

Evaluation of Inverter Topologies Suited for Integrated Modular Motor Drive Applications

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Abstract—In this paper, evaluation of inverter topologies for integrated modular motor drive (IMMD) applications is presented. Two-level voltage source inverter (2L-VSI), three-level voltage source inverter (3L-VSI) and series/parallel combinations of these topologies using the modularity of the system are investigated in terms of motor side and DC link side voltage and current harmonic spectrum, passive component sizes and motor drive efficiency. New generation wide band-gap GaN power semiconductor devices are utilized in modular topologies and they are compared with a conventional motor drive utilizing IGBTs under the same system ratings. The effect of phase-shifting between the PWM carrier signals of parallel connected modules and its contribution to size reduction is investigated. IMMD structure has proven to have a superior efficiency performance over conventional motor drives, thanks to the utilization of GaNs. It has been shown that 98.5% motor drive efficiency can be achieved using series and parallel connected modules for an 8kW output power.

I. INTRODUCTION

The percentage of electric motor drives in global electricity consumption is over 45% which makes energy conversion efficiency highly significant. Many of the electric motor drives are becoming variable frequency adjustable speed drives (ASDs) each day due to the need for precise speed or motion control. Power density also plays a critical role in designing motor drives in several applications such as electric traction and aerospace.

Conventional ASDs are composed of motor drive inverter power electronics, passive components, cooling structures, control/communication interfaces and sensors for speed control. In integrated motor drives, the aforementioned drive components are integrated on the electric motor to reduce the system size, eliminate the connection cables for better EMI/EMC performance and eliminate the need for separate enclosures [Abebe-2016]. A more compact approach for integration is dividing the system in modules which is called the Integrated Modular Motor Drive (IMMD) concept. A dedicated drive is integrated onto each motor segment in IMMDs. The advantages of using such an arrangement are reduction of power semiconductor device and motor winding voltage and current stresses, improvement of fault tolerance capability, distribution of heat sources to get an easier thermal management and manufacturing, maintenance and repair cost reduction [Wang-2015].

With the introduction of modularity to the system, the variety of available topologies suitable for motor drive increases significantly in IMMD applications. Three-phase voltage source inverter (VSI) topologies for different applications such as motor drive or grid-connected renewable

energy converters have been proposed, evaluated, tested and reported thoroughly for many years. Most of these reports include two-level VSI (2L-VSI) and three-level VSI (3L-VSI), cascaded H-bridge (CHB) and modular multilevel converter (M2LC) for higher voltage ratings. On the other hand, different motor poles can be connected to separate and dedicated drive inverters in IMMDs which brings design flexibility in terms of motor drive topology selection [Yciu-2014].

To integrate the drive on its motor, significant size reduction should be achieved to fit all the drive components in a small volume [Abebe-2016]. The largest components in an average power converter are the passive components and heatsinks [Marz-2010], therefore the size reduction challenge can be addressed by either minimization DC link capacitor or heat sink volume (or both) in an integrated drive. Considering the design flexibility, investigation of the most suitable motor drive topology in terms of DC link ripples, AC side harmonics and efficiency is mandatory.

There have been several studies in search for the most suitable motor drive arrangement for an IMMD design. The first integrated regenerative motor drive was proposed in 2002 for industry applications which was based on a matrix converter topology [Klumpner-2002]. Another prototype based on matrix converters was built for a 30kW induction motor [Wheeler-2005]. The aim of these studies were to eliminate the need for filtering elements. In [Klumpner-2002], converter topologies on the rectifier front-end are evaluated for integrated motor drives, keeping the inverter side the same. An IMMD design with soft magnetic composite (SMC) core material for a five-phase machine is developed in [Brown-2007], where each phase leg is composed of independent IGBT based half-bridges. A similar approach is used in [Shea-2014] for a six-phase machine, grouping each three-phase with a common neutral point. This was the first IMMD prototype with dedicated controllers on each module to further increase the reliability and fault tolerance. A 50kW, 6-phase integrated fault tolerant permanent magnet motor drive is proposed in [Wolmarans-2008], where each phase of the drive is composed of a full-bridge converter, instead of half bridges. GaN FETs were firstly introduced into the IMMD designs in 2013 to reduce the DC link capacitor size as well as eliminate the heat sink by operating at high switching frequencies [Wang-2013]. In this work, series connection of inverter modules is proposed to match the low voltage rating of GaNs to higher DC link voltages. Evaluation of the aforementioned conventional inverter topologies (2L-VSI, 3L-VSI and CHB) has been investigated by the authors of [Wang-2014, Yciu-2014, Wang-2015] for IMMDs, and compared with their proposed

