouring the compactness and a common cooling. All these specifications may not be addressed independently from each other, as they are closely imbricated. To address these questions, several proposals exist in the state of the art, some of them as prototypes [12-15], others as proofs of concept [16-17], others at a design stage, and some also at the commercial stage [5],[10],[18].

These proposals differ from each other by the system structure [5] – the inverter is located on one side of the machine [6], [16], or split into several parts and put around the circumference of the machine [4], [15], or again located on one axis side of the machine [3], [8-10], [12-14]. The number of legs for the VSI and phases for the machine is often a design parameter according to the power requirements, and the value of voltage DC bus. From that, the choice of the wide band gap components is deduced, among GaN and SiC technologies. High voltage applications (DC bus over 300V) [12] [14], [16-17] can already benefit from SiC component with a significant level of maturity. Nevertheless, high voltage solutions require expensive Battery Management System, dielectric constraints for the motor windings [19], and human security levels. For DC voltages under 48V (normalized maximum voltage for human), GaN components are potentially well adapted with small size packaging but the maturity for high currents is still ongoing due to constraint associated with thermal dissipation.

This paper aims at giving an example of the multidisciplinary approach leading to an original topology of integrated drive [27], dealing together with the thermal, power electronics and electromagnetism issues. The targeted market concerns rather the low-voltage automotive one with power up to 40-50 kW but the topology could be extended to higher voltage level with SiC components for high torque applications (truck, marine, plane). It relies on the experience of a project on "smart integrated drives" (CE2I project) performed together by three laboratories with regional funding.

The outline of the paper is as following: in the second part, the general approach and the available technological choices are described regarding the requirements. The third paragraph presents in more details the different parts of the integrated drive and the first performances.

II. General approach for smart integrated drive design

The "CE2I" project (French acronym for smart integrated drive) is achieved by four academic laboratories which target to design and realize integrated drive prototypes in an affordable power range of about 40kW, that is clearly relevant for mass-market low-voltage terrestrial mobility applications, such as light automotive and also motorbikes. But before reaching this power, intermediary steps have been performed to test the different technological possibilities.

The choice of the drive topology presented in the paper is an innovative multiphase tooth-concentrated open-winding drive with two multiphase inverters as shown in figure 1. In order to guarantee a high torque/volume ratio, PMSM is chosen. With a 48V DC bus, it is possible, thanks to open-winding choice, to impose 48V for each phase which is an advantage in comparison with a classical star configuration (24v in that case). Two inverters allow to keep easily a symmetrical spatial repartition of the coil connections, identical on both sides of the machine, in comparison with asymmetry due to internal connection between elementary coils. Moreover, the symmetry will be complete if the two inverters are located respectively on front side of the machine. The inverters can be supplied either by only one DC source or by two independent ones to warrant a higher reliability.

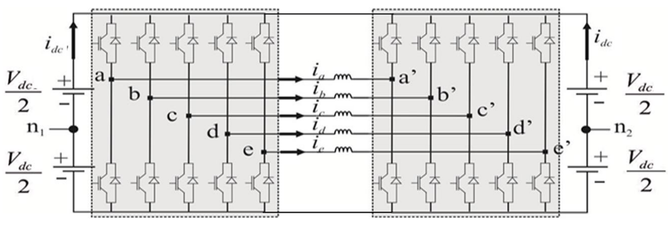


Figure 1: Multi-phase open winding PMSM and its inverters

The symmetrical topology is an advantage to design a relevant cooling system: the thermal dissipation should be the same on both axial sides of the machine and hot spots may be avoided by that way.

By increasing the number of phases, the aim is to avoid the use of transistors working in parallel. Thereby, necessary oversizing with three-phase solutions for reaching required reliability can be alleviated. With multiphase solution, the loss of one transistor can be tolerated without oversizing if a given loss of power is accepted. With transistors working in parallel, the transistors must be sized in order to support the death of one of them if snowball effect must be avoided.

Regarding the choice of the transistors, it highly depends on the power range. With wide band gap transistors, the chosen integrated solution can benefit of higher switching frequencies to simultaneously reduce the size of passive components such capacitors but also the heat associated to the component losses. Last but not least, for GaN transistors, as the maximum temperature is of the same order than the windings' ones, a common thermal cooling system could be shared.

