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Abstract – The effective integration of electric power in future naval ships requires the development of technologies that allow for volume and mass reduction of critical components. The University of Texas at Austin Center for Electromechanics is studying the potential for volume and mass reduction through the integration of power electronics into an electric propulsion motor. Two conceptual designs of a motor with integrated power electronics are presented. Integration of power electronics into the motor frame offers space saving advantages, allowing the motor and power electronics to share the same housing and cooling system. Accordingly, significant mass and volume reductions are possible in the power electronics housing and cooling auxiliaries.

I. INTRODUCTION

As part of ongoing research within the Electric Ship Research and Development Consortium (ESRC), the University of Texas Center for Electromechanics (UT-CEM) developed a baseline design for a 20 MW electric propulsion drive train [1]. After the initial baseline study, UT-CEM recognized an opportunity for space savings by incorporating power electronics into the motor and the generator. This paper considers an electric drive train for a ship that includes a large, high-power motor (20 MW) running at low speeds (0 to 150 rpm). This unique machine has a large diameter with a significant amount of unused space in its hollow rotor, making it a prime candidate for incorporation of power electronics.

UT-CEM modeled and compared two integration approaches. The first design places the power electronics external to the rotor but still within the stator housing while the second design places the power electronics within the rotor, taking advantage of the unused internal space. The different approaches result in tradeoffs on shaft and bearing design. The external design allows for a smaller shaft using standard bearings; however, the shaft and stator housing must be extended axially to account for more components inside the stator housing. The internal design allows for a shorter shaft and overall space savings, but a larger hollow shaft is necessary for access, and larger endplates are required for supporting the internal inverter structure.

II. MOTOR LAYOUT

To optimize the power density of the baseline motor design, UT-CEM selected a 12-pole, 15-phase, radial flux permanent-magnet motor with a speed range of 0 to 150 rpm. Thermal management consists of direct water cooling of the stator armature conductors with air cooling for the rotor. Spherical rolling element bearings were selected because of their high load capacity, their ability to support loads at zero speed, and their self-aligning characteristics. The motor is intended to directly drive a ship propeller, and an external thrust bearing is assumed though not considered part of the integration evaluation.

Figure 1 shows the available space inside the large rotor. The stator housing is 3.25 m in diameter with 4.87 m for the overall length of the machine. The inside diameter of the rotor at the stub shafts is 1.7 m, and the bore of the spherical bearings measures 0.4 m in diameter. The overall mass of the motor is 102,000 kg (225,000 lb) with an enclosure volume of 48 m^3 (1,700 ft^3).

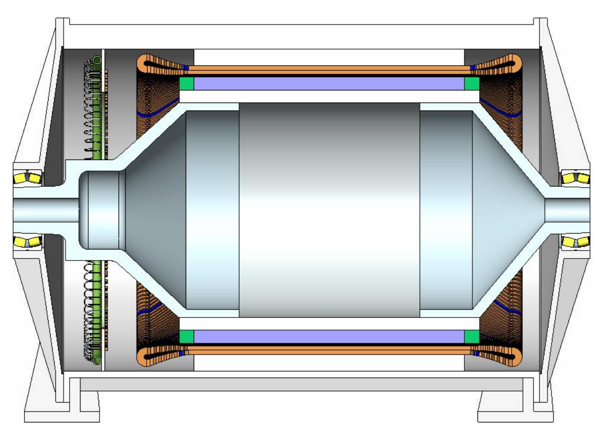

Figure 1. Baseline 20 MW motor design

III. POWER ELECTRONIC COMPONENTS

The motor drive power electronics assembly consists of a rectifier which converts generator-supplied ac power to dc, a dc-link filter which smoothes the rectifier output voltage, and a dc-to-ac converter (inverter) which converts dc power to a variable frequency output to drive the motor at variable speed. In this research, only the inverter portion of the power electronics has been integrated into the motor housing to evaluate potential mass and volume savings over an externally located inverter. The inverter uses five single-phase pulse width modulated (PWM) modules, composed of insulated gate bipolar transistors (IGBTs). Each module provides power to three individually isolated motor phases as shown in Figure 2. The IGBTs shown schematically in this figure consist of four series connected IGBTs, each rated at 3.3 kV and 1,200 A (Eupec model no. FZ 1200 R 33 KF2). For the 4.16 kV rms generator input to the power electronics, each IGBT will experience a peak voltage of 1.47 kV during normal operation, thus providing an adequate margin of safety.

