Power Converter Design for an Integrated Modular Motor Drive

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***Abstract*— The Integrated Modular Motor Drive (IMMD) concept provides a promising approach to integrating motor drive electronics into the machine housing by modularizing both the machine stator and the power converter. The basic module of the IMMD consists of a stator pole-piece wound with a concentrated coil and fitted with a dedicated power converter unit. This paper addresses several of the challenges associated with the design of an IMMD power converter module. In particular, the issues associated with configuring the dc bus capacitance to meet the demanding size requirements of the power converter are addressed, including the effect of dc bus connections. Experimental results for converter operation are presented, and opportunities to further reduce the capacitor size using active control strategies are discussed.**

Keywords - integrated motor drive; PM motor drive; modular electronics; segmented stator; concentrated windings.

I. INTRODUCTION

Continued improvements in the efficiency, power density, and packaging of power electronics technologies have opened opportunities for new motor drive configurations. Drive designs that allow integration of the drive electronics into the same housing as the machine are attractive in a wide range of applications that include white goods and heating, ventilating, and air conditioning (HVAC) equipment.

Integration of the machine and drive provides a number of potential advantages, particularly at the system level. Integrated drives makes it possible to reduce the total drive volume by eliminating the need for separate housings for the motor and drive controller electronics. Elimination of cables connecting the drive electronics to the machine reduces the drive system weight. Risks of high radiated EMI levels and winding overvoltages caused by PWM voltage waveforms sent over long machine cables are also reduced.

The integrated drive also opens opportunities for simultaneously optimizing the machine and drive electronics that can be used to minimize drive system cost and complexity for the end user. Engineering the motor and drive together can improve the feasibility of introducing advanced features such as self-sensing technologies for rotor position sensing and condition monitoring. In view of these advantages and significant advances in power electronics and permanent magnet (PM) motor technology, it is expected that integrated motor drives will become increasingly popular during coming years [1, 2].

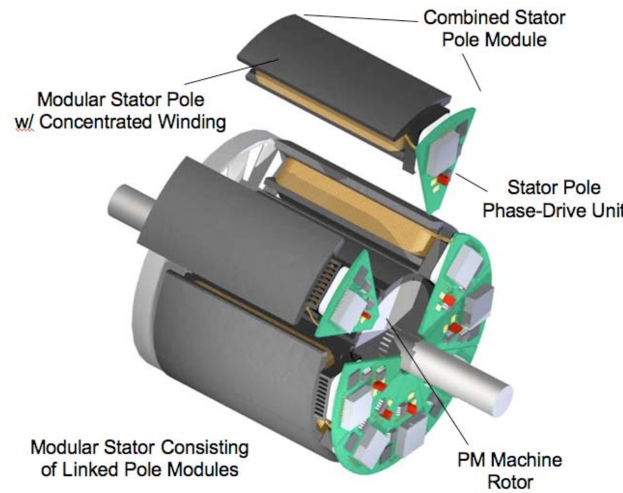

Fig. 1: Illustration of integrated modular motor drive (IMMD) concept including modular stator assembly.

Power converter design for integrated drives poses a host of significant challenges that originate both from the limitations on available space and the need to adapt the power converter to the thermal, vibration, and electromagnetic field stresses inside the motor housing. Continued advances in power electronics component and packaging technologies, including the development of high-temperature power semiconductor materials such as silicon carbide and gallium nitride, will help make it possible for the power converter to meet these environmental demands [3, 4].

In view of these special requirements placed on power converters in integrated motor drives, it is extremely difficult for such drives to offer cost savings compared to conventional motor drives based on today's technology. In fact, others have suggested that "plug and play" motor drives available in the market today that mount the power electronics in a separate housing attached to the outer surface of the motor housing require a cost premium up to 20% [5]. While this cost premium can be justified in some applications today because of the available savings in system cost, the full realization of the integrated motor drive concept awaits further improvements in power electronics technology that will lead to significant cost reductions.