The cooling system can be liquid if external pump already exists, as in numerous automotive, or with air in lighter solutions such as scooter or other light vehicles. In the last case, non-linear cooling of the machine by heat pipes has a particular interest in order to allow transient operations (such as acceleration or breaking): when the heat is increasing too much during a transient, the heat pipes start to operate. Their thermal résistance is decreasing slowing down the rise of the temperature winding. Moreover, heat pipes fulfil compactness requirements, and do not need extra external liquid cooling system. In the rotor, rotating heat pipes can also be chosen to protect the magnets in case of an increase of the rotor losses. In that case, the machine structure has to be designed accounting for the heat pipes' location.

It can be noticed that for high power solutions, eg for trucks (P> about150kW), such a kind of topology can be used with profit, but with SiC components and high DC bus voltage.

III. Details on technological choices and first results

1) Annular Voltage Source Inverter

To take into account the open phase winding of the machine (figure 1), the voltage source inverter (VSI) is split into two inverters located on both sides of the axis as shown in figure 2. The main constraints which have to be considered for the power electronics design is the PCB surface which is limited and the thermal pad of the GaN transistors which must be on the top side of the packaging regarding the PCB location near the machine [1], [20].
For a 5-phase machine, two 5-leg inverters are installed on both sides as shown in figure 2.

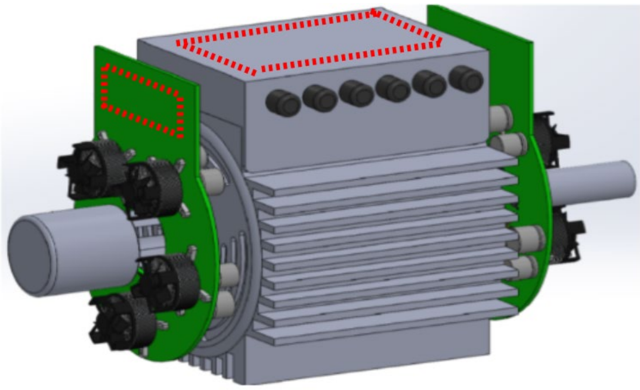


Figure 2: location of the two inverters in the machine

Top-side cooled 100V enhancement mode GaN transistors (GS61008T- GaN Systems) have been chosen, according to their high switching frequency, their low $R_{ds(on)}$ (7mΩ), and their high current (90A@25°C). Their PCB footprint is very low (7.0x4.0mm², with 0.54mm thickness) which meets the surface constraint available for the converter.
The geometry of one inverter side is shown in figure 3: an annular shape has been chosen in order to adapt itself to the machine geometry. The new PCB structure has been studied in simulation in order to determine all parasitic elements as well as the thermal behaviour of the active parts; it is important to determine parasitic inductances of power and gate loops which have the more influence on the transistors switch losses [21-22]. The calculation of the total power losses of the transistors are used to design the cooling systems of the converter.

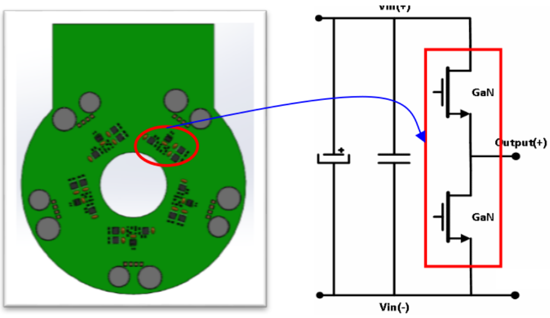


Figure 3: PCB geometry including devices placement of the 5 legs and the basic structure of one GaN inverter leg

As a first step towards the final full integrated drive with a single cooling system, the double 5-leg inverter has been designed with its own thermal environment, and use "classical" dissipators thermally connected to the top size of the transistors, thanks to spreaders and thermal interface material (TIM) system [23]. One of the realized inverter is shown in figure 4. To minimize the parasitic inductances of the power switch loops, the connections of the 5-legs of the inverter are carried out by busbar. The wire connections shown in figure 4 are only used to determine the conduction losses of GaN transistors.

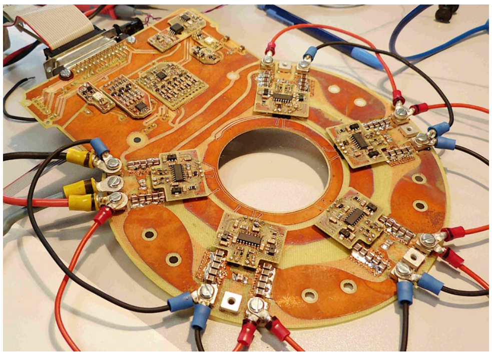


Figure 4: Control side of 5-leg GaN inverter

The inverter has been tested first separately from the machine, on a passive resistive and inductive load, and gave the expected results on the voltage control.

