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Integrated drives for transport – A review of the enabling thermal management technology

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Abstract— **Electric drives which are deployed in transport applications often have stringent volume/mass constraints requiring that the subsystems of electric drives are incorporated in a tightly packaged mechanical arrangement. As integration of mechanical and electronic subsystems becomes more intricate the thermal management issues relating to dealing with the loss in the converter and actuator in tandem become more complex. This paper presents a review of the state of the art manufacturing techniques and technologies which are enabling ever greater integration in electric drives for transport applications through better thermal management.**

Keywords—Integrated drive, thermal management

I. INTRODUCTION

INTEGRATED drives, consisting of the combination mechanical, thermal and electrical aspects of an electric drive system have been proposed in literature claiming to exhibit significant benefits over traditional electrical drive systems [1-12]. The key advantages in using an integrated drive versus a traditionally packaged drive can be summarized by these points;

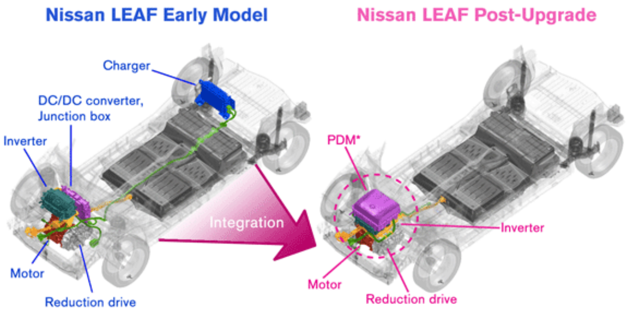
- Volume/mass reduction over traditional separately constructed systems
- Possible reduced EMC issues due to elimination of cables transferring power at high frequency
- The ability to replace direct online start machines (traditional grid connected) with variable speed machines without significantly altering the associated plant
- Single package installation – reduced installation time/cost
- Integrated or common cooling reducing hose lengths and chiller sizes
- Greater flexibility in the machine and drive topologies from greater design synergy

The rationale for perusing research in integrated drives can be justified not only from the technical advantages above but also by recognizing that whilst some work has been undertaken with respect to integrated drives the technology streams associated with them are by no means mature and there is growing interest in the academic and industrial community in research on them.

Broadly, an electric drive can be considered to consist of all plant which is located between the electrical supply and the mechanical output of an actuator. Common examples are variable speed drives in applications such as pumps, electric vehicle drivetrains, renewable energy generators, aircraft actuators, mass transit traction, air conditioning units and many more. The actuator in an electric drive is commonly a rotating machine however linear actuators may also be considered. A gearbox may also be incorporated into the drivetrain to regulate the actuator. However, since where they are used, gearboxes are generally well integrated to the machine, gearbox integration is not considered in this review.

Most of the technical advantages discussed above are well suited to electric transportation applications where reduction of total volume/mass, better mechanical packaging and integrated and common cooling are all very beneficial.

The nature of the actuators employed in electric drives is very diverse, even within vehicle propulsion applications, and may consist of one of a number of machine types. Since, in variable speed drives, the supply characteristics rarely match the requirements of the actuator it is usual for a power electronic converter to provide an interface between the supply and the actuator. The power electronic converter consists of main power devices – the power switches – and their associated driving, sensing and control electronics. Again, there is significant variance in the topology of the power electronic converter for transport related drives as they can perform a number of functions. Both the mechanical actuator and the power electronic converter (and in some cases the passive components) have significant thermal management demands. Although efficiencies for a whole drive may be better than 90% [13] the loss management is still significant, particularly when considering high power drives. Cooling of the various constituents of the electric drive is therefore an important aspect of any drive design. In most applications the power electronic components and the electrical actuator are considered physically separate entities with their mechanical and thermal design aspects approached in isolation – although they may be on the same cooling circuit. The result of this is that the power electronic converter and the actuator are usually packaged individually and installed separately. Fig. 1a shows a drivetrain schematic for the Nissan Leaf showing the original distributed nature of the electric drive. Better integration of the component parts of the drive such as in the upgraded Nissan Leaf drivetrain (Fig. 1b) will yield some of the advantages discussed above however the constituent parts of the drive (machine, electronics and controller etc.) are still being considered as separate physical entities.