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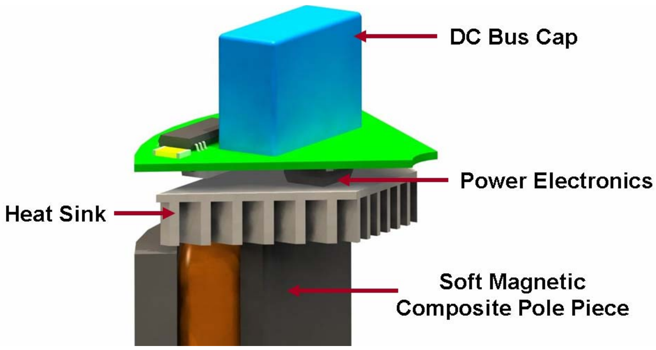


Fig. 2: Drawing of IMMD stator pole module consisting of an iron pole piece, a concentrated stator winding, and a dedicated single-phase power converter.

Some examples of motor drives integrated inside the machine housings have been reported by other researchers [6,7,8]. The integrated modular motor drive (IMMD) concept that is being pursued in this project (Fig. 1) takes a major step beyond these previously reported drives by modularizing the motor and the power converter as discussed in more detail in Section II.

The objective of this paper is to address technical issues encountered during the design of a modular power converter module intended to demonstrate the key features of the IMMD concept. Particular attention is placed on the method of connecting the dc bus to the individual phase modules and the effects this has on the dc link capacitor size. Test results for the first generation of experimental hardware are presented, and several suggestions for future improvements are discussed based on the lessons learned from project efforts to date.

II. Integrated Modular Motor Drive Overview

The IMMD concept is based on the adoption of a modular motor phase-drive unit for the stator assembly (Fig. 2) that includes the following key components:

- A segmented stator pole piece fabricated from either conventional magnetic steel laminations or soft magnetic composite (SMC) material [9]
- A concentrated coil winding on 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 stator is fabricated from a number of these pole-drive units interconnected to form the annular stator assembly.

In addition to the benefit of modular construction, the IMMD configuration incorporates discrete control of each motor winding, opening up opportunities for special control and fault management techniques that have been explored in [10] and [11]. According to these concepts, each module communicates with all of the others to determine the proper switching operation of its dedicated phase-leg converter.

Since each phase-drive module is expected to operate independently of the others, dc bus capacitance is built into each module so that external capacitors are not required. One approach to minimizing the required capacitance is to add a controlled rectifier to each phase-drive unit [12]. This approach has the advantage of maintaining symmetry among all of the phase-drive units. The rather obvious disadvantage is the significant increase in the amount of power electronics required for each phase-drive power converter.

In contrast, the adoption of a single rectifier stage to supply dc power to all of the module dc links requires special care to ensure approximately equal input impedance for each stator pole converter. Options for dc link bus connections are discussed in more detail in the following section.

III. Power Converter Design

A. Overview

In order to explore the basic IMMD features and identify areas for further study, concept demonstration hardware has been designed and built for use with a five-phase machine designed at UW-Madison [9]. This machine has been designed using soft magnetic composite (SMC) material in the initial prototype IMMD hardware.

The prototype machine consists of five stator coils and a six-pole surface PM rotor. A detailed list of machine parameters is provided in the appendix. For this discussion, it is particularly relevant to note that the prototype machine has a power rating of 2.7 kW; its rated phase current is 5.5 Arms, and the machine's outer diameter is 120 mm. Both the machine and converter have been designed to operate from a 400V dc bus.

The objective of the initial concept demonstration for the IMMD electronics is to design and build a modular power converter with five annular phase-drive units that has an outer diameter no larger than that of the prototype machine. Since the focus of this initial demonstrator hardware has been on the power electronics, the controller functions are provided by a separate external unit.

Each phase-leg converter is configured as a hard-switched half-bridge inverter phase-leg consisting of two IGBTs and anti-parallel diodes together with the necessary gate drives, bus capacitance, and current sensors. The motor windings are configured in a wye connection with a floating neutral so that that only one terminal of each stator pole winding is directly excited by a converter phase-leg.

The initial demonstrator versions of the IMMD power converters are mounted outside the machine in order to simplify electrical testing. Each power converter module includes power devices, gate drive circuitry, dc bus capacitors, current sensors, and all of the necessary electrical connectors. DC power is provided to the five phase-leg inverters by one or more rectifier units mounted external to the phase-leg inverters. However, all of the necessary dc bus capacitance is distributed among the phase-leg inverter units without being supplemented by the rectifier.

