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Considerations when developing a motor generator solution for green commercial vehicles

White Paper

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Abstract

STAMFORD | AvK has developed an electrical motor generator for hybrid electric vehicle applications.The machine architecture, power range and dimensions are optimised for a range of commercial vehicles, in addition to consumer marine and power generation applications. A critical requirement is ease of integration to the engine and transmission driveline of a commercial vehicle powertrain; the machine needs to be relatively short to provide minimal impact on the existing vehicle powertrain length and to reduce cost and complexity of any vehicle modifications. STAMFORD | AvK considered several different machine configurations including induction, switched reluctance and axial and radial flux permanent magnet. The selection process identified the best solution to be a liquid cooled, multi-pole, radial flux permanent magnet machine (Figure 1). Critical criteria such as short length, high efficiency, ease of manufacture, simple integration to the driveline and low inertia are met with the selected machine topology. A relatively high number of poles with a concentrated, non-overlapping, stator winding arrangement has been selected to achieve very high torque (660Nm) and maximum machine length requirement (200 mm).

I. Introduction

The journey of designing and developing permanent magnet machines at STAMFORD | AvK began in 2000 when a brand new Research & Technology Team was established to design and validate new topologies for permanent magnet alternators and power electronics converters. The team's original focus was power generation applications where the objective was to reduce fuel consumption of diesel generating sets. New opportunities in mobile power applications also drove a focus on size and weight reduction. The first specially packaged permanent magnet alternators and power conditioning systems developed by this team were commercially released in 2004 for military applications where reduced size, weight and fuel savings are of critical importance. In 2006, the team began development of a permanent magnet machine and power electronics converter for hybrid commercial vehicles. The resultant system, which was developed in collaboration with Cummins' engine and powertrain specialists, can be used in a wide range of hybrid architectures such as series, parallel and combined parallel and series hybrid.

The universal design of the machine enables coupling to any driveline using the SAE 2 housing layout and is capable of using any manufacturer's driveshaft. Also, since the torque produced by the engine is transmitted only by the driveshaft and not through the rotor, the rotor casting need not be a high strength material or, alternatively, can be optimised for relatively low mass.

The Cummins machine has a water-glycol cooling passage within the aluminium housing making it compatible with traditional engine and vehicle cooling systems. The water cooling manifold contains two threaded o-ring ports to allow the customer to fit a range of inlet and outlet connector pipes. Hoses from the relevant cooling system can then be connected to these pipes. To facilitate integration, the manifold has been designed as a separate component which allows significant variability of the machine's radial orientation.

Figure 1: Cummins radial flux motor generator

II. Machine Design

The need for the motor generator to produce high torque with high efficiency, coupled with requirements of low mass and small volume has driven analysis led design optimisation of the thermal and mechanical design. Specifically, constraints on machine length and on the ratio of machine diameter to machine length drove the selection of a permanent magnet topology with high number of poles and concentrated non-overlapping stator winding. The non-overlapping winding enables a shorter machine and also reduces cost by reducing the ratio of the length of the end winding to the length of the stator core pack. Open stator slots enable the use of externally wound coils on plastic bobbins which are then inserted in the stator. This aids manufacturing and delivers very good slot fill factor. The machine stator arrangement is shown in Figure 2.

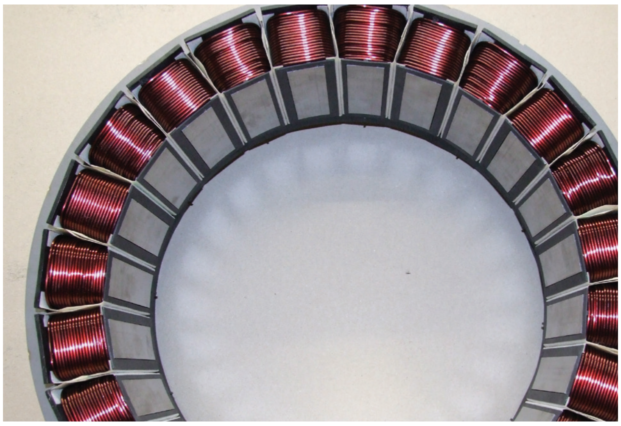


Figure 2: Concentrated non-overlapping wound stator

Several different permanent magnet rotor topologies were considered during the concept selection process:

