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Design of a GaN Based Integrated Modular Motor Drive

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Abstract - In this study, design procedure of an Integrated Modular Motor Drive (IMMD) is presented focusing on high power density. The design is based on a permanent magnet synchronous motor (PMSM) and GaN FETs. Fractional slot concentrated windings are used on the stator. Slot/pole combination and winding configuration is selected based on having low cogging torque and high winding factor. An extended motor drive inverter topology is proposed where 2-level voltage source inverters are connected both in series and parallel. Optimum selection of number of modules is discussed and power semiconductor devices are selected based on loss characterization. Optimum DC link capacitor bank is determined and the effect of interleaving is investigated. The performance of the motor is validated with ANSYS/Maxwell simulations. Motor drive performance is obtained with MATLAB/Simulink simulations. The efficiency of the motor drive is enhanced by 2% compared to a conventional motor drive. An overall system power density over 1 kW/lt has been achieved with the proposed series/parallel motor drive configuration having GaN FETs.

Introduction

In **conventional motor drive** systems, drive units are placed in a separate cabinet, and they are connected to the motor via long cables.

In **integrated modular motor drives (IMMD),** the motor drive is integrated directly to the motor back-end and the system is modularized by dividing into several parts.

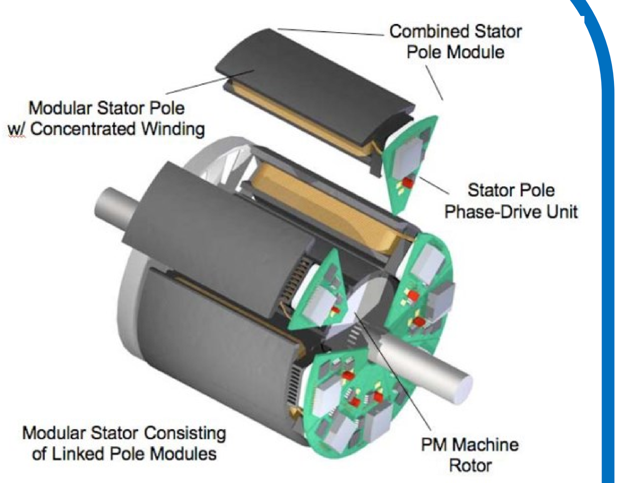

Figure 1. IMMD Example [1]

Integration

- ✓ **Power density** of the overall system is enhanced significantly.
- ✓ **Voltage overshoots** due to cabling effect is eliminated [2].

Modularization

- ✓ **Fault tolerance** is increased [3].
- ✓ **Voltage stress** on modules is reduced.
- ✓ **Heat dissipation** is distributed to a wider area.

IMMD Structure

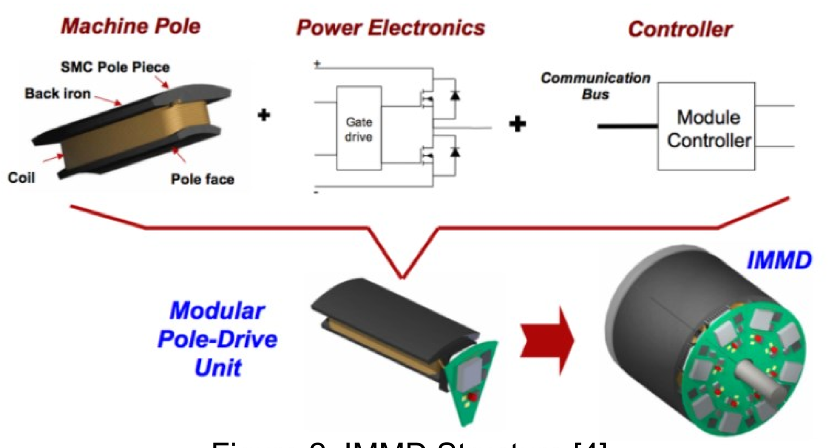

Figure 2. IMMD Structure [4]

Challenges

- ❖ Fitting into a small volume requires size reduction and optimum placement.
- ❖ Cooling of both units should be achieved simultaneously.
- ❖ Electronic components are subjected to high temperature and vibration [4].

