An Integrated Modular Motor Drive With Shared Cooling for Axial Flux Motor Drives

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Abstract—In this article, a circumscribing polygon integrated modular motor drive topology with shared cooling for the power converter and the electrical machine is proposed and benchmarked with the nonintegrated version. The proposed topology is applied on an axial flux permanent magnet synchronous machine. The topology is capable of mechanically mounting the power converter, sufficiently cooling both the power converter and the electrical machine, and combining both of them into the same housing. The mechanical and the thermal design are done to ensure thermal decoupling between the power converter and the motor winding, and to provide a low thermal resistance from the power converter and the electrical machine to the ambient. Due to the limited space available for the power converter module, wide bandgap semiconductor technology is chosen for the implementation of the converter module, thanks to their small package size and low power losses. A highly modular, integrated, and compact drive is achieved compared to the nonintegrated one. A computational fluid dynamics (CFD) model is developed for one module of the proposed integrated drive to evaluate the maximum current that can be injected by one converter module without exceeding the junction temperature limit of the switches and the maximum winding temperature. An experimental setup is built to validate the results of the introduced multiphysics models.

Index Terms—Axial flux machines, integrated motor drives, power density, thermal modeling, wide bandgap devices.

I. INTRODUCTION

THE integrated modular motor drives (IMMD) combine the benefits of both worlds of integrated and modular drives. The integrated drive is a physical integration of the motor and the driving power electronics into one unit [1].

This physical integration means a close proximity between the power electronics and the machine windings. This proximity leads to the elimination of the expensive and usually shielded cables needed to connect the power electronics to the motor in the conventional drives.

This structural integration involves a shared housing and cooling system for both the machine and the power electronics. The combined benefits of the elimination of the cables and the separate cooling and enclosure for the power electronics are reduced electromagnetic interference (EMI), reduced winding voltage stress caused by the surge impedance mismatch between the cables and the windings, volume and weight of the whole drive [2]–[3]. In terms of numbers, the elimination of such components can reduce the whole volume of the drive by 10–20% [3]–[4].

In modular drives, the power electronics converter is divided into modules, each module is supplying a part of the stator windings. The modularity enhances the fault tolerance of the whole drive as each module can be controlled to contribute by certain amount to the whole torque by proper control. Moreover, the system can tolerate the fault in one or more module depending on the number of modules [5]. Having several converter modules sharing the power of the whole drive improves the thermal performance of the power electronics devices as the surface area used by the converter modules increases and requires a smaller voltage rated devices as well [6].

The IMMD adds many challenges on the design of the power converter module from the space and the thermal management point of view [7]–[8].

IMMD-topologies can be classified according to the position of the power converter into radially housed mounted (RHM), axially housing mounted (AHM), radially stator iron mounted (RSM), and axially stator iron mounted (ASM) [4].

In the RHM configuration, the power converter is mounted on the outer periphery of the machine in the radial direction in a separate enclosure. In [9], an RHM-integrated motor drive is proposed for switched reluctance machines. The power converter is implemented as one unit in a separate housing sharing the same water cooling loop with the motor.

The RHM is more suitable for sausage design type of electrical machines, where the stack length is longer than the stator diameter. Despite of being a simple way for integration, the converter still needs its own separate housing, which increases the diameter of the machine considerably.

In the AHM configuration, the power converter is mounted axially in a separate enclosure. In [10], a water-cooled six-phase
inverter is designed for axial integration with a six-phase machine. This configuration is suitable for pancake design type of electrical machines, and it has the same merits and drawbacks of the RHM configuration.

The RSM and ASM configurations are providing more compact-integrated drive topology while adding more challenges in the thermal management of the power converter due to the close proximity to the major heat sources in the drive (the windings and the core).

In [2], an RSM three-phase-integrated drive is proposed for hybrid vehicles. The power converter is synthesized from three half-bridge modules mounted on a water jacket separating between the power converter and the stator of the machine.

In [11], an ASM five-phase-integrated modular drive is proposed for switched reluctance machines, where the power converter modules are mounted axially on a ring-shaped heat sink sharing the same enclosure with the machine.

The design of the IMMD converter using WBG commercially available devices like the silicon carbide (SiC) or the Gallium nitride (GaN) can be of great benefit in having a high-power density converter suitable for the IMMD challenges [12].

