GaN power ICs drive Efficiency and Size Improvements in BLDC Motor Drive Applications

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Abstract

BLDC motor inverters with IGBTs for single-phase grid have seen little progress in the last decade. GaN FETs with precise gate drive as used in Navitas GaN power ICs can improve performance, system and operating cost. Very low power losses enable much simpler thermal engineering, and high switching frequency enables further efficiency improvements. In this paper a 400W inverter designed for motor integration, operating off 230V AC grid power, is presented along with full documentation of the design and measurement results, highlighting the quantified improvements in component count, assembly and cooling cost, alongside several performance parameters, and cost of operation.

1. Introduction

For many years, the IGBT (and more recently, the superjunction MOSFET) has been the workhorse as power switch in inverters for motor drives. But both IGBTs and silicon MOSFETs feature p-n junctions in the current path, requiring reverse recovery when the device turns off, contributing significantly to the switching losses. Legacy silicon-based drives operate at low switching frequencies, around 8-16 kHz, with an overall efficiency around 80%.

With the availability of power switches in GaN, the situation is changing. These devices offer resistive characteristics much like a MOSFET, but without p-n junctions in the current path there is no reverse recovery. Switching losses are much lower compared to their silicon counterparts and essentially dominated by output capacitance and overlap losses, significantly easing the thermal design.

GaN FETs require different driving schemes to unlock the full performance and reliability, and integrating them with the driver, voltage regulator, level shifter as well as sense & protect circuitry, like in the new half-bridge products from Navitas, turns them into a versatile building block for many applications, without the added circuit overhead and complexity.

While for lower supply voltages like 48V, the potential advantages of GaN switches for motor inverters have been recognized and different circuits have been proposed, few designs address the particular challenges of higher DC bus voltages as common in many consumer and industrial applications.

2. Selection criteria for GaN power switches in motor inverters

Figure 1 shows a comparison of total losses for GaN power switches, superjunction MOSFETs and IGBTs. The low switching losses of GaN transistors are clear, enabling significantly lower losses in the application, leading to easier thermal engineering and a smaller heatsink, and lower electricity cost. In lower power applications up to 300-400W, it may be possible to eliminate the heatsink completely.

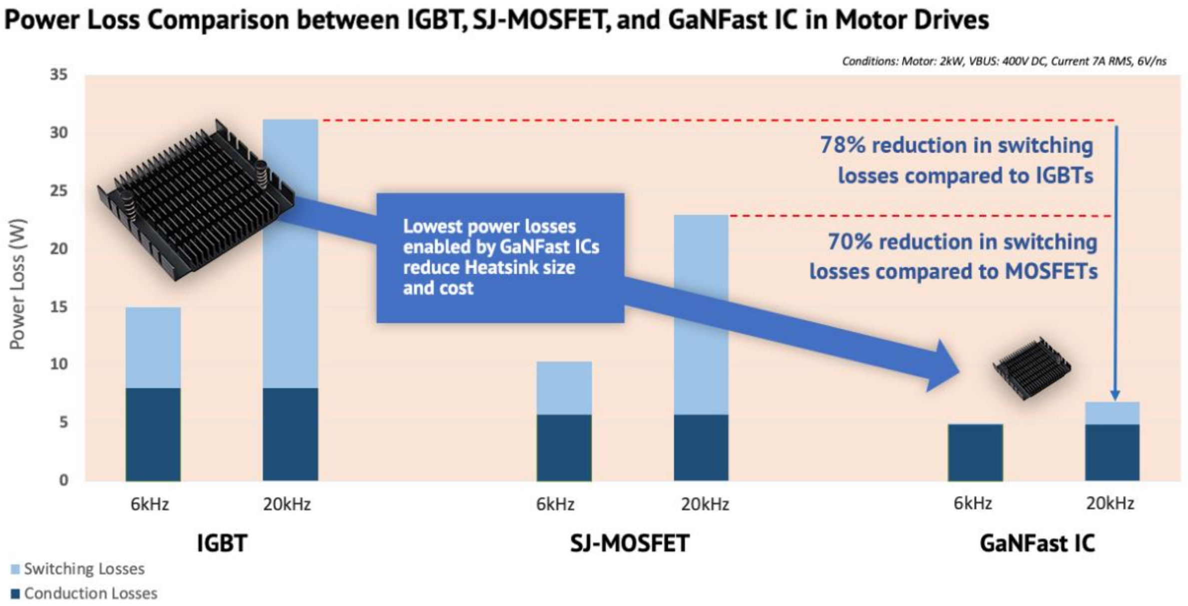

Figure 1: Comparison of total losses for different switch types

When selecting the proper switch for a motor drive application, the total loss budget can still serve as a guideline. However, this could lead to a trade-off where a GaN switch with very high R_{DSON} could be selected, as – even with high conduction losses – the total power dissipation which is dominated by conduction losses would still be acceptable. GaN switches with high R_{DSON} will then see a very high current density, which may be too high in motor startup or abnormal operating conditions. It is therefore important to consider the maximum current possible for the GaN power switch.