Gallium Nitride (GaN) utilization

- Low semiconductor loss: **heat sink** size is reduced
- High operation frequency: **passive component** size is reduced

Figure 3. GaN [5]

Design of the IMMD System

IMMD Topology

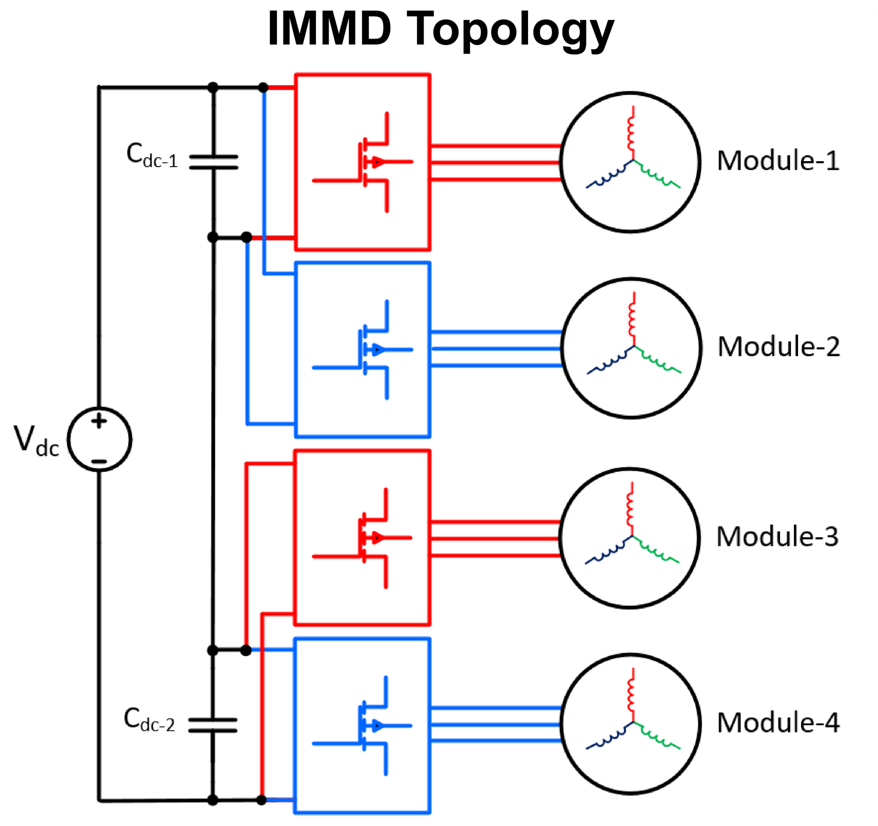

Figure 4. IMMD topology with 2-series and 2-parallel connection

- Permanent Magnet Synchronous Motor
- Output power: **8 kW**
- Rated speed: **600 rpm**
- DC Link voltage: **540 V**
- **2-series** connection is required due to voltage requirement of GaN
- Number of parallel connected modules is decided based on **interleaving effect**

