

Multi-physics optimization of a GaN based integrated modular motor drive system

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design approach in integrated drives as one may affect the other significantly [3].

Abstract

In this paper, a multi-physics approach is presented for the design optimization of an integrated modular motor drive (IMMD) system. The system is composed of a modular permanent magnet synchronous motor and a GaN based modular motor drive power stage. The multi-physics model includes the motor drive inverters and DC link capacitor bank (electrical model), the stator windings and rotor magnets (electromagnetic model), the heat sink (thermal model) and a geometrical model. The main purpose of the design optimization is to obtain the highest power density, which is quite critical in integrated drives. As the system has several interdependencies due to integrated structure, selection of parameters is based on those relationships. A 8 kW IMMD system design is proposed and the resultant system is simulated using various simulation platforms for verification.

1 Introduction

Conventional variable frequency motor drive systems are composed of two distinct parts: the drive and the motor, where drive units are placed in separate cabinets and connected to the corresponding motors with long cables. This causes reduction in the overall system power density, cost increase and electromagnetic interference (EMI) problems [1]. In integrated modular motor drive (IMMD) systems, the drive is integrated onto the motor back iron forming a single package such that the power density of the overall system is enhanced and the connection cables are eliminated [1]. Furthermore, each pole of the motor is driven by its own drive module which are then interconnected via a common DC link. By doing so, the fault tolerance of the system is increased, heat dissipation is spread on a wider surface area and voltage stress on windings and power semiconductor devices are reduced [2].

In IMMDs, the space available for the drive system components is drastically reduced due to integration. Therefore, fitting all the components requires design optimization with integrated model approach and careful spatial and layout design. Moreover, the interdependencies between the main system components yields a multi-physics approach where the design of motor, drive power electronics and thermal management system should be considered all together. Therefore, it is highly difficult to propose a decoupled

The current IMMD prototypes proposed in the literature are usually based on new generation wide band-gap power semiconductor devices, such as Gallium Nitride (GaN) power FETs [4]. These devices are capable of switching at much higher switching frequencies compared to their silicon counterparts with low switching losses [5]. It is possible to reduce the size of passive components with high switching frequencies as well as reduce the size of heat sink with superior efficiency values with the utilization of enhancement mode (e-mode) GaNs. Considering that the largest components on an average power converter system are passive components and the heat sink [1], utilization of these devices is critical for IMMD designs. Moreover, thanks to the modularity of the system, interleaving technique can be used to further reduce the size of DC link capacitor bank [6]. Although several studies have been published regarding power electronics design, modular inverter topologies, DC link capacitor selection etc. for IMMDs [1,3,7,8], most of these prototypes lack a unified design. One example for such a dependency is that, the cross-sectional area available for the motor drive printed circuit board (PCB) and heat sink is determined by the diameter of the motor.

In this paper, optimum design of an IMMD system is presented considering both the motor and drive parameters to obtain the highest power density. It is also aimed to maximize the overall system efficiency which keeping the active material costs in acceptable limits. A permanent magnet synchronous motor (PMSM) having fractional slot concentrated winding (FSCW) stator is utilized for its superior torque density, low cogging torque and fault tolerance capability which makes it suitable for IMMD applications [9]. The content of the multi-physics design optimization approach includes electrical, electromagnetic, thermal and geometrical models. First, the multi-physics model is presented in Section 2. In section 3, the basic relations between the system parameters and the cost and constraint functions are obtained and the inter-dependencies are discussed. Using the results of Section 3, an optimum system design is proposed in Section 3. In Section 4, the presented models are verified and the proposed system design is evaluated using simulation results. The paper is concluded in Section 5.

2 System modelling

Motor drive integration onto the modular stator back iron is considered in this paper, an example of which is shown in Fig. 1 [7]. The structural configuration of the proposed system is also shown in Fig. 2.