topology having series connected 2L-VSI inverters in terms of number of components used, flexibility in voltage levels, modularity and fault tolerance [Wang-2014]. Gate signal interleaving has been applied to decrease the capacitor size requirement [Wang-2014]. Additional medium-voltage inverter topologies are mentioned in [Yeiu-2014] where separate DC links are used for each inverter. Moreover, the series connected topology is further extended with replacing the 2L-VSI with 3L-VSI either in Neutral Point Clamped (NPC) or Flying Capacitor (FC) configuration [Yeiu-2014]. Similar evaluation parameters are considered in these studies; however, these evaluations are generally conceptual rather than providing numerical comparisons.

In this paper, a detailed analysis is presented for the evaluation of selected inverter topologies suited for IMMD applications. A conventional 2L-VSI IGBT based inverter is considered in addition to the 2L-VSI and 3L-VSI GaN based IMMD inverters and their series and/or parallel connected derivations. Gate signal interleaving is applied in parallel connected converters to reduce the DC link capacitor size. Motor terminal voltage and line current, DC link voltage and capacitor current spectral analyses are performed using MATLAB/Simulink simulations. Furthermore, power semiconductor losses are analyzed for varying switching frequencies using numerical integration method applied to device waveforms obtained from MATLAB/Simulink simulations.

II. SYSTEM DESCRIPTION

A. Integrated Modular Motor Drives

There are several ways of integration proposed in the literature [Abebe-2016]. The IMMD structure considered in this paper is called stator iron mount integration where each stator pole piece has its own drive module consisting of power electronics, and control electronics as shown in Fig. 1 [Shea-2014]. In this study, and IMMD having a nominal output power of 8 kW is considered. Depending on the number machine poles, the topology and configuration of modular pole-drive modules can be arranged. The rated values of the system are shown in Table 1.

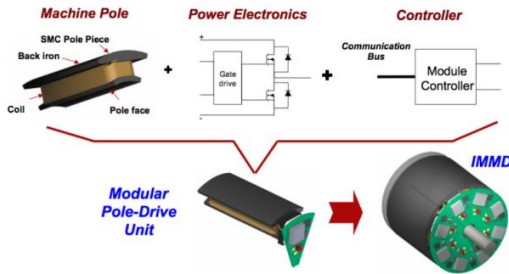


Fig. 1. An IMMD illustration with stator iron mount integration

TABLE I
RATED VALUES OF THE SYSTEM

Parameter	Value
Drive total output power, P_{out}	8 kW
DC link voltage, V_{dc}	540 V
Number of phases in each module, m	3
Power factor, pf	0.9

B. Classification of Topologies

Five different IMMD topologies are considered and evaluated which are shown in Fig. 2. 2L-2S-VSI is the same as the ones proposed in [Wang-2014]. 2L-2S2P-VSI and 3L-2P-VSI are topologies derived from the series connected one. These are newly developed topologies where both series and parallel connection are applied simultaneously. The 3-level topologies are in diode clamped (neutral point clamped) multilevel configuration.

The modulation technique is Sinusoidal Pulse Width Modulation (SPWM) for all topologies. Additionally, interleaving is applied for the topologies where parallel connected modules share the same module capacitor. In fact, the same technique can be applied to series connected modules; however, while decreasing the ripple voltage on the overall DC input, it does not affect the percent ripple on the individual module DC buses. The aim of restricting the percent ripple on the DC link is to make sure that the AC side voltage waveform quality is not affected by the DC link ripples, therefore it is meaningless to decrease the overall DC link voltage ripple.