Fractional Slot Concentrated Winding

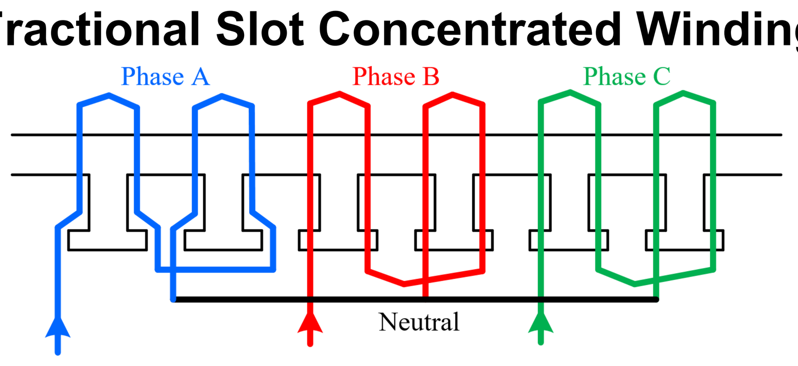

Figure 5. Winding diagram of one module

Design Procedure

- **Slot/pole (24/20)** is selected based on low cogging torque and high winding factor
- Motor dimensions are designed **by electric (A) and magnetic (B) loading**
- **Voltage requirement** is obtained and number of turns are calculated
- Three different **power semiconductor devices** are selected for comparison
- An analytical power semiconductor loss model is used for **efficiency**
- **A DC Link model** for a modular converter is obtained and capacitance and RMS ripple current are calculated

Simulation Results

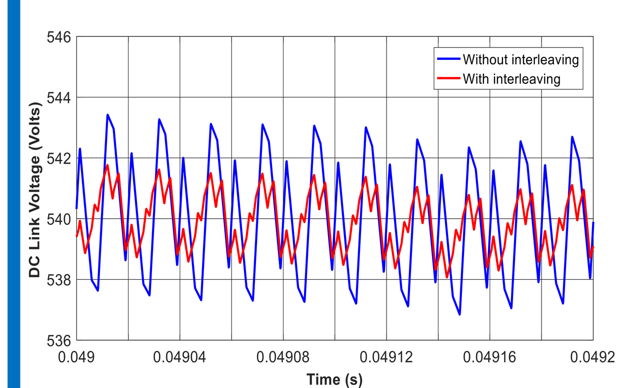

Figure 6. Interleaving effect on DC Link voltage

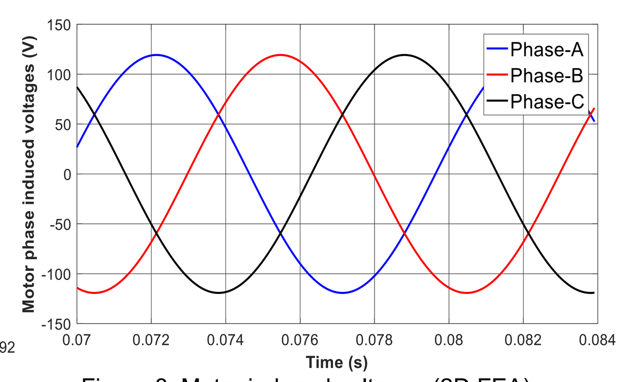

Figure 8. Motor induced voltages (2D FEA)

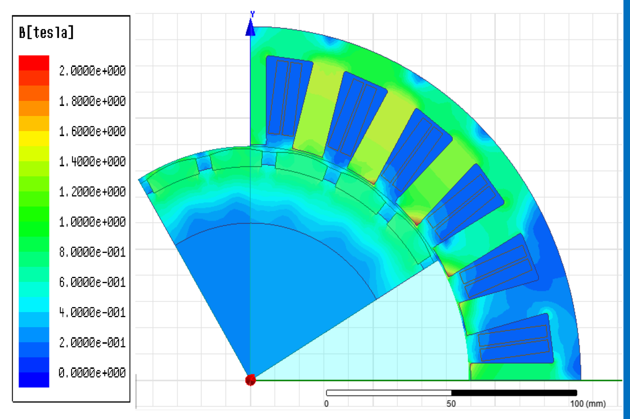

Figure 10. Flux density distribution (2D FEA)