New optimization possibilities exist out of the combination of GaN FET and drive and protection circuitry, in order to increase switching speed and frequency, as well as the system size and number of components. Fully integrated GaN power FETs can be considered a digital power stage that can be controlled with signals from the microcontroller, removing gate drivers and the associated complexity. Additionally, the integrated protections do not need to be built with additional external components.

The two most important protection circuits built in are the overtemperature and overcurrent protection. The temperature sensor will detect high junction temperature and turn off switching when the device gets too hot (160°C). Switching resumes after cooling down by approximately 50K. This protection serves as a redundant, second-level protection to aid in the system FMEA as additional means of protection against overheating.

This GaN power IC includes a low-side cycle-by-cycle over-current detection and protection (OCP) circuitry to protect the GaN power FET against high current levels. During the low-side on-time of each switching cycle, should the peak current exceed the internal OCP threshold (1.9V, typical), then the internal gate drive will turn the GaN power FET off quickly and truncate the on-time period to prevent damage from occurring to the IC. The IC will then turn on again at the next low-side PWM rising edge at the start of the next on-time period. This OCP protection feature will self-protect the IC during each switching cycle against fast peak over current events and greatly increase the robustness and reliability of the system. This built-in circuit can safely turn off the GaN FET in less than 100ns. External circuits as known e.g. from IPMs lead to the requirement of a short-circuit withstand time in the range of 3-5µs, which would be too long. This fast overcurrent turn-off is a very good means to protect the power switch and consequently the robustness of the system.

The lossless current sensing also enables motor drives without shunt resistors, further helping with system cost reduction and integration. The GaN power IC provides a current output, which can be scaled using an external resistor to match the input voltage range of the AD converter of the motor controller. The scaling factor and calculation formula for the resistor value is given in the datasheet of the respective device. As the bandwidth of the signal is very high, it can be used for the current control loop.

3. Design considerations

The schematic of one leg of the inverter is shown in figure 2, and a picture of the final board is shown in figure 4.

This inverter consists of three half-bridge GaN power ICs from Navitas, the new NV6247. It contains the input logic, level shifter, voltage regulators and gate drivers, and the current and temperature sense circuits, as well as the bootstrap supply. As a result, the external component count is very small.

The schematic for one of the three legs of the inverter is shown below in Figure 2. Shown is the circuit for the second phase, with all three phases being identical. The main component is the NV6247, integrating the two power switches in a half-bridge configuration, as well as the gate drivers and their regulators, and the input logic labeled “PWM”. A built-in bootstrap circuit is used to provide the gate drive power to the high-side driver. Also included is a level shifter, so that the input signals can be ground-referenced, making this device a digitally-controllable power stage in the best sense of the word.

Furthermore, several sensing functions are included. First, the current flowing through the internal low-side GaN power FET is sensed internally and then converted to a current at the current sensing output pin (CS). Second, the junction temperature is sensed with a circuit on the gate driver and used to turn off the power switches when too hot.

The IC pins include the drain of the high-side GaN power FET (V_{IN}, connected to V_{BUS}), the half-bridge mid-point switched node (V_{SW}, connected to PHB), the source of the low-side GaN power FET and IC GND (P_{GND}), low-side IC supply (V_{CC}), low-side gate drive supply (V_{DDL}), low-side turn-on dV/dt control (R_{DDL}), low-side 5V supply ($5V_L$), low-side referenced PWM inputs (IN_L, IN_H), low-side current sensing output (CS), auto-standby enable input (/STBY), high-side supply (V_B), high-side gate drive supply (V_{DDH}), and high-side 5V supply ($5V_H$). The external low-side components around the IC include V_{CC} supply capacitor (C_{VCC}) connected between V_{CC} pin and P_{GND}, V_{DDL} supply capacitor (C_{VDDL}) connected between V_{DDL} pin and P_{GND}, turn-on dV/dt set resistor (R_{DDL}) connected between V_{DDL} pin and R_{DDL} pin, current sense amplitude set resistor (R_{SET}) connected between CS pin and P_{GND}, 5V supply capacitor (C_{5VL}) connected between $5V_L$ pin and P_{GND}, and auto-standby enable pin (/STBY) connected to P_{GND} to enable auto-standby mode or connected to $5V_L$ to disable auto-standby mode.

