Variable-Speed Motor Drives Reap Benefits Of Integrated GaN

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Modern variable-speed drives (VSDs) for electric motors are at the heart of applications ranging from domestic appliances and HVAC to industrial automation, robotics, and electric vehicles (EVs). These applications typically use three half bridges to create a three-phase topology. Most motor drives in mass production today are low-frequency (~6 kHz) and hard-switched with silicon IGBTs or FETs.

Initial thinking was that the lower frequency of motor-drive operation makes it hard to gain significant benefits from deploying gallium nitride (GaN). However, when replacing silicon with integrated GaN half-bridge power ICs, performance improvements are realized. These include reduced system power consumption, component count and size; simplified thermal management and improved overall drive control and robustness.

In this article we consider the benefits of GaN versus silicon in VSD applications and the latest technologies that are simplifying the implementation of GaN-based half-bridge designs.

Variable-Speed Motor-Drive Applications And Market

Historically, most motors were designed to operate at a constant speed and provide a constant output. Modern technology requires different speeds in many applications and so the availability of VSDs that can regulate the speed and rotational force, or output torque of mechanical equipment has been a game-changer.

According to Strategic Market Research's August 2022 report,[1] the electric-motor market will exhibit strong growth of over 6% CAGR, taking it from $121 billion in 2021 to reach around $210 billion globally by 2030. The future growth trend is unsurprisingly dominated by automotive (41%) with the increased development and adoption of EVs (Fig. 1). Industrial automation including robotics and both industrial and residential HVAC and refrigeration are other big users of motors.

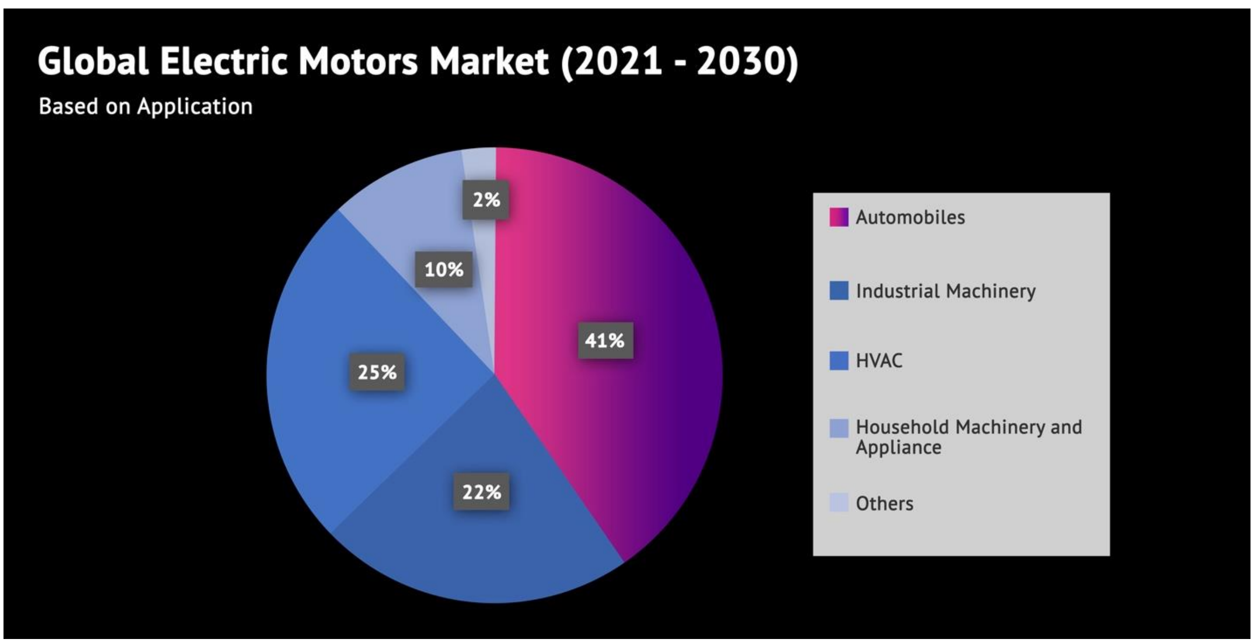

Fig. 1. Application split for motors by 2030. (Source: Strategic Market Research's August 2022 report[1]).