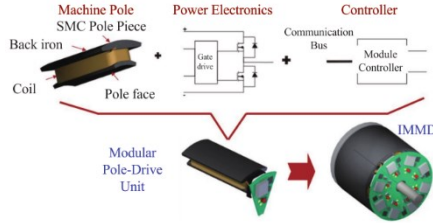


Figure 1. An example of the IMMD structure [7]

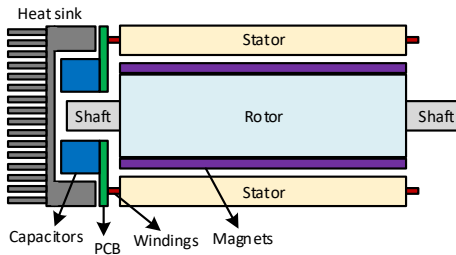


Figure 2. Structural configuration of the proposed IMMD

The fundamental blocks of the system model and the coupling of different aspects used in the integrated design are shown in Fig. 3. Basically, the system is composed of the electrical model, electromagnetic model, thermal model and geometrical (spatial) model. The system specifications and constraints are listed in Table 1.

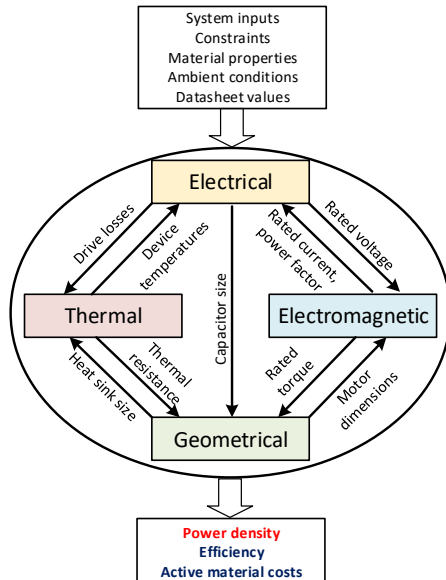


Figure 3. Fundamental blocks of the system model

Moreover, the independent variables and their corresponding sub-models are also shown in Table 2.

Parameter	Value
DC link voltage, V_{dc}	540 V
Number of phases in each module, m	3
Motor total output power, P_{out}	8 kW
Motor rated speed, N_r	600 rpm
Machine electric loading, A_{rms}	35 kA/m
Machine magnetic loading, B_{avg}	0.6 T
Maximum winding current density, J_{rms}	4 A/mm ²
Maximum stator teeth flux density, B_{ts}	1.8 T
Maximum stator yoke flux density, B_{ys}	1.4 T
Maximum fill factor, k_{cu}	0.6
Maximum device junction temperature, T_{j-max}	150 °C
Maximum capacitor temperature, $T_{cap-max}$	70 °C
Maximum DC link voltage ripple, V_{dc-r}	1 %
Minimum motor efficiency, η_{m-min}	94 %
Minimum drive efficiency, η_{d-min}	98 %
Minimum power factor, $\cos(\phi)_{min}$	0.9
Ambient temperature, T_{amb}	50 °C

Table 1. System specifications and constraints

Optimization parameters	Sub-model
Number of modules, n	Electrical
Number of series modules, n_s	Electrical
Switching frequency, f_{sw}	Electrical
Modulation index, m_a	Electrical
Aspect ratio of the motor, α	Geometrical
Slot/module/phase, w_s	Electromagnetic

Table 2. Optimization parameters (independent variables)

The IMMD system has a modular structure where each three-phase inverter module drives its own part of the stator pole. The modules can be connected in series and/or parallel configuration via a common DC link. A block diagram of the system is shown in Fig. 3 with 2-series and 2-parallel connected modules.

