

High-Frequency, GaN Diode-Free Motor Drive Inverter with Pure Sine Wave Output

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This article presents the first kW-Class, 3-phase GaN-based inverter. Hard-switched at 100-kHz PWM, its heart is a 6-in-1 power module with 600-V GaN power HEMTs, achieving a new efficiency of 98.5%, a more than 2% improvement.

Introduction

Silicon-based power switching devices have improved dramatically since their inception decades ago. An impressive example: Si super-junction MOSFETs, such as CoolMOS FETs, broke the theoretical Si limit in the tradeoff between blocking voltage and resistance (Ref. 1).

However, the large amount of minority charge in the body diode results in large reverse recovery losses in hard-switched bridge circuits—typical for motor-drive inverters. Thus insulated-gate-bipolar-transistors (IGBTs) are preferred in applications also requiring additional reverse-connected diodes for freewheeling current. With the relatively low-frequency bandwidth, IGBT-based inverters typically operate at 4–20 kHz and directly apply pulse-width-modulation (PWM) power to the motor with the intention of utilizing the motor windings as energy storage inductances. The resultant voltage transients induce high stresses between motor windings and cause current spikes through motor bearings, leading to issues such as insulation breakdown and excessive bearing wear (Refs. 2–3). This paper demonstrates the use of wide-band-gap semiconductor GaN for hard-switched motor drive applications. The functionalities and frequency capabilities of the GaN high-electron mobility transistor (HEMT) eliminate the need for freewheeling diodes and allow a much higher PWM frequency, in turn enabling compact filters and resultant, spike-free, pure sine wave power output.

Devices and Module

The unit cell device used in this study is a GaN hybrid HEMT (Transphorm, Inc.). It incorporates a normally “off” low-voltage Si device at the input and a normally “on” high-voltage GaN HEMT at the output in cascode form (Fig. 1). The combined device is normally “off” with a gate threshold of +2.1 V—typical at 1 mA drain current—and a drain leakage of 10 μ A—typical at $V_{gs}=0$ V and $V_d=600$ V. The “on” resistance is

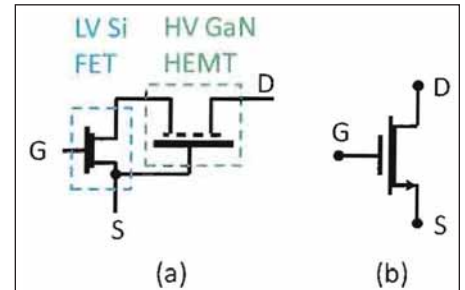


Figure 1 Hybrid HEMT with low-voltage, normally “off” Si FET and high-voltage, normally “on” GaN HEMT (a) to achieve a combined, normally “off” device (b).

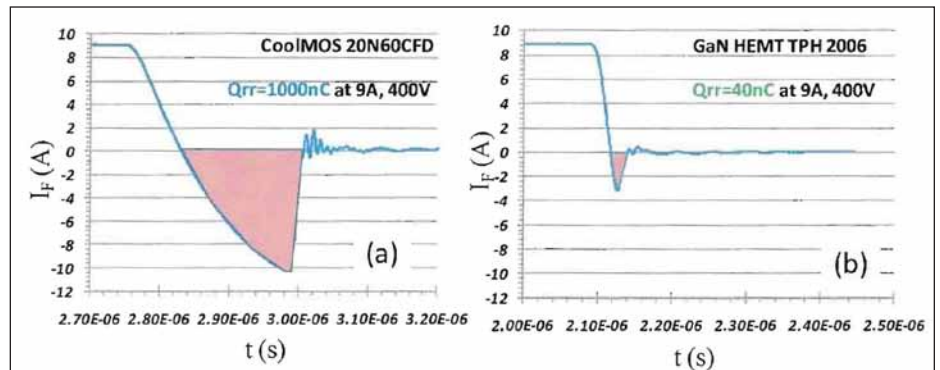


Figure 2 Reverse-recovery charge test result for (a) fast-recovery CoolMOS and Transphorm GaN HEMT, with reduction of Q_{rr} by 25x by GaN. Note current transient is 450 A/ μ s for GaN HEMT and only 100 A/ μ s for CoolMOS, due to excessive ringing at higher dt/dt values.