The smaller package size, lower losses, higher thermal conductivity, and higher junction temperature of the WBG devices compared to the Si devices result in a much higher power density converter suitable for the IMMD stringent ambient conditions [13].

In this article, a fully modularized integrated motor drive topology is proposed and designed for a double-rotor single-stator yokeless and segmented armature (YASA) axial flux permanent magnet synchronous machine (PMSM).

YASA axial flux machines are gaining popularity in many applications like electric vehicles and wind energy generation systems, thanks to their high efficiency and power density [14].

The integration approach proposed in this article provides a solution for the most challenging aspect of the integrated drives, which is the thermal management of the power converter residing in close proximity to the electrical machine winding with its high heat generation. The topology proposed keeps the power converter modules close to the machine winding and efficiently decouple the heat generated by both of them.

One more advantage of the proposed topology is that it makes it possible to synthesize the full-integrated drive from several identical pole drive units combining the machine stator parts, their associated driving converter, and a shared cooling for both of them. In that way, the manufacturing process can be greatly simplified and a fully modular drive approach can be achieved.

The proposed topology is optimized from the thermal point of view in order to maximize the current that can be injected by the inverter modules. The maximum current that can be injected without exceeding the rated temperature of the switches and the winding insulation is calculated.

This article is organized as follows. Section II demonstrates the mechanical design of the proposed integration topology, Section III explains the design of the WBG-based discrete converter module, Section IV calculates the maximum power of the proposed integration approach, and the experimental results are given in Section V Section VI concludes this article.

**II. MECHANICAL DESIGN OF THE PROPOSED INTEGRATED DRIVE**

Fig. 1 shows the construction of the original nonintegrated YASA machine. It consists of a number of coils of the concentrated winding type, where each coil consists of a copper winding wound around a silicon steel core. All the coils are arranged circumferentially, impregnated with epoxy resin and casted to form the active part of the stator with an aluminum housing around the stator to evacuate the heat generated by the stator elements to the ambient [15].

The YASA machine has two-rotor disks with surface-mounted permanent magnets (PMs).

Table I lists the key specifications of the nonintegrated machine.

**Fig. 1**. Cross-sectional view of the nonintegrated YASA prototype. (1) Housing. (2) Winding. (3) Core. (4) Shaft. (5) Rotor Diak. (6) PMs.

**TABLE I**

| Quantity                  | Symbol | Value |
|---------------------------|--------|-------|
| Rated power (kW)          | $P$    | 4     |
| Rated speed (rpm)         | $n$    | 2500  |
| Rated rms current (A)     | $I_r$  | 9     |
| # Pair poles              | $p_r$  | 8     |
| # Slots                   | $n_s$  | 15    |
| Axial length (mm)         | $L_{ax}$ | 60   |
| Outer diameter (mm)       | $D_{out}$ | 190 |

**Fig. 2** shows the geometry of the housing lamination of the nonintegrated drive. It consists of a circular-shaped outer periphery with inward fins in contact with the stator windings for more effective heat transfer to the ambient [15].

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Fig. 2 shows the geometry of the housing lamination of the nonintegrated drive. It consists of a circular-shaped outer periphery with inward fins in contact with the stator windings for more effective heat transfer to the ambient [15].

In order to utilize the same housing for cooling both the stator modules and the power converter modules, two-main modifications should be done to the housing: the first one is to introduce a flat surface on the housing to mechanically mount the power converter modules (mechanical reason) and to have a good contact between the switch thermal pad and the housing (thermal reason). The second one is to thermally decouple the
stator modules and the power converter modules to avoid over temperature of the power modules.

Fig. 3 shows the proposed housing lamination construction for integrating the power modules and the machine. The outer surface of the housing lamination has been modified from being circular to polygon shape. In that way, the converter modules can be mounted on the outer surface of the housing. Also, an axial cooling channel has been introduced between the stator module and the power converter module. By injecting a cooling fluid in the circular channels, the stator modules and the power converter modules will be thermally decoupled and the heat generated by both of them can be dissipated in the cooling fluid.