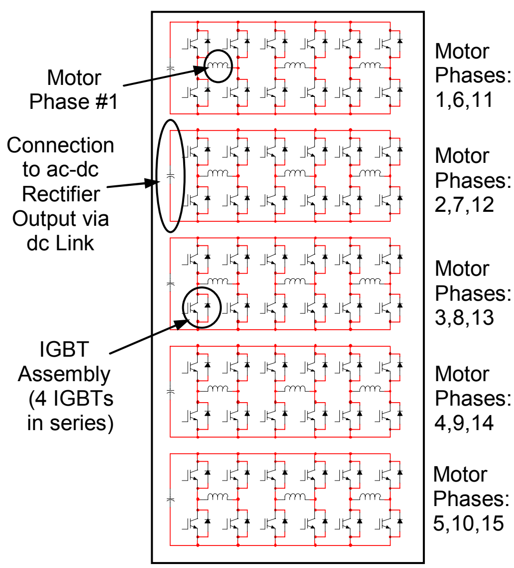

Figure 2. Inverter schematic
(details omitted for clarity)

One of the advantages of integrating the inverter with the motor housing is that the same water cooling system used for the motor windings can also be used to cool the inverter power electronics. Based on an average efficiency of 97.5% derived from power electronics simulations, the power electronics system requires 500 kW of cooling capacity for a 20 MW motor drive. For a 5.7 l/s water cooling system at an inlet temperature of 38°C, the corresponding water temperature rise is 21°C; finite element thermal analysis indicates that under these conditions the IGBTs are kept below their rating of 125°C.

IV. INTEGRATION LAYOUT OPTIONS

a. External to Rotor

The first approach is to simply integrate the inverter components into the stator housing. Though this approach does not take advantage of the large space available inside the rotor, it does allow for space-sharing inside the stator housing. The inverter shares the same cooling system with the motor and eliminates the need for an inverter housing and long cables.

The inverter is assembled as five individual segments (refer to Figure 3). Each segment contains 48 IGBT's and their associated capacitors and resistors. Water-cooling channels run axially throughout the arc segments so that the IGBT mounting plates also act as chilling plates. A single cooling manifold routes water to each individual segment. The water then flows through the segment in a serpentine pattern before it exits into the transfer manifold. The transfer manifold transports the water to the stator armature conductors.

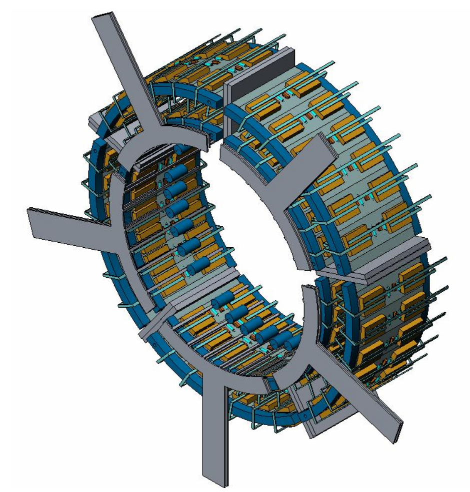

Figure 3. Inverter with five individual segments

Modifications to the baseline motor design include the extension of the stator housing plus the addition of a copper shield to protect the inverter components from the electromagnetic field generated by the stator windings (refer to Figure 4). The motor with the inverter included increases in overall length to 5.77 m and in mass to 110,000 kg (243,000 lb). The enclosure volume increases to 60 m^3. Despite the increase to the motor size, the overall system becomes more optimized due to the elimination of housing, cooling, and cables for a stand-alone inverter. The shaft diameter and the spherical bearings bore diameter remain the same as in the baseline design.