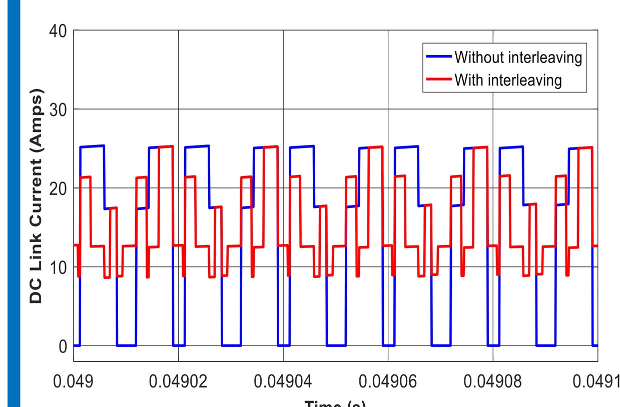

Figure 7. Interleaving effect on DC Link current

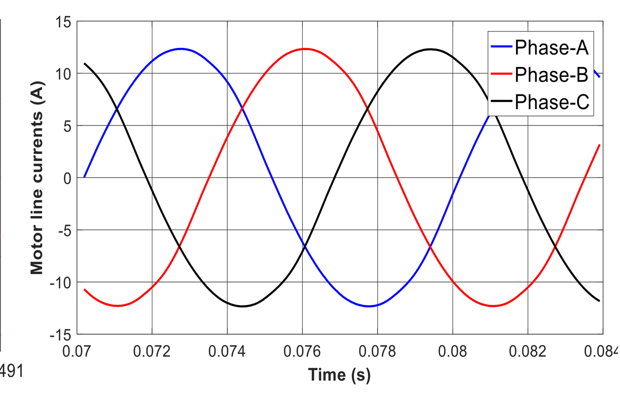

Figure 9. Motor line currents (2D FEA)

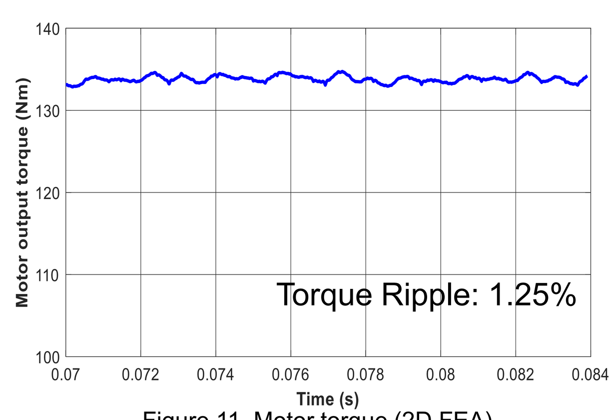

Figure 11. Motor torque (2D FEA)

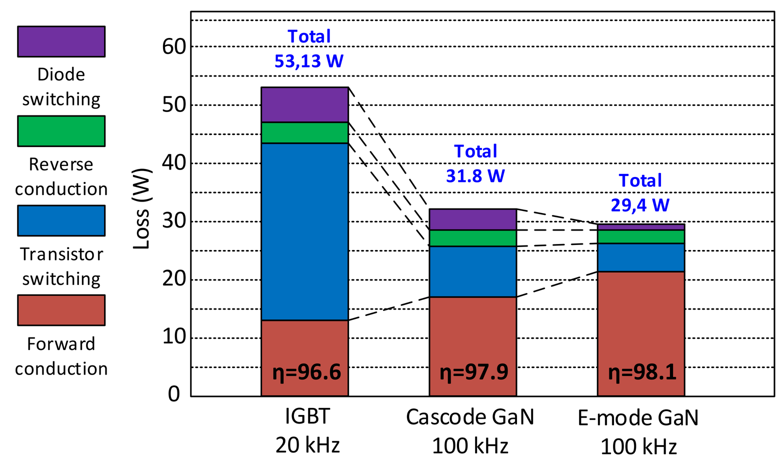

Figure 12. Loss comparison of devices

- RMS of DC Link ripple current is reduced by half with interleaving
- Capacitance requirement on the DC Link is reduced by half with interleaving
- A 1 kW/lt power density is achieved with 50 kHz switching frequency with GAN
- Torque ripple and cogging torque are reduced with optimum magnet shape design

