# How Three-Phase Integrated GaN Technology Maximizes Motor-Drive Performance

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## At a glance



Given the energy consumption of consumer appliances; building heating, ventilation and air-conditioning (HVAC) systems; and industrial drives, efforts are underway to establish system efficiency ratings through programs such as the seasonal energy efficiency ratio (SEER), minimum energy performance standards (MEPS), Energy Star and Top Runner.

Variable frequency drives (VFDs) offer the best system efficiency in heating and cooling systems, especially if they have an accurate and very wide range of speed control. VFDs use an inverter to control motor speeds, along with high-frequency pulse-width modulation (PWM) switching to obtain truly variable speed control.

Although these inverters are currently realized using insulated-gate bipolar transistors (IGBTs) and metal-oxide semiconductor field-effect transistors (MOSFETs) as the power switches, the switching frequency and power delivery are limited given high overall losses. With advancements in wide band-gap technology, however, gallium nitride (GaN)-based power switches in motor drives can help increase power density, power delivery and efficiency.

## How GaN increases inverter efficiency

The conduction losses attributable to GaN FETs are proportional to the on-state resistance of the GaN, similar to a MOSFET. For an IGBT, however, conduction losses depend on the knee voltage and dynamic on-state resistance, which are typically higher than GaN FETs or MOSFETs.

As for switching losses, GaN FETs offer much lower losses compared to MOSFETs and IGBTs because of these reasons:

- GaN offers zero reverse recovery. With zero reverse recovery, it is possible to switch a GaN FET at a very high current slew rate (di/dt) and voltage slew rate (dv/dt). In MOSFETs, the body diode suffers from high zero reverse recovery, limiting the switching di/dt and dv/dt and causing additional losses and phase-node voltage ringing. With an IGBT, even the addition of an optimized antiparallel diode can still cause challenges related to reverse recovery.
- When switching off, IGBTs suffer from minority carrier recombination current, commonly known as tail current, which increases turnoff losses. GaN doesn't have any tail current.
- GaN offers lower capacitance compared to IGBTs and MOSFETs, resulting in lower capacitive switching losses.
- Controlled and faster di/dt and controlled dv/dt help optimize voltage-current overlap losses during switching.

Figure 1 shows a theoretical inverter efficiency comparison between GaN-, IGBT- and MOSFET-based solutions with a 20kHz switching frequency, the phase-node voltage slew rate for the GaN-based inverter limited to 5V/ns, and an ambient temperature of 55°C. You can see that the GaN solution helps reduce power losses by at least half.

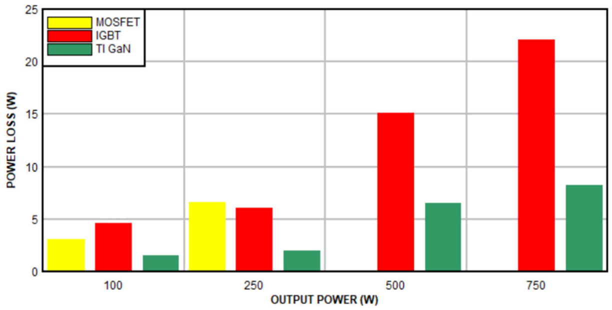


***Figure 1.*** *Efficiency comparison of GaN, MOSFET and IGBT solutions.*

Figure 2 compares the efficiency of the Texas Instruments (TI) DRV7308 three-phase GaN intelligent power module (IPM) to a 5A peak-current-rated IGBT IPM with a $300V_{DC}$ supply at a 20kHz switching frequency with a fan motor that has 2m of cable at a 25°C ambient temperature, delivering 0.85A of root-mean-square winding current and 250W of inverter output power. The slew rate of the GaN IPM is configured for 5V/ns.