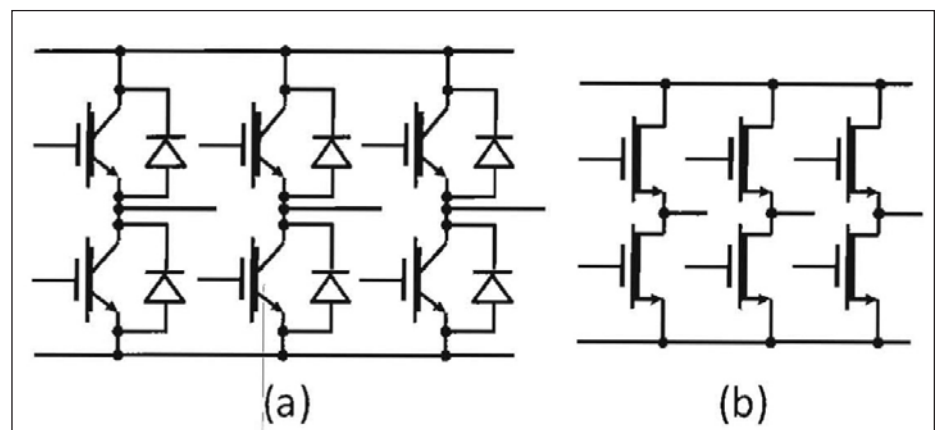


Figure 3 Schematics of 3-phase bridge circuits using (a) IGBTs and freewheeling diodes, and (b) GaN HEMTs without diodes.

a normal $0.15\ \Omega$; pulsed drain current is 70 A. This first-generation GaN device not only exceeds performance of the best-competing Si MOSFETs in terms of “on” resistance, switching speed and parasitic capacitances; it is also capable of operating in reverse-conduction mode, with little reverse-recovery charge (Q_{rr}). As seen (Fig. 2), a gate-source-shorted, reverse-recovery charge of a fast-recovery CoolMOS FET and a GaN hybrid HEMT with similar “on” resistances and current ratings, were tested from a reverse conduction of 9 A current to forward blocking of 400 V. It is clear that the GaN device cuts the Q_{rr} by 25x. Because of these properties the GaN FET is a strong candidate for high-frequency, hard-switched bridge topologies, and achieves this function without a freewheeling diode. Figure 3 compares two 3-phase bridge circuits using Si IGBTs and GaN HEMTs. In addition to expected efficiency and frequency benefits, the GaN implementation slashes the high-voltage device count by half, significantly simplifying the inverter circuit.

A 6-in-1 module was engineered using these GaN device cells with the schematics and package photo shown (Fig. 4). The module design follows high-frequency circuit principles and features kelvin-source leads for stable gate drives to ensure misfire-free, high dV/dt operation. Based on device specifications, the module is capable of 600 V blocking voltage and 14 A continuous operation current for each switch, at a case temperature of 100°C . Each half-bridge was inductively switched to confirm a current handling capability greater than 18 A at a rail voltage $> 400\text{ V}$.

Inverter and Performance

A 3-phase inverter was constructed using the GaN power module based on the schematics (Fig. 5). A Texas Instruments TMS320F28069 DSP was chosen to generate high-resolution PWM signals at 100 kHz. Three complementary PWM peripherals were configured to generate the non-overlapping pulses to each of the three transistor pairs forming the bridge. A lead time of 62.5 ns was directly inserted by the PWM peripheral. Space vector modulation was used to intentionally introduce odd harmonics instead of pure sinusoidal envelopes to maximize usage of the DC rail voltage. A startup sequence with constant V/Hz was incorporated for driving induc-

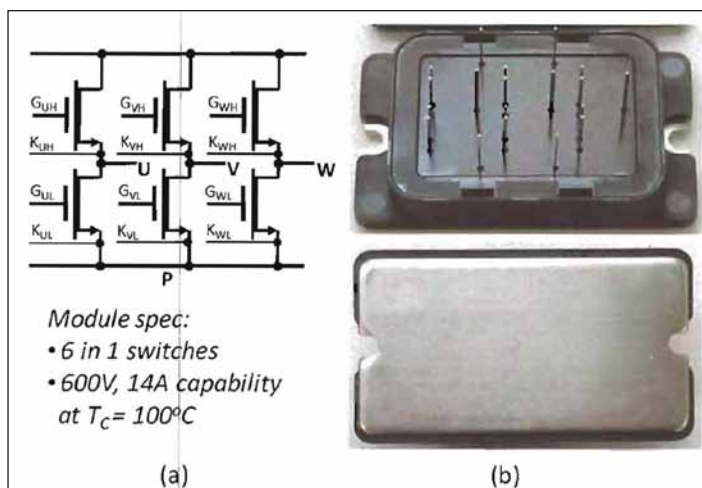


Figure 4 (a) GaN module schematics and (b) packaged module.