- Surface magnet
- Inset magnet
- Embedded magnet: Flat and V-shape

After a rigours process of analysis led design using Six Sigma tools and processes, the embedded magnet topology (Figure 3) was selected mainly due to:

- Very good magnet mechanical retention and environmental protection
- Relatively low magnet losses
- Good field weakening capability
- Low short circuit current

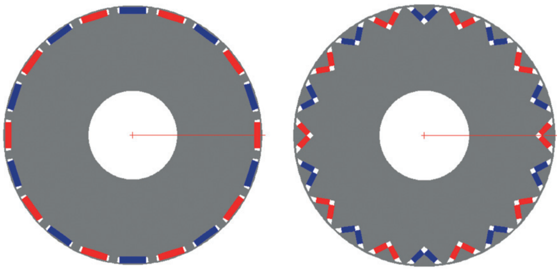


Figure 3: Flat and V-shape magnet topologies

The flux focusing V-shape magnet arrangement enables an increase in machine power density. This usually leads to an improvement in reluctance torque by increasing the ratio between Lq and Ld machine inductances. However, for this system, the high flux density was not an advantage due to a very strong adverse impact on machine no-load losses. High machine no-load losses will reduce the system's average efficiency over typical hybrid vehicle drive cycles meaning high flux density in the air gap is not optimal for this application. The stator arrangement with concentrated non-overlapping winding also reduces the reluctance torque in comparison to a typical stator with integral wounding. Therefore, a higher percentage of low reluctance torque was not attractive either.

Based on further analysis led design, the "flat" magnet topology was selected mainly due to:

- Lower magnet mass per unit - lower flux leakage than in V-shape topology
- Lower rotor inertia and constrains for rotor internal diameter
- Simple manufacturing process - lower number of magnets

To optimise complex electromagnetic, thermal and mechanical interactions and to ensure that application requirements were met, several different methodologies and design tools were utilised. Preliminary electromagnetic design and analysis using bespoke software with an embedded simplified Finite Element Analysis (FEA) solver allowed many design options to be considered within a short period of time. Figure 4 depicts an example of how this software with embedded FEA solver was used to assess the magnetic saturation levels within the rotor and stator laminations.

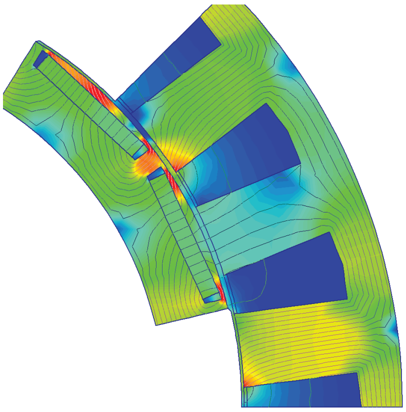


Figure 4: Example FEA of the motor generator

High fidelity FEA models were then used to confirm final results and to do detailed three dimensional design and analysis of the rotor. This work led to segmentation of the rotor (Figure 5) in order to reduce eddy current losses within the magnets. Low magnet losses are key to maintaining magnet temperature at an acceptable level since, unlike the stator, the rotor is not in direct contact with the liquid cooling circuit.

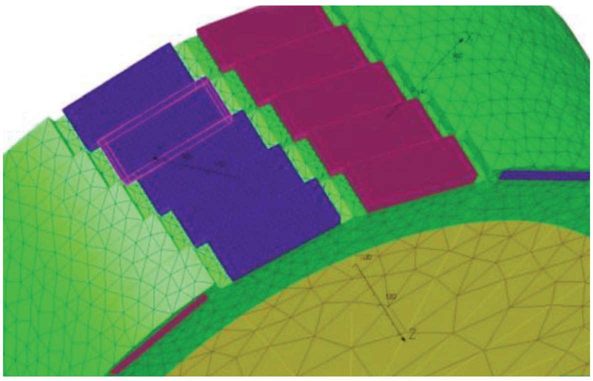


Figure 5: Rotor segmentation and magnet skew

Segmentation of the rotor further enables an offset ("skew") between each of the five rotor segments (Figure 5). This skew reduces cogging torque and improves machine voltage total harmonic distortion (THD). The "skew" angle selection is a compromise between acceptable levels of cogging torque and machine performance due to reduction of fundamental order harmonic voltage. The selected angle reduces cogging torque by five times and impacts the machine voltage by less than 2%.

