

Development of Integrated Modular Motor Drive for Traction Applications

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ABSTRACT

This paper introduces a promising approach for developing an integrated traction motor drive based on the Integrated Modular Motor Drive (IMMD) concept. The IMMD concept strives to meet aggressive power density and performance targets by modularizing both the machine and power electronics and then integrating them into a single combined machine-plus-drive structure. Physical integration of the power electronics inside the machine makes it highly desirable to increase the power electronics operating temperature including higher power semiconductor junction temperatures and improved device packaging.

Recent progress towards implementing the IMMD concept in an integrated traction motor drive is summarized in this paper. Several candidate permanent magnet (PM) machine configurations with different numbers of phases between 3 and 6 are analyzed to compare their performance characteristics and key application features. A 6-phase, 10-pole PM machine topology has been selected as the most

promising configuration for meeting the major requirements in the areas of power density, efficiency, and module count. A parallel investigation of fault-tolerant distributed control configurations for the IMMD traction drive has led to selection of a heterarchical controller configuration that requires each phase module to be equipped with its own independent microcontroller operating as a peer with all of the other phase module controllers.

The potential of silicon (Si) insulated gate bipolar transistors (IGBTs) operating at junction temperatures up to 200°C has been evaluated using a hardware testbed in terms of device losses and thermal issues. Based on these study results, a 10 kW phase-leg package design using Si IGBTs has been investigated including die selection, material selection, layout design, parasitic extraction and thermal characterization. Thermal performance characterization has been conducted for different packaging structures, operating conditions and coolant selections. The proposed packaging design and cooling approach can maintain the Si IGBT junction

temperature below 200°C with an ambient temperature of 150°C.

INTRODUCTION

Today's hybrid electric vehicle (HEV) traction drives cannot meet the aggressive power density and cost targets for 2015 and 2020 because the electric machine and drive electronics are packaged as separate components, each with its own housing and thermal management system. The connectors and cables needed to interconnect the machine and drive add to the weight and cost.

The integration of motor and drive offers a number of attractive features such as reduced drive volume and the elimination of power transmission cables. Radiated electromagnetic interference and voltage transients due to power transmission over long cable distances are also reduced. Motor and drive integration can also offer fault-tolerant features not possible with conventional drives [1,2].

However, there are many challenges associated with achieving the physical integration of the motor drive inside the machine housing. Designing power electronics to operate in the hostile thermal and vibrational environment inside an electrical motor is a challenging task. In addition, the desire to minimize the added volume and weight associated with the motor drive electronics while simultaneously minimizing cost generates requirements that push the limits of available technology.

A promising approach for achieving the desired traction drive integration has been proposed and will be referred to as the Integrated Modular Motor Drive (IMMD) concept [1,2]. As illustrated in Fig. 1, the basic building block of the IMMD is comprised of the following components:

- A segmented stator pole piece fabricated from either conventional steel laminations or soft magnetic composite (SMC) material
- A concentrated coil winding surrounding the stator pole
- An autonomous power converter dedicated to the motor pole that includes the required power electronics and controller to excite the pole winding in a coordinated fashion with the other stator phase-drive units

The complete IMMD is then constructed by assembling the desired number of basic building blocks into an annulus to form the integrated stator assembly.

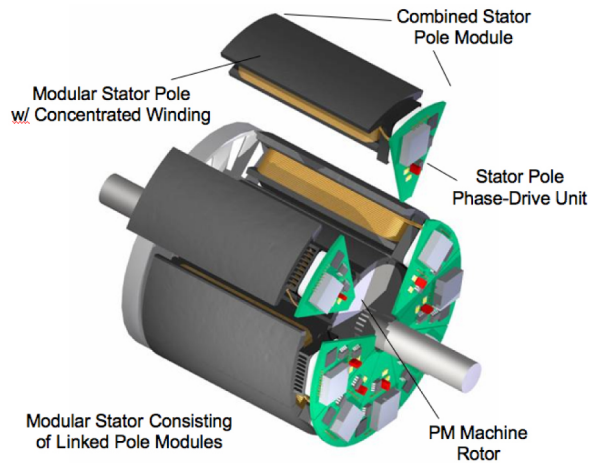


Figure 1. Integrated Modular Motor Drive (IMMD) concept highlighting the modular stator assembly