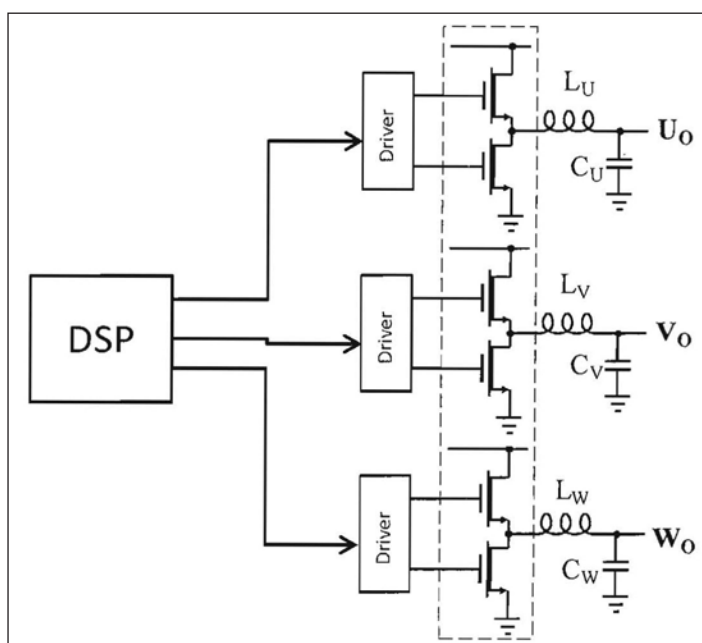


Figure 5 Simplified schematics of 3-phase, high-frequency GaN inverter. Module is indicated with dotted box. L_u and C_u (200uH and 0.3uF) form a compact filter. U_o , V_o and W_o are the three output terminals.

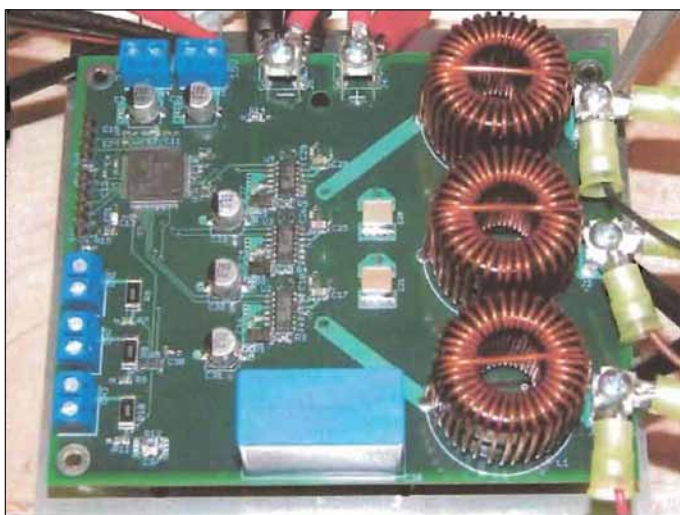


Figure 6 Photo of 2-kW, 3-phase GaN inverter operating at 100 kHz PWM with on-board compact filters for pure-sine-wave output.

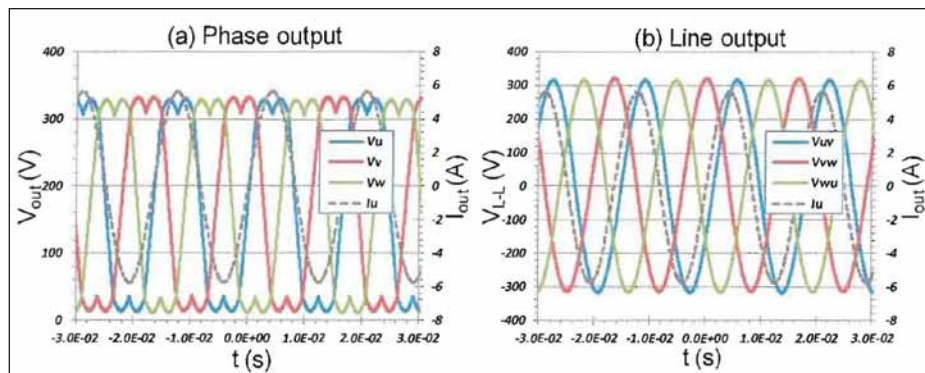


Figure 7 Output voltage waveforms of (a) each phase (or “negative rail”); (b) line-to-line.

tion motors from zero to rated rotation speed. Low-cost sand dust power core inductors and SMD ceramic capacitors were used for the compact L-C filters (L_u/C_u , L_v/C_v and L_w/C_w). A photo of the finished inverter is shown (Fig. 6). The outer dimensions are about 4"×4.5"×1.6" with no heat sink; with some optimization, a heat sink can be fitted to the same volume.

