GaN enables efficient, cost-effective 800V EV traction inverters

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The number of electric vehicles (EVs) on the road has increased rapidly over the past few years and continues to accelerate. Industry analysts expect 56 million new EVs will be sold in 2040. The electricity consumption that accompanies this growth will rise to 1,800TWh representing 5% of global power, according to Bloomberg NEF's Electric Vehicle Outlook, and that assumes an associated boost in electric vehicle efficiency, convenient charging infrastructure, and faster charging solutions. Smaller, lighter-weight electronics are key in creating changes for the EV industry and ecosystem.

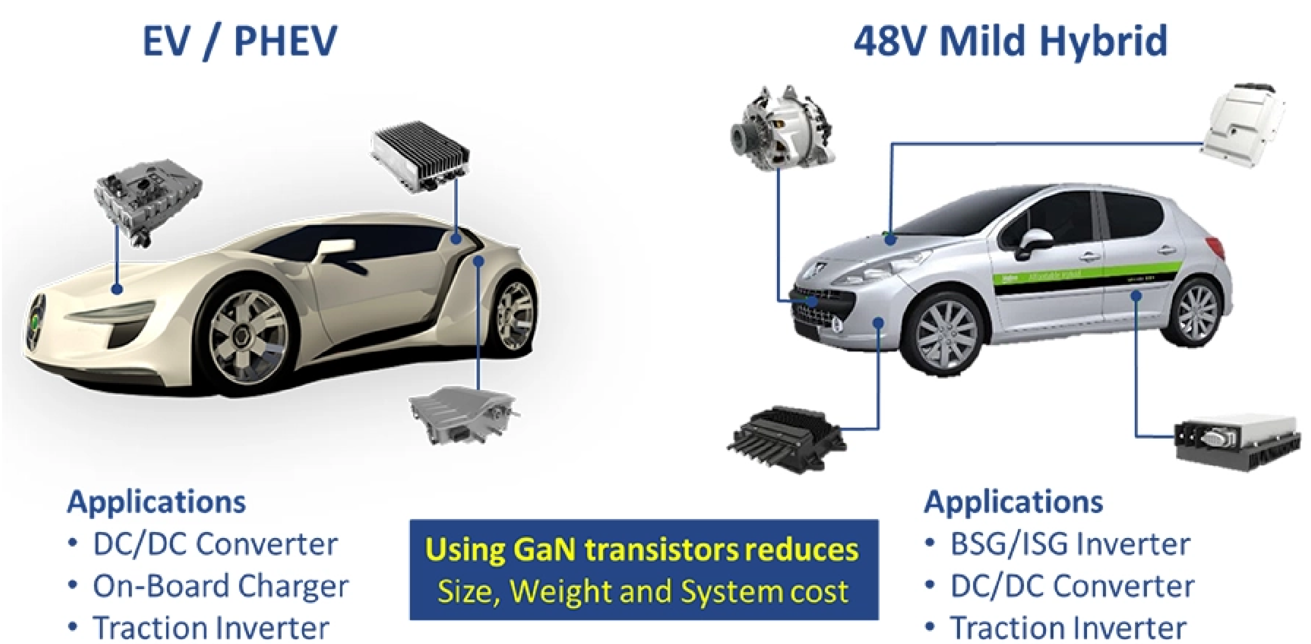

Figure 1 Using GaN devices in automotive applications reduces size, weight, and system cost.

There's no better example of the need for greater efficiency than the main inverter in an EV. Within an electric drivetrain, the traction inverter converts DC current from the electric vehicle's battery to AC current to be used by the motor to drive the vehicle's propulsion system. Improving the traction inverter's efficiency will enable:

1. longer range, fewer charging cycles, and extended battery life with the same battery cost, or
2. the use of smaller, lower-cost batteries to achieve the same range, both of which will help improve the viability of alternative vehicle technologies.