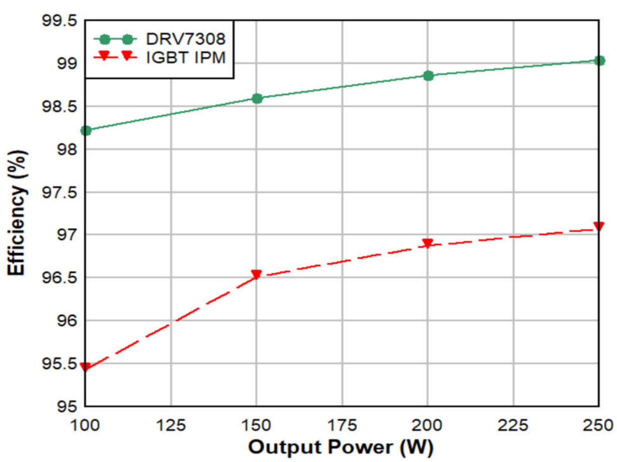


***Figure 2.*** *Efficiency comparison of the DRV7308 and an IGBT IPM in a 250W application.*

## Motor performance improvement with GaN power switches

Permanent-magnet synchronous motors designed for high speed or motors with a lower inductance often need a high PWM frequency to reduce current ripple and achieve optimum motor performance. End-equipment examples include hair dryers, air blowers and pumps.

Higher current ripple in the motor winding can cause unwanted torque ripple, increased copper and core losses, and inaccuracies in the average motor current sensed during switching.

MOSFET- or IGBT-based IPMs are typically rated for usage at 20kHz; however, they are normally used at a lower switching frequency (6kHz to 16kHz) because of high switching losses. With GaN offering much lower switching losses even at a lower dv/dt, it is possible to switch at a much higher frequency to improve motor efficiency and performance.

**Figure 3** shows the functional block diagram of the DRV7308, which integrates predrivers for all GaN FETs with slew-rate control of phase-node voltages. The DRV7308 helps achieve more than 99% inverter efficiency for a three phase-modulated, field oriented control-driven 250W motor-drive application in a quad flat no-lead (QFN) 12mm-by-12mm package, eliminating the need for a heat sink.

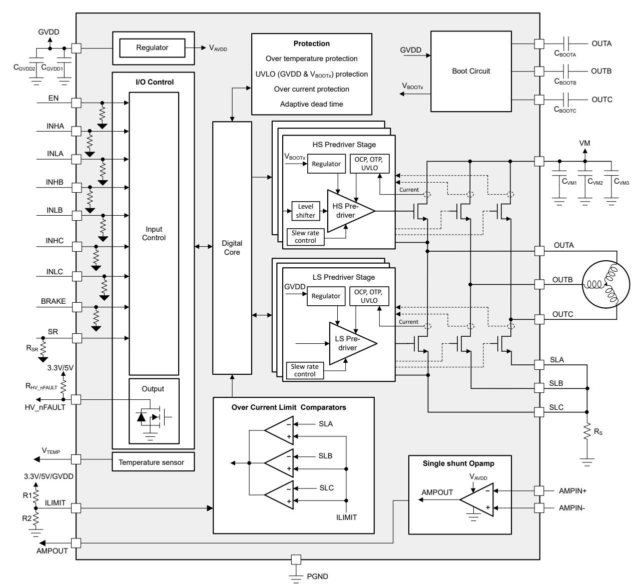


***Figure 3.*** *DRV7308 functional block diagram.*

## Design considerations when using GaN in motor drives

Designers often have to consider how dv/dt affects motor insulation, bearing lifetime, electromagnetic interference (EMI) and reliability.

The DRV7308 incorporates an integrated predriver slew-rate control circuit that controls dv/dt at the phase node. It is possible to control the slew-rate settings down to 5V/ns and to configure the slew rate as a trade-off between the motor winding insulation and switching-loss optimization. The lower slew-rate settings of the DRV7308 cover the ranges offered by existing IGBTs, while higher slew rates help hold switching losses to much lower values.