The inverter was tested at a DC rail of 350 V and a PWM frequency of 100 kHz. Figure 7A shows voltage output waveforms of all three phases after the L-C filters, referred to as the “negative rail.” As mentioned, the odd harmonics are apparent, which were intentionally introduced to fully utilize the DC potential. The line-to-line voltages fed to the delta-connected loads are sinusoidal (Fig. 7B). In contrast to conventional motor-drive-outputting, high-voltage PWM power, the GaN inverter generates pure sine wave power without a bulky filter. This allows motors to operate with ideal excitations and,

therefore, improved electromechanical efficiency and reduced bearing wear. The inverter performance was tested with resistive loads (Fig. 8). Even hard-switched at a high PWM frequency of 100 kHz and with low-cost sand dust inductors, the GaN inverter is capable of efficiencies as high as 98.5%. This performance—obtained at such a high switching frequency for a true DC-to-sine wave inverter—is not possible with conventional semiconductors.

Electromechanical Test

The GaN inverter was then evaluated in a motor drive test lab at Yaskawa America, Inc. The test motor was model MTRY541 (Marathon Electric), rated at 2.2 kW. A 2.2-kW Si-based motor-drive inverter (A 1,000 series, model CIMR-AU2A0012FA) operating at 15 kHz PWM frequency with no output filter (reactor), was used for a direct comparison to the GaN inverter; it employed an IGBT power module CP30TD-12 A rated at 600 V, 30A. Both inverters were

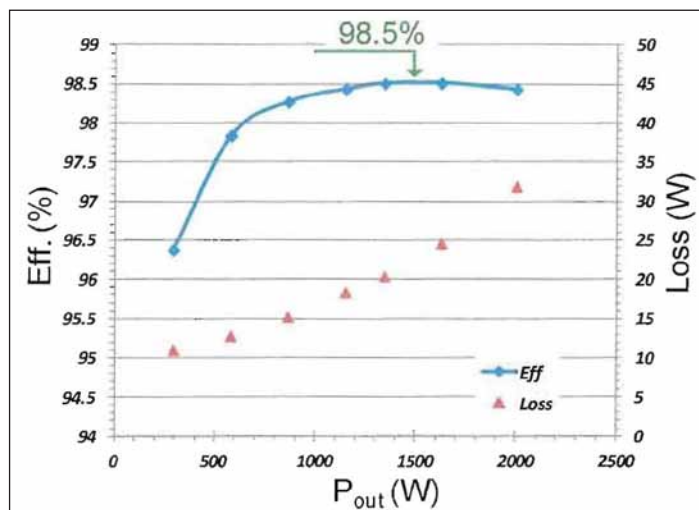


Figure 8 Efficiency and loss as function of output power to resistive loads (digital control and filter loss included).

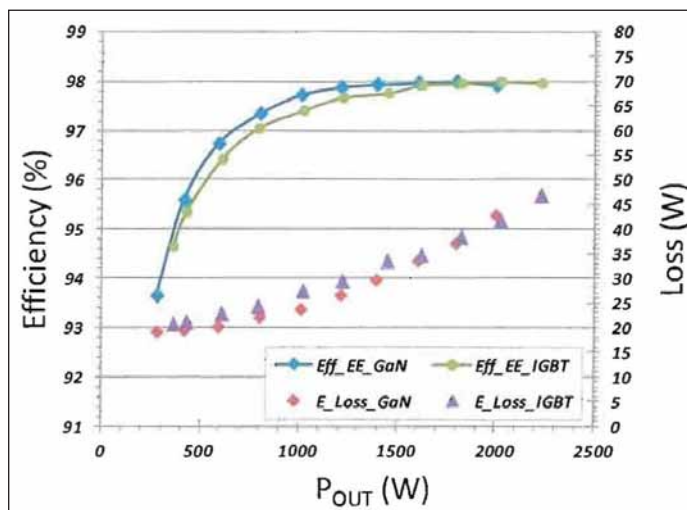


Figure 9 Electrical efficiency as function of output power for GaN inverter at 100 kHz and IGBT inverter at 15 kHz PWM. Efficiency for GaN inverter includes output filter loss; IGBT inverter has no output filter.