B. DC Bus Capacitors

With a machine outer diameter of 120 mm, the impact of the maximum diameter size restriction on the converter design is relatively severe. This size constraint is particularly challenging because the power density of the prototype

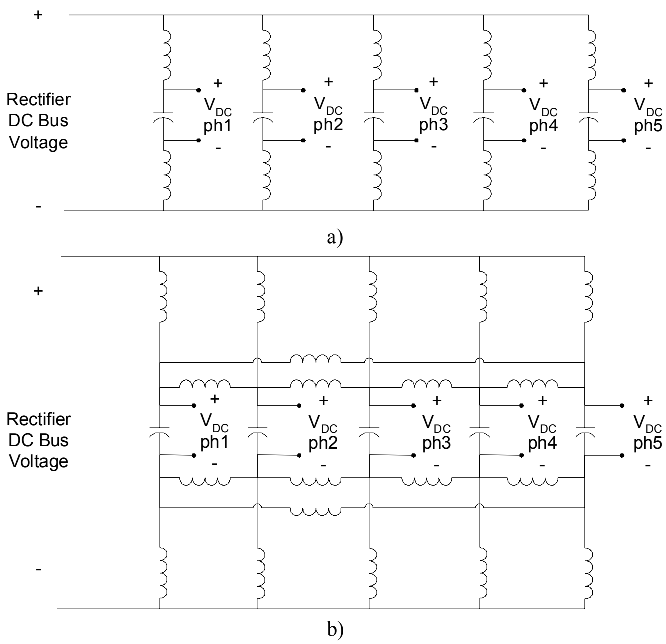


Fig. 3: Two candidate IMMD dc bus architectures: a) Configuration with modules supplied individually from dc bus source ; b). Alternative connection configuration with separate connections to adjacent modules, as well as individual dc link connections. All inductances represent parasitic impedances contributed by dc bus interconnections, including connectors.

machine is relatively high compare to that of a conventional induction machine with the same power rating. It is assumed for this power converter design exercise that all of the cross-sectional area of the stator and rotor (excluding the rotor shaft area) is available for the converter.

Sizing of the capacitor is largely determined by current handling requirements, although this is at least partially dependent on the configuration of the front-end power converter. Thermal and size limitations also severely constrain the amount of capacitance that it is possible to include in the module. Electrolytic capacitors, the standard choice for dc link storage in conventional motor drives, are not a preferred option for integrated drives due to their limited current handling capabilities and operating temperature limitations.

Alternatively, ceramic capacitors have much better current-handling and thermal characteristics for the IMMD power converter, albeit at a significantly higher cost. There is concern that the brittle nature of the ceramic material would require a very careful mechanical design of the IMMD power converter in order to limit the vibration amplitudes that these capacitors would experience inside the motor housing.

After considering the alternatives, metalized film capacitors were selected for the construction of the concept demonstration hardware. This type of capacitor has excellent current-handling capability and attractive operating temperature limits exceeding 110 degC. However, the capacitance per unit volume is much lower for metalized film capacitors than for electrolytic capacitors. When sized for this application, the resulting capacitor unit is the largest component in the phase-leg power converter, as illustrated in Fig. 2. As a result, reducing the size of this capacitor is a major objective of future work.

C. *DC Bus Interconnections*

The size of the phase-drive converter capacitor is influenced by the configuration of the dc bus connections. That is, the manner in which the modules are interconnected will determine how effectively capacitance is shared between the several modules that together form the stator. A series of simulations have been carried out to evaluate different dc link connection schemes, as well as to provide sizing information for the capacitor.

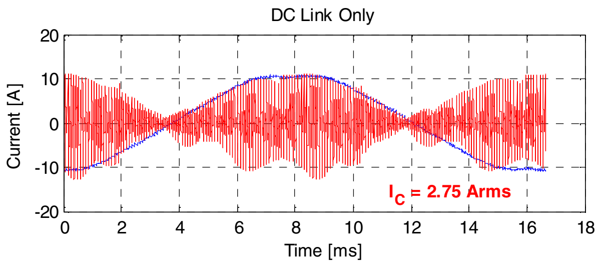
Figure 3 shows two different candidates for the dc link configuration associated with the five-phase concept demonstrator unit. The first configuration is the most straightforward, consisting of five modules that are each separately connected to a common dc link. The second case modifies this basic configuration by adding direct connections between each of the adjacent phase-leg converter modules, forming a bus ring. All inductances in Fig. 3 represent parasitic values arising from both the connectors and leads.