(a) (b)

Fig. 1 – (a) Early distributed drive LEAF drivetrain, (b) Upgraded integrated drivetrain [43]

Clearly, there are aspects of the packaging and thermal and mechanical management which are common to both the actuator and converter and it may therefore be desirable to combine the physical construction of the whole drive in order to remove duplication and reduce the space envelope of the system as a whole. Further examples of even deeper integration of an electric drive are given in literature such as that shown in Fig. 2.

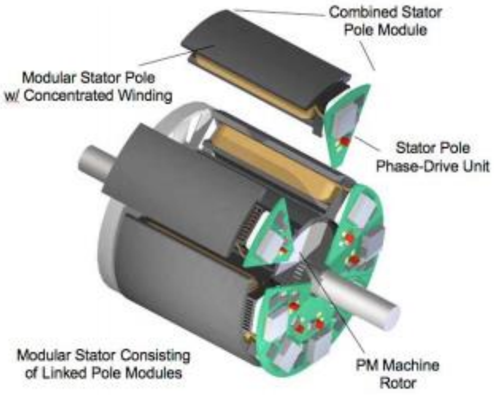


Fig. 2 - An example of an integrated drive from academic literature (2.7kW, OD = 120mm) [7]

This configuration is aimed at producing a more compact, high power density motor drive. The power converter is mounted on the stator back iron which acts as a heat sink and mounting platform for the converter. This configuration is particularly beneficial when the height of the converter components is small, allowing the converter fit in the space between the back iron and end plate.

Compared to a standard packaged variable speed drive the thermal management of an integrated motor drive is complicated due to the converter being in close proximity with heat sources in the machine (copper windings and stator back iron).

II. DRIVE THERMAL CONSIDERATIONS

A. *Drive thermal impact*

In most electric drives the greatest loss generating components, the power electronic switches, are mounted onto a heatsink which, in most large drives, have forced convection cooling. In some applications, particularly in automotive, the heatsink is liquid cooled on a cold plate. In these cases, the ambient temperatures may be up to 40-50℃ whereas liquid coolants can range from -20 to more than 100℃ dependent on the application. In an integrated drive the power electronics are mechanically mounted to the same structure as the electric machine. This combines the thermal management requirements of the machine and the power electronics into a single design problem. A unified cooling circuit which operates to cool both the machine and drive poses some questions on the topology of the cooling system. Particularly, since the thermal sink is common to all heat sources in the drivetrain. The thermal paths can be notionally arranged in parallel or series configuration. In parallel, the thermal flux paths are independent and do not influence each other. In practice, when the two heat sources are in close proximity this may require some thermal isolation such as that used in [5]. Series cooling paths can be considered by a thermal gradient which starts with the hottest component – which is assumed to be the machine – down to an intermediate thermal source – power electronics – and finally to the common sink. This, in practice, would be difficult to achieve since the thermal gradient between the machine and the power electronics must be carefully managed so as not to overheat the devices. Another configuration may be considered whereby the two thermal energies sink to the thermal path in such a way that there is a thermal gradient in the coolant circuit between the two physical sink points, this concept could be termed parallel/series cooling.

Where integrated cooling systems have been discussed in literature there has been general consensus either to use purely parallel cooling paths or to use the parallel/series method. The complexity of managing the thermal gradient in the pure series case appears to be the driving factor behind this.