Since the axial length of the machine will be maintained, the dimension of the converter module PCB in the axial direction will be the same as the axial length of the machine \(L_{ax}\). The value of the other dimension \((L_y)\) depends on the diameter of the inscribed circle, which is the outer diameter \((D_{out})\) of the machine and the number of stator modules \((n)\). The value of \((L_y)\) can be calculated from the following:

\[
L_y = D_{out} \tan \left( \frac{180}{n} \right). \tag{1}
\]

The size of the resulted flat surface per module for the 15-phase case study is 40\(\text{mm}\) in the circumferential direction and 60\(\text{mm}\) in the axial direction. This means that the dimensions of the power converter module are limited to \((60 \times 40)\text{mm}^2\).

III. DESIGN OF THE POWER CONVERTER MODULE

Due to the limited space available per converter module, the power electronics switches should be selected to have a small form factor and low power losses beside the electrical ratings suitable for the application.

A. Selection of the Switching Devices

GaN technology has been selected for the implementation of the integrated converter module due to their low figure of merit \((\text{FOM} = R_{ds} \times Q_g)\), which is an indication for the low losses in the forward conduction path [16] and the zero reverse recovery charge which indicates a zero switching losses in the reverse conduction path.

B. Heat Flux Density of the Power Switches

For the choice of a GaN device for the converter implementation, the heat flux density of two commercial GaN devices GS66508B & LMG341xR070 is evaluated at different modulation indices \((M)\). The heat flux density is defined to be the total power losses generated by the switch during one fundamental power cycle divided by the case (thermal pad) area of the device. The heat flux density is considered for the calculation to consider the influence of the thermal pad area on the heat transfer from the switches.
The losses in the forward conduction path can be calculated from the following [17]:

\[
\begin{align*}
    P_{\text{cond}} &= I_{\text{rms}}^2 R_{\text{ds}} \\
    P_{\text{ton}} &= [V_{\text{dc}} f_{\text{o}}] \\
    &+ \sum_{n=1}^{m_f} (t_{\text{on}}(nT_s)i_{\text{on}}(nT_s) + Q_{\text{rr}}(nT_s)) \\
    P_{\text{off}} &= [V_{\text{dc}} f_{\text{o}}] \sum_{n=1}^{m_f} t_{\text{off}}(nT_s) S_{\text{off}}(nT_s) \\
    P_t &= P_{\text{cond}} + P_{\text{ton}} + P_{\text{off}}
\end{align*}
\]

where \( P_{\text{cond}} \) is the conduction losses in the forward conduction path, \( I_{\text{rms}} \) is the rms value of the transistor current, \( R_{\text{ds}} \) is the drain-to-source resistance of the switch, \( f_o = \frac{f_{\text{pwm}}}{60} \) is the fundamental output frequency, \( m_f = \frac{\theta}{360} \) is the frequency modulation ratio, \( t_{\text{on}}(nT_s) \) is the turn ON transition time of the switch at the sample \( (n) \), \( i_{\text{on}}(nT_s) \) is the forward conduction current sampled at the rising edge of the gate signal, \( t_{\text{off}}(nT_s) \) is the turn-OFF transition time of the switch, \( i_{\text{off}}(nT_s) \) is the forward conduction current sampled at the falling edge of the gate signal. \( P_t \) is the total losses in the forward conduction path.

The losses in the reverse conduction path can be calculated from the following:

\[
P_{\text{d}} = f_o \int_{t}^{t+T_o} i_d(t)v_d(t)dt
\]

where \( T_o = \frac{1}{f_o} \) is the fundamental power cycle, \( i_d(t) \) is the instantaneous current in the reverse conduction path for one complete power cycle, \( v_d(t) \) is the voltage drop in the reverse conduction direction for one power cycle, \( P_d \) is the loss in the reverse conduction path.

Due to the zero reverse recovery charge and reverse recovery current, the switching losses in the reverse conduction path are zero.

Figs. 5 and 6 show the heat flux density versus the modulation index for the two GaN switches at \( V_{\text{dc}} = 400 \) V, \( I_{\text{phase}} = 9 \) A, and switching frequency of 50 kHz for sinusoidal pulsedwidth modulation (SPWM) and space vector pulsedwidth modulation (SVPWM), respectively. Both curves are generated at 150 \degree C junction temperature.

By inspecting Figs. 5 and 6, the heat flux density of (GS66508B) is smaller than the other device, and this makes it the best choice for the implementation of the integrated converter module. Also, the power losses generated at SPWM are lower than the SVPWM, which makes the SPWM a better choice for controlling the converter.