The Simulink™ simulations have been carried out assuming five-phase wye-connected *RL* loads (10 Ω, 4.4 mH) excited with PWM phase voltages using sine-triangle modulation and a 10 kHz carrier frequency. The value of each phase-drive dc bus capacitor is 7.5 µF, the same value used in the concept demonstrator hardware design. The equivalent series resistance (ESR) of the metalized-film capacitors is included in the capacitor model (20 mΩ per capacitor) along with resistive parasitics in the connection paths. However, these resistors do not appear in the Fig. 3 schematics for simplicity. An ideal three-phase diode bridge is simulated to supply the dc link voltage.

The value of the parasitic inductance was experimentally determined to be 280 nH for the dc link-module connections and approximately 28 nH for the module-module connections. Parasitic resistance values were calculated based upon the length and gauge of the wire used for the connections. In the experimental setup, there is some distance between the rectifier and modules, resulting in the larger parasitic values. The observed switching transient effects are not particularly sensitive to the inductor values, but the addition of series resistive parasitic elements is important because these resistors provide a significant amount of system damping.

The predicted capacitor and phase current waveforms for the two configurations are shown in Figs. 4 and 5. The capacitor current waveforms indicate that a large portion of the ripple current is the result of *LC* oscillations between the dc link capacitor and the parasitic inductances. Changing the value of parasitic inductance alters the frequency of these oscillations, but the magnitude is affected very little since the capacitors are the dominant energy storage elements.

Examination of the waveforms in these two figures shows that the addition of the direct interconnections between the phase-leg modules reduces the rms amplitude of the current ripple by approximately 30%. However, the peak capacitor ripple current value changes very little because of the additional interconnections. These simulation results highlight an important engineering trade-off since the bus ring architecture in Fig. 3b significantly increases the mechanical complexity of the power converter assembly.



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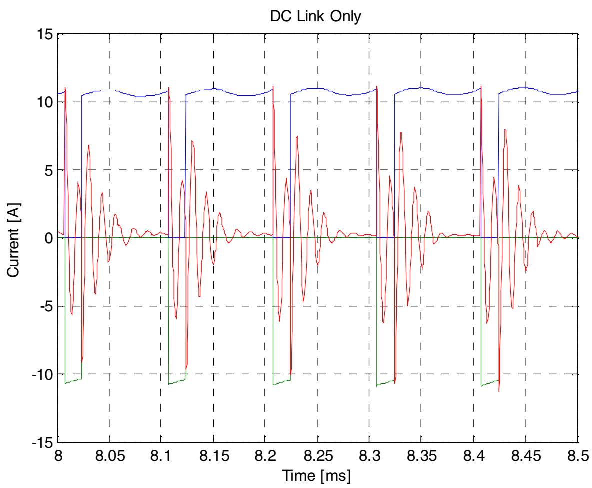

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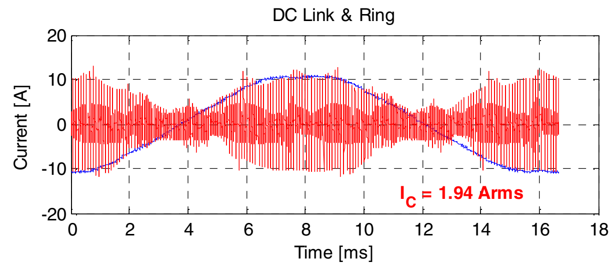
Fig 4. Simulation results for dc bus architecture with dc bus source supplied to each phase-drive module (Fig. 3a): a) a-phase module capacitor current [red], phase current [blue]; b) close-up view of capacitor current ripple at switching transient (capacitor current [red], switch currents [blue and green]).