**Figure 4** and **Figure 5** show the phase-node switching voltage of the DRV7308 at a 1A load, at 300V, with a 10V/ns slew-rate setting and a 2m motor cable. The zero reverse recovery of the GaN FET with lower parasitics and predriver slew-rate control help achieve a clean voltage switching waveform.

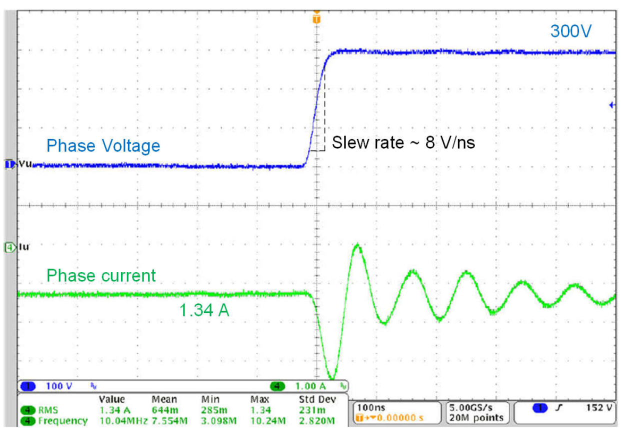


***Figure 4.*** *Phase-node voltage rising slew rate with a 2m cable and fan motor.*

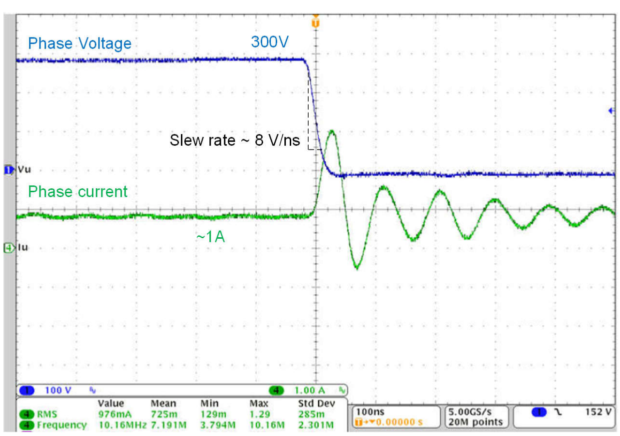


***Figure 5.*** *Phase-node voltage falling slew rate with a 2m cable and fan motor.*

## Impact on system efficiency

Air-conditioning and refrigeration systems often need a very wide variation of speed control to achieve the highest compressor and heating system efficiency. Traditional IPMs with more than 1µs of dead time and more than 500ns of propagation delay limit the maximum and minimum operating PWM duty cycle and reduce the operating speed range. A higher dead time also reduces the available voltage to the motor and increases the amount of motor current for the same power delivery.

The DRV7308 offers an adaptive dead time, with a maximum dead time less than 200ns and a propagation delay lower than 200ns, helping designers enhance the operating PWM duty-cycle range and thus the speed range, while also increasing the available voltage to the motor. For example, the ability to obtain an ultra-low to high speed in air-conditioning systems helps designers set the highest speeds at startup so that the systems cool and heat faster. Then, after achieving the set temperature, designers can use a finer low speed and capacity control, depending on the air-conditioning load changes. This finer, optimum load-point control helps increase system efficiency.

Ultra-low dead time and propagation delay – with low propagation delay mismatch – enable accurate average current sensing and thus increase the accuracy of control, especially for field-oriented control drives. Figure 6 shows the impact of propagation delay on average current-sensing accuracy. During PWM, sampling the current at the middle of the PWM on-time period will obtain the average motor current in every PWM cycle. **Figure 6** also illustrates how the propagation delay deviates the current sensing from the mid value. The error in current sensing (∆I) depends on the propagation delay, applied voltage, PWM switching frequency and motor inductance. For low-inductance motors, the error will be high. The current-sensing error also affects motor position sensing (estimator) accuracy in a sensorless control driver. A motor position estimation error will result in reduced motor efficiency. The DRV7308, with ultra-low propagation delay and propagation delay mismatch, helps achieve accurate average current sensing and improves motor efficiency.