From the same figures, it can be observed that the power losses decrease with the modulation index. This can be explained by the significance of the losses in the reverse conduction path compared to the forward path due to the high voltage drop on the reverse path compared to the forward path. As the modulation index increases, the forward conduction duration prevails over the reverse one, which means lower reverse losses and, hence, total losses reduction with the modulation index.

C. Thermal Design of the Converter Module

The maximum power density that can be achieved by the proposed integrated drive topology depends on the maximum current that can be injected by the converter module without exceeding the maximum junction temperature of the switches.

The junction temperature of the switch depends not only on the junction power losses but also on the thermal impedance from the junction to the coolant. This thermal impedance has two components: one from the junction to the case and the other from the case to the coolant. The latter can be greatly reduced by a proper thermal design of the power converter board.

Fig. 7 shows the (GS66508B) package seen from the bottom. Besides the electrical function of the source pin (pin 2), it also receives most of the heat generated in the switch die. So, the thermal impedance from the pin 2 (see Fig. 7) to the coolant should be minimized.

The PCB is designed as a four-layer board for enhancing the electromagnetic and thermal performance of the whole converter [18].

Fig. 8 is a photo for the implemented half-bridge module.
Fig. 8. Implemented half-bridge module.

The copper layers act as heat spreaders while the thermal vias reduce the thermal impedance of the heat path from the top layer to the bottom layer. Spreading the thermal vias beyond the thermal pad of the switch helps reducing the overall thermal impedance around the PCB [19].

Fig. 9 shows the copper plotted area beneath the thermal pad of the switch (see Fig. 7) with the thermal vias distributed around. The copper area with the via pattern in Fig. 9 is included in the four copper layers.

To evaluate the amount of thermal impedance reduction resulting from the via patterns in Fig. 9, two thermal finite element models have been built. One without the thermal vias and the other with them included. The dimensions of the copper plot area and the thermal via barrel are in Fig. 9 and Table II, respectively. The material properties of the different parts are in Table III.

Table II: Thermal Via Dimensions

| Quantity                        | Value |
|---------------------------------|-------|
| Via outer diameter (mm)         | 0.35  |
| Thickness of via plating (μm)   | 25    |
| Via spacing (mm)                | 0.65  |

Table III: Thermal Properties of PCB Materials

| Property                      | Copper (Cu) | FR4  | Air  | Solder(SnAgCu) |
|-------------------------------|-------------|------|------|----------------|
| Density (kg/m³)               | 8890        | 1250 | 1.1614| 7500           |
| Specific heat capacity (J/kg K)| 592        | 1300 | 1009 | 250            |
| Thermal conductivity (W/m K)  | 385         | 0.35 | 0.0281| 57.3           |

The boundary conditions are 1 W of heat losses imposed on the top part of zone 1 (Psw) (see Fig. 9) while the whole bottom surface is isothermal at temperature of (Tbottom = 20 °C), the other surfaces are adiabatic.

Fig. 10 shows the temperature distribution of the model without thermal vias. The following can be used to calculate the thermal resistance from the case of the switch to the bottom layer:

\[ R_{th} = \frac{T_{case} - T_{bottom}}{P_{sw}} \]  \hspace{1cm} (4)

where \( T_{case} \) is the case temperature of the switch.

From Fig. 10, the maximum temperature of the switch case 86.9 °C, this results in a thermal resistance of 66.9 °C/W.

Fig. 11 shows the effect of the thermal vias on the maximum switch case temperature for the same boundary conditions. It can be seen that the maximum temperature reduced to 22.2 °C, which means a thermal resistance of 2.2 °C/W and this amounts to a reduction of about 98.7% in the thermal resistance from the case of the switch to the bottom of the PCB.

This significant reduction in the thermal resistance will extremely increase the upper bound of the current that can be supplied to the motor before reaching the junction temperature limit of the switch.

IV. DRIVE MAXIMUM POWER PER MODULE

The maximum output power that can be achieved by the proposed drive is limited by the maximum junction temperature of the switches and the maximum temperature of the insulation of the windings.

The method used for the calculation of the power density of the proposed drive is as follows.

1) Calculate the switch power losses that result in a junction temperature of 115 °C, a margin of 35 °C is left with zero winding and core losses.
2) From the power losses versus temperature model of the power transistors, calculate the line current that results in the losses calculated in the previous step at 115 °C.

3) Calculate the machine losses (winding and core) at the current calculated in step 2.