Machine thermal performance was analysed and optimised using a proprietary thermal analysis tool coupled with Computational Fluid Dynamics (CFD) analysis. Figure 6 depicts a typical CFD analysis of the machine cooling jacket.

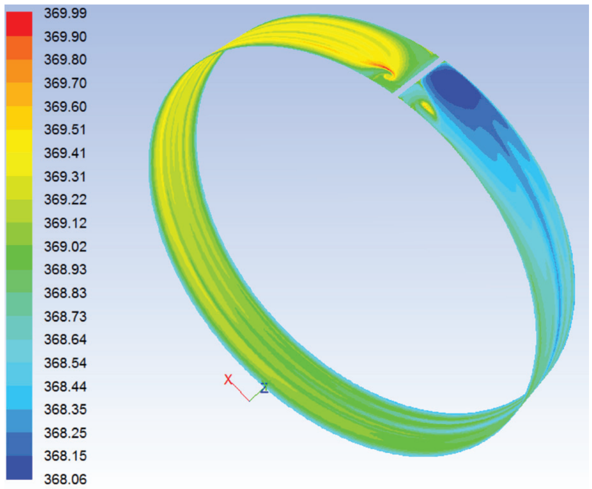


Figure 6: CFD analysis of the machine cooling jacket

III. Machine Performance

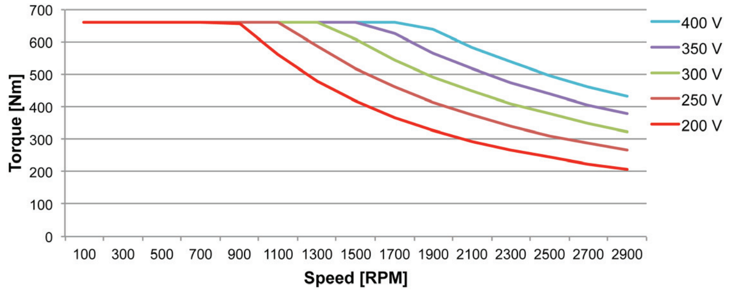
The main motor generator performance parameters are shown in Table I.

Peak Torque (60sec)	660 Nm
Peak Power (60sec)	90 kW @ 1300rpm
Continuous Power	35-40 kW @ 1300rpm
Efficiency	> 95 %
Length	200 mm
Diameter (Interface)	SAE 2
Mass	108 kg
Cooling	Water/Glycol, 12 l/min
M/G Inertia	0.41 kg-m2
Cogging Torque (Pk-Pk)	15.2 Nm
Max. Current @ 660Nm	418 A
Short Circuit Current	275 A
Position Sensor	Resolver
Temperature Sensor	2 x RTD PT1000
Safety	High voltage interlock in terminal box cover

Table I: Motor generator performance parameters

Very high torque and efficiency over the torque-speed operating range of the motor generator allow flexible and fuel efficient operation of the machine in any hybrid powertrain system. In the very unlikely event of a machine or system failure, high impedance and low short circuit current guarantee very low fault torque which is critical in applications where the motor generator is an integral part of the vehicle powertrain. Continuous power is 35kW in applications where high peak torque and high peak power are required. In applications where peak power and peak torque can be reduced, continuous power can be increased to 40 kW. This flexibility allows optimisation of the entire powertrain without risk of magnet demagnetisation due to excessive temperature.

Battery voltage determines the machine's torque over the speed range (Figure 7). Although peak torque is limited by the machine's electromagnetic capability, peak power can be extended to higher values as depicted on the graph if the battery voltage also increases. During regenerative braking, the battery voltage increases due to an additional voltage across the internal resistance of the battery.



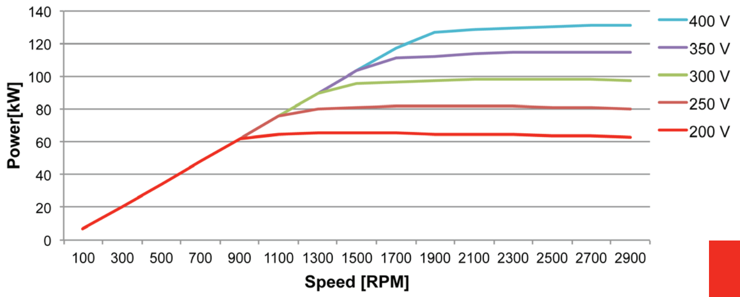


Figure 7: Torque and power vs. speed and voltage

The design of the motor generator enables high efficiency over a wide operating range of torque and speed (Figure 8). The average machine efficiency over a typical hybrid vehicle city drive cycle is better than 92% with peak efficiency greater than 95%.