An air cooled system is described in [5] whereby the power electronics are to be placed on one of the axial end plates of a commercially available 30 kW induction machine. The mounting position of the end power electronics is as a result of available space between the endplate and the machine housing. There is a thermal isolation layer inserted to stop any thermal interference from the end-winding losses. The standard fan has to be enlarged and altered in design to take care of the different thermal flow and added loss source (the power electronic converter) and a heat sink plate was placed over the end windings to radiate loss away in a radial direction. It is assumed the machine components are robust enough to accommodate elevated temperatures compared to the power electronic devices.

In [2] the drive is located in a separate enclosure which is fixed to the machine casing. The power electronic components are mounted to a cold plate which is fed from the chiller unit. The outlet of the drive cold plate is then fed to the inlet of the machine cooling jacket. The level of integration in this example is quite low.

Both of these schemes incorporate the parallel/series cooling concept by first cooling the electronics and then using the same coolant to cool the machine.

The traction drive system in [1] uses a rectangular profile machine with sunken cooling pipes in the machine core-back. The purpose of the flat edge profile of the machine is to provide a fixing surface directly on the machine body for the power electronic components. Various cross sections are tested for the shape of the coolant flow; the best solution uses a rectangular void which physically isolates the thermal paths of the machine generated loss and the power electronic loss effectively using the coolant as the isolation medium. This system is more indicative of the parallel cooling concept.

III. ENABLING TECHNOLOGIES

A. *Improvements in machine thermal performance*

For an integrated drive the point, or node, at which a power electronic switch is attached to the machine has a maximum temperature limitation dictated by the maximum junction temperature, power electronic loss and the thermal conductivity of the packaging. Assuming that all of the heat generated by the power electronics flows through this connection point, or node, then the maximum temperature for this node, T_{max}, is given by

$$T_{max} = T_{jmax} - (R_{th} + R_{int})P_L \qquad (1)$$

where T_{jmax} is the maximum junction temperature of the device, R_{th} and R_{int} are the thermal resistances of the device between the junction and the casing and the thermal resistance of the casing to mounting node interface and P_L is the losses in the device. In the cases where the thermal paths of the machine and electronics are isolated then the treatment of this node's thermal design is no more involved than for a normal drive. However, if the temperature of this node is in any way dictated by the machine temperature then the thermal performance of the machine becomes an important factor.

Various component bodies within the electrical machine make up its thermal performance. The impregnation factor in a potted coil has significant impact, non-linearly, on the thermal performance of the slot. Fig. 3 shows the simulation results (obtained using MotorCAD software) giving variation in temperature of parts of an example PMAC machine due to variances in the impregnation factor of the slot. Impregnation factor in this context refers to the percentage of available space which is impregnated with potting compound, the rest is assumed to be air.

The simulation results in Fig. 3 clearly show that the relationship between the thermal performance of the slot is not linearly proportional to the impregnation factor, indicating that endeavoring to accomplish at least some level of impregnation gives a significant performance enhancement, however, striving to accomplish total impregnation results in diminishing returns.

Further improvements can be made in the slot thermal performance with reported reduction of coil thermal resistance by nearly 50% through compression of coils [15]. Cross-sections of compressed coils are shown in Fig. 4. Fill factors can also been improved to less than 3% difference to the practical maximum [15].

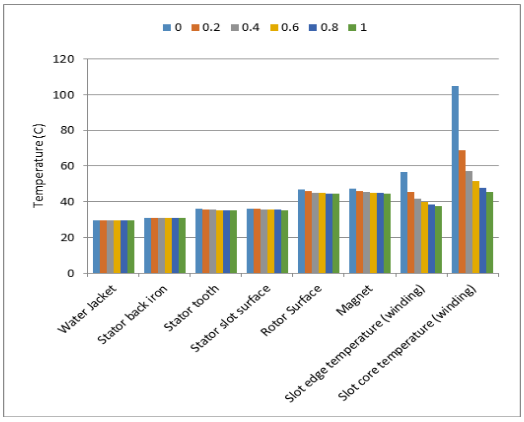


Fig. 3 – Simulated temperature of electrical machine parts over a range of impregnation factors; 0-100%. (Machine: 3kW, 100mm OD, 70mm l_a, 12 tooth surface mounted PMAC)