4) Recalculate the switches junction temperature and the winding temperature with the machine power losses taken into account.

5) If the junction and the winding temperatures are within the limits, then consider the current calculated in step 2 as the maximum safe operating current, if not, reduce the current up to the level that keeps the temperature within the limit.

6) Calculate the maximum power per module from $V \cdot I \cdot \text{PF}$, where $V$ is the rms of the phase voltage, $I$ is the rms of the current, and PF is the power factor. The total drive power can be obtained by multiplying the result by the number of modules.

To apply the abovementioned described method, a thermal model for one integrated drive module is needed along with a power loss model for the machine components and a power loss versus temperature model for the power switches.

The power loss of the machine components is calculated using the method of loss separation developed in [20].

A. Module CFD Model

A computational fluid dynamics (CFD) model is built for one drive module to calculate the switch losses at which the junction temperature of the switches is 115 °C.

Fig. 12 shows the simulated geometry of one module. The winding, the core, and the housing of the machine have heterogeneous structures. Each consists of the main constituting material (i.e., copper in case of the windings, silicon steel for the core, and aluminum for the housing), insulation around the wires and the laminations and epoxy for impregnation. The approach used for modeling such a heterogeneous structure is the Hashin–Shtrikman approach for homogenization [21].

Equation (5) can be used to calculate the thermal conductivity of the winding, the core, and the housing, where $f_{w,c}$ is the winding or stacking factor, $K_{w,c}$ is the thermal conductivity of the main winding/core/housing material, $K_e$ is the thermal conductivity of the impregnation material.

Equations (6) and (7) can be used to calculate the specific heat capacity and mass density of the winding, the core, and the housing, where $C_{w,c}$ is the specific heat capacity of the winding/core/housing, $\rho_{w,c}$ is the mass density of the winding/core/housing, and $\rho_e$ is the mass density of the impregnation epoxy.

$$\begin{align*}
K_1 &= f_{w,c} \cdot K_{w,c} + (1 - f_{w,c}) \cdot K_e \\
\rightarrow & \text{lapping & nonstacking directions} \\
K_2 &= K_e \cdot (1 + f_{w,c}) \cdot K_{w,c} + (1 - f_{w,c}) \cdot K_e \\
\rightarrow & \text{other directions}
\end{align*}$$

$$\begin{align*}
C_{ph} &= f_{w,c} \cdot C_{w,c} + (1 - f_{w,c}) \cdot C_e \\
\rho_{ph} &= f_{w,c} \cdot \rho_{w,c} + (1 - f_{w,c}) \cdot \rho_e.
\end{align*}$$

Table IV contains the thermal properties of the different parts of one drive module.
The adiabatic boundary condition is used for all surfaces, the cooling fluid used is water with inlet temperature 22.5 °C and flow rate of 1 L/min.

**Fig. 13** shows the module temperature distribution resulted from 8.25 W loss per switch and zero winding and core loss. The maximum resulted case temperature at 8.25 W losses per switch is 111.6 °C, the thermal resistance of the switch from junction to case is 0.5 °C/W, which means a junction temperature of 115.7 °C.

**Fig. 14** shows the variation of the switch losses versus junction temperature at different line currents. From that figure, the maximum line current is 14 A.

The operating conditions considered for the generation of **Fig. 14** are: SPWM, 400 V dc-link voltage, 2500 r/min speed, power factor of 0.85, switching frequency of 50 kHz, and unity modulation index.

The winding and the core losses are calculated at 14 A peak line current considering coil resistance of 128 mΩ at 100 °C winding temperature. The electromagnetic models developed in [22] for the axial flux PMSM are used for the computation of the flux density distribution in the core, and then the loss separation method developed in [20] is used for the core loss calculation. The resulted copper loss per module is 12.55 W and the core loss per module is 3.7 W. The simulation is done again considering the machine losses, and the result is shown in **Fig. 15**.

From **Fig. 15**, the maximum switch case loss is 114.8 °C and this results in 118.6 °C maximum junction temperature, which is still 31.4 °C less than the junction rated temperature.

The maximum power per module is calculated and rated at 1147.5 W. This means that the 15-modules prototype machine can provide 17 212 W total power using the proposed integration topology.

The nonintegrated drive was originally designed to have 4 kW rated power at 2500 r/min rated speed [23]. Besides the power enhancement, the elimination of the separate inverter cooling, its separate housing and the connection cables further reduces the overall weight and volume of the whole drive.