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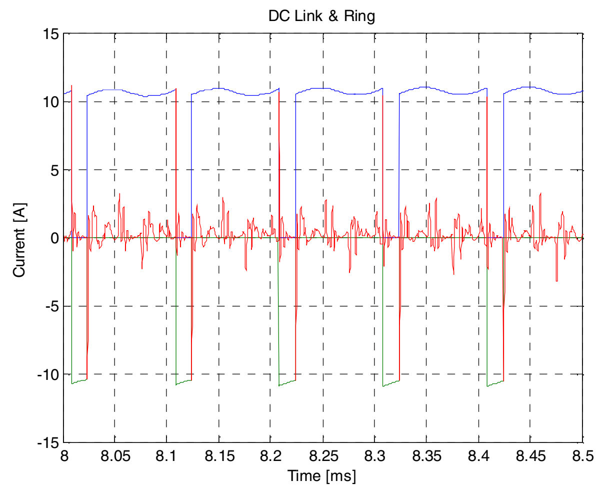

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Fig 5. Simulation results for dc bus architecture with dc bus source supplied to each phase-drive module, and inter-module connections (Fig. 3b): a) a-phase module capacitor current [red], phase current [blue]; b) close-up view of capacitor current ripple at switching transient (capacitor current [red], switch currents [blue and green]).

It should be noted that the chosen value of capacitance in each phase-drive module does not provide sufficient energy storage to create a near-constant dc bus voltage. (Approximately 50µF/phase would be required to maintain 5% voltage ripple on the bus.) As a result, the simulated dc bus voltage has a six-pulse wave shape that closely resembles that of the basic three-phase diode rectifier without capacitance. The dc link capacitors are thus unable to provide drive ride-though capability, and their ability to dampen transient voltage changes on the dc link due to motor load changes is limited. Nevertheless, the presence of some dc bus capacitance remains necessary since the parasitic inductances cause unacceptably large voltage overshoots and ringing at the inverter switch terminals in the absence of any bus capacitance.

D. *Front-End Design Issues*

Although selection and design of the front-end converter configuration falls beyond the scope of this paper, some introductory comments are offered here since this is one of the important areas of continuing investigation of the IMMD concept.

There are many options for the front-end converter that offer advantages for the integrated drives [12], but they each come with the price of added converter complexity, size, and cost. For example, an active front-end power converter stage offers the opportunity to absorb the current ripple from the inverter stage by coordinating the dc link input current with the output current. Past work [14] has shown that this approach can be used to minimize the required dc bus capacitance value. Control schemes can also be introduced to cope with the reduced dc bus capacitance [15], although they generally limit the fractional percentage of the dc bus voltage that can be used to excite the motor.

There are also significant issues surrounding machine-drive dynamics with reduced dc link capacitance [16]. Design of the control strategies for the front-end and motor must be carefully performed to avoid potential instabilities or destructive dc link voltage transients. These issues suggest that the entire motor drive must be designed as an integrated system to insure that reductions in the dc link capacitor volume are not offset by increased passive component requirements elsewhere in the converter.

E. *Thermal and Mechanical Considerations*

Due to the compact size of the converter and its proximity to the motor windings and back iron, operational temperatures for the power converter electronics pose a significant technical challenge for this integrated motor drive application. Motor component temperatures are expected to reach at least 90°C during continuous operation. As a result, the temperature limitations of the semiconductors and capacitors require special consideration in the IMMD.

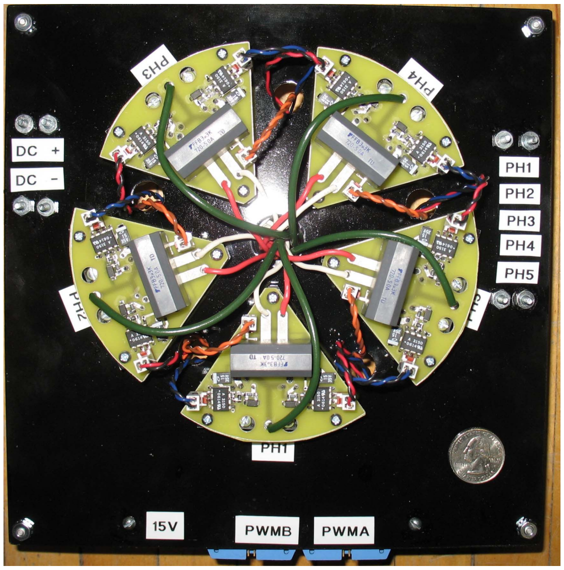


Fig. 8: Experimental concept demonstrator converter hardware.