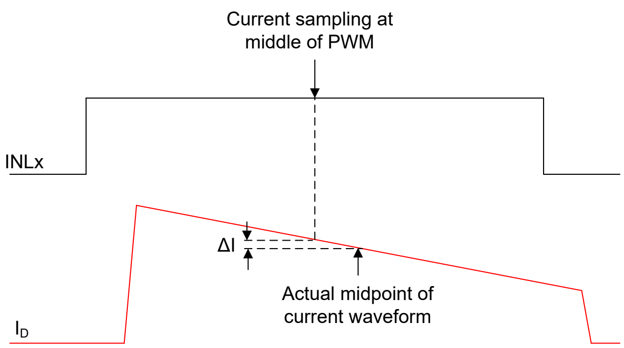


***Figure 6.*** *The impact of propagation delay on current-sensing accuracy.*

## Impact on audible noise

In motor-drive systems, one of the main sources of audible noise is torque ripple caused by current distortion. For a motor, current distortion depends on multiple factors, including the PWM frequency, dead time and current-sensing accuracy.

The DRV7308 offers significantly reduced switching losses, and enables higher PWM frequencies compared to IGBT- or MOSFET-based solutions. With a higher switching frequency, the reduced winding current ripple enables low torque ripple, beyond the audible range of frequency.

In IGBT- and MOSFET-based systems, the dead time is 1µs to 2µs or more, resulting in considerable motor current distortion. The dead-time distortion occurs at every 60-degree electrical angle and results in sixth harmonics on the current waveform, which typically falls in the audible frequency range. The DRV7308's adaptive dead-time logic enables less than 200ns of dead time, resulting in minimal current distortion and thus lower audible noise.

Figure 7 compares the motor winding current total harmonic distortion (THD) when testing the DRV7308 with a 0.2µs dead time and an IGBT IPM with 2.5µs of dead time. The DRV7308 distortion is very low compared to the IGBT IPM. This distortion will go exponentially high for the IGBT IPM at a lower power delivery because of the low duty cycle or low inverter modulation index, where the impact of dead time is greater.

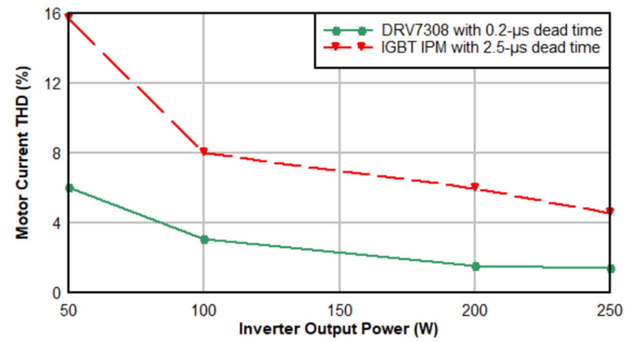


***Figure 7.*** *Motor current THD comparison with dead time.*

## Conducted and radiated emission considerations

Conducted and radiated emissions depend on the switching frequency, dv/dt, di/dt, switching voltage oscillations and reflections, and the switching current loop area.

The DRV7308 incorporates these multiple design techniques and printed circuit board (PCB) layout options to address EMI and electromagnetic compatibility concerns:

- **PWM switching frequency**. The higher the switching frequency, the greater the impact on the EMI frequency spectrum. A higher switching frequency helps reduce current ripple and capacitor requirements to meet the conducted emissions. The DRV7308 offers a wide range of switching frequencies, from very low values up to 60kHz. Designers can choose the optimum frequency based on the system performance and EMI requirements.
- **The dv/dt**. The DRV7308 predriver can control the phase-node switching slew rate to meet EMI requirements.
- **The di/dt**. With zero reverse recovery and low parasitics, GaN can offer better switching

performance without creating voltage overshoot and oscillations at the phase node during switching. Figure 4 and Figure 5show the clean switching of the DRV7308, which translates to lower EMI.