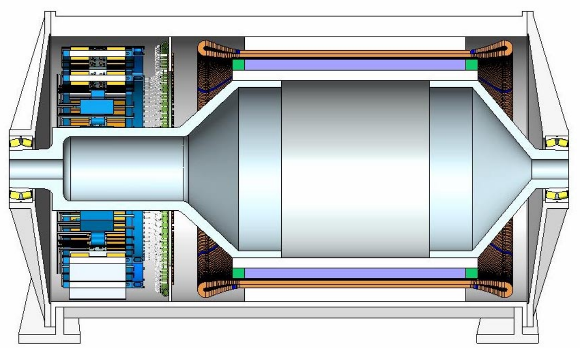

Figure 4. Motor with inverter external to the rotor

b. Internal to Rotor

The second integration approach is to place the inverter components inside the rotor. While the apparent advantage of the design is the space savings, the disadvantages include difficulty in assembly and maintenance.

To optimize the available space inside the rotor, the inverter components were distributed among eight linear segments (refer to Figure 5). As noted earlier, there are 15 phases, so each segment supports two phases of the inverter (except for one segment which only supports one phase).

Cooling water flows into a manifold at the cooling end of the motor and is distributed to each of the eight segments. As in the first integration approach, the water flows through the segments in a serpentine pattern. The water then travels back the length of the inverter to a transfer manifold at the cooling end of the motor. The transfer manifold then routes the water to the stator armature conductors. The power from five rectifiers/dc links and the connections to the motor windings also enter and exit at the cooling end of the motor.

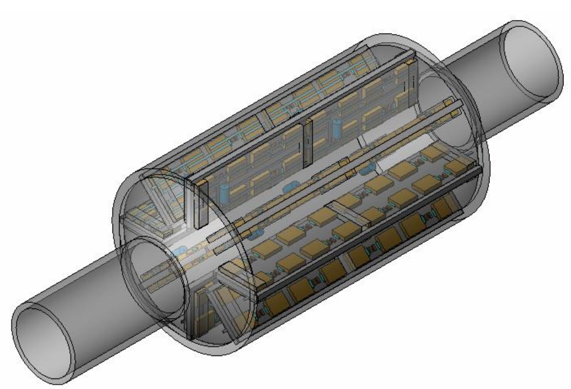

Figure 5. Internal inverter distributed among eight segments and enclosed in the support shaft

Three of the largest obstacles to putting the inverter inside the rotor include 1) an appropriate support structure to hold the IGBT segments, 2) ease of assembly, and 3) ease of maintenance. Unlike the 'external' design where the IGBT segments can be mounted to the stator housing, the IGBT segments for the 'internal' design cannot be mounted to the rotor. Therefore, a substantial support shaft was designed as a permanent, stationary fixture inside the rotor and mounted to the endplates. The hollow shaft provides an access port for assembly and maintenance of individual IGBT segments. The inner diameter of the shaft is 0.6 m (24 in.) and provides adequate clearance for servicing an individual segment. With the assistance of assembly tooling, the segment is inserted axially into the rotor then "lifted" into its designated slot in the support shaft. Once in place, the segment is latched down. After all segments are in place, a support rod is inserted from the cooling end. The support rod provides additional support for the suspended IGBT segments. Additionally, it bears the quick-disconnect umbilicals for power, data, and cooling.

The access port diameter of 0.6 m (24 in.) was determined by the size of the largest available catalog-listed spherical rolling element bearing. The bearing in this particular design has a bore diameter of 0.95 m (37.43 in.). A spherical rolling element bearing was selected to more easily compare designs. A person would likely be able to access the necessary hardware through a port of this size; however, this access becomes more of a challenge as tooling rods and support rods obstruct the center of the port. A valid option for a future design might include hydrostatic bearings which would allow for a larger bore diameter and therefore a larger access port.