It can be noted from **Fig. 15** that the maximum winding and core temperature are 41.5 and 38.5 °C, respectively. This indicates that higher current can be injected in the windings before reaching the thermal limits of the windings insulation, and this can be achieved by parallel connections of the GaN transistors to keep the junction temperature within the limit as well.

### V. Experimental Results

A three teeth setup is built to validate the cooling efficiency of the proposed integration topology.

**Fig. 16** shows a picture for the experimental setup.

The temperature of the switches is measured using a thermal camera and the temperature of the winding is recorded by a PT100 RTD sensor.

The experimental work is done using dc current to generate a well-defined heat in the switches, and the windings to validate the CFD results and pulsewidth modulation (PWM) waveforms to evaluate the validity of the dc thermal measurements at real waveforms. The dc measurements are performed as follows, the inverter switches and the winding of the three coils are heated by connecting the switches in series and supplying them from...
a dc source, and the coils in series and supplying them from a separate dc source.

Fig. 17 shows the switch temperature versus power losses in case of zero and 25 W losses per coil at 1 L/min and 22.5 °C inlet water temperature. It can be seen from the figure that the junction temperature reaches 114.5 °C at 7.6 W switch losses and 25 W per coil losses, which proves the possibility to operate the switch up to that loss level safely. Note that the extrapolation of Fig. 17 results in a junction temperature of 116.55 °C at 8.25 W per switch loss compared to 115.7 °C junction temperature estimated by CFD simulations in Fig. 13, a good agreement between the simulations and the measurements.

Figs. 18 and 19 show the temperature distribution on the power converter module without winding losses and with 25 W per coil losses, respectively, at 1 L/min and 22.5 °C water inlet temperature. In both cases, the loss per switch is 7.6 W.

Note from Figs. 18 and 19 that the low power components on the converter PCB remain at low temperature, which ensures high reliability of the converter module.

Fig. 20 shows the winding temperature at 25 W per coil losses and 7.6 W per switch losses, 1 L/min and 22.5 °C water inlet temperature.

From Fig. 20, the steady-state winding temperature at 25 W coil losses is 52.8 °C, which proves an efficient winding cooling as well.

For the evaluation of the validity of the thermal measurements performed with dc current and reported in Figs. 17–19, the three inverter modules are operated as three-phase inverter supplying an $R = 8 \, \Omega$, $L = 3 \, \text{mH}$. The PWM pulses of 10 kHz frequency are generated using the MicroLabBox dSPACE. The PWM technique used is the SPWM. The windings of the three stator coils are not supplied directly from the inverter because of the small impedance of the coils resulting in the rated switch temperature at a few dc-link volts instead, a 25 W loss per coil are generated by injecting a dc current in the windings.
without exceeding the junction and the winding insulation rated temperature. A discrete low form factor GaN-based half-bridge module of 60 × 40 mm² size was designed and implemented. A CFD analysis had been performed for one drive module to calculate the maximum power per module. The module was capable of delivering up to 1147.5 W at 400 V dc-link voltage. A much smaller drive with enhanced power compared to the conventional one was resulted. The experimental results were collected at dc and real PWM waveforms. The real PWM waveform thermal measurements confirmed the dc measurements and both measurements confirmed the CFD simulation results.

VI. CONCLUSION

A highly modular, integrated, and compact motor drive was proposed in this article and applied on a YASA axial flux PMSM. The proposed integration topology was fully modular in the sense that the whole drive could be synthesized from the separate modules comprising the stator coil, the driving power converter module, and the cooling system for both the machine and the converter module. The topology presented a feasible solution for the shared cooling of the inverter switches and the windings by efficiently decoupling and dissipating the heat of the switches and the windings by the same cooling circuit. The thermal design was optimized to get the maximum possible switch current without exceeding the junction and the winding insulation rated temperature. A discrete low form factor GaN-based half-bridge module of 60 × 40 mm² size was designed and implemented. A CFD analysis had been performed for one drive module to calculate the maximum power per module. The module was capable of delivering up to 1147.5 W at 400 V dc-link voltage. A much smaller drive with enhanced power compared to the conventional one was resulted. The experimental results were collected at dc and real PWM waveforms. The real PWM waveform thermal measurements confirmed the dc measurements and both measurements confirmed the CFD simulation results.

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