2) 5-phase Internal Permanent Magnet Synchronous Machine (IPMSM)

The first machine prototype chosen for the project was intended for mild-hybrid 48V application. It is a 20slots/14poles tooth concentrated windings IPMSM with five phases in open winding configuration. This choice leads to several advantages: in general, a multiphase machine is tolerant to fault from the semi-conductor components of the inverter. For high compacity in integrated drive the safe margins of the components must be small and faults must be taking into consideration at the drive design stage. For a given torque the current per phase can be reduced, avoiding to work with transistors in parallel and providing a better dispatching in space of the VSI legs with also a better repartition of the thermal effects. Regarding the choice of the phase number -here 5-, as it is not a multiple of 3, additional advantages exist such as higher torque density with non-sinusoidal emf while ensuring low torque ripples in normal and fault operations. For fault operations, specific fast sensitive fault detections and more efficient reconfiguration strategies can be implemented [24-26].

The open-winding structure is suited to the low voltage DC bus (48V) since it allows roughly to double the voltage applied to each phase in comparison with star connexion. It is also well adapted to the solution with two VSI, one at each side of the machine.

In a first step, a "classical" 5-phase PMSM has been tested and equipped with the two annular VSI presented before (figure 6). The connection between the two parts of the VSI and the end of the phases has been realized thanks to busbars. Mechanical adaptation rings have been designed in order to fix the PCBs to the end side of the machine (figure 5).

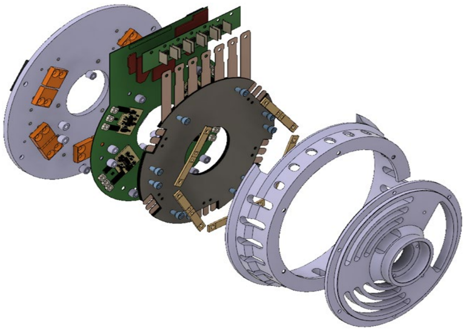


Figure 5: exploded view of the annular inverter

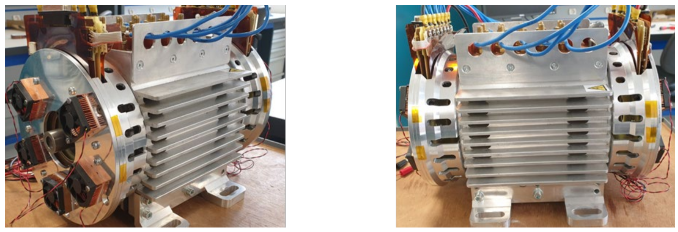


Figure 6: Views of one 5-phase PMSM prototype with the two VSI parts on each rotating axis side

To go further towards integration, and especially towards integration of the cooling system, another prototype has been designed and realized. It is also a multi-phase PMSM with twelve coils allowing 5-phase or 10-phase configurations depending on the disc connection between the coils and the VSIs. Thanks to the symmetrical topology and tooth concentrated winding, statoric heat pipes can be inserted symmetrically in the bottom of each slot (Figure 7) and condensers placed just over copper coil (Figure 8) with very short end-winding

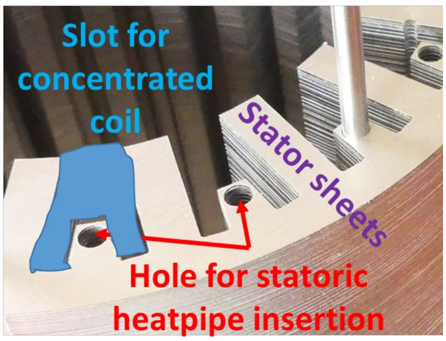


Figure 7: open slots of stator sheet with hole for heat pipe insertion

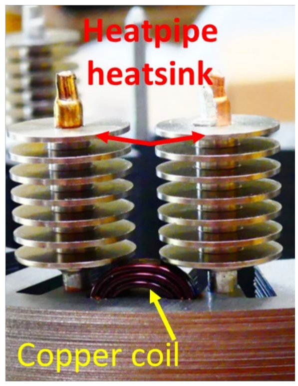


Figure 8: Condenser of the heat pipe over short end-winding coils (stator)

In figures 9 and 10 more global views of the topology are given.