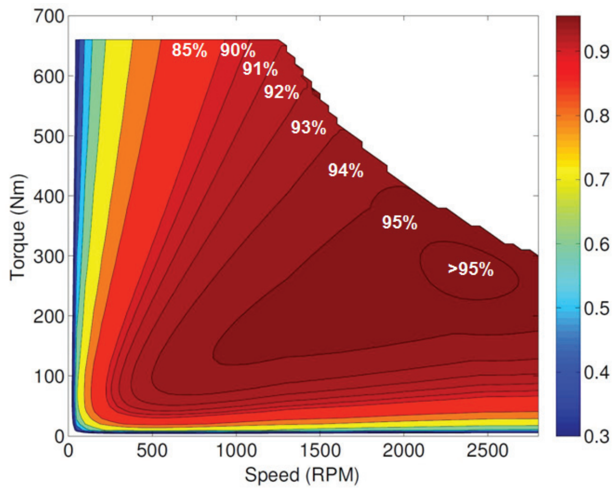


Figure 8: Efficiency map of the motor generator

IV. Power Electronics

Power electronics and control strategies are an integral part of the hybrid system operation. These need to be considered together with the motor generator during the analysis led design process in order to optimise total system performance. In support of this work, a suite of several analytical tools and methods was developed. The end result is a complete system combining the motor generator and liquid cooled (water/glycol) power electronics operating proprietary software from Cummins and compatible with Cummins' service tools. See Table II for the power electronics performance parameters.

Continuous AC Current	350 A
Peak AC Current (30 sec)	500 A
Nominal (Max) Voltage	375 (450) V DC
Switching Frequency	< 20 kHz
Discharging System	Passive and Active
Position Sensor	Resolver
Dimensions H x W x L	(109 x 244 x 475) mm
Mass	15 kg
Cooling	Water/Glycol, 12 l/min

Table II: Power electronics performance parameters

The Cummins' software and control strategy embedded in the power electronics, coupled with high continuous and high peak current capability, enables very efficient operation of the motor generator and power electronics over a wide range of torque and speed (Figure 9). In the unlikely event of a system failure, the control system also includes algorithms to detect that failure and to protect the motor generator and power electronics. Examples include excessive temperature of the motor generator stator or power electronics, demagnetisation of the magnets due to excessive temperature of the rotor, rotor over speed operation and over voltage faults.

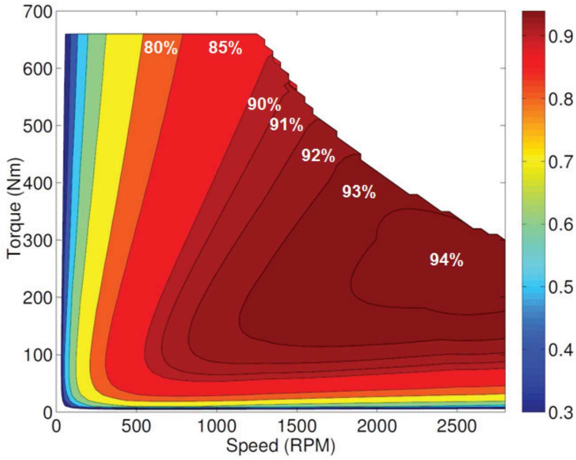


Figure 9: Efficiency map of the motor generator and power electronics system

Conclusion

Building on more than a decade of permanent magnet motor generator and power electronics analysis led design experience, STAMFORD | AvK has developed a highly efficient, compact radial flux permanent magnet motor generator machine and power electronics system for integration in to a range of commercial hybrid vehicles, including series, parallel and combined parallel and series architectures. This high torque, high power system is also ideal for use in consumer marine and power generation applications. The minimal length motor generator can be easily integrated to any driveline of a commercial vehicle powertrain via the SAE 2 housing and flexible coolant connections. The Cummins' power electronics control and protection algorithms guarantee serviceability plus optimum operation and efficiency of the motor generator and power electronics system.

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