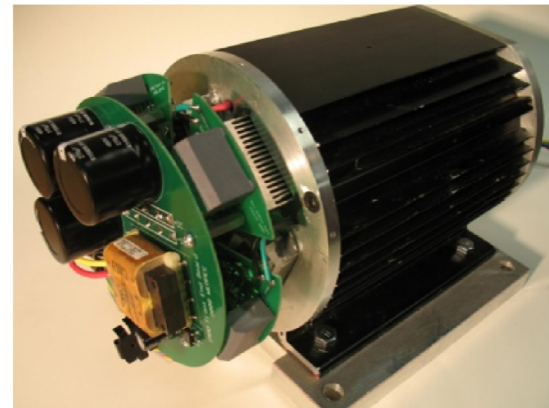


Figure 2. Concept demonstrator version of IMMD (<3 kW) [2]

Work accomplished to date has demonstrated key principles of the IMMD at a low power level (<3 kW) in a concept demonstrator unit shown in Fig. 2 [2]. However, significant work remains to realize its full potential, including scaling the power rating up to traction drive levels. For example, the choice of machine configuration appropriate for the low-power concept demonstrator is not likely to be optimum for a traction drive with power ratings at least an order of magnitude higher. Furthermore, the opportunities for developing a fault-tolerant controller configuration that can take full advantage of the modular machine structure have not yet been fully explored.

One of the major sources of technical challenges for the IMMD concept is the challenging thermal environment for the drive electronics. Currently, the power electronics in hybrid vehicles uses 70°C coolant supplied by a separate cooling loop in the automobile. To reduce cost and complexity, it is desirable to eliminate the need for the additional cooling loop and cool the power electronics with

105°C engine coolant instead. Considering the harsh environment and the challenging power density and cost targets, it is also desirable to extend power electronics device operation to higher temperatures and to utilize advanced packaging approaches. Current commercial silicon (Si) devices usually have a maximum junction temperature rating of 150°C, with some devices rated at 175°C. Silicon carbide (SiC) power devices including junction gate field-effect transistor (JFETs), metal-oxide-semiconductor field-effect transistors (MOSFETs) and Schottky barrier diodes (SBDs) can theoretically operate at high temperature above 500°C, but they are developmental and expensive [3,4]. As an alternative, it is desirable to investigate the prospects for raising Si device junction temperatures to 200°C as a lower-cost approach for meeting the thermal challenges [5,6].

The objective of this paper is to describe recent progress towards extending the IMMD concept to meet the challenges of high-performance integrated traction machine drives intended for use in future hybrid-electric vehicles. This work includes a thorough review of alternative concentrated winding PM machine configurations to determine the machine topology that offers the most attractive combination of performance features required for implementing the IMMD concept. Similarly, results of a parallel study are reported that have been used to identify the most promising controller architecture for providing a high-level of fault tolerance and robustness in future IMMD traction drive systems.

This paper also evaluates the prospects for using Si IGBTs with suitable packaging at 200°C junction temperatures considering important issues associated with device characteristics, losses, and cooling. The potential of Si IGBTs operating at high temperatures is studied using a combination of analysis and experimental testing to explore device losses and thermal issues. Based on the results of this study, a 10 kW phase-leg package using Si power devices combined with a 2-pass-tube coldplate is proposed that shows promise for holding the junction temperatures below 200°C with an ambient temperature of 150°C.

IMMD MACHINE COMPARATIVE EVALUATION

PERFORMANCE SPECIFICATIONS

A set of specifications originally developed in 2006 by the US Department of Energy for the FreedomCar Advanced Traction Motors has been adopted as the basis for the new machine designs in this project. Table 1 provides a summary of these specifications.

Table 1. Summary of Freedom Car Advanced Traction Motor Specifications

<i>Requirements</i>	<i>Target Specifications</i>
Maximum speed	14,000 rpm
Peak power at 2800 rpm for 18 s	55 kW
Continuous power (20 to 100% of max. speed and nom. voltage)	30 kW
Battery operating voltage	Nominal: 325 Vdc Range: 200 to 450 Vdc
Maximum motor current	400A _{rms}
Efficiency at 10 to 100% of max. speed for 20% of rated torque	> 95%
Back-emf at 100% of max speed, peak line-to-line	< 600 V
Torque pulsations, % of peak torque	< 5%

MACHINE PERFORMANCE COMPARISONS

Optimal Slot/Pole Combinations for Different Numbers of Phases

This section presents the set of criteria for choosing the optimal slot/pole combination for different numbers of stator phases [7]. The basic building block of the IMMD consists of a stator pole piece fitted with a concentrated winding and a dedicated power converter unit. Considering the nature of the application, the optimum slot/pole combinations can be chosen according to the following criteria:

- (1). Choose a high value of the fundamental winding factor K_{w1} to maximize torque production.
- (2). Choose the highest least common multiple (LCM) of N_s and N_m to minimize cogging torque. $\text{LCM}(N_s, N_m)$ indicates the number of cogging torque periods per full mechanical rotation.
- (3). Choose the greatest common divisor (GCD) of the number of slots, N_s , and the number of poles, N_m , greater than 1 and even. $\text{GCD}(N_s, N_m)$ indicates symmetries in winding layout and magnetic pull between the stator iron and the rotor magnets.
- (4). Consider the magnetomotive force (mmf) space harmonic distribution to minimize the rotor losses.