- **A small switching current loop area**. Local decoupling capacitors will provide pulse currents during switching. The DRV7308 is designed such that the switching current loop area to the DC voltage decoupling capacitor ($C_{VM}$) is very minimal, as shown in **Figure 8**.

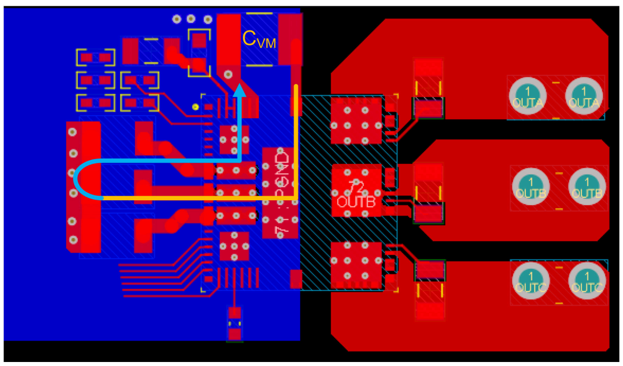


***Figure 8.*** *Typical layout reference for the DRV7308, illustrating the small current loop area.*

## Impact on solution size

Apart from the small package size and heat-sink removal, the DRV7308 offers high-level integration including an operational amplifier for motor current sensing, three comparators for current limiting, a temperature sensor and a suite of protective features These integrations enable an inverter board size reduction of as much as 55% compared to IGBT- or MOSFET-based solutions.

The size reduction also enables the integration of the inverter close to the motor, which is beneficial in use cases such as fans, blowers and pumps, and eliminates the need for cabling from the inverter board to the motor. The elimination of this cable also removes switching losses attributed to cable capacitance, and alleviates conducted and radiated EMI caused by long cables.

## Protected and reliable system designs

GaN needs faster and reliable overcurrent protection to eliminate saturation. Integrated protection eliminates the effect of parasitics and provides a faster response, on the order of a few hundreds of nanoseconds. The inverter and motor need overcurrent protection to eliminate thermal runaway during overload conditions.

$230V_{AC}$ line-powered motor drives can provide a rectified DC bus voltage of up to $450V_{DC}$, either from the voltage tolerance of the AC line or by using active power factor correction circuits. The inverters need to be designed for a 450V operating voltage. Some motor drives need to handle higher voltages for short durations in case the motor-generated back-electromotive force exceeds the supply voltage, or if there is inductive kickback. The inverters also may need to handle a higher off-state blocking voltage to prevent damage in the event of overvoltage scenarios such as input line-voltage surges or electric fast transient events.

The DRV7308 is designed with integrated drain-to-source voltage protection to protect the GaN FET during overcurrent events. It also has integrated overcurrent comparators for cycle-by-cycle current limiting, designed for a 450V operating voltage with a 650V off-state blocking voltage rating. Other protections monitor fault scenarios such as undervoltage, overcurrent and pin-to-pin short circuits.

## Conclusion

Advancements in GaN-based IPMs such as the DRV7308 will continue to help increase power density, power delivery and efficiency in motor drives for appliances and HVAC systems, while saving system costs and increasing reliability.

## Additional resources

- DRV7308 Three Phase 650V, 5A, GaN Intelligent Power Module Data Sheet
- GaN IPM portfolio
- Learn more about TI GaN technology
- Influence of PWM Switching Frequency and Modulation Index on the Iron Losses and Performance of Slot-Less Permanent Magnet Motors
- Wide Bandgap Devices in AC Electric Drives: Opportunities and Challenges

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