Wireless Power Transfer at Your Fingertips: Enhancing Functionality for Battery-Powered Applications
Wireless-power-transfer capabilities have been widespread in commercial, industrial and automotive applications over the past decade. Battery-powered items demanding high-power charging are trending. Companies have created many highly integrated wireless charging ICs to suit these severe system and regulatory requirements for higher-power wireless charging. In this issue, Infineon Technologies principal applications engineer Nicholas Smith and senior staff systems engineer Harion Agrawal discuss a typical wireless power system and how to design it for optimal thermal management. Ever since wide-bandgap materials have been incorporated into various manufacturing technologies, it has been possible to achieve high efficiency in various power systems. Although there have been several developments in SiC and GaN devices, the optimization of such devices for electrical conductivity remains a major setback. In this issue, we will analyze different aspects about wide-bandgap semiconductor devices for high-voltage applications. Other topics include AC/DC converters for fast-charging stations, vertical GaN, PoE-powered devices, electric power steering (EPS), SiC power module packaging solutions for medium-voltage grid applications and other power-design trends. Sales of electric vehicles have increased significantly compared with previous years and will continue to do so. Technological innovations include better design and test methods across the electronic cosmos of power devices. In this issue, we explore some recent automotive innovations and test methods that are enabling the rolling chassis. According to current research, the global cost of living shows no signs of improvement due to the rising population. Furthermore, energy consumption is increasing as a result of unsatisfied consumer demands. According to reports, domestic appliances waste approximately 20% of all electricity. These energy vampires have the potential to save money and energy by reducing rising demand. A collaboration between Pulsiv and Salom has produced a 150-W laptop power supply using flyback technology. In this issue, we will analyze Pulsiv’s technology that delivers a flat efficiency profile, with almost no energy wasted in standby mode. Moreover, an interview with Power Integrations CEO Balu Balakrishnan will analyze the last 50 years of innovation in power semiconductors.

Yours Sincerely,
Maurizio Di Paolo Emilio
Editor-in-Chief, Power Electronics News
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Expanding Wireless Power Transfer for Higher Power Delivery

*High-power wireless transmitters and receivers designed for mobile phone fast-charging and battery-powered applications*

By Nicholaus Smith, principal applications engineer and Hariom Agrawal, senior staff systems engineer, both at Infineon Technologies

Over the past decade, wireless-power-transfer functionality has been broadly adopted across various commercial, industrial and automotive applications. Market trends are moving toward battery-powered products requiring higher power charging. The number of products needing charging is increasing, and so is the need for fast-charging, high-capacity batteries.

**Wireless charging** designs can now deliver much higher power than the mobile phone and wearable markets require. Modern mobile phones can draw up to 50 W but for quite a limited time due to thermal constraints. On the other hand, true high-power applications, such as laptops, tablets, portable kitchen appliances, power tools, robots and drones and light electric vehicles, can sustain higher power delivery and charge for prolonged periods.

However, higher-power designs beyond Qi extended power profile (EPP) are generally considered complex and costly, as standards are still evolving, leading to interoperability and coexistence concerns. The most discussed challenge is related to the IEC-62368 safety requirements for touch-temperature limits on consumer portables. In addition to an efficient charging subsystem, this also implies the need for dynamic foreign-object–detection (FOD) features that ensure protection while enabling charging across the load range, including transients. Therefore, robust communication protocol between the transmitter (Tx) and receiver (Rx) also becomes an essential requirement of such high-power charging.

To meet these stringent system and regulatory requirements for higher-power wireless charging, Infineon developed a broad range of highly integrated wireless charging ICs. These include a USB-PD/PPS sink with an on-chip 32-bit ARM Cortex-M0 processor, 128-KB flash, 16-KB RAM and 32-KB ROM. They are also equipped with various analog and digital peripherals, integrated gate drivers and DC/DC controllers. The ICs are offered together with a system solution and a software stack based on Infineon’s high-power charging protocol with unique identification and configurable protection features to maintain safe, high-power charging environments. In addition to the proprietary mode, Infineon’s *WLCx family of products* also supports the latest Wireless Power Consortium (WPC) Qi EPP (≤15 W) specifications to enable compliant and interoperable solutions.

In the following sections, we present an overview of a typical wireless power system and some insight into designing the solution for optimal thermal management, take a deeper dive into coil design and present an overview of Infineon’s solution features and a couple of applications to explain why wireless power is a suitable and convenient choice for high-power products in any environment.

**WIRELESS POWER SYSTEMS AND DESIGN CONSIDERATIONS**

Wireless power systems are unique power-management solutions that include mixed-signal analog and digital sensing, communication circuits alongside AC and DC power-conversion stages and, most importantly, a software stack to provide a reliable handshake between the Tx and Rx side. The block diagram in Figure 1 shows the main functional blocks of a typical high-power inductive wireless system.

In Figure 1, the incoming power source will be a DC power supply based on USB-C (PPS or PD) or fixed-rail–voltage supply. This supply can be passed directly to or converted by an intermediate...
DC/DC regulator to power the DC-to-AC power inverter. The inverter creates an alternating magnetic field using an $L_p$ and $C_p$ series resonance tank to transmit power to the receiver. On the receiver side of the system, series resonance components $L_s$ and $C_s$ convert the incoming magnetic field to current, and a high-power rectifier converts the AC current into a DC voltage. Finally, an output regulator is used to provide a stable DC voltage to a load that can be a specific work function of a product or a battery charger.

There are several additions to the typical wireless power system (≤15 W) to qualify as a high-power solution (>15 W). The first is an increased need to improve the performance of the magnetics to reduce power loss and the associated heat developed due to power loss during transmission. Additional guidance for high-power designs will include extra safety and authentication procedures to prevent counterfeit designs from drawing or providing high power. At the same time, it will ensure that proper FOD mechanisms are in place to safely and efficiently deliver high power to receivers and their loads. Most end products will use the Rx output to charge a battery; however, there can be standalone applications, such as pool lighting and washlets, in which wireless power is simply the means to power the load without a battery.