IMMD Prototype

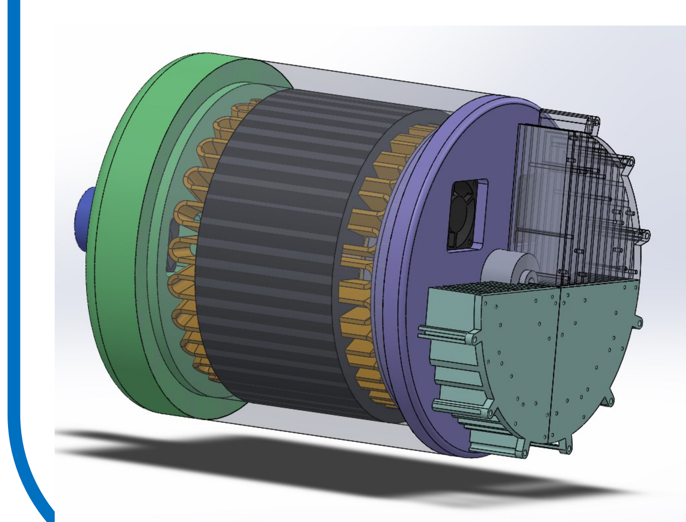

Figure 13. Assembly of the motor

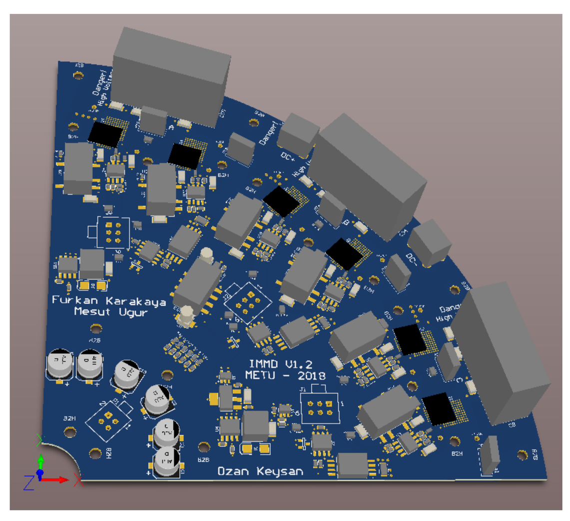

Figure 14. Drawing of one-module PCB

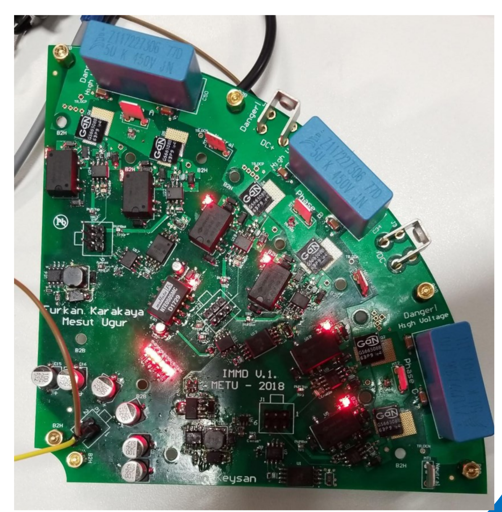

Figure 15. Picture of one-module PCB

Conclusions:

- A **8 kW IMMD** is designed with Permanent Magnet Synchronous Motor
- A novel topology is proposed with **2-series and 2-parallel** connection
- Interleaving is used to reduce the **size of DC link capacitors**
- **GaN FETs** are utilized with high switching frequency
- A complete design is achieved with **98% drive efficiency** and **96% motor efficiency**
- A total of **1 kW/lt power density** is achieved
- A **fault tolerant** motor drive system is achieved with ½ redundancy

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