The external high-side components around the IC include V_B supply capacitor (C_{VB}) connected between V_B pin and V_{SW}, V_{DDH} supply capacitor (C_{VDDH}) connected between V_{DDH} pin and V_{SW}, and 5V supply capacitor (C_{5VH}) connected between $5V_H$ pin and V_{SW}. The high side V_B, $5V_H$, and V_{DDH} bypass capacitors must be chosen carefully to accommodate various system considerations such as high side wakeup time, high side holdup time, and standby power.

On the right side, the V_{BUS} blocking caps can be seen, and the PCB allows the use of film or electrolytic caps. Their purpose is to dampen any kind of ringing that might occur because of parasitic inductance in the supply and the switching action, since the board is designed for DC input. Finally, R_{17} and C_{18} can be used to dampen ringing on the switch nodes, as it might be caused by long cables and their inductance, and are optional.

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The layout of the board has been designed to enable integration with a motor. The diameter of the board is 56mm, and the DC input as well as the control signals are connected in the middle, as shown in figure 4. The layout follows the recommendations in the datasheet, where more details are given about placing thermal vias and copper areas to optimize thermal resistance, as shown in figure 3. As a result, the thermal resistance of this board has been measured as ~12.5K/W without heatsink.

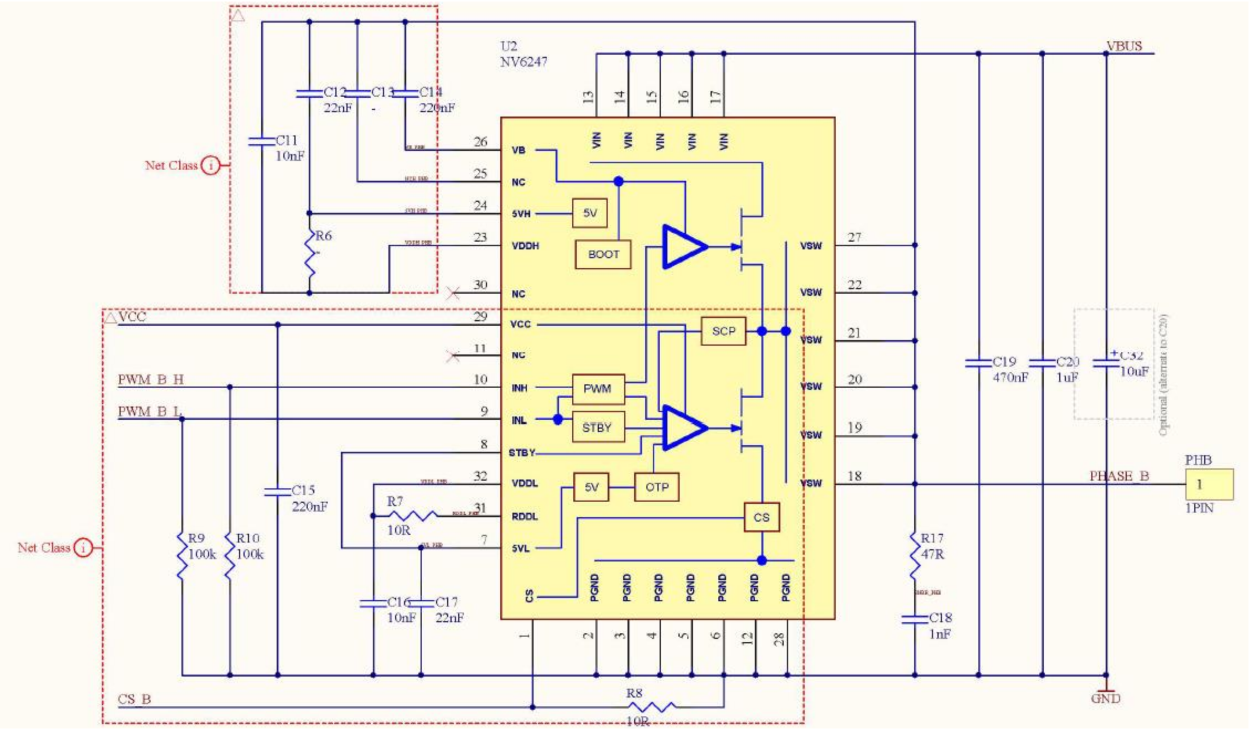


Figure 2: Schematic of one leg of the GaN-based motor inverter

The thermal resistance with heatsink is much lower and depends on the heatsink size, and the GaN power ICs are thermally connected through the PCB which works very well with this layout.