Modifications to the baseline motor design include thickening of the endplates, increasing the rotor shaft diameter, changing to larger bearings, and adding a support bearing at the propeller end of the inverter support shaft (refer to Figure 6). The endplates are modified to accommodate the larger bearings, plus they are thickened (and two bores added) to mount the inverter support shaft and rod.

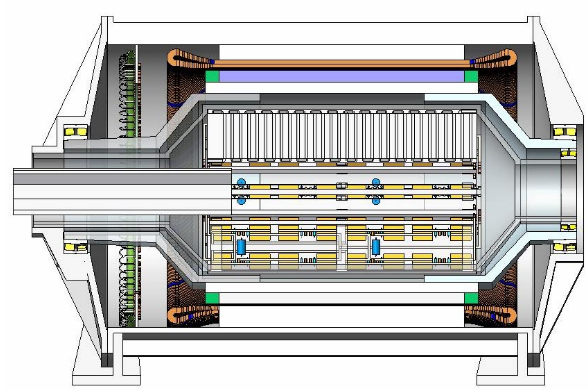

Figure 6. Motor with inverter internal to the rotor

Unlike the external design which required an additional EM shield, this internal design does not require any additional shielding. An existing EM shield already shields the rotor magnets from the switching harmonics of the armature winding, and the rotor back-iron acts as a shield between the magnets and the enclosed inverter components.

The motor with an internal inverter increases in overall length to 5.3 m and in mass to 113,000 kg. The enclosure volume increases to 53 m^3. This design approach is greater in mass (2.7%) but less in volume (11.6%) than the external design. The mass is accounted for by the support shaft, which is essentially an inverter housing, and the increased length of cables and hoses between the inverter and stator winding leads. The key advantage is the volume savings. By incorporating the inverter components into essentially the same volume as the baseline motor design, the power density of the drive train increases significantly. The main results are presented in Table 1.

	Baseline Motor + Stand-alone Inverter*	Motor with External Inverter	Motor with Internal Inverter
Mass	102,000 kg + 16,000 kg = 118,000 kg	110,000 kg	113,000 kg
Gravimetric Power Density	0.169 kW/kg	0.182 kW/kg	0.177 kW/kg
Volume	48 m^3+20 m^3 = 68 m^3	60 m^3	53 m^3
Volumetric Power Density	294 kW/m^3	333 kW/m^3	377 kW/m^3

*Mass and volume of stand-alone inverter obtained by comparison with components of Integrated Power System (IPS) tests [2].

Table 1. Summary of Masses and Volumes

V. CONCLUSION

Due to the inherent characteristics of a high-power, low-speed electric propulsion motor, there is large potential for integrating power electronics into the motor. Whether the inverter is external or internal to the rotor, significant space-savings are achievable. The external approach has more significant mass savings with the elimination of an inverter enclosure, a shared cooling system, and reduced cable length. The internal approach has more significant volume savings with only minor additions to the endplates from the baseline design.

Both designs contribute to the optimization of an electric drive train. Even though this research was performed for a 20 MW motor, the same techniques apply to larger motors. Of particular interest is the 36.5 MW motor presently under development for the U. S. Navy's DDX ships. Since this motor is also a permanent-magnet machine, the integration concepts developed in these studies are directly applicable. Even if the U. S. Navy elects to use an induction motor for propulsion, it would still be a good candidate for integration of power electronics.

There are plenty of challenges facing the further development of integrated power electronics, such as tooling, assembly, and maintainability; however, the increased power density of the overall drive train is a technological development with payoffs in the optimization of the all-electric ship.

VI. REFERENCES

1. "Baseline Prime Power System Used by the University of Texas," UT-CEM report, 2003.

2. McCoy, T.J., "Full scale land based testing of the U.S. Navy's Integrated Power System (IPS)," Proceedings of the 5th International Naval Engineering Conference, p. 155-162, INEC (2000).

VII. ACKNOWLEDGEMENTS

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