Tables presenting the synchronous winding factor, $LCM(N_s, N_m)$, and $GCD(N_s, N_m)$ for 3, 4, 5, and 6 phase slot/pole combinations that support fractional-slot concentrated windings (FSCWs) have been generated. Using these tables, the most promising slot/pole combinations for FSCW-surface PM (SPM) machines with phase numbers between 3 and 6 have been selected; [Table 2](#) compares basic performance features of these designs, referred to as 3P, 4P, 5P, and 6P, where the integer represents the number of phases.

Table 2. Key Metrics of Machines with Different Phase Numbers

	3P	4P	5P	6P
Poles	10	14	14	10
Slots	12	16	15	12
Slots/pole/phase (SPP)	2/5	2/7	3/14	1/5
LCM	60	112	210	60
GCD	2	2	1	2
Winding factor	0.933	0.962	0.980	0.966
Max elec. freq. (Hz)	1167	1633	1633	1167
Overtating factor (%)	n/a	33	25	20
Number of modules	6	8	5	12

Table 3. Machine Dimensions and Material Constraints

Stator OD	274 mm
Active axial length	75 mm
Air-gap thickness	1.0 mm
Rotor OD	142 mm
Magnet thickness	11 mm
Magnet remanent flux density	1.0 T

[Table 3](#) presents the key machine dimensions and magnet characteristics that were held constant for all of the machine designs. [Figures 3, 4, 5, 6](#) provide key graphical information for each of these four machine designs including a machine cross-sectional view, a plot of the winding function for a single-phase winding and a plot of the spatial harmonic components present in the winding function. The highlighted entries in [Table 2](#) identify the notable strengths of each candidate. The 3P design has relatively low electrical frequency and an even GCD that minimizes the risk of unbalanced magnetic pull on the rotor. Since the 6P design has the same stator and rotor structure as 3P, their characteristics are quite similar to each other. However, the higher winding factor and reduced torque ripple of 6P are advantages due to the increased number of phases. The slot/phase/pole (SPP) value of 2/7 is highlighted for the 4P design because previous work has shown that the families of $SPP=2/5$ or $SPP=2/7$ are particularly well suited for high-speed SPM machines achieving optimal flux weakening conditions [3]. The 5P design has the highest LCM

(appealing for low torque ripple) and winding factor (desirable for high power density) and the minimum number of modules.

EFFECTS OF STATOR MMF SPACE HARMONICS ON CANDIDATE DESIGN PERFORMANCE

The stator mmf distributions in FSCW machines generally contain a rich set of spatial harmonics. As a result, the magnet eddy-current losses in modular PM machines with concentrated windings are typically larger than those in conventional PM synchronous machines with distributed windings. The torque in modular PM machines is produced by the interaction of a higher order synchronous harmonic component with the PMs. Harmonic component analysis of the phase winding functions has been conducted to compare the spatial harmonics.

In the comparison, a constraint has been introduced requiring the same synchronous component magnet flux-linkage in all of the candidate designs. This constraint forces the amplitude of the synchronous frequency component in [Figs. 3, 4, 5, 6](#) to be the same for all of the candidate designs. Consequently, all the machines produce the same torque when the windings are excited with a current that is inversely proportional to the number of phases.

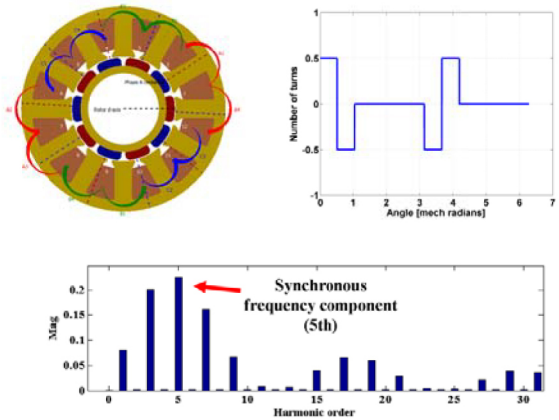


Figure 3. 3 phase machine (3P): 12 slots/10 poles.