For EVs, the semiconductors used in traction inverters have a significant impact on efficiency, power density, and cooling requirements. The three-phase AC motors used in today's EVs run at voltages up to 1,000V and switching frequencies up to 20 kHz. This is very close to the operational limits of the silicon-based metal-oxide semiconductor field-effect transistors (MOSFETs) and insulated-gate bipolar transistors (IGBTs) currently used in traction inverters. Without a significant technical breakthrough, silicon-based MOSFETs and IGBTs will have difficulty meeting the higher operational requirements of next-generation EVs.

These limits arise from properties inherent to the physics of silicon semiconductors, and the structure of the devices themselves. Large IGBTs and MOSFETs have difficulty switching at high frequencies and suffer from switching losses caused by their slow transition between ON and OFF states. Although inverters become more efficient at higher frequencies, the devices' inherent switching losses rapidly outweigh those gains as the operating frequency increases. In addition, the devices' long switching times place a limit on the inverter's operating frequency, beyond which operation is not possible.

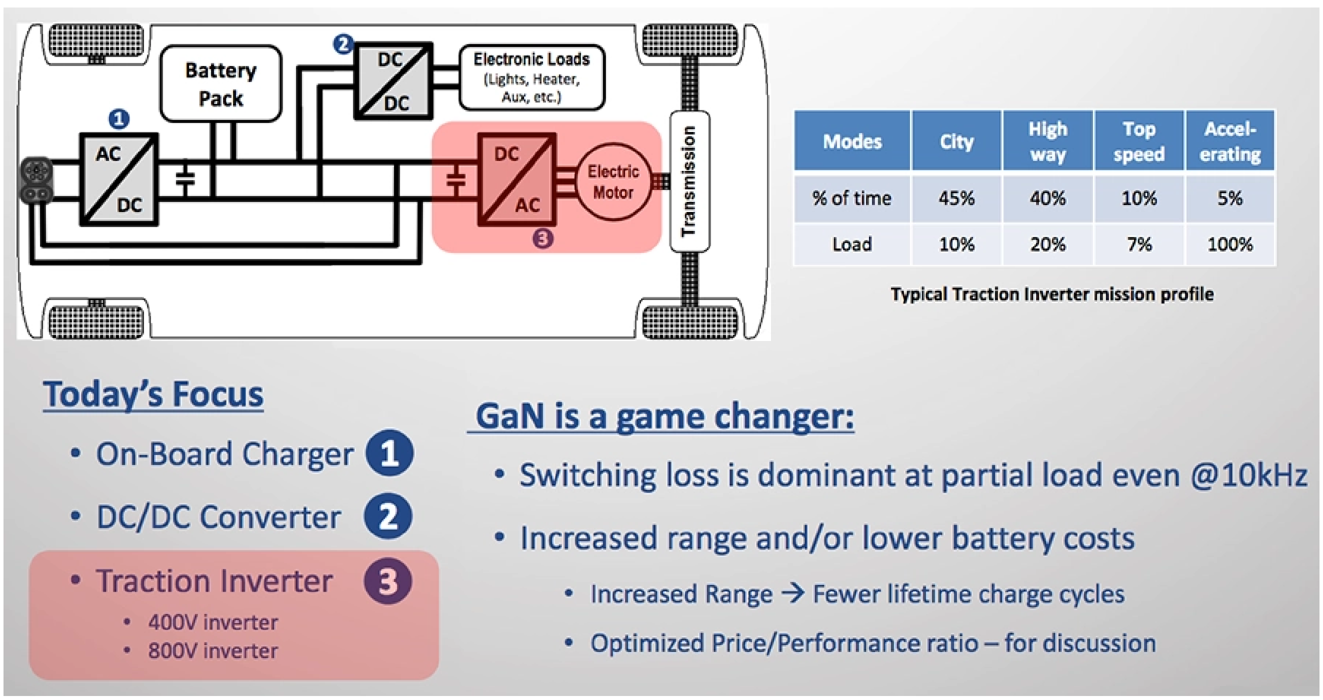

Figure 2 Use of GaN in EV traction inverters can increase range or lower battery costs.