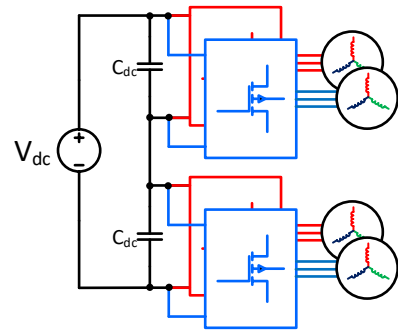


Figure 3. A general block diagram of the IMMD

2.1 Electrical sub-model

The electrical model includes, determination of rated parameters of the motor drive inverter, selection of power semiconductor devices, calculation of motor drive losses, determination of required DC link capacitor parameters and selection of DC link capacitors. A set of 650V e-mode GaN

FETs suitable for high voltage applications having different current ratings from GaN systems are used for the design [ref]. The devices are selected from these commercial products based on the number of series and parallel modules (n_s , n_p), modulation index (m_a), power factor ($\cos(\varphi)_{\min}$) and motor efficiency ($\eta_{m-\min}$) limitations. By using the selected device parameters, the motor drive losses are determined as shown in (1) for forward conduction loss, (2) for reverse conduction loss, (3) for switching loss, where E_{on} , E_{off} and E_{oss} are the on state, off state and output capacitance switching energies, respectively, R_{ds-on} is the on state resistance, I_p is the peak line current. All of the datasheet parameters are calibrated according to operating temperature, voltage and current.

$$P_{cf} = I_p^2 R_{ds-on} [1/8 + m_a \cos(\varphi)_{\min} / (3\pi)] \quad (1)$$

$$P_{cr} = I_p^2 R_{ds-on} [1/8 - m_a \cos(\varphi)_{\min} / (3\pi)] \quad (2)$$

$$P_{sw} = [E_{on} + E_{off} + E_{oss}] f_{sw} / \pi \quad (3)$$

The analytical models for the determination of required capacitance (C_{dc}) and RMS current rating (I_{c-rms}) for a typical inverter are given in (4) and (5), where I_{rms} is the rms line current [ref]. For a modular motor drive, it is possible to use interleaving technique to reduce these requirements. The effect of interleaving is determined by proper phase shifting angle for each possible case using computer simulations and added to the capacitance and ripple current requirements. It has been shown that series connection has no effect on the ripple current and ripple voltage for any phase shifting angle. The normalized effect of interleaving on these parameters is shown in Fig. 5.

$$C_{dc} = \frac{I_{rms} m_a}{16 f_{sw} V_{dc-r}} \sqrt{(6 - 96\sqrt{3}/5\pi + 9m_a^2/2)\cos(\varphi)^2 + 8m_a\sqrt{3}/5\pi} \quad (4)$$

$$I_{c,rms} = I_{rms} \sqrt{[2m_a (\sqrt{3}/4\pi + \cos(\varphi)^2 (\sqrt{3}/\pi - 9m_a/16))]} \quad (5)$$

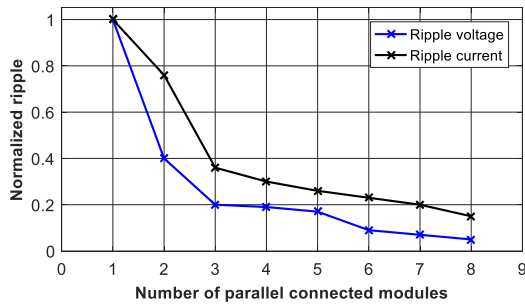


Figure 5. The effect of interleaving for parallel connected modules

A database of film capacitors are used from commercial products [ref] for capacitor selection model which is based on the capacitance, ripple current and DC voltage requirements. The selected capacitor is used to test whether its core temperature exceeds the specified limit or not, by using the implicit thermal model expressed in [ref] and capacitor datasheet values such as ESR, thermal conductance etc. Temperature dependency is especially critical since it affects the lifetime of the capacitors significantly. The capacitor

dimensions are used in the geometrical model. The required phase induced voltage per module (E_{phm}), which is the link between the electrical and electromagnetic models is determined using the inverter model as in (6).