Successfully solving the thermal problems posed by the integrated motor drive requires a coordinated approach that addresses the thermal management technique, the converter efficiency, and the safe operating temperature of the phase-drive electronics. Most commercial IGBT devices available today are rated for operation with maximum junction temperatures of 150°C. The configuration of the IMMD is likely to require the power electronics to operate at temperatures exceeding 100°C, making it critical to minimize temperature rises between the ambient and the device junctions. This is particularly important since it is well understood that improving power electronics reliability benefits from minimizing component temperatures [17].

In order to address these reliability issues, a two-zone thermal design is being developed to ease the thermal stress on the temperature-sensitive components including the dc link capacitors. According to this approach, the power converter printed circuit board (PCB) or substrate is used to provide some measure of thermal isolation between the hotter components facing the machine and the capacitors and other-heat sensitive components that are on the other non-motor side of the PCB. Figure 6 illustrates this concept by showing an axial cross-section of the machine and power converter.

The intended airflow path is identified in Fig. 6, indicating that ambient air is drawn in through vents in the machine housing and passes first over a heatsink for the power electronics components before being used to cool the machine. A shaft-mounted fan mounted on the opposite end of the motor is assumed to provide the necessary airflow. If extensive periods of high-torque, low-speed operation are desired, an additional auxiliary cooling fan would likely be necessary.

Thermal analysis has been carried out [18] to investigate the effectiveness of air cooling with this type of IMMD architecture. More effort is required to determine the best mechanical configuration of the machine and power converter components in order to maximize the effectiveness of the available cooling. Nevertheless, work to date suggests that air cooling of the power electronics and machine is feasible.

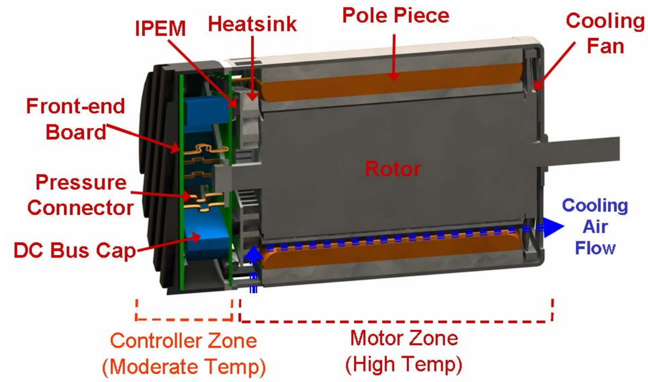


Fig. 6: Cross-section view of IMMD and motor illustrating thermal partitioning to separate higher-temperature machine from lower-temperature electronics.

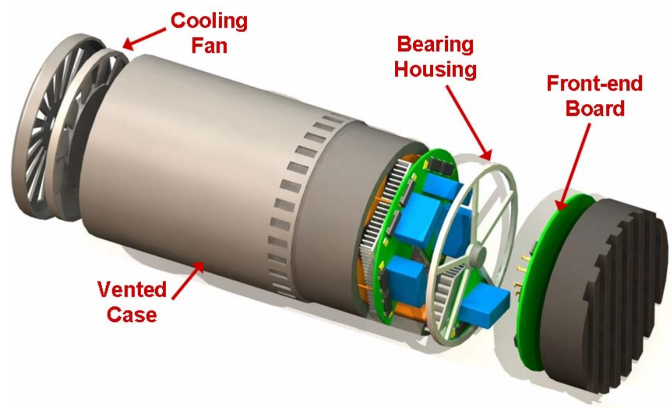


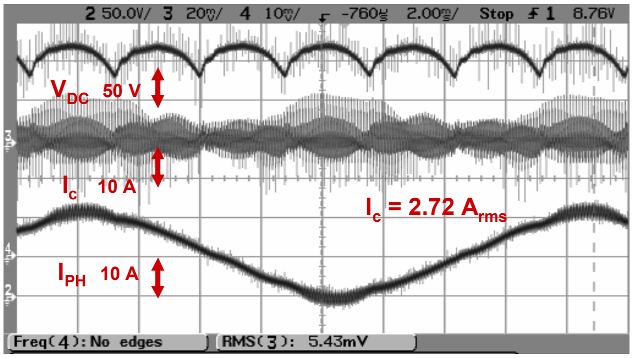
Fig. 7: Exploded view of one possible IMMD assembly showing front-end interface board, bearing housing, and cooling fan.