Conventional Approach—Silicon Discretes

For a long time VSDs used IGBTs as their main power switches. These legacy silicon transistors are robust but are bulky, have slow switching speeds and high losses. Silicon MOSFETs have also been used but have lower power density than IGBTs even though losses can be lower. MOSFETs can also have very poor internal body diode recovery losses that add to total losses.

In light-load operation, MOSFETs do show advantages over IGBTs due to their linear current-voltage relationship. Though still suitable in certain scenarios, neither technology provides the answers for the latest applications. More recently, silicon-based integrated power modules (IPMs) have emerged to reduce solution component count, save board space, and bring some of the reliability benefits associated with integration.

However, silicon's weakness is compounded by an increasing focus and regulation around efficiency, and it's easy to understand why. Taking Europe as an example, motor drives consume around 50% of all electricity produced.[2] Industrial VSDs do reduce energy use compared to older constant-speed induction motors, as well as having the added benefits of reduced motor size, improved dynamic performance and reliability.

While VSDs have achieved a vital improvement in energy efficiency complemented by the implementation of other technologies such as active power-factor correction (PFC) and pulse-width modulation (PWM) techniques, the imperfections and limitations of silicon-based solutions create a need for something better—enter GaN.

GaN Half-Bridge Technology

In recent years GaN has emerged as the technology to achieve lower losses, greater efficiency and a range of associated design, operational and reliability benefits and as an alternative to silicon in half-bridge designs in VSDs. Compared to constant-speed motors that had an efficiency of around 60%, VSDs using GaN can achieve efficiency levels of 95% to 97%.

Due to exposed gates, discrete GaN solutions are speed-limited by circuit parasitics and complexity. New GaNFast half-bridge ICs with GaNSense technology integrate two GaN FETs and GaN drivers, plus control, sensing and autonomous protection, to create a one-package solution that has a 60% smaller footprint and reduced weight and complexity. Efficiency, power density, and reliability are also improved when compared to a discrete GaN design.

Hard-switched half-bridge circuits are typical for VSDs. Here, the switching losses of GaN ICs, which have low capacitance and zero reverse-recovery losses, can be 4x to 5x lower than for Si IGBTs or Si MOSFETs, reducing total power losses by around 50%.

Integrated GaN enables the full potential of the technology and mitigates some of the pitfalls of adopting discrete GaN in half-bridge designs. One major issue is that discrete GaN devices typically require a gate drive of 5 V to 7 V and may also require a negative voltage to turn off. If not correctly optimized, both performance and reliability will be impacted. This is because, while GaN is an advanced material, the Achilles' heel of a discrete part is that the gate node must be carefully driven.

If the voltage on the gate is too low, the FET is not turned on completely so $R_{DS(ON)}$ and losses are high. If the voltage is too high, the gate can be damaged. GaNFast's integration of the GaN power (FET) and GaN drive plus control and protection in a single package overcomes the issue and the result is reliable, easy-to-use, high-speed, high-performance "digital-in, power-out" building blocks.

When using GaN for a fully-integrated driver, design margins can be reduced. This is due to the high, stable, and repeatable performance that comes from an integrated design where outside effects are much less able to compromise device operation.

Improved Efficiency Through Reduced Switching Losses

Pressure to increase efficiency means that the ability of integrated GaN power ICs to reduce switching losses is important. They cut these losses by up to 78% versus silicon IGBTs and 70% compared to MOSFETs. These reductions in switching losses become even greater at higher switching frequencies (see Fig. 2). As an example, if we consider deploying GaN power ICs in a 2-kW motor drive inverter switching at 6 kHz, we might expect to see an overall efficiency improvement from 96% to 98.5%, with total losses dropping from 15 W with Si IGBTs to 6.8 W with GaN as depicted in Fig. 2.