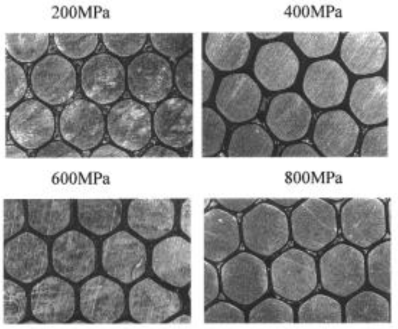


Fig. 4 - Cross-sections of compressed coils [15]

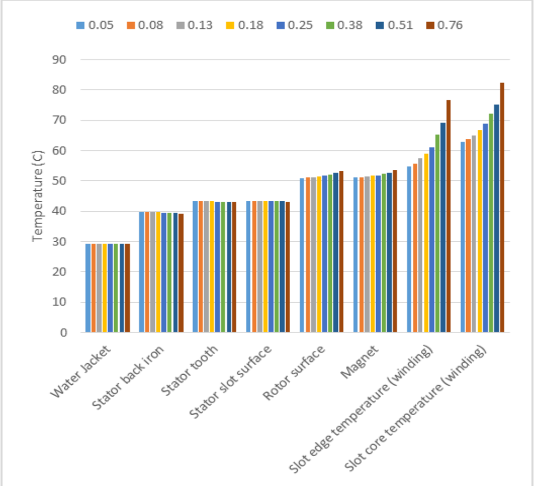


Fig. 5 - Simulated temperature of electrical machine parts over a range of slot liner thicknesses; 0.05-0.76mm.

The thickness of the slot liner also plays a significant role in the ability to remove heat from the slot.

Fig. 5 shows the simulation results for the same machine as for Fig. 3 giving variation in temperature of parts of an example PMAC machine due to variances in the thickness of NOMEX slot liner. The slot liner provides mechanical protection for the machine windings but has relatively poor thermal performance. It also introduces a further, or pair of, air gaps between the loss generating windings and the cooler stator further deteriorating the thermal performance.

Through careful combination of pressure treatment (compression) of the coils, a degree of potting impregnation and refinement on the type and mounting of the slot liner significant thermal performance improvements can be achieved for the machine slot.

B. *High temperature devices*

The current trends in SiC and GaN power devices theoretically offer operation at far higher maximum junction temperatures (250-300℃) than standard Si technology (150℃). However, the packaging materials of these devices, such as the encapsulate gels, are unable to work operate beyond around 250℃ [16]. Indeed, most SiC modules currently commercially available have datasheet values of T_{jmax} no more than their Si counterparts [17, 18]. There are however devices which are packaged for higher temperature operation up to 225℃ [19, 20].

Devices' ability to operate at elevated temperatures is a significant advantage for integrated drives. Since, as described above, integrating the mechanical fastening of machine and electronics in to one package closely couples the thermal dissipation paths. Utilizing higher temperature devices therefore gives a greater scope for locating them in different parts of the mechanical package and running the machine at elevated temperature it also reduces cooling requirements.

It should be noted that the gate drive circuits for the devices are also subject certain thermal restrictions. In order to reduce parasitic loss and timing errors it is essential to physically locate the gate drive near to the switching device, particularly for high frequency operations. In this case the driver circuit is equally subject to the ambient thermal conditions as that of the switch. It may therefore be necessary to consider that whilst the switch is dissipating a much higher loss level and therefore will operate with higher junction temperatures – facilitated by the use of SiC or GaN – the ambient conditions will mean the driver circuit, which will likely be Si based, also sits in a high ambient temperature location. Gate drive chips matching the higher operating temperature SiC are available [19] but care should be taken when specifying the passives and PCB.