The current vision for the IMMD structure includes a shared front-end converter/rectifier board that distributes dc power to the individual phase-leg modules. Figures 6 and 7 illustrate how such a structure might be implemented. Pressure contacts have been identified as a promising technology to use in the IMMD assembly to electrically interconnect the front-end board to the phase-drive converter modules. Such contacts are mechanically compliant and have demonstrated high reliability in commercial applications [19]. They offer advantages for the IMMD configuration because they can be designed to not require extremely tight tolerances during fabrication of the power converter.

It is anticipated that the output dc bus of the front-end converter/rectifier would likely be configured as an annulus to distribute dc power as symmetrically as possible to all of the phase-drive units. The details of how these power converter assemblies would be mounted inside the machine housing to withstand mechanical vibrations while making provisions for the motor bearing assembly are important issues that fall beyond the scope of this paper. However, the exploded view of the IMMD in Fig. 7 suggests one alternative approach to the mechanical construction.

F. *Current Sensing*

The compact size requirements of the IMMD power converter make it an appealing candidate application for the use of giant magneto-resistive (GMR) field detectors for the



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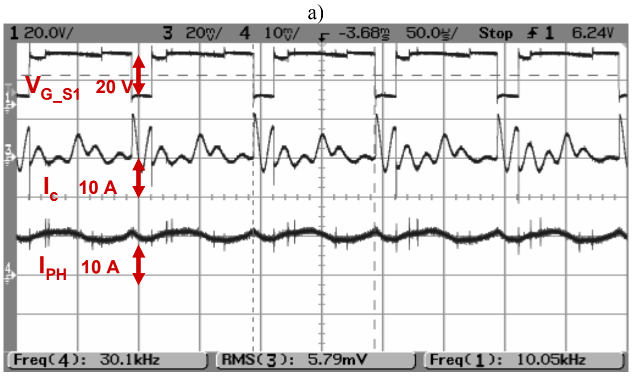

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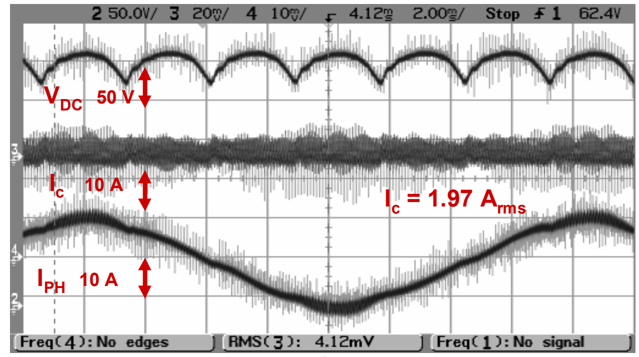
Fig 9. Experimental results for dc bus architecture with dc bus source supplied to each phase-drive module (Fig. 3a): a) module dc link voltage, capacitor current and phase current; b) close-up view of capacitor current ripple at switching transient, with high-side gate signal shown.



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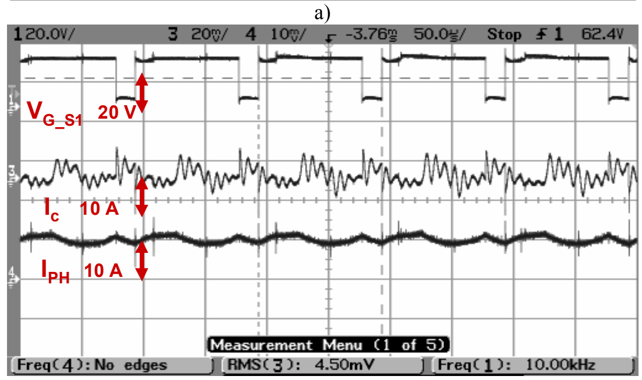

b)

Fig 10. Experimental results for dc bus architecture with dc bus source supplied to each phase-drive module, and inter-module connections (Fig. 3b): a) module dc link voltage, capacitor current and phase current; b) close-up view of capacitor current ripple at switching transient, with high-side gate signal.

current sensors [20,21]. The introduction of GMR sensors will provide a valuable opportunity to test the sensors in an environment where many sources including the machine are contributing to the local electromagnetic field distribution.