**DESIGN FOR BETTER THERMAL MANAGEMENT: COOLING OPTIONS**

There are concerns that the heat development and the efficiency of higher-power wireless systems may impede or delay meeting safety requirements. Still, these can be mitigated by designing for heat dissipation and optimal efficiency. A full stackup of a Tx-Rx coupled inductive wireless charger is shown in Figure 2 to better understand the avenues for heat trapping and cooling.

The physical construction of the PCB can influence the operating temperature of the system as well. The copper surface areas connected to power components and the board thickness will play a role in the final operating temperature. Thinner PCB designs will transfer more heat between inner layers due to the lower thermal resistance and the larger areas. Designing a thin PCB will improve thermal performance compared with thicker PCBs having more dielectric FR-4 between copper layers. Other solutions include adding a fan to force airflow across the circuits and the interface (Figure 3). If forced air is used, it is crucial to provide tunnels or airflow channels in the interface by either designing grooves so the air may flow through or using semi-porous materials that allow the air to flow freely.

At this stage of the evolving higher-wireless-power market, the most common application is a mobile phone. Some mobile phones can draw up to 50 W but for a very limited time. As the emerging market takes shape, laptops, robotics and other similar high-power applications will be able to sustain power delivery indefinitely. Also, because the charging stands and devices are typically quite small, high power dissipation is challenging without using a fan to move the warmer air from the products’ interface, where touch temperatures are measured.
DESIGN FOR BETTER THERMAL MANAGEMENT: IMPROVING COIL EFFICIENCY, ROUTING

In inductive wireless charging systems, one of the most prominent sources of thermal concern is the magnets themselves. Hence, the main idea behind improving efficiency is to use a higher-quality Rx coil. For example, a Litz wire coil with a nanocrystalline shield can substantially reduce the interface temperature compared with multi-stranded wires or PCB coils. There is usually a tradeoff between cost and performance, where the superior performing Litz wire Rx coil designs tend to be the most expensive while the PCB-type coils cost less and are the least efficient.

Nanocrystalline shields will yield high saturation levels in thinner materials and are superior in performance compared with a standard, sintered ferrite core. When using PCB-type coils, it is beneficial to utilize heavier copper foil weights (i.e., 2-ounce or 4-ounce copper as opposed to the standard 0.5 ounces found on most flexible PCB substrates). Because these conductors carry high currents and are typically relatively large, they serve as heat dissipators as well as current conductors. Therefore, an essential mitigation technique is connecting large copper planes to the Tx and Rx coil contacts and other heat-generating sources, such as power MOSFETs, inductors and ICs. In this case, it is critical to include significant areas of copper planes to absorb the developed heat resulting from power consumption by the electronics.

When the solution requires creating a custom coil, it should be noted that wireless power systems demonstrate optimal performance when the combined air gap (Rx and Tx interface height or the space from the coil-to-coil facing surfaces) is between 3 and 8 mm, depending on the final geometries. This will help to ensure the coupling factor is between 0.5 and 0.85, which is the sweet spot for inductive wireless power systems. Consequently, this enables the design to meet appropriate mutual inductance values when the Tx and Rx coil inductances are kept within a range of about ±25% of each other. In addition, it ensures that the gain curve is neither too steep nor too shallow to allow proper power-regulation steps throughout the operating voltage and frequency range.

Utilizing the First Harmonic Approximation (FHA) analysis, many parameters and most operating modes can be modeled and simulated. Infineon’s High Power Tx Design Guide includes the necessary derivations, the recommended model and comprehensive system design guidelines. For example, this design guide can be used to create the graph shown in Figure 5. In this graph, the typical Tx coil power versus frequency slope indicates how the gain responds to changes in
Ideally, shielding should be continuous and exceed the outer coil diameter by at least 1 mm. The Tx and Rx coil geometries (inner diameter/outer diameter) should be within ±25% of each other. The number of turns should be similar (within ±3). Free-air inductance should be within ±20% of each other. The Rx shielding should be nanocrystalline or fractured ferrite types and as thick as possible. The AC and DC resistance should be minimized. Using Litz wire, multi-strand conducted wire or wide/thick copper foil on PCB can increase the amount of "skin" of the conductor. Ideally, shielding should be continuous and exceed the outer coil diameter by at least 1 mm up to 3 mm (as space permits).

By following these guidelines, the coupling factor, mutual inductance and magnetic field volume will be appropriate to operate and provide decent active areas in lieu of complex iterative simulations. The above guidelines aim to prepare coil prototypes immediately so that testing and final design adjustments can be completed by checking efficiency, transient response and communication fidelity across load and voltage. It is recommended to get a few prototypes of Rx coils with different permeabilities and inductances and experiment with the air gap, if possible, to find the optimal configuration and coil design. For additional details and descriptions of the governing equations, see the WLC1150 Design Guide.

Figure 5: Typical power vs. frequency curve for an inductive wireless power system with 20-V input and output

The next major design decision will be operating voltage after defining the required output power. The output power can then be used to estimate the power losses of the rest of the system going back to the incoming DC power supply to the Tx. This will enable thermal modeling and help determine limits for the resistance and the \( R_{\text{loss}} \) value of the MOSFETs. It should be noted that the highest efficiency is achieved by operating the system at the highest possible voltage to reduce the current and the associated \( I R \) power losses. For example, a 50-W output is best suited to use a 20-V output at 2.5 A instead of a 10-V output at 5 A. The reason is that the higher rectifier voltages require lower rectifier currents leading to a lower coil current, and the bulk of Rx losses will occur in the rectifier and Rx coil. It is a good assumption that the root-mean-square Rx coil and rectifier currents will be \( \pm 11 \times \) the rectified DC current (assuming a fairly sinusoidal wave shape). Again, the WLC1150 Design Guide offers comprehensive insight, recommendations and estimates of the operating points for high-power wireless transmitter designs.