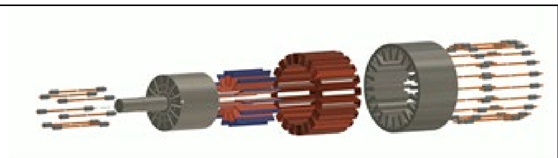


Figure 9: Exploded view of the machine with statoric and rotoric heat pipes

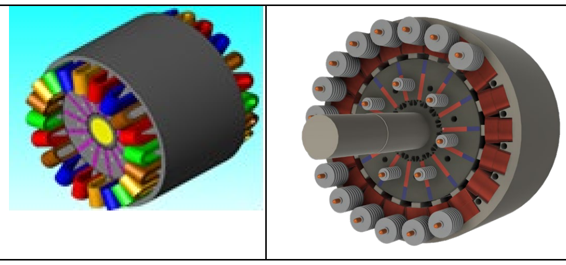


Figure 10: Prototype with twenty coils and internal radial magnets without heat pipe left with heat pipe right

3) Thermal cooling system

Thermal simulations have been performed on the VSI equipped with GaN transistors as well as on the machine core in order to determine the cooling requirements regarding the maximum power range of the integrated drive [27]. Special attention has been paid to take into account the location of the transistors. First, nodal thermal model of a single GaN transistor and its associated TIM, spreader and heat sink has been established. The cooling device proposed for the two GaN transistors (1-leg inverter) is shown in Fig. 11.

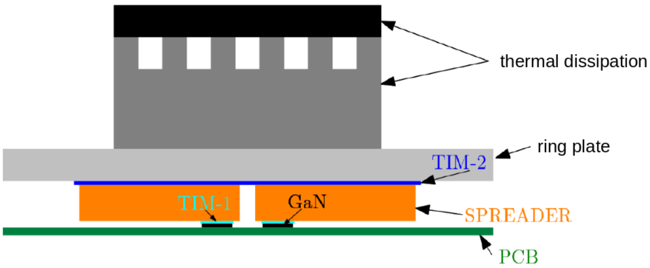


Figure 11: Cooling system of the 1-leg inverter

Then, the typical geometry of the annular VSI and the 5 legs have been considered in order to study their thermal interaction depending on the choice of the Pulse Width Modulation. Figure 12 gives an example of the thermal simulation of the 5-legs for two configurations: when 2-legs or 3-legs are ON-state.

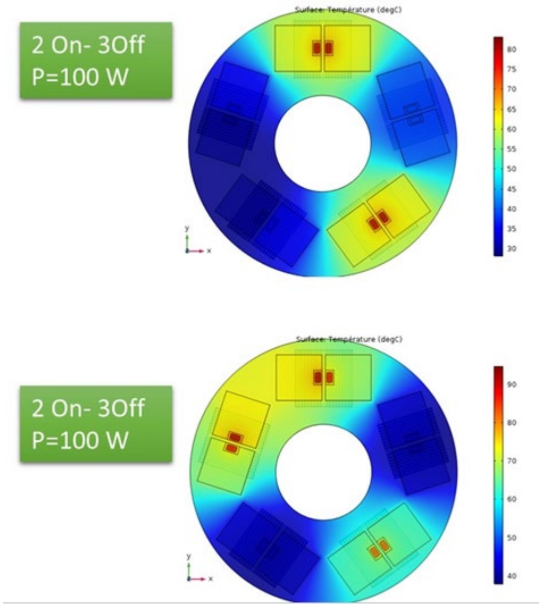
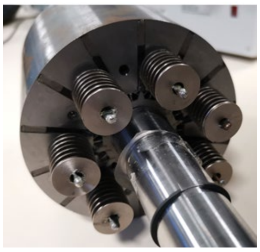


Figure 12: thermal simulations of different conducting situations for the 5-legs inverter

As for the machine cooling, simulations have also been performed using coupled FEM to determine the heating sources and thermal software to calculate the temperature of the sensitive areas [28]. From these simulations, the heat pipes solution has been proposed, which can be really integrated to the machine core, as it is shown in Figures 3 and 13. The tests on stator heat pipes gave the expected results, whereas the first experimental trials on the rotor heat pipes have shown the accurate operation of the heat pipes, despite the centrifugal effect due to the rotation speed. The revolving heat pipes used for the cooling of the rotor are hollow copper tubes, with an outer diameter of 4 mm and a wall thickness of 0.4 mm. The length of the evaporator (part inserted in the rotor) is 40mm and the condenser part (equipped with annular fins) is 15.5mm. This heat pipe uses water as a working fluid.

A specific test bench has been developed in order to determine the thermal conductance of these heat pipes as a function of the rotation speed and the applied heat power at evaporator (Figure 14).