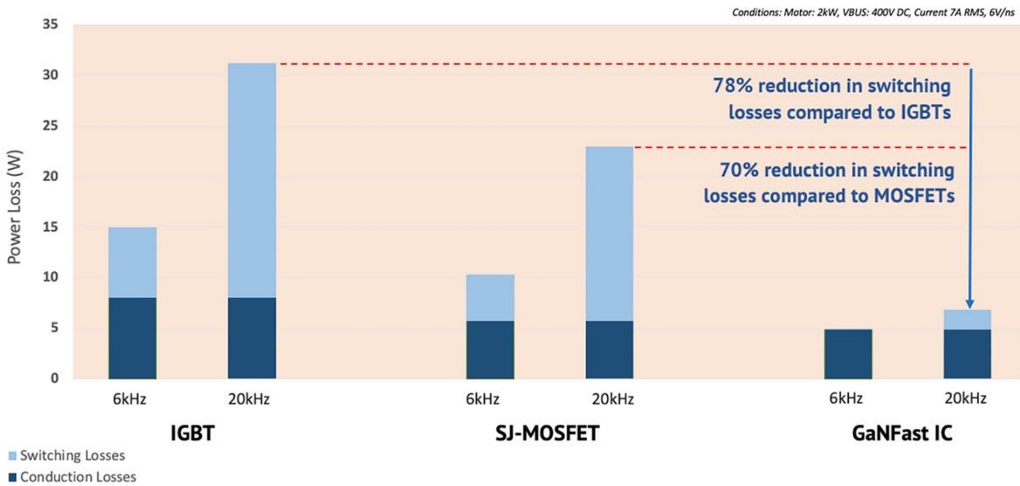

Fig. 2. Comparison of switching and conduction losses of silicon IGBTs and MOSFETs and fully integrated GaN solutions for VSDs.

Adopting Soft Switching

Unlike the silicon FETs for motor drives that are hard switched, integrated GaN solutions have the potential to be soft switched. This prevents overlap of voltage and current during switching transitions meaning power switches turn on and off at nearly zero current or voltage and switching losses are greatly reduced (Fig. 3). As well as improving efficiency, the integrated GaN solution also reduces EMI and supports system miniaturization as a result of higher frequency switching.

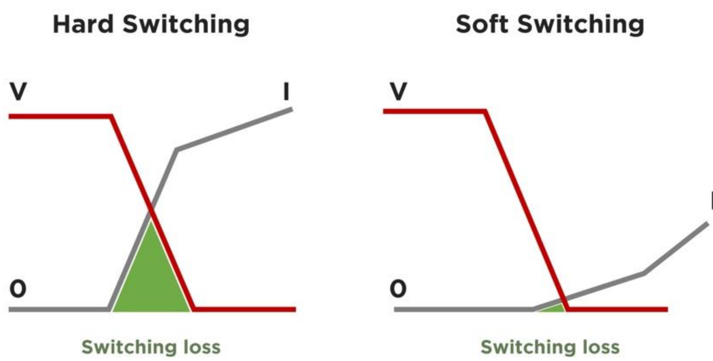

Fig. 3. Soft switching reduces losses and EMI and allows system miniaturization.

Simplified Thermal Management

Losses and poor efficiency create heat that must be managed to keep a device within specified operating parameters to ensure reliability and safety. Designers who have worked with silicon technologies in IGBTs and MOSFETs will be well versed with the need to design-in heatsinks to prevent issues such as thermal runaway. In some scenarios, designs may also need fans to dissipate heat effectively.

Heatsinks add size, weight, and significant cost to a design, so the reduced losses of integrated GaN devices mean smaller or even no heatsinks are needed. This is valuable not only in terms of space and weight savings, but also total cost of ownership. In silicon designs where fans might have been necessary there is also the issue of reliability associated with active cooling plus the additional power use and audible noise.

Improved Reliability And Protection

Integration is a key contributor to reliability. In the case of motor drives, reducing external component count reduces ringing and glitching. Parasitics are also lessened making megahertz-frequency operation a reality for a broad range of applications. In addition, and as illustrated by GaNFast, integrating other features can enhance protection and therefore the reliability of the design.