C. Power Semiconductor Devices

A conventional drive topology (2L-VSI) is considered having IGBTs and anti-parallel diodes as power semiconductor devices, to be able to compare the power density and efficiency of IMMDs with a conventional motor drive. For the other topologies, a kind of series connection is used purposefully, either directly connecting 2-level modules in series, or using 3-level inverters, to make the drive having an input of 540 V_{DC} compatible with commercially available GaN FETs with the highest voltage rating. Two different GaNs having 650V blocking voltage rating are used from GaN Systems with suitable current ratings according to the having parallel connection or not. Finally, Silicon Carbide (SiC) Schottky diode from Wolfspeed is selected for the clamping diode of the 3-level topologies. All the selected devices and their basic parameters are shown in Table 2 [GanS-Infinion-Wolfs].

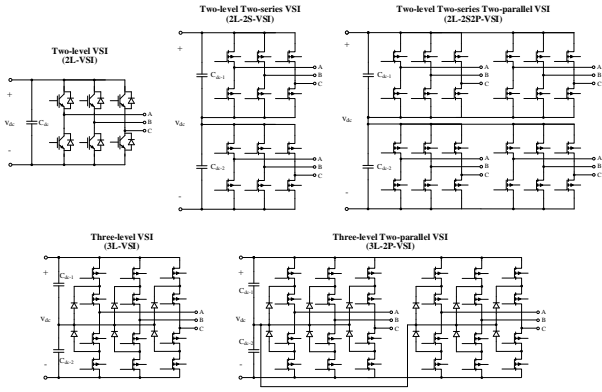
TABLE II
SELECTED DEVICES AND THEIR PARAMETERS

Device	FF50R12RT4	GS66508B	GS66516B	C5D50065D
Type	IGBT	E-mode GaN	E-mode GaN	SiC Schottky
Voltage	1200 V	650 V	650 V	650 V
Current	50 A	30 A	60 A	50 A
$V_{ce,sat}$	2.15 V	-	-	-
$R_{ds,on}$	-	50 mΩ	25 mΩ	-
V_f (diode)	1.65 V	-	-	2.0 V

III. EVALUATED PARAMETERS

The model of the IMMD system and the single phase equivalent of the motor model are shown in Fig. 3.

Dxzsvf



C. DC side

For papers

Akım RMS formülü?

voltaj ripple formülü? % 1 olacak

D. Efficiency

For papers

Efficiency hesabında kullanılan yöntemin çizimi

Factors for switching frequency:

1. Losses => efficiency => heat sink size
2. Ripples => filter size
3. EMI/EMC considerations
4. Speed of control architecture, sensors etc.
5. Effect on motor insulations

Optimal selection of f_{sw} is critical. Size'ı küçültüyor ancak heat sinki büyütüyor

Other considerations:

- Fault tolerance: series'de kötü

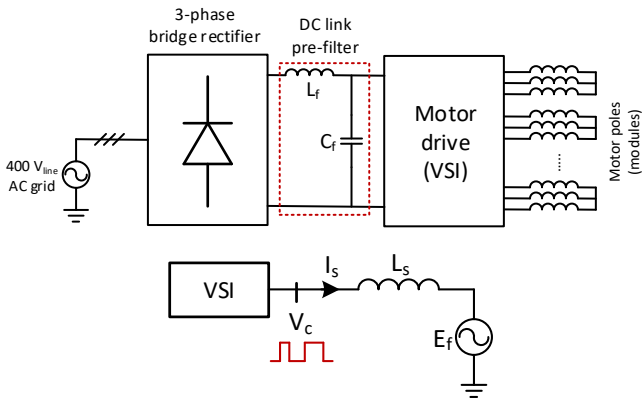


Fig. 2. Classification of topologies

A. AC side

The model of the IMMD system and the single phase equivalent of the motor model are shown in Fig. 3.

Multipliers

THD_v, THD_i formülleri

B. AC side

Multipliers

THD_v, THD_i formülleri

Motor modelini çizelim

IV. SIMULATION RESULTS

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CONCLUSIONS

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ACKNOWLEDGMENT

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