$$E_{phm} \approx 0.612 m_a V_{dc} \cos(\varphi)_{\min} / (\sqrt{3} n_s) \quad (6)$$

2.2 Electromagnetic sub-model

The rated torque (T_m) of the machine is found using the power output and rated speed, to be used in the geometrical model for the dimensioning of the machine. The number of stator slots (Q_s) is determined by using w_s , m and n . The machine stator structure is FSCW as it is more suitable for high torque modular motor applications thanks to its high power density and torque density, low cogging torque, low manufacturing cost and fault tolerance capability. The number of magnet poles (p) is determined for each possible Q_s to get low cogging torque while keeping the winding factor high enough and harmonic content at minimum. Tables with pre-determined winding factor values (k_w) for different Q_s/p combinations are used for winding factor [ref].

The air gap distance (l_g) is found using the target peak air gap flux density (B_{gp}) and the properties of the selected magnet (NeFe40) as in (7), using the lumped parameter magnetic circuit model shown in Fig. 6, where B_r is 1.25 T and μ_r is 1.1, l_m is the magnet length. The same methodology is used for the determination of tooth width (b_t) and back core height (h_{bc}) using the maximum allowable flux density (B_{ts-max} and B_{ys-max}), as in (8) and (9), where e_m is the magnet embrace and D_{is} is the bore diameter.

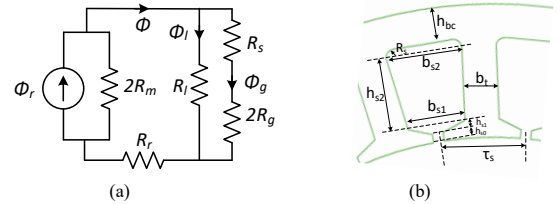


Figure 6. (a) Electromagnetic lumped parameter magnetic circuit, (b) Slot dimensions

$$B_{gp} = C_\phi k_l B_r / (1 + K_r \mu_r l_g / l_m) \quad (7)$$

$$h_{bc} = \pi e_m D_{is} B_{gp} / (2 p B_{ys-max}) \quad (8)$$

$$b_t = \pi D_{is} B_{gp} / (Q_s B_{ts-max}) \quad (9)$$

The determination of the number of turns is based on E_{phm} and flux per pole (Φ_{pp}). Φ_{pp} is found using pole area and flux density. Induced voltage on one turn is determined as in (10), where L_a is the axial length and f_r is the mechanical frequency. The number of turns per coil side (N_{cs}) can be found using (11), where l is the number of layers. The phase current of each module is found by assuming that the motor is operated in vector control where the induced voltage is always in-phase with the current, as in (12). The electric loading of the machine is verified using the rated phase current as in (13). Once the rated current is established, winding is selected from standard

AWG wires with the specified current density limit (J_{rms}). The only remaining parameter on the machine dimensions is the slot height (h_{s2}) as shown in Fig. 6. The limiting factor for h_{s2} is the maximum slot fill factor (k_{cu-max}), as seen in (14). Now, all the dimensions of the machine are set including the stator outer diameter (D_{os}) which is critical for power density.

$$E_{coil} = 4.44 f_r k_w B_{gp} L_a D_{is} \quad (10)$$

$$N_{cs} = 2 E_{phm} / (E_{coil} w_s l) \quad (11)$$

$$I_{phm} = P_{out} / (m n E_{phm}) \quad (12)$$

$$A_{rms} = l N_{cs} Q_s I_{phm} / (\pi D_{is}) \quad (13)$$

$$h_{s2} = 2 l N_{cs} A_{wdg} / [k_{cu-max} (b_{s1} + b_{s2})] \quad (14)$$

Once all the machine dimensions, winding configuration and turn numbers are set, the machine losses are calculated for the evaluation of the design. Copper loss is directly related to the selected winding cross-section (A_{wdg}) and the mean-length-turn as expressed in (15). The temperature effect is added via the temperature coefficient of copper, where ρ_{cu} is the resistivity of copper for a given temperature. For core loss, the selected lamination (M250-50A) is used in several FEA simulations to determine the core loss density with worst case flux density values in several parts of the core. A core loss density of 4 W/kg is obtained including fundamental and harmonic components and used for core loss calculation.