C. *Passive component cooling*

A typical layout of a cabinet mounted industrial drive's filter components is shown in Fig. 6. In this case the packaging of input inductors and filter capacitors are not optimized for transport applications nor integration. However, increasingly research is tending towards integrated magnetics in particular with planar [14, 21], PCB and Si integrated magnetics [22, 23] which are more suitable to mechanical integration. In some cases the magnetic components are integrated into the machine itself [24]. With greater integration of passives into tighter packages their thermal management becomes a more important design factor. Planar magnetics, discussed in the previous section, have higher surface area to volume ratio than conventional cores and therefore have more efficient heat conduction away from the component. A comparison of thermal performance between a conventional core and a planar core is given in [14] and shows clear thermal performance benefit in the planar core giving it greater than 10% reduction in peak temperature above ambient.

Fig. 6- Cabinet layout of variable speed drive with filter magnetics highlighted in red

Modern power capacitors are now being specifically developed with low profile (short thermal path) and high electrode conductivities. The ceramic electrolyte is also able to withstand far higher temperatures (150℃). These design aspects mean the capacitor can be better thermally integrated with the power device [25].

D. *Coolant types*

Integrated drives have been demonstrated utilizing both forced air [6, 7, 11, 12] and water [1, 2, 9] however oil or aero fuel are also well-known methods for cooling electrical machines [26-29]. Whilst the utilization of the coolant type will depend to a great extent on the application other factors may also be factored into the decision. Liquid coolants require a heat exchanger which will likely need to be located remotely from the drive. Liquid coolants such as water glycol are traditionally preferred coolant used in electric transport systems, particularly in hybrid applications, since they can be incorporated into the traditional ICE cooling system. Although coolants may be shared in some applications, such as automotive, there is a trend to move away from centralized cooling in some applications [30]. For air cooling there must be good access to a readily available supply of cooler air. The coolant (air) is more directly affected by the ambient temperatures and therefore the thermal performance of air cooled systems is more susceptible to environmental circumstances.

Given a suitably sized heat exchanger the inbound coolant temperature of a liquid cooled system is far more controllable/measurable than for air. This allows far greater scope sensor-less prediction of the drive's component temperatures which can greatly aid condition-based de-rating and health monitoring.

E. Power Electronics packaging

Careful thermal and mechanical analysis is required in packaging power electronic devices to ensure efficient heat dissipation, mechanical stability, protection from hostile environments and reduction in stray inductances. A high temperature operating power module can potentially lead to a smaller system size of the IMD and reduced costs of the cooling system.

The packaging of the power electronics module restricts its maximum operating temperature due to critical failures of some module components at high temperature [31-32]. The module undergoes degradation of polymeric materials, high thermal and thermo-mechanical stresses at high temperatures [33-34]. Die attachments and interconnections like solders and wire bonds respectively suffer degradation and failures at high temperatures. [35-37].

Packaging technologies have been reported in literature and industry that improves reliability and heat dissipation in power modules ranging from compact wireless modules to pressure contact technologies. [38-41]. Dual sided cooled modules utilizing a flip-chip bonding configuration are reported to operate at temperatures over 220°C [42].

IV. CONCLUSIONS

Integrated drives have been presented in past literature as the logical culmination of integration of drive technology for a number of modern transport applications. The advantages in reduction of volume and mass, EMI reduction, control flexibility and general miniaturization of the drive are well documented. Integrating a variable speed drive results in a number of issues with the drive including thermal management, electrical and mechanical considerations. This paper has outlined the recent research advances which yield technologies which can be exploited by an integrated drive design in order to improve thermal performance.

In the future it can be expected that manufacturing techniques such as potted, compressed windings and the inclusion of high temperature devices and integrated passives will further improve the thermal performance of integrated drives allowing greater power densities to be reached.

Integrated drives would still not be considered a mature technology area and given the advances constantly being made on the technologies reported in this paper it is perceived that integrated drive technology will continue to evolve over the coming years.

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