Wide bandgap materials

These limits can be transcended with the use of alternative materials, known as wide bandgap (WBG) semiconductors, whose characteristics are better suited for high-power, high-frequency applications. There are several promising WBG semiconductor technologies, with gallium nitride (GaN) and silicon carbide (SiC) being the most mature and commercially-available today. WBG materials have large energy separation between their conduction and valance bands. For example, the difference between silicon's 1.1eV bandgap value and GaN's 3.4eV bandgap allows them to operate at much higher voltages than silicon-based devices. While this is important in itself, GaN has several other properties that make it a good choice for inverters and other high-power applications.

One of GaN's other important properties is its high critical electric field strength (~5×10^6 V cm), which gives a GaN transistor, a much higher breakdown voltage than a silicon transistor of similar dimensions. This property allows GaN semiconductor devices for a given operating voltage range to be fabricated using much smaller transistor structures. The smaller structures result in devices with much less distributed capacitance that can operate at much higher switching frequencies.

Equally remarkable is GaN's electron mobility, more than 1,000 times greater than Si. This property gives GaN devices half the $R_{DS(on)}$ (on-resistance) per unit area of an equivalent Si-based MOSFET, which results in 50% lower conduction losses. Because GaN power transistors can produce less waste heat, they require much smaller heat sinks and simpler thermal management systems that enable designers to create simpler, more compact products.

GaN and SiC technologies are largely complementary and will continue to coexist. They currently cover different voltage ranges, with GaN devices best used in applications ranging from tens to hundreds of volts, and SiC better suited for supply voltages from approximately one to many kilovolts. For mid- and low-voltage applications (below 1200V), GaN's switching losses are at least three times lower than SiC at 650V. SiC has some product availability at 650V, but is generally designed for 1200V and higher.

The value of GaN from a system perspective comes from size, weight, and cost reductions, the latter including BOM cost (the cost of other system components such as capacitors, heat sinks, and inductors), usage cost, and cooling cost. For example, changing from Si to GaN in a power supply can slash the size of magnetic components such as transformers. All of this can be accomplished while achieving better efficiency, or better power density, and possibly both.

GaN device manufacturers' rapid progress in material and process technologies has resulted in significant improvements in both performance and cost of products for high-voltage (800V+) high-power applications, such as electrified vehicles (EVs, PHEVs, and mild hybrids).

Benefits

Among its other advantages, GaN has a lower gate and output charge than an equivalent Si device. This enables GaN-based designs to achieve much faster turn-on times and slew rates, while reducing losses. As a result, a GaN-based inverter can not only reduce the conduction loss, but also reduces the switching losses in high-power applications. In EVs, these added efficiencies translate directly into longer range or equivalent range with a smaller battery.

For EVs and many other applications, the limitations of electric motor design usually limit the switching frequency of the traction inverter to 10 kHz, because high switching frequencies produce higher switching losses, thus reducing the efficiency of the inverter.

But why do we care about the switching loss, when the inverter switching frequency is typically only 10 kHz? The answer is the EV's nominal mission profile. During 95% of the driving time, the EV's traction inverter is operating under 30% of its full rated load. At low loads, the switching loss of the inverter will be much more dominant than the conduction loss. The typical mission profile of the traction inverter is presented in **Table 1**.

Table 1 Mission profile of a typical EV traction inverter

Modes	City	Highway	Top speed	Accelerating	Regeneration
Percentage of time	45%	40%	10%	5%	Braking
Load	10%	20%	7%	100%	30%

Let's look in more detail at an example that compares a typical EV's system efficiency across its range of operating modes. For this example, the vehicle in question has a 150 kW three-phase inverter (50 kW per phase) employing pulse width modulation (PWM) control, a battery with an output voltage of 500-800V, and a motor with a nominal operating voltage of 400VAC (phase to phase). Our study will examine three use cases:

1. Replacing the inverter's high-power Si devices with equivalent GaN components
2. Adopting an all-SiC solution with SiC MOSFETs and SiC diodes to reduce losses
3. Adopting a T-type hybrid design, consisting of an IGBT and a GaN solution

Since the traction inverter is operating at <30% of its rated current for 90% of the time, this third case is aimed at improving drivetrain efficiency at low loads (all operating modes other than "top" speed).