Table 4. Comparative Machine Performance Metrics

Feature	3P	4P	5P	6P
Series turns/phase	32	32	33	32
Rated current density @ A/mm ²	5.64	5.69	5.16	5.75
Peak current density @ A/mm ²	10.89	11.84	11	11.74
Rated current (A rms)	150	118	82.2	76.6
Phase back EMF @ 14,000 rpm (V _{peak})	458	455	460	458
Torque ripple @ peak power conditions (%)	5.9	2.0	0.7	2.3
Copper mass (kg)	6.8	7.8	10.4	13.6
Iron mass (kg)	19.1	18.3	18.1	19.2
Magnet mass (kg)	2.3	2.2	2.2	2.3
Total mass (kg)	28.2	28.3	30.7	35.1
Peak PM flux linkage (mWb)	71.5	53.8	43.4	35.9

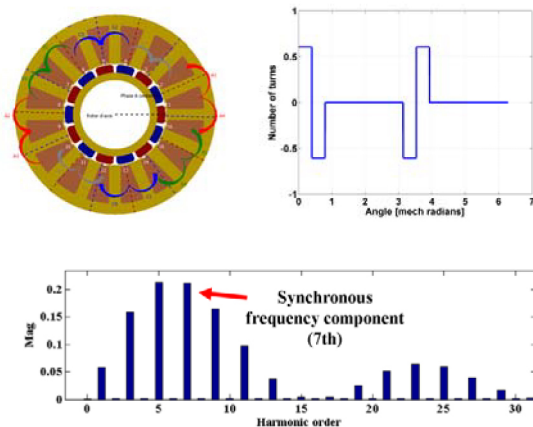


Figure 4. 4 phase machine (4P): 16 slots/14 poles.

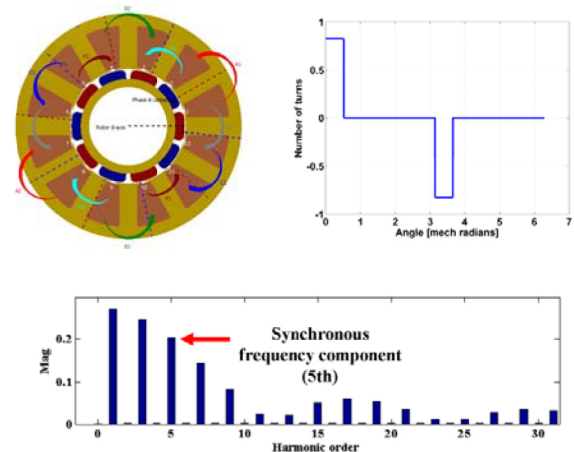


Figure 6. 6 phase machine (6P): 2 slots/10 poles.

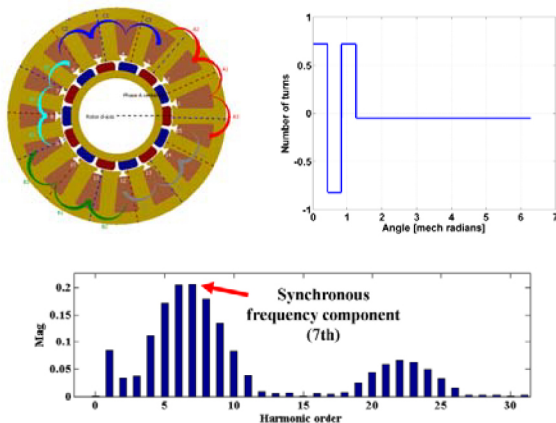


Figure 5. 5 phase machine (5P): 15 slots/14 poles.

FEA VALIDATION OF MACHINE PERFORMANCE

Finite element analysis (FEA) has been used to design the four candidate machines presented in [Figs. 3, 4, 5, 6](#) and to analyze their performance. [Table 4](#) provides a summary of the key performance predictions for the candidate machines.

To begin, [Figure 7\(a\)](#) presents comparisons of the predicted phase back-emf waveforms for all four machines at maximum speed operation (14,000 rpm), emphasizing their electromagnetic similarities. The predicted average torque for these machines is plotted in [Figure 7\(b\)](#) as a function of the phase current, with both variables plotted in per-unit to simplify the comparisons. All four machines begin to exhibit the effects of magnetic saturation at elevated phase current amplitudes between 1.5 and 2.0 pu, although the nonlinearity is mildest for the 3P machine. Finally, [Figure 7\(c\)](#) compares the predicted torque ripple for the four machines during peak torque operation (i.e., 55 kW @ 2800 rpm), demonstrating