Title: Multi-Physics Optimization of an Integrated Modular Motor Drive System

Author 1: Mesut Uğur, Department of Electrical and Electronics Engineering, Middle East Technical University

Author 2: Ozan Keysan, Department of Electrical and Electronics Engineering, Middle East Technical University

Preferred topic area: C4 - Integrated drives

Abstract: (up to 1,000 words plus an additional 250 words for references / appendices)

Objectives and context

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 power density, cost increase and electromagnetic interference (EMI) problems [1]. In integrated modular motor drive (IMMD) systems, the drive is integrated into the motor back iron forming a single package so that the power density of the overall system is enhanced and the connection cables are eliminated [2]. Furthermore, each pole of the motor is driven by its own drive module which are then connected on the 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 [3].

In this paper, optimization of an IMMD system is presented considering both the motor and drive parameters to obtain the highest power density and efficiency. The content of the **multi-physics optimization** includes **electrical, electromagnetic, thermal and spatial model**. A high torque, permanent magnet synchronous motor (PMSM) having a stator with fractional slot concentrated windings (FSCWs) is utilized for its superior torque density, low cogging torque and fault tolerance capability which makes it especially suitable for IMMD applications [4]. Gallium Nitride (GaN) power semiconductor devices are used with high switching frequency in the drive inverters to meet the system requirements and design challenges caused by the integration [5]. It is well-known that in an average power converter, passive components and heatsinks are the components constituting the largest portion of the overall volume [1]. With high drive efficiency values, which are achievable thanks to the fast switching capability of GaNs, heatsink size can be reduced. Moreover, size of the passive components, especially the DC link capacitor can be reduced with high switching frequencies applied to GaNs as well as with the utilization of interleaving technique which is already applicable thanks to the modular motor drive structure.

Methods/approach:

The integration of the drive onto the motor poses several challenges such as volume reduction, cooling both units simultaneously, vibration due to the motor etc. which are difficult to address without a broad scope work including all the components and an optimization process. Modularity of the system also increases the possibilities making the design more flexible which can be performed easiest with the help of an optimization procedure. Integrated motor drive system design with GaNs and modular fault tolerant PMSMs have been studied separately, in several papers [2], [5], [6], nonetheless none of these research work has considered the motor and the drive simultaneously during the design process. **In this paper, a multi-stage nonlinear**

optimization program is developed which starts with the main decisions effecting the system architecture such as the number of modules, types of the main components, connection of motor drive inverter modules etc. The system constants are the DC link average voltage, the total mechanical output power, rated speed of the motor, topology of each motor drive inverter module, pulse width modulation (PWM) technique and type of the motor. **The aim of the optimization program is to obtain a drive efficiency higher than 98%, motor efficiency higher than 94%, drive power density higher than 15 W/cm^3, and motor power density higher than 5 W/cm^3.** The system model includes the DC link, drive inverters, heat sink, stator and the rotor. Genetic algorithm is used as the optimization algorithm for its superior performance with large systems having high number of parameters and probability of having multiple local minima. Using a unique sort and select method yields more realistic and reliable results.

Outcomes:

During the optimization process, **DC link capacitors, power semiconductor devices, switching frequency, heat sink dimensions, stator slot and rotor pole numbers, machine dimensions such as axial length, bore diameter, outer diameter, air gap distance, magnet thickness etc., and stator windings** are used as the **optimization parameters**. DC link capacitor requirement is modeled based on voltage ripple, current ripple, temperature rise and dimensions. The DC link capacitor is usually not only the largest but also the tallest component of the motor drive which affect the drive power density significantly. The motor dimensions depend on machine torque requirement, magnetic loading and electrical loading which are treated as constraints in the optimization and they are accordingly formulated to model the power density of the motor. **Loss models** for both drive and the motor are obtained analytically including power semiconductor conduction and switching loss, and PMSM copper loss as well as core loss due to eddy currents and harmonics for efficiency modeling. The size of the heat sink is obtained using the loss results and the overall power density is found. When the results are interpreted, the main focus is given on several trade-off parameters. For example, the switching frequency decreases the drive efficiency and increases the power density of the drive due to passive component size reduction. Moreover, the heat sink size increase due to the efficiency reduction may overcome the passive component size reduction which cannot be directly visualized in the absence of a complete model and an optimization process.

Conclusions:

In this study, **optimization of an IMMD system** is performed using **genetic algorithm**, considering several aspects such as electrical, thermal, electromagnetic and spatial models. The program takes both drive and motor into consideration to attain more realistic results. In the final paper, a formal analytical model for the multi-physical structure will be presented which will be used in the optimization. The multi-stage optimization methodology and the implementation of the genetic algorithm will be given. The results of the optimization process will be presented under different weights given to the power density and efficiency constraints. Analytical models and numerical results will be verified by the help of simulations carried on MATLAB/Simulink for the motor drive and Ansys/Maxwell for the motor. The effects of fundamental parameters to the system performance will be discussed thoroughly which will yield a better understanding to the IMMD system.

References:

[1] R. Abebe, G. Vakil, G. Lo Calzo, T. Cox, S. Lambert, M. Johnson, C. Gerada, and B. Mecrow, “Integrated motor drives: state of the art and future trends,” *IET Electr. Power Appl.*, vol. 10, no. 8, pp. 757–771, 2016.

[2] M. D. Hennen, M. Niessen, C. Heyers, H. J. Brauer, and R. W. De Doncker, “Development and control of an integrated and distributed inverter for a fault tolerant five-phase switched reluctance traction drive,” *IEEE Trans. Power Electron.*, vol. 27, no. 2, pp. 547–554, 2012.

[3] M. Gerber and M. Marz, “System integration in automotive power systems,” *Power Electron. Appl.*, pp. 1–10, 2005.

[4] N. Bekka, M. E. H. Zaim, N. Bernard, and D. Trichet, “A Novel Methodology for Optimal Design of Fractional Slot with Concentrated Windings,” *IEEE Trans. Energy Convers.*, vol. 31, no. 3, pp. 1153–1160, 2016.

[5] J. Wang, Y. Li, and Y. Han, “Integrated Modular Motor Drive Design With <roman>GaN</roman> Power <roman>FETs</roman>,” *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3198–3207, 2015.

[6] A. Shea and T. M. Jahns, “Hardware integration for an integrated modular motor drive including distributed control,” in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2014, pp. 4881–4887.