Again, the inverter specifications for all of our cases are: V_{BUS}=800V, V_{AC}=400V_{RMS}, rated phase power=50 kW, I_{PEAK} =~180A, I_{RMS}=~125A.

Case 1. Replace Si with GaN devices

We know that due to GaN's low FOM and zero reverse-recovery charges (Q_{rr}), the switching frequency, magnetic design, and switching loss will be significantly reduced. We also know that Si MOSFETs have a typical reverse-recovery charge in the 50- to 60-nC range, depending on their size and characteristics. When the MOSFET turns off, the Q_{rr} in the body diode produces losses that add to the total system's switching losses. These losses rise proportionally with switching frequency, and make MOSFETs impractical for use at higher frequencies in many applications.

Case 2. Replace Si with SiC devices

SiC MOSFETs have gained attention from EV system developers due to their operating properties in comparison to Si-based MOSFETs and IGBTs in a two-level, three-phase inverter topology. SiC devices can raise the switching frequency in comparison to Si devices, which leads to a reduction in system cooling and filtering requirements. At higher frequencies we know that we can reduce the size and weight of elements like inductors, capacitors, and transformers. Unfortunately, SiC MOSFETs are relatively new, and still experiencing growing pains as the technology matures. As a result, high-current SiC MOSFETs are known to have problems such as low single-chip current-carrying capability and deterioration at higher temperature. In addition, SiC MOSFETs and IGBTs require special gate drive and circuit protection, and tend to be significantly more expensive than other solutions.

Case 3. Replace Si with GaN/IGBT hybrid

This GaN/IGBT hybrid solution combines the advantages of different power semiconductor technologies, i.e. the low cost and low conduction loss of IGBT and the good switching performance of GaN (**Figure 3**).