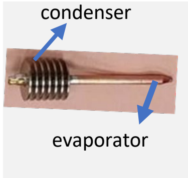


Figure 13: Rotor of the 5-phase PMSM equipped with heat pipes. Structure of the heat pipe

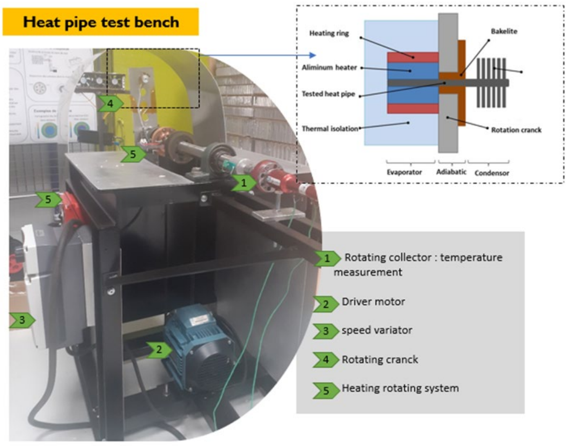


Figure 14: Experimental setup for revolving heat pipe

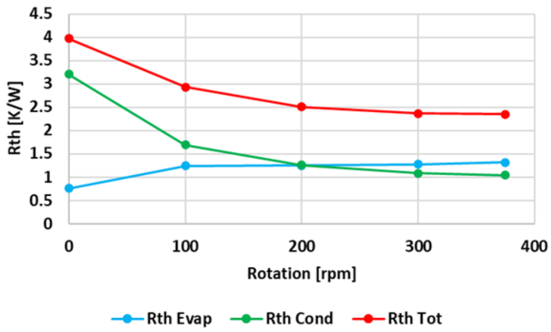
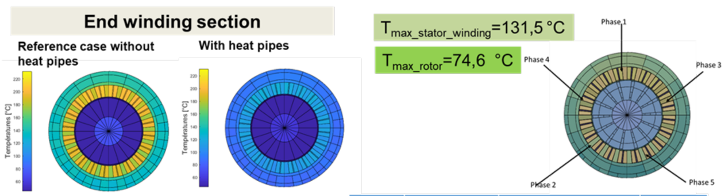


Figure 15: Thermal resistance function of rotation speed

The thermal conductance, which is the inverse of thermal resistance (figure 15), was then used in the global modeling with the nodal method and showed the interest of these revolving heat pipes to improve the cooling of the machine. Thereby, the contribution of heat pipes for a given operating point has been studied. In this case, Figure 16 shows the temperature distribution with and without the heat pipes. We can distinguish an extreme operating case with the losses of 35 W at the rotor and 1010 W at the stator, the maximum temperature is estimated at 131.5 °C according to the nodal modelling.



Phase	Refernce case 3000rpm (T en °C)	With static and revolving heat pipes (T en °C)	ΔT
1	194,6	119,4	75,2
2	185	108,9	76,1
3	189,8	114	75,8
4	189,3	113,5	75.8
5	185,9	109,7	76,2

Figure 16: Thermal performance comparison between a machine without heat pipe and machine with heat pipes

As the statoric copper heat pipes have been inserted in stator iron sheets (figure 7), it has been verified at first by FE software and then by measurements of losses that no significant supplementary losses were induced in the heat pipes despite their proximity to electromagnetic fields at the bottom of slots (figure

7). The insulation with resin between iron sheets and each heat pipe prevents effectively from huge induced eddy currents predicted by FE software in case of no insulation of heat pipe.

IV. Conclusion

This paper describes the simultaneous studies which have to be performed in order to design an integrated drive: on the power electronics side, on the point of view of the machine design and control, and of course on the thermal side, regarding the crucial importance of the cooling system within the compacity constraints. Elements of the design method of the integrated inverter in a multiphase PMSM has been presented. With the choice of an original symmetrical topology, heat pipes for cooling can be inserted close to loss locations in a machine which is adapted thus to transient operations. Considering the number of phases as a parameter of design allows more flexibility for the VSI design while giving tolerance to a transistor fault.

The presented configuration of integrated drive is based on the location of two multi-leg inverters on each axial side of the machine. The number of chosen legs is depending on space and thermal constraints of the VSIs. To increase the power density of the converter and meet with the volume constraints, GaN transistors are used because of their small dimensions of their packaging and high switching frequency.

A 10-phase configuration with two separate supplies and two controls is ongoing.

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