GaNFast includes ESD protection to all pins as well as a sensitive eMode gate node that is protected from system noise and voltage spikes. Also included is a monolithically integrated gate drive that eliminates parasitic inductance, turn-off, and false turn-on of the eMode gate. Other protection features that improve reliability and robustness, and which distance integrated GaN even further from silicon or discrete GaN solutions, are overcurrent protection, overtemperature turn-off and on-chip temperature sensing for better thermal design margins (Fig. 4).

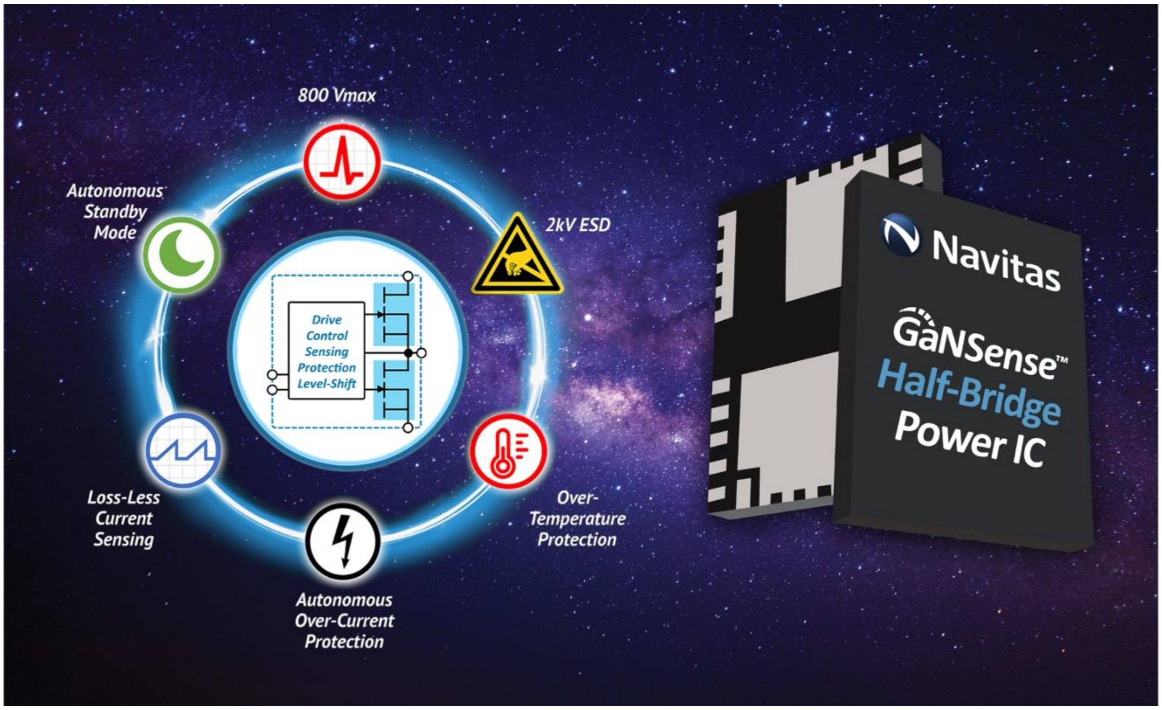

Fig. 4. Integrated GaNFast with GaNSense power ICs from Navitas ease design and incorporate features and functionality to optimize efficiency, reliability, cost and size.

Further Reducing Form Factors

Shunt resistors are a common feature of silicon-based VSD solutions. For integrated GaN, however, the incorporation of on-chip, lossless current sensing into the chip itself eliminates the need for these external passives. As a result, cost, space, reliability, and performance can all be improved.

Removing shunt resistors is a small part of the overall component count and form factor reduction possible with an integrated GaN approach for VSDs. Discrete silicon solutions, for example, need significant numbers of supporting components. IPMs improve this but still have the inherent limitations of silicon. Discrete GaN still needs many external components so, the full benefits only come with the evolution to fully integrated GaN.

GaNFast with GaNSense incorporates level shifters, the bootstrap and the gate drivers as well as mitigating the need for numerous other previously external passive components. If we compare a typical discrete GaN half bridge to a fully integrated solution, we see an overall component count reduction from 33 to just 13; this translates to board real estate needs dropping from 250 mm^2 to 90 mm^2.