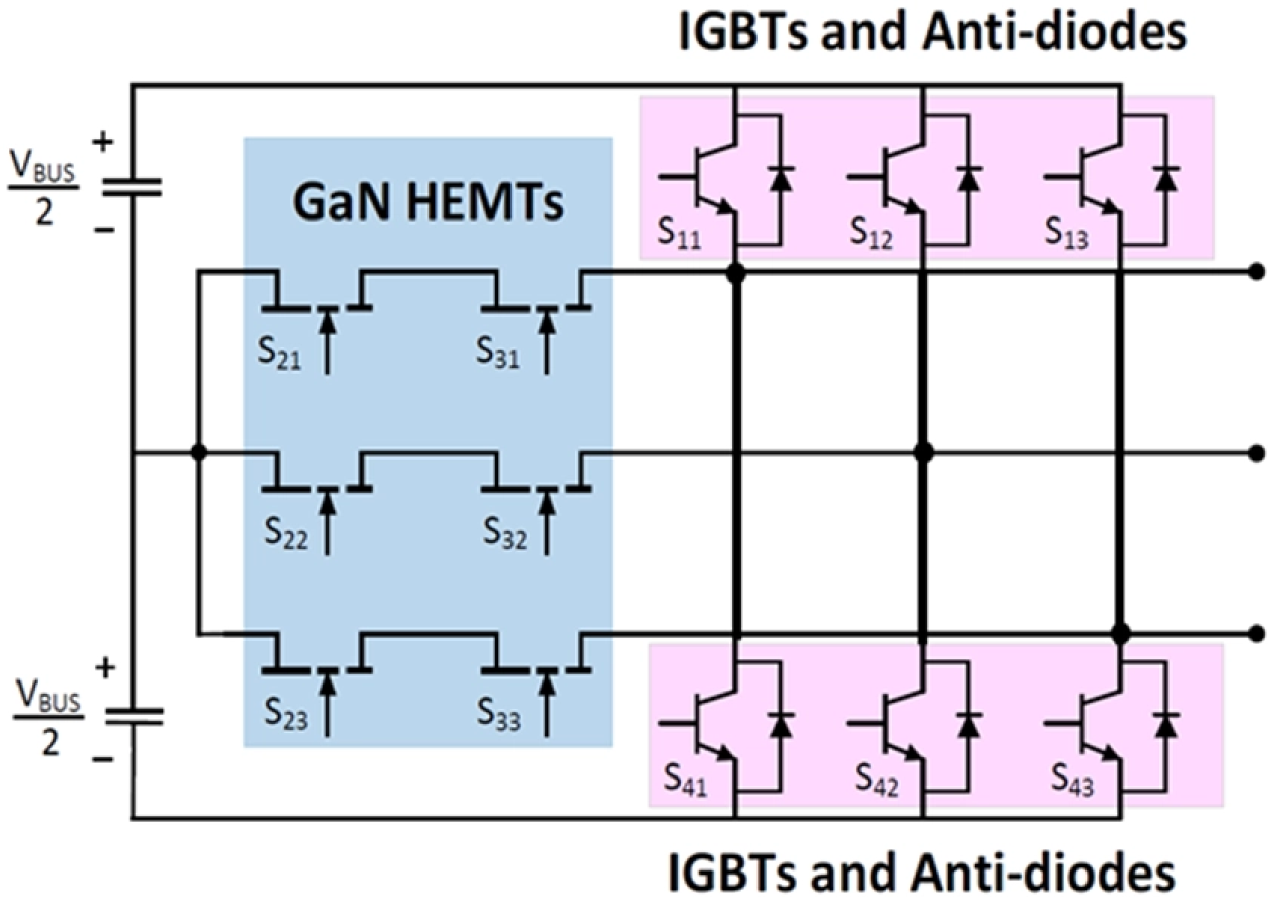

Figure 3 A GaN/IGBT T-Type inverter combines the advantages of different power semiconductor technologies.

Also changed is the operating rule that now combines two-level and three-level control under different load conditions. At a partial load (80 A peak), the inverter is operated in the three-level mode, in which the voltage across IGBT is only 400V, half of the bus voltage, thereby reducing losses in the IGBT. And at full load, the inverter is switched to the two-level mode, where the neutral clamping leg (S2 and S3) is disabled, allowing the voltage across the IGBTs to rise to the full buss voltage, i.e. 800V.

Having set out the operating rules of this solution, let's review inverter topology choices. Inverter topologies can be classified in terms of the number of output AC line voltage levels they produce (e.g. two-level, three-level). In a two-level inverter output voltage waveform is produced by using PWM with two voltage levels. This can cause the inverter's output voltage and current waveforms to be distorted, creating high levels of total harmonic distortion (THD). The standard two-level, three-phase inverter architecture, which is commonly used for permanent magnet (PM) traction motor applications, also requires a bulky DC link capacitor to absorb the large ripple current created by the PWM's switching frequency.

With a conventional two-level phase leg topology, all of the switching transitions happen at higher V_{BUS} levels and the Si devices' reverse recovery losses are high. As a rule of thumb, we can say that the faster the switching frequency, the greater the proportion of power that is dissipated in the reverse direction; in high-power circuits this becomes a limiting factor.

The three-level T-type inverter is well understood in applications such as photovoltaic inverters and industrial motor drives. The difference here is to employ a GaN device on the neutral clamping leg. This neutral-point clamped (NPC) topology has been popular for high-power applications because it can achieve better harmonic reduction than traditional two-level voltage source inverters, and associated control strategies can be employed to minimize semiconductor losses. By implementing the T-type in three phases, THD is reduced in the output voltage, thereby improving the overall efficiency of the system.

Thanks to the hybrid inverter's zero-reverse recovery of its GaN HEMTs and halved voltage stress across the IGBT, its switching-on loss is reduced by 92%, and its switching-off loss is reduced by 83% (in comparison with conventional two-level configurations).