For the initial tests, a wire loop is being incorporated into some of the phase-drive power converter modules to assist in the calibration of the GMR sensors. In addition, the availability of these current test loops will provide a convenient means of evaluating the dynamic performance of the GMR sensors during inverter operation.

IV. Experimental Results

Construction of a concept demonstrator version of the five-phase power converter has recently been completed (Fig. 8). Although the converter hardware does not have the exact form factor required for physical integration inside the machine, this drive provides an excellent platform for electrical testing. With this objective in mind, some phase-leg modules have measurement sensors and extra pins built in for confirmation of the capacitor current simulation results.

Examples of measured switching waveforms for the two alternative dc link configurations presented in Section III are shown in Figs. 9 and 10. Operating conditions are the same as the simulation results presented previously in Figs. 4 and 5, using a 4.4 mH, 10 Ω *RL* load attached to each module output. Waveforms for the dc link voltage, capacitor ripple current, and phase current are pictured for each of the two configurations. An expanded view of the phase voltage and phase current waveforms is provided in Figs. 9b) and 10b) to illustrate the switching details.

The agreement between the predicted and measured waveforms is generally quite favorable. As a result, confidence has been established in the usefulness of the simulation models to predict the rms capacitor ripple current during a variety of inverter operating conditions. A slight discrepancy in the peak ripple current amplitude remains, likely due to the ideal switch models employed in the simulation to reduce calculation time.

Testing of the concept demonstrator hardware has confirmed that each module is capable of operating at the required voltage and current level with only modest cooling. Work is continuing towards the objective of testing the converter with the prototype five-phase PM machine.

V. Conclusion

The IMMD architecture offers several attractive system advantages, but it also presents serious technical challenges to the power converter designer. The first generation of the IMMD power converter hardware has been designed and fabricated, setting the stage for extended electrical testing that is now under way. Although physical integration of this power converter with a machine and controller inside the same housing will not be achieved with this first-generation hardware, the power converter is serving its intended purpose of enabling the testing of IMMD operating characteristics.

The dc bus capacitor size has been identified as one of the most pressing electrical design issues for practical realization of an IMMD. Ambient thermal conditions do not permit the use of electrolytic capacitors, and aggressive sizing of the alternative metalized-film capacitor does not provide sufficient size reduction. Current-handling capability of the capacitors represents the most important characteristic determining the physical size requirements in this application. Finding the ultimate solution to this challenge requires that attention be directed at identifying power converter architectures to minimize the bus ripple current in addition to choosing the best capacitor type.

Several different configurations of dc bus interconnections have been evaluated by simulation in order to explore the impact on capacitor performance requirements. These results assist the design engineer in selecting an interconnection scheme that balances mechanical complexity with electrical performance to best meet the design objectives.

Addressing the thermal challenges presented by the IMMD architecture requires that attention be devoted to the thermal management, power converter efficiency, and availability of high-temperature power electronics. On the positive side, thermal analysis suggests that air cooling of the IMMD is feasible with careful design. However, there are still many thermal and vibration issues associated with the IMMD architecture that require attention.

Continuing work on the power converter is focused on evaluating methods for reducing the dc bus capacitor size, including promising alternative configurations for the front-end converter. Work is proceeding in parallel on the development of higher-temperature power electronics [22] and hardware implementation of a distributed control scheme for the phase-leg modules. Efforts are under way to interconnect the demonstrator phase-leg converters to a prototype 5-phase PM machine for combined testing of the IMMD configuration.

APPENDIX

PROTOTYPE 5-PHASE PM MACHINE PARAMETERS AND METRICS

Rated Power	2.7 kW
Rated Current (per phase)	5.5 Arms
Outer Diameter	120 mm
Inner Diameter	72 mm
Rated Speed	1800 r/min
Machine Length	140 mm
Rated Torque (T)	13.3 Nm
Active Volume	1.58×10^{-3} m^3
Torque Density	8.37×10^3 Nm/m^3
Cogging Torque	5.5 % of rated torque

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