$$P_{cu} = 2 m n I_{phm}^2 \rho_{cu} [L_a + \pi^2 D_{is} / (4 Q_s) + h_t / 2] / A_{wdg} \quad (15)$$

2.3 Thermal sub-model

The structure of the thermal model with the selected GaN devices and its lumped parameter thermal circuit used at steady state to determine the maximum heat sink thermal resistance (R_{th-sa}) are shown in Fig. 7. Natural cooling is considered in the design due to the reliability issues and speed dependence of fans. The calculation of R_{th-sa} is expressed in (17) to ensure that the junction temperature of any device does not exceed its maximum value (T_{jmax}). The thermal resistance of PCB and thermal interface material (TIM) are determined using manufacturer's application notes [ref]. Analytical models are used for heat sink, as the heat sink structure and range of size and fin geometry are established. The fin geometry and model of the heat sink is shown in Fig. 8.

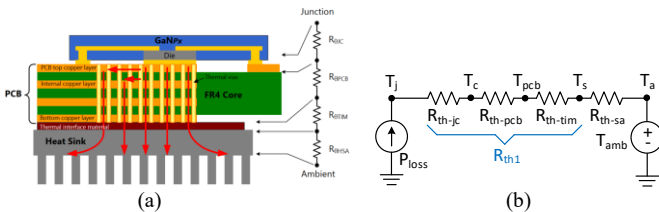


Figure 7. (a) Thermal model structure [ref] (b) Lumped parameter thermal equivalent circuit

$$R_{th-sa} = (T_{jmax} - T_{amb}) / (n P_{loss}) - R_{th1} / n \quad (17)$$

Figure 8. The model of the heat sink

Extruded fin channel length

2.4 Geometrical sub-model

A, B, J neye göre seçildi [ref]

The basic objective function, the volumetric power density (PD_v) of the system is determined using the dimensions of each part as shown in Fig. X, as in 1.

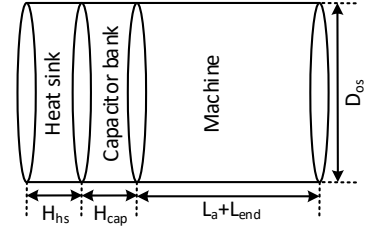


Figure X. Calculation of the overall system power density

$$PD_v = P_{out} / [(\pi (D_{os}/2)^2 (H_{hs} + H_{cap} + L_s + L_e))] \quad (1)$$

W/kg da dahil edilebilir mi?

Volume formüllerini verelim mi? hayır....

3 Dependencies between design parameters

The final format in which the papers will appear in the
Değişken parametreler: modül sayısı + seri modül sayısı, anahtarlama frekansı, magnet kalınlığı, aspect ratio, slot/module/phase, ma
Bakılacaklar: motor verimi, drive verimi, power density, Active material cost (mass)?, GaN ve Cap costu
Malzeme ağırlıkları

Çelişkiler

Evrensel ilişkiler

Limitler (fsw şunun üstünde mantıklı değil, max 5 modül feasible gibi)

IMMD'ye özel ilişkiler

4 Discussions

Your full paper should be submitted
On the choice of

Effect of
On the choice of

5 System design and simulation results

Your full paper should be submitted
Modellerin verification'ı ???

IGBT'li single system ile karşılaştırma yapacak mıyız?

Analytical vs FEA % error ??? for verification

Add also efficiency vs output power

6 Conclusions

An 8kW, 540V DC link system is designed using the developed optimization tool.
The resultant system has the performance indices of x kW/lt, x % drive efficiency and y % motor efficiency

Acknowledgements

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