System Solution Example

Integrated half-bridge power components are a fundamental building block for many power conversion systems, and motor inverters are no exception. In this motor inverter system design (Fig. 5), they are used for both the PFC as well as the inverter stage. This example in Fig. 5 also contains a compact and efficient auxiliary supply in an active clamp flyback (ACF) quasi-resonant (QR) topology.

We can see how fully integrated GaN half bridges support a simpler design with many of the benefits versus discrete approaches described in this article. The motor inverter uses GaNFast half bridges to give a compact and highly efficient power stage with significantly reduced cooling requirements, while the PFC again uses GaNFast in a totem-pole configuration to achieve the utmost efficiency and smallest external passive component count and footprint.

Comparing this implementation to legacy silicon or GaN discrete designs, one concern might be that the new components are not as robust as the older, larger chips, which is true. GaN power switches can only deliver their full performance potential if well-protected. The slow adoption of discrete GaN transistors is partly due to the complexity of additional protections required to make them work. Full integration with protection circuits finetuned for GaN enable similar or better reliability compared to legacy silicon components, while the much better performance is preserved.

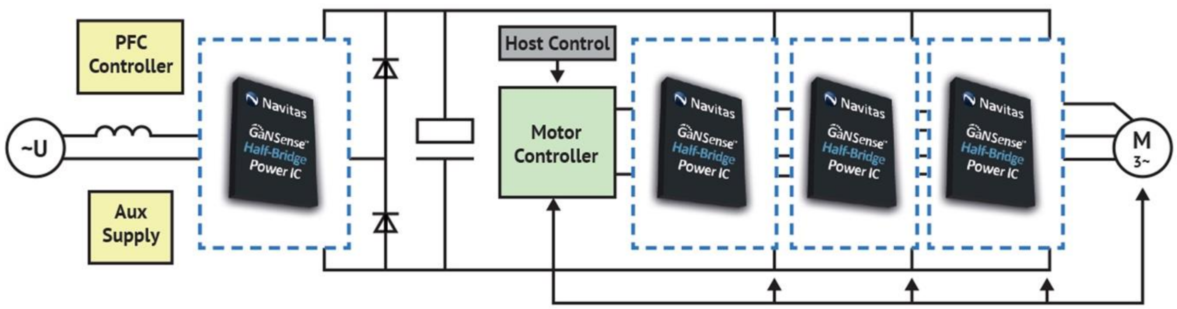

Fig. 5. System solution using integrated GaN power ICs for an auxiliary supply in an active clamp flyback, quasi-resonant topology.

Summary

As with many other applications, conventional silicon semiconductors are struggling to meet the performance and efficiency demands of the latest VSD motor designs. Replacing silicon with GaN technologies in half-bridge motor drive applications, however, provides designers with ways to deliver the requisite performance while reducing power consumption, component count and size and simplifying thermal management.

The system cost of this new solution and approach compared to legacy silicon implementations is much improved, in particular since the thermal management and heatsinks contribute a lot to the cost, size and weight of the final systems. While it is easy to quantify the cost of a piece of aluminum, the increased competitiveness of a smaller, lighter, more elegant and efficient appliance in the end market may be much more significant.

The latest integrated GaNFast with GaNSense power ICs from Navitas deliver all these benefits at the same time as improving overall drive control, while offering advantages over both silicon and discrete GaN alternatives.

References

1. Industry Report and Statistics (Facts & Figures) – Sales Volume, ASP & Demand Analysis by Motor Type, Power Output & Application," Strategic Market Research, August 2022.

2. "Electric motors and variable speed drives," European Commission, 2021.

About The Author

Alfred Hesener is a senior director industrial and consumer applications with Navitas Semiconductor. The company is headquartered in El Segundo Calif., while Alfred is based in Munich, Germany. His current work focuses on driving the state of the art in industrial power conversion and electric motor applications using wide-bandgap semiconductors. Alfred's previous positions include head of application engineering and product definition for Infineon Technologies, Industrial Products Division, and head of regional marketing and application engineering, Fairchild Semiconductor. He holds an MSEE in Microelectronics from Darmstadt University of Technology.