configured to be fed with 320 Vdc and produced a 225 Vrms 3-phase AC output at 60 Hz. Electrical power was measured by a WT1800 Yokogawa power analyzer, the mechanical power by a torque transducer power meter. The system was loaded in steps of 0.2 kW up to the rated power. Figure 9 shows the electrical performance as a function of load. Although operating at 7x high PWM frequency and including output filter losses, the GaN inverter matched the IGBT inverter efficiency at 2 kW and outperformed it at lower load. The reduced overall efficiency compared to the case of resistive load (Fig. 8) is due to the less-than-ideal power factor of the motor.

The main advantage of the GaN converter is its pure sine wave output, as shown in the motor current waveform shown (Fig. 10). The direct PWM power from the IGBT inverter led to substantial, high-frequency content in motor current, causing higher dissipation in the motor windings and iron cores. In contrast, the on-board compact filters (enabled by the high PWM frequency) in the GaN inverter produced smooth, pure sine wave drive current. A compel-

ling benefit of this sine wave output is revealed in the motor efficiency plots as a function of load for both IGBT and GaN inverters (Fig. 11A). The improvement in motor efficiency is 8% at low load; -4% at mid-load; >2% at full load. This directly translates to markedly improved system efficiencies (Fig. 11B) and substantial energy savings. The high-quality drive power will also prolong motor life as a result of less bearing wear, an absence of current spikes, and a cooler operation temperature due to reduced motor-induced heating. **PTE**

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Y-F. Wu, D. Kebort, J. Guerrero S. Yea and J. Honea serve in various, executive, technical and engineering-related capacities at Transphorm Inc.; K. Shirabe and J. Kang are in similar roles at Yaskawa America.

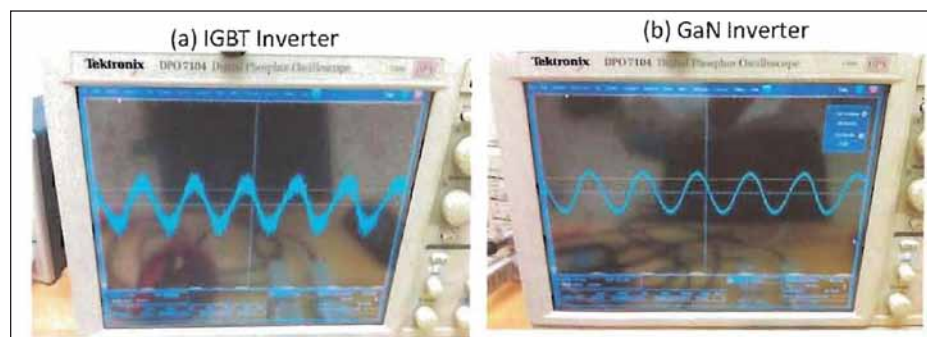


Figure 10 Motor current waveform when driven with (a) IGBT inverter; and (b) GaN inverter.

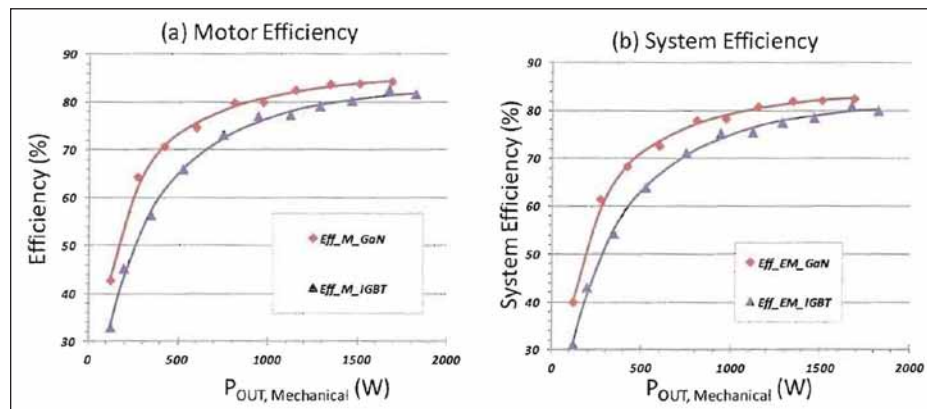


Figure 11 Electromechanical performance using IGBT inverter and GaN inverters; (a) motor efficiency vs. load; (b) system efficiency vs. load. Pure sine-wave output from GaN inverter substantially improved motor efficiency.