Using these reference guides will allow making power-loss estimations for the rectifier MOSFETs and the Rx LC tank and the Tx pre-regulator (if used), inverter and Tx coil. It will become evident that the AC losses in the coil are dominant, and thus, this resistance should be reduced as much as possible by using heavier-gauge Litz wire, multifilar stranded wire or parallel thick copper PCB tracks to create the Rx inductor while meeting the cost and thickness requirements of the end product.

Moving back to the output, once the output power and voltage are determined, the post-regulator between \( V_{\text{rect}} \) and \( V_{\text{out}} \) should be considered. In general, for high-voltage output (>15 V), the LDO-type output is more efficient, as \( V_{\text{rect}} \) and \( V_{\text{out}} \) will be within 0.2 V of each other. Thus, the output regulator losses and coil currents will be minimized. The output stage power calculations are simplified, and by using the power and voltage, the rectifier DC current can be calculated. Then the rectifier and Rx coil current can be found, as it is nearly equal to the output current (controller IC quiescent current and switching currents have to be added to the output current to get rectified current).

For systems that will use <15-V output, the buck regulator is advantageous because the system can regulate the \( V_{\text{rect}} \) at higher voltages and step down the output. This allows lower coil currents while enabling high output currents at lower voltages. System specifics may impact the decision between LDO and buck (especially near the 15-V \( V_{\text{out}} \) target value) and should be considered before the design launch, depending on which output type maximizes the efficiency. With the infineon solution, these tests can be run quickly and easily due to the configurable design concept. With the buck regulator used, the rectifier current can also be estimated by dividing the output current by the ratio of \( V_{\text{rect}}/V_{\text{out}} \).

Once the Rx side of the system has been estimated, appropriate components can be selected and designed while thermal modeling is conducted. The final components may be determined within a couple of design iterations, and the PCB design may start. Using the determined Rx coil current and
the coupling factor (use of $k = 0.65$ is good guidance to account for optimal to misaligned charging conditions). Tx coil currents and power calculations may now be estimated (assuming the above coil guidance is utilized) using the WLC1150 Design Guide.\textsuperscript{1}

The Tx coil and inverter currents can be determined using the Design Guide and the selected output power and input/output voltages. Also, the Tx coil AC resistance, Tx coil and inverter MOSFET selection may take place to meet efficiency targets. It should be noted that MOSFETs with lower $R_{\text{ON}}$ have a higher parasitic capacitance, thus increasing the switching losses. Therefore, simply reducing $R_{\text{ON}}$ will not always result in better performance. In general, MOSFETs in the range of 10- to 20-mΩ $R_{\text{ON}}$ will have a reasonable balance between switching and conduction losses and are ideal for wireless power systems. For systems with a pre-regulator between the DC input and the inverter (variable voltage or hybrid-variable voltage and variable-frequency systems), the DC/DC regulator needs to be designed to handle wide input-to-output differences to the $V_{\text{out}}$ range of 4 V to 19 V and be designed to deliver at least 3 A of current. Note that $V_{\text{out}}$ should be designed to operate from the designated $V_{\text{in}}$ voltage range (typically 12 V to 20 V).

The Tx input power is now easily estimated by dividing the Rx output power by the target system efficiency (90% for Litz wire coils and 85% for PCB wire Rx coils, i.e., dividing by 0.9 or 0.85). Then the BRG power is estimated using the design calculator (or assuming a 4% to 5% loss if using the WLC1150 Design Guide).\textsuperscript{2}

The coupling factor (use of $k = 0.65$ is good guidance to account for optimal to misaligned charging conditions). Tx coil currents and power calculations may now be estimated (assuming the above coil guidance is utilized) using the WLC1150 Design Guide.\textsuperscript{1}

The WLC1150 to power the inverter). When placing the MOSFETs, multiple layers should be used to connect to the drains and sources. Also, wide copper planes should be used to transfer the heat to the PCB, where it can be spread to reduce the device's operating temperature. The simplified diagram in Figure 6 shows the heat paths created by having solid copper planes connected with multiple vias to inner layers for heat distribution. Outer layers are the most effective, but internal layers should also be utilized whenever possible.

There are also several additions to the typical wireless power system to move from the standard power levels to the high-power realm. These include, but are not limited to, faster FSK patterns to reduce the communication throughput required for sending messages to the Rx. It is also important to force authentication, or at least a soft credential check using encryption, to avoid the possibility that a counterfeit product can power and charge devices at high power. The primary reason for this is to prevent damaging the high-voltage sensitive electronics and limit the voltages and currents of the inverter and rectifier to safe values.

Improper control of the primary LC tank can lead to excessively high-voltages within the inverter LC tank and on the rectifier. These high-power systems are carefully designed to avoid operating cases where damage may occur. Still, counterfeit solutions may not be so cautious, and this could be destructive if there are sudden coupling improvements or large transient load dumps while the incoming magnetic field strength is too strong for the Rx to handle or is sustained for long periods. These systems are designed to have reactive power clamps to absorb excess incoming energy when needed.

**CURRENT TRENDS AND INFINEON’S SOLUTIONS**

Aside from being designed to charge at 50 W safely, the Infineon WLC1150 Tx solution has some differentiating key features to safely provide higher power. These include:

- High-voltage (up to 24 V) with high-side current sensing
- Integrated USB-PD controller
- Direct-voltage control from USB-C PPS adapters
- Integrated gate drivers for full-bridge inverters and DC/DC
- Adaptive FOD algorithms
- Customizable configurations with full-stack software
- Safe magnetic-field operating range based on the output power levels

In addition, Infineon offers the complete solution, including the upcoming WLC1x Rx, which supports either LDO or buck output for post-regulators; thus, the transmitter can be adjusted for cost and power supply type (Figure 7).

High-power wireless systems are very useful for powering and charging larger devices like laptops, vacuums and drones. These designs are perfect for high-humidity environments or where condensation is expected due to the lack of exposed contacts. These designs also reduce ESD-related failures, as the electronics are further isolated from outside environments where static charge is typical.

The high-power solutions are scaled-up versions of the low-power counterparts while still relying on the same design fundamentals. They require attention to the placement and routing of the PCB, particularly the current-loop area of switching regulators. In addition, it is important to use wide copper planes to reduce the IR voltage drops in the conduction path and spread heat away from
the power components. Using a robust in-band communication scheme with variable modulation depths based on operating conditions, the system reliably, safely and conveniently transfers high power to any load via the mated Tx and Rx coil pairs.

In industrial settings, these systems are great because they can eliminate the need to have wires and cables present while supporting corrosion-free charging that lasts for years. A high-power design is slightly more complicated and requires the use of higher-current-rated and lower-resistance components to reduce power losses throughout the system. However, they can efficiently be designed by following the recommendations of this article and Infineon’s high-quality reference designs and design guidelines.²

High-power wireless systems require multiple improvements to maximize performance, but the sequential step from 15 W to 50 W does not result in proportional design time or challenges. The desired increase in power can be achieved with a minor scaling of some key components when utilizing Infineon’s high-power solution to deliver the highest wireless power possible in the market today.

Click here to find out more information and support for our highly integrated wireless charging ICs that offer advanced customizable options to meet industry compliance standards and proprietary requirements.

The WLC1x high-power four-layer Rx PCB will launch soon. Click here to request engineering samples.

References

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Resonant Boost DC/DC Converter in Class E with Dual-Frequency Control

By Giovanni Di Maria, technical writer for EEWeb

There are many different types of DC/DC converters, each with a unique mode of operation. The one proposed in this article involves the analysis of a DC/DC boost converter operating in Class E with dual-frequency signal drive. This solution allows the output power to be adjusted if the load should change. One of the most important features of the circuit is that it can ensure very high efficiency under all operating conditions. The boost converter examined in this article allows the output DC voltage to be higher than the input DC voltage with maximum efficiency.
**FIXED LOAD AND VARIABLE LOAD IN CLASS E**

When a Class E converter is designed for a precisely valued load, it has no control to adjust the output parameters. The output signal characteristics are fixed and always operate under the same conditions. If, on the other hand, different loads are to be used, a series of controls must be arranged to perfectly adjust the output signal. With Class E converters, it is possible to obtain special waveforms that pass through zero before the instant of switching. In this way, the switching losses are very low. In Class E converters, the switching frequency can be greatly increased compared with conventional converters, even by a factor of 50, allowing high efficiencies to be achieved.

Due to this aspect, circuit sizes can be kept small, resulting in a significant reduction in weight, footprint and final cost. The EMI aspect is also dramatically reduced. In normal switching, power-electronic switches interrupt the current within very short moments, which causes great stress to the electronic components. They must endure high-voltages and high currents simultaneously, causing great power dissipation and stress, which results in power losses and low efficiencies.

By adopting resonant circuits in converters, waveforms can be shaped to create zero-voltage-switching and zero-current-switching conditions. By reducing power dissipation (ideally to zero), increasing switching frequency and eliminating transient spikes, overall system efficiency is increased for very low EMI.

**DUAL-FREQUENCY CONTROL IN BOOST CONVERTERS**

Class E converters usually work for a single load case because they are designed to operate only under a specific operating condition. Normally, they provide for a specific type of load, and in this case, the converter operates at maximum efficiency, with only one optimum operating point. By changing the load, the waveforms of the circuit change, and therefore, optimal operation is no longer guaranteed. A change of load results in a drastic reduction in system efficiency.

To solve these problems, it is possible to modulate the output current using dual-frequency control, with which an optimal operating point is always guaranteed, and the efficiency of the entire system is maintained at very high values. In switching converters, the most critical components are the inductors. Fortunately, in this circuit implementation, these components do not have to be replaced, and the optimal operating point can be equally achieved by adopting two different switching frequencies. Specific precautions must be taken when implementing a dual-frequency Class E boost converter, as shown in Figure 1.

The same inductors can be used in this circuit without having to replace them. Instead, the optimal operating point at both frequencies is obtained simply by changing the value of the capacitors connected in parallel with the electronic switches. Maximum efficiency is obtained only if the product of the output current and the switching frequency of the transistor remains constant. This solution is derived from the single-frequency boost, in which there are no electronic switches that alternately connect and disconnect the additional pair of capacitors. It is easy to see that when such switching devices are in conduction, they allow additional capacitors to be connected in parallel to increase the capacitance to those already existing in the scheme. Another condition required by the circuit is that the product must be kept constant to protect maximum efficiency at the two switching frequencies:

\[
I_{out1} \omega_{s1} = I_{out2} \omega_{s2}
\]

**CIRCUIT OPERATION**

Unlike the scheme with only one operating frequency, this one has two switches in series, with the two capacitors labeled Cinv1 and Crec1, allowing the total capacitance to be changed. If the switches are closed, the capacitances of Cinv1 and Crec1 are added to the Cinv2 and Crec2 capacitors, respectively. In this case, the converter works at a lower frequency. On the other hand, if the additional capacitances are disconnected, the converter works at the higher frequency. Note that the additional switches are two MOS transistors. However, the one in series with Cinv2 is N-channel, while the one in series with Crec2 is P-channel. The converter operates at one of two switching frequencies, depending on the input voltage and load conditions, in the following two ways:

- If the input voltage is high, or the load is light, the circuit adopts the higher switching
frequency so that the on/off transition losses and conduction losses produced by the resonant inductor can be reduced.

- When the voltage is low, or the load possesses low impedance, the circuit adopts the lowest switching frequency.

At the design stage, the input and output operating voltages, at which the converter is to work, must be chosen. Likewise, the designer must choose the two maximum powers dissipated by the load, at the two frequencies. With these, the currents of the two branches, INV and REC, can be easily calculated. The determination of the inductive components is extremely delicate, as it must also consider the two frequencies involved. The graphs in Figure 2 show the waveforms of the voltage between the drain and source of the electronic switch V(D,S) and the voltage between the cathode and anode of the diode V(K,A).

The following steps should be followed to obtain two good working conditions at the two chosen frequencies. Usually, it is better to prefer one frequency twice as high as the other:

- Choose the input voltage and the output voltage.
- Determine the maximum relative powers at the two frequencies involved.
- Calculate the relative currents.
- Choose the inductors and determine the respective q-values, at the two frequencies.
- Calculate the switching losses.
- Optimize the results by slightly adjusting the component values.

The first sizing of the components is done at a given frequency; the second sizing is done, however, at twice the frequency. The switching losses are again calculated, and finally, further optimization is performed. This is far from a simple procedure.

![Figure 2: Oscillograms of the voltages V(D,S) and V(K,A) in the circuit operating at the lower frequency](image)

![Figure 3: A very small step is formed on the V(D,S) signal during transistor switching, which is completely acceptable.](image)

A well-designed circuit results in very high efficiency, and the peak values of the two voltages examined earlier are not critical and are supported by most devices on the market. The value of the average output current is equivalent to the average current of IREC. Parasitic resistive components in series with the reactive components (capacitors and inductors) must be considered when designing the circuit. These parasitic resistances are subject to change in relation to frequency; indeed, they are more relevant at high frequencies. To make a single circuit work at the two frequencies, it is necessary to combine two equivalent designs to implement a Class E boost converter that can work at the two frequencies.

As mentioned before, if the two switching devices in series with the capacitors Cinv1 and Crec1 are open, the circuit can operate at the higher frequency. Conversely, if these electronic switches are closed, the circuit operates at a lower frequency. At such frequencies, therefore, the presence of parasitic resistances varying according to the frequency itself is inevitable. Such reactances will be minimal as far as capacitors are concerned, while for inductors, they may reach important values due to their low Q.

In the graph in Figure 3, there is a small step on the oscillogram related to the V(D,S) voltage, just at the instant when the electronic device is turned on and goes into conduction. This step cannot
be eliminated altogether and results in a very small increase in the power dissipated in switching, which is completely acceptable and insignificant.

CONCLUSION

Experimental results show that, with this dual-frequency methodology, the conversion efficiency improves by at least 6% to 7%. By performing a good analysis and design, the circuits behave as planned, achieving their intended goals. It is interesting to compare the voltage waveforms at the ends of the MOSFET and diode, at the two switching frequencies, to verify the efficiency of the system. It is useful, too, to analyze the currents transiting the LINV and LREC inductors.

The oscillograms in Figure 4 show, respectively, the activation pulse of the electronic switch and its two signals at the ends of the two semiconductor components (the first two oscillograms above) at the base frequency. The other two oscillograms (bottom) show, respectively, the activation pulse of the electronic switch and its two signals at the ends of the two semiconductor components, at the double frequency. The second mode of operation uses twice the frequency and half the current on the load. These results, at such high frequencies, could not normally be achieved with conventional solutions.

Class DC/DC converters are extremely complex and critical, but they provide enormous benefits by allowing loads of varying nature and impedance to be driven. With special arrangements and substantial circuit modifications, and with an exponential increase in system complexity, a DC/DC converter can also be implemented for three types of loads.

Overview of AC/DC Converters for Fast-Charging Stations

By Saumitra Jagdale, contributing writer for Power Electronics News

Electric vehicles constitute a major segment of the promising technologies for achieving a sustainable transport sector in the future. AC/DC converters are the backbone components for expanding and improving the functioning of EVs. This article gives an overview of AC/DC converters, types of charging stations, problems faced with conventional two-level (2L) AC/DC converters and the significance of using multilevel converters (MLCs).
SIGNIFICANCE OF AC/DC CONVERTERS

Primarily, an outlet delivers AC power, whereas EV batteries function with DC power for charging the battery. Thus, there is a need for an AC/DC converter for converting AC power to DC power. It is also the major component of an EV battery charger and acts as an input current shaper for power-factor correction and harmonic reduction.

The above circuit diagram illustrates a simple AC/DC converter: Four general-purpose rectifier diodes are used here to rectify the AC input. The functionality of the transformer is to step down the 230-VAC supply to 13 VAC, and arrangement of the circuit is a full bridge, as it consists of four diodes. The rectifier will rectify both the positive and negative peaks of the AC signal. A filter capacitor is added after the bridge converter to smooth out the output voltage. Additionally, a Zener regulator is connected in reverse bias before the output to regulate the output voltage.

The charging duration on Level II is approximately less than half the time of Level I charging. Furthermore, Level III fast-charging stations use an external charger (off-board) to supply high-voltage. It is capable to charge the EV in as little as 20 to 30 minutes, while Level I or Level II charging stations can charge the vehicle in four to eight hours.

TYPES OF CHARGING STATIONS

As rechargeable batteries are the power source for EVs to function, it is very important to understand some parameters of charging stations. Most fundamental parameters like power efficiency, compact architectures and fast charging will determine the overall productivity of the target charging stations.

EV charging stations are classified into Levels I, II and III.

Level I constitutes the segment of smaller battery sizes. The charging duration of Level I is approximately eight to 10 hours; however, this may vary depending on the energy capacity of the battery. It only uses AC charging and there is an on-board charger, as the charging component is located inside the EV.

The different number of levels of MLCs achieves a smoother output waveform, which reduces the harmonics and the output filter size. The major types of MLCs are neutral-point clamped (NPC), cascaded H-bridge (CHB) and flying capacitor (FC). Out of these, the most popular CHB has the capability of utilizing different DC voltages on the individual H-bridge cells, which results in splitting the power conversion amongst higher-voltage/lower-frequency and lower-voltage/higher-frequency inverters.

The figure on the next page represents one phase of a three-level NPC inverter. They are a family of MLCs characterized by the use of clamping diodes for guaranteeing the proper voltage sharing.

REQUIREMENTS FOR ENABLING FAST-CHARGING STATIONS

The power range of fast charging is above 50 kW, which is considered high according to industry standards. So there is a need for a larger AC/DC converter to supply this extra power for fast charging. Thus, high-power charging is best carried out where AC/DC converters are built into the charging station and not installed inside the vehicle due to size constraints.

Another requirement of a fast-charging station, defined by the Society of Automotive Engineers (SAE) standard, is “the galvanic isolation between the distribution grid and the battery pack.” There are two architectures available for achieving this, either through using a low-frequency transformer at the input side or through the implementation of a high-frequency transformer included in the DC stage by means of isolated DC/DC converters.

CONVENTIONAL AC/DC CONVERTERS AND THEIR DRAWBACKS

Conventional AC/DC converters like 2L voltage-source converters (VSCs) are commonly used. The drawback of using these converters is that they have limited power ratings and high harmonic pollution. To avoid such drawbacks, hybrid filters are used, but these filters also increase the cost of the system. These converters have an undesirable high switching frequency as well. In high-power applications, the switches suffer from high amounts of voltage and current, and they are limited by the existing technologies of semiconductor devices.

IMPORTANCE OF MLCs

To overcome these setbacks, 2L AC/DC converters should be replaced by MLCs. MLCs have been demonstrated to have many advantages, such as low harmonics, low voltage stress and high-power capability. The MLC is used for reducing the switching element and produces the multilevel output by the single-phase T-type converter.

The different number of levels of MLCs achieves a smoother output waveform, which reduces the harmonics and the output filter size. The major types of MLCs are neutral-point clamped (NPC), cascaded H-bridge (CHB) and flying capacitor (FC). Out of these, the most popular CHB has the capability of utilizing different DC voltages on the individual H-bridge cells, which results in splitting the power conversion amongst higher-voltage/lower-frequency and lower-voltage/higher-frequency inverters.

The figure on the next page represents one phase of a three-level NPC inverter. They are a family of MLCs characterized by the use of clamping diodes for guaranteeing the proper voltage sharing.
across the power switches. Each leg of the NPC inverter has four transistors that can be controlled, giving $24 = 16$ total possible states, but only three of these states are feasible, as others create short-circuits on the DC-link.

**FUTURE OF EV CHARGING**

The transformation from combustion engines to EVs is a long-term process. Many oil companies are already claiming a stake in the EV networks by creating charging stations or promoting products aimed at EV maintenance. Future expected works look forward to using MLCs in FCs to benefit from the various advantages of these converters while proving high-power and ultra-fast charging systems for EVs. To help EVs reach ubiquity, governments and EV charging companies must ensure the availability of fast-charging infrastructure. Without an efficient charging infrastructure, EV uptake may be a slow-rolling process.

Figure 3: One phase of a three-level NPC VSC (Source: ScienceDirect)

Taking on Home Energy Waste from Vampire Devices

By Saumitra Jagdale, contributing writer for Power Electronics News

According to current research, the global cost of living shows no signs of improvement due to the rising population. Furthermore, energy consumption is increasing as a result of unsatisfied consumer demands. According to reports, domestic appliances waste approximately 20% of all electricity. These energy vampires have the potential to save money and energy by reducing rising demand.

**OVERVIEW OF VAMPIRE DEVICES**

Any device that uses energy even after being turned off or when not in use is referred to as a vampire device. Integrated circuits are used in devices that automate and simplify routine actions like turning on the TV or a coffee maker. Even while in idle mode, these circuits use the internet actively for ongoing updates and monitoring, which uses energy.
Many are designed to be accessed quickly with a straightforward operation like activating a TV, coffee machine or microwave. Devices with integrated “smart” functionality like smart speakers will continue consuming energy to perform various tasks like updates, monitoring and data recording, as they require a constant internet connection.

Figure 1 shows some examples of devices that consume more energy. Other devices continue an active connection and consume power when idle (Figure 2).

**HOW ENERGY IS WASTED ON VAMPIRE DEVICES**

When it comes to energy waste, laptop chargers are a prime example of a vampire device because they are designed to charge devices at a faster rate. However, in some cases, users continue to charge the device despite a full charge. In such cases, the devices operate in low-power mode and are warm to the touch, resulting in increased energy waste.

Working from home during the Covid-19 pandemic has led to an increased waste of power due to laptops being plugged into chargers continuously. This practice is widespread and applies to all household appliances, affecting electricity expenditures.

**THE INEFFICIENCY OF EXISTING POWER SUPPLIES DURING STANDBY MODE**

In domestic applications, power supplies are made of conventional technologies that convert AC to DC for higher efficiency, consuming more power. This technology is great for active power usage; however, it can be inefficient for low power consumption. The low-power mode can cause energy wastage despite being in standby mode. Moreover, when the device is inactive, more power is wasted than utilized.

**HOW ARE REGULATIONS HELPING?**

Several regulations have been implemented around the world to reduce energy consumption and save money. The rules are critical for informing consumers as well as ensuring that manufacturers adhere to proper efficiency standards.

**FOR CONSUMERS**

In 1994, various energy labels ranging from A to D were introduced for various household appliances. These labels were later expanded in 2004 to assist consumers in distinguishing between devices that operate in a more energy-efficient and cost-effective manner. An EU survey conducted in 2019 confirmed that 93% of consumers recognized energy labels, with 79% confirming that it had influenced their purchase decision.

In March 2021, the energy-regulation labels were updated to a more simplified A–G scale. This new scale was stricter in its implementation, to allow fewer products to achieve the “A” rating and to allow for a broader range of efficient products to be included in the future.

**FOR MANUFACTURERS**

Manufacturers must comply with several rules and regulations globally for energy efficiency. These rules have been in effect since 2004 and set minimum efficiency levels for energy consumption in domestic appliances. They include:

- California Energy Commission
- United States Department of Energy
- Energy Star
- Energy-related Products
- EU Code of Conduct

**DOES UNPLUGGING DEVICES SAVE ENERGY?**

The short answer is yes. Various devices provide “smart technology” but a consistent supply is required for the completion of multiple tasks like updates, remote monitoring, data recording and so on. Home security (video doorbells and cameras), intelligent lighting and internet routers are a few examples. In such cases, unplugging devices to save energy may be impractical. As technology advances, more devices are connected to our homes, causing an increase in electricity bills.
INTRODUCING PULSIV OSMIUM TECHNOLOGY

Pulsiv developed a patented solution to this problem, in which AC/DC conversion provided an unrivaled efficiency profile even at lower power levels. Compared with traditional methods, this technology can exceed the latest efficiency standards by 20% using commodity system components. The power supply is still effective and less energy is lost, whether a device is in standby mode, full power or somewhere in between.

LAPTOP POWER SUPPLY WITH PULSIV OSMIUM

A collaboration between Pulsiv and Salom has produced an innovative 150-W laptop power supply using flyback technology. To date, Salom has shipped over 3 billion low-cost power supplies in the name of major brands. According to the results, Pulsiv OSMIUM delivers an unrivaled flat efficiency profile compared with other conventional techniques. Low power efficiency was also significantly improved, with almost no energy wasted in standby mode. Higher efficiency at low power has a direct impact on energy waste in off/standby mode, which can be useful in lowering energy bills.

THERE IS NO DENYING THE RESULTS

Currently, consumers are more conscious about their electronic devices directly tied to their monthly energy bills. With increasing technological advancements and gadgets, manufacturers must consider the right regulations to reduce energy utilization.

Some of the frequently used power devices in 2021 were:

- Smartphones: 6.37 billion users (with the average consumer owning three chargers)
- Laptops: 276 million units sold
- Televisions: 178 million units sold
- Tablets: 168 million units sold

References

- "Intelligent Controller Boosts Efficiency in Power Electronics," Power Electronics News

Figure 3: Charger plug

Figure 4: Efficiency of Pulsiv PFC with active bridge and flyback load
Short-Circuit Robustness in Vertical GaN Fin-JFET Power Devices

By Sonu Daryanani, contributing writer for Power Electronics News

Gallium nitride’s superior material properties have driven its usage in power device applications. The lateral high-electron–mobility transistor (HEMT) device has been commercialized over a wide range of voltage classes, mostly 650 V and below. The high-switching-frequency capability and smaller device capacitances of GaN HEMTs, compared with silicon and silicon carbide devices with similar voltage ratings, enable improvements in system efficiency and power density. Hence, GaN HEMT–based power converters, chargers and adapters have gained widespread adoption in consumer electronics applications.

GaN HEMTs face several obstacles in their use for automotive, industrial motor drive and power-grid applications. Voltage scaling for use in 800-V applications and beyond is challenging from a device area scaling perspective for the lateral device, when compared with the vertical SiC devices. Another key factor to consider in these applications is the short-circuit (SC) robustness of the device. SC faults in the load can create conditions in which the device is under high source-drain voltage ($V_{DS}$) and current ($I_{DS}$). As a result, the device is subject to high temperature, electric fields and mechanical stress. These can be catastrophic and result in system failure.

The short-circuit withstand time (SCWT, or $t_{sc}$) is a metric used to gauge the device’s ability to withstand this condition. $t_{sc}$ needs to be long enough for the gate driver to take necessary action and turn the device off. In Si IGBTs, the $t_{sc}$ time is typically rated at about 10 µs, while current SiC MOSFETs are typically in the 3-µs range, with active research activities on expanding this further. Several studies on GaN power HEMTs have reported much shorter times, especially at voltages close to the device maximum $V_{DS}$ ratings, with many reports showing $t_{sc} < 500$ ns for $V_{DS} > 400$ V.

An SCWT safe operating region was presented in Reference 1, where the authors also showed that although the HEMT survived a single SC event (with a $t_{sc} > 300$ µs) at a $V_{DS}$ of 400 V, repeated SC events resulted in a $t_{sc}$ of only 20 ns. In another study, the SC failure in GaN HEMTs was identified to result from the propagation of high electric fields from the gate to the drain. In this article, we will present SC performance on the vertical Fin-JFET GaN device from the work done by a group at the Center for Power Electronics Systems at the Virginia Polytechnic Institute and State University and NexGen Power Systems. This device is in the process of being commercialized by NexGen Power Systems.

A simplified cross-section of the GaN Fin-JFET is shown in Figure 1. The device has a high-electron mobility channel with a low gate resistance and a low reverse leakage current.

Figure 1: Simplified cross-section schematic of the GaN Fin-JFET
shown in Figure 1. The JFET consists of an array of ~1-µm–tall n-GaN fins and a p+ GaN gate-all-around design. Some characteristics of the device tested are:

- 650-V $V_{DS}$ rating
- 0.1-mm$^2$ device active area, assembled in either TO-247 or DFN 56 packages
- ~0.7-V threshold voltage ($V_{TH}$)
- ~0.7-mΩ-cm$^2$ on-state resistance ($R_{DS(on)}$) at 25$^\circ$C and 3-V gate-source voltage ($V_{GS}$)
- ~4.8-A device saturation current ($I_{DSAT}$) at 25$^\circ$C
- ~800-V avalanche breakdown voltage ($BV_{AVA}$) at 25$^\circ$C

SC RESULTS

Figure 2 shows the gate and drain waveforms of these devices taken to a single-event SC fail at various $V_{DS}$ voltages.

For a 400-V bus voltage ($V_{BUS} = V_{DS}$), the part survives to a $t_{sc} > 30$ µs, while at 600 V, the $t_{sc} = 17$ µs. Under the $BV_{AVA} V_{BUS} = 800$-V condition, the part still survives a $t_{sc} > 10$ µs.

The parts fail SC in a failure-to-open (FTO) mode, which is evidenced by Figure 3. This compares the $I_{DSAT}$-$V_{DS}$ waveform between a fresh part and that which has been taken through the SC test to fail. The $BV_{AVA}$ characteristics show the failed part with good source-drain junction behavior, along with a slight increase in gate leakage ($I_{G}$).

These parts also exhibit robust performance under repetitive SC tests. Figure 4 shows the double-pulse–test (DPT) turn-on and turn-off waveform comparisons between a fresh part, versus one that was subjected to 30,000 cycles of 10-µs SC events at a $V_{BUS}$ of 400 V. These waveforms, with the parts switching at 400 V/4 A, show no degradation from the repeated SC cycles.

At a $V_{BUS}$ of 600 V, parts survived such 10-µs SC tests to >8,000 cycles. A progressive, non-destructive failure was seen in parts after cycle #8786 to the final fail at cycle #9785. Gate functionality is retained between these cycles, with $I_{G}$ gradually decreasing. The output characteristics of the device during these conditions are shown in Figure 5.

DISCUSSION OF SC RESULTS

The $t_{sc}$ times measured on this device set a new record for GaN power devices. The waveforms in Figure 2 show a rapid decrease in $I_{DSAT}$ and this is a key enabling factor in the device SC robustness.

To further understand this $I_{DSAT}$ decrease during the SC event, let’s look at the factors that affect this. Figure 6 shows a simulation of the total current density at a $V_{DS}$ of 3 V and 400 V. Significant narrowing of the fin channel is seen near the bottom of the fin at the higher voltage.

The $I_{DSAT}$ at the foot of the channel can be expressed as:

$$I_{DSAT} = q \times n \times A \times V_{sat}$$

Here, $q$ is the electron charge, $n$ is the carrier density, $A$ is the area cross-section at the narrowest current path and $V_{sat}$ is the saturation velocity. Simulations show a decreased $n$ and $A$ at the bottom of the channel due to depletion effects and pinch-off in the channel at higher drain biases in the JFET structure. Further, $V_{sat}$ also naturally decreases with higher temperature due to a decrease in carrier.
mobility. Simulations show the maximum temperature ($T_{j}$) coincides with the narrowest current path location at the foot of the channel, aiding to the lowering of $V_{sat}$. The combination of these factors leads to a significant decrease in $I_{DSAT}$ during SC events. This, in turn, lowers the stress on the device, enabling longer $t_{sc}$ withstand times.

FTO mode is advantageous, as it allows the source-drain junction to sustain the bus voltage even after device failure. Figure 7 shows simulations of the peak electric field when $V_{DS}$ approaches $BV_{AVA}$ under SC conditions. The peak is located at the gate-drain junction and is hence spatially separated from the location of the peak current density. This is different from SiC MOSFETs, where peak current and electric fields coincide at the p-base/n-drift region. This can then lead to latch-up/thermal runaway from the turn-on of the parasitic bipolar transistor and typically create a short failure signature in SiC MOSFETs.

Simulations on the GaN Fin-JFET also show that effective removal of holes generated during SC events is a key factor in improved SC capability at voltages near $BV_{AVA}$. Under these conditions, impact-ionization rates peak at the foot of the fin channel. Simulations show that the dominant path for hole removal is via the p-GaN gate. These holes injected into the gate then facilitate electrons to be pumped from the source to recombine with them, through a process described as "avalanche-through-fin." 

In summary, these 650-V vertical Fin-JFET GaN devices are shown to exhibit excellent single and repetitive SC withstand capability, even at voltages at or near the device breakdown voltage. This can make them well suited for use in harsh automotive, industrial drive and power-grid applications.

References


50 Years of Innovation in Power Semiconductors

EE Times turned 50 last year and has reported on innovation in all electronics fields throughout its history. In the world of analog and power electronics, Power Integrations has been a key innovator since its inception in 1988. Power Electronics News spoke with CEO Balu Balakrishnan about his experience and vision.

By Power Electronics News Editorial Staff

Balu Balakrishnan: First, let me congratulate EE Times on your half-century — I have been an avid reader for many years. It is an essential publication.
In 1972, I was studying for my bachelor’s degree in electronics but already had a great foundation of knowledge about electronics. As a ham radio operator from a young age, I had to build my own power supplies for transmitters and receivers. Of course, in those days, it was all linear. A major change occurred in the late ’80s, when transistors and MOSFETs became available at much higher voltages — all the way up to 600 V. Then it became really practical to use switch-mode power supplies for commercial products. For high power conversion, it wasn’t until the end of the ’90s that IGBTs became the mainstream technology.

Power Electronics News: By the late ’80s, you were successful at National Semiconductor but had not focused on power. What attracted you to join Power Integrations?

Balakrishnan: I was itching to go to a startup. I liked the idea of taking the risk for a big reward. You get stock options, which could be worth a lot if the company succeeds. So I started talking to several companies. Power Integrations intrigued me because it was high-voltage and very different from anything I had done. It was at Power Integrations that I started designing with high-voltage CMOS, but the company’s early implementations were too expensive. I talked with customers and realized it was due to a packaging issue. When you integrate the high-voltage switch with a controller