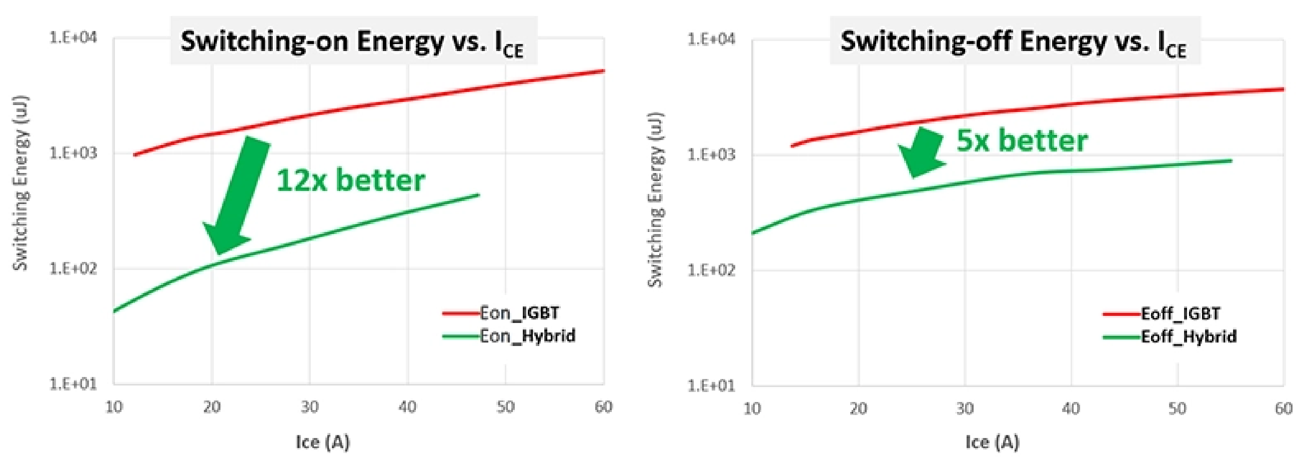

Figure 4 These graphs compare switching energy at Eon (left) and Eoff (right). Source: GaN Systems

Comparing efficiency

We can now take a system weighted average efficiency analysis of a 150 kW, 800V traction inverter for each of the three cases presented. For Case 3, a GaN 3L (a three-level active neutral-point-clamped architecture), the inverter operates efficiently in a majority of the operating range (less than 30% load), and uses 2L IGBTs to meet the demands of the peak conditions (**Table 2**). The inverter's back-to-back GaN switches contribute less conduction load than IGBTs, reducing battery consumption, and extending range for 90% of the mission profile.

Table 2 Weighted average of energy consumption (power loss) of each solution across the mission profile cycle

Device Type	Weighted average loss of Leg (Watts)	Improvement over IGBT
IGBT	125	-
SiC	40	67%
Hybrid (GaN/IGBT)	51	59%

(Source: GaN Systems)

The weighted average efficiency of the hybrid solution is shown to be similar to the SiC solution, and close to an 80% improvement versus the IGBT solution. And since GaN HEMTs rated for 30% of the inverter's maximum current output are employed, the BOM cost is significantly lower than the SiC solution, which requires 100% current rating SiC MOSFETs and 100% current rating SiC anti-paralleled diodes. SiC offers several other benefits for this application, including reduced system volume, weight, and material usage (due to smaller inductors, transformers, capacitors, and heatsinks).

EV propulsion systems require compact, efficient, and cost-effective traction inverters. When comparing semiconductor solutions for traction inverters, standard solutions using state-of-the-art silicon IGBTs may result in a low-cost traction inverter, but not necessarily achieve the size, weight, and efficiency the vehicles require when battery/range costs are included. SiC-based designs, while demonstrating higher efficiency than Si solutions, can come at a high cost.

- A GaN/IGBT hybrid T-Type configuration enhances light load efficiency. Due to the zero-reverse recovery of GaN HEMTs and the halved voltage stress across the device, the switching energy of the IGBT is significantly reduced.
- As part of the operating rules, the GaN neutral clamping leg is disabled at full load to avoid employing full current-rating GaN HEMTs for BOM cost reduction.
- According to lab tests, compared with conventional solutions, the switching-on loss of an IGBT in the hybrid T-type configuration is reduced by 92%, and the switching-off loss is reduced by 83% in the whole operating range.

Taken together, the GaN/IGBT hybrid T-Type configuration combines advantages of different power semiconductor technologies (the low cost and low conduction loss of IGBT and the low-loss switching performance of GaN), demonstrating that among the available topologies it offers an optimized price, performance, and range solution for EV inverters.

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