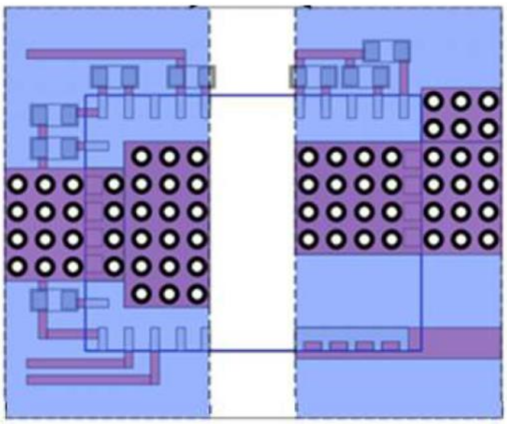


Figure 3: PCB layout around the GaN power IC, to optimize thermal resistance

It should be noted that this inverter power stage has been designed to operate from a DC bus voltage, and local decoupling capacitors have been added. In a fully integrated design with input rectification, EMI filter, power factor correction and DC link capacitors this would be realized differently.

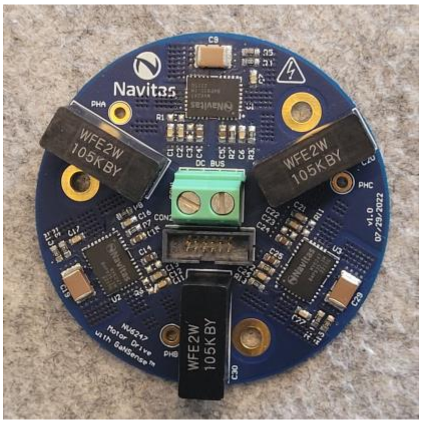


Figure 4: Photo of the circuit board without heatsink (board diameter 56mm)

4. Experimental results

The inverter has been designed and built in Navitas application engineering labs. It has been tested along with a BLDC motor and mechanical load under the following operating conditions: DC input voltage 300 V, ambient temperature 25°C, FOC (field-oriented control) algorithm with a switching frequency of 20 kHz. The thermal resistance from PCB to ambient has been measured with ~12.5 K/W. Figure 5

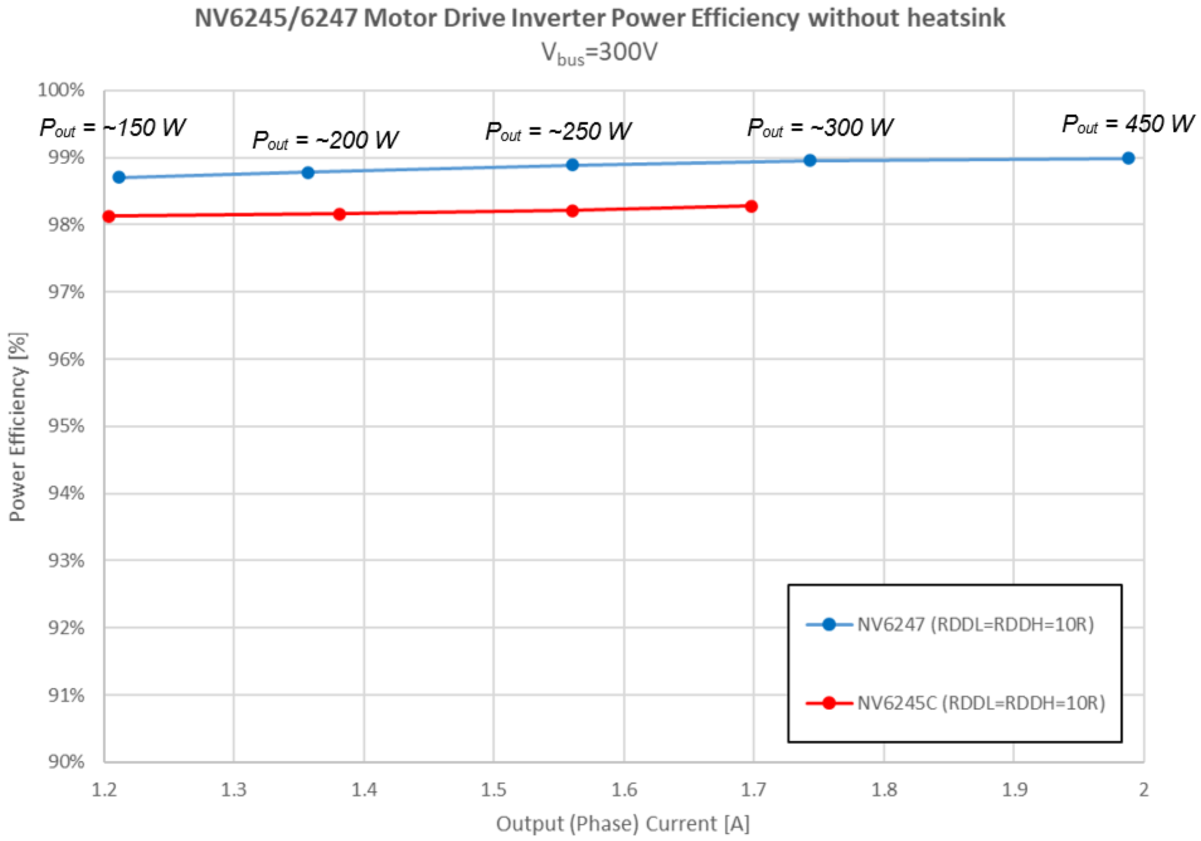
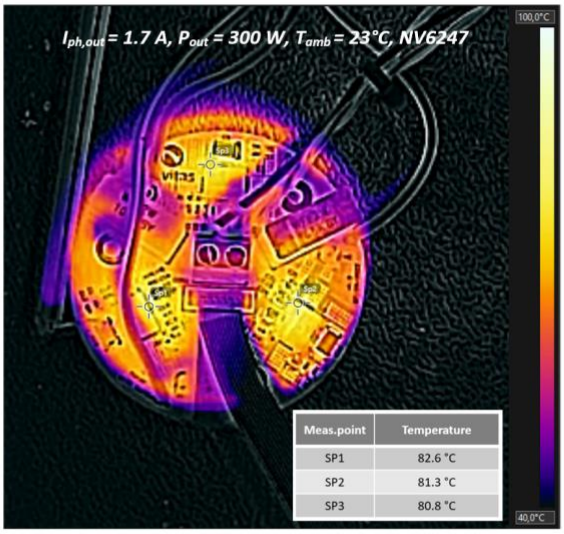


Figure 5: Inverter efficiency over output power (bus voltage 300V, switching frequency 20kHz)

shows the resulting inverter efficiency (electrical output power versus input power, not considering the motor efficiency), which is approaching 99% for output power of 300 W. While the efficiency of the inverter usually is much better than the motor efficiency, it is still important to understand the losses produced in the inverter, in order to design the cooling system accordingly. With a power dissipation of <3W at full load, the heatsink can be reduced a lot, and the thermal design of the system is much easier, eventually avoiding a lot of manual assembly work usually associated with attaching large heatsinks. The two curves shown correspond to different GaN power ICs (NV6245C: 275mΩ, NV6247: 170mΩ per switch, both in PQFN6x8 package).

Figure 6 shows the temperatures across the PCB while operating the inverter at an output load of 300 W. With an ambient temperature of 25°C, the package surface temperature stays below 60°C, not surprising given the very low losses. As the PQFN power switches are thermally well connected to the PCB, the maximum power output is thermally limited by the allowable PCB temperature, usually 105°C. The GaN power switches themselves do tolerate much higher temperatures, and as a result, this design offers both exceptional reliability as well as great robustness for abnormal operating conditions like output short-circuit or rotor stall, that may drive the power switch temperature up very quickly until the controller or the built-in overtemperature protection circuit can react.



Meas.point	Temperature
SP1	82.6 °C
SP2	81.3 °C
SP3	80.8 °C

Figure 6: Thermal measurement of the inverter power stage in operation

5. Conclusions and Future Work

The motor inverter power stage implemented with Navitas' GaNSense™ Half-Bridge power ICs, integrating the GaN power switches, gate drivers, regulators and protection, demonstrates a very high power density and low power losses, operating at >99%% peak efficiency at full load, making the integration of the inverter with the motor much easier. Key reason for this is the much lower power dissipation, making the thermal design of the system much easier. The ability to remove the heatsink completely (depending on the system conditions) yields much smaller system size.

Furthermore, the system and operational cost is much reduced, due to the reduced electricity consumption, which is particularly important for industrial installations such as pumps and fans, that operate continuously.

At the same time, integrating the drivers enables high switching frequencies with little penalty, and this allows to raise the bandwidth of the control loop and improve the dynamic performance of the complete system, including the mechanical load. This is needed e.g. for algorithms reducing vibrations that can be transmitted as unwanted noise. In future designs, different motors with lower inductance and number of turns could be considered, enabling further potential for cost reduction.The integration of the protection circuits and their fast reaction time gives very good robustness against abnormal operating conditions.

Future work will explore the possibility to extend the power range up to a target of several kW, utilizing different packages for the GaN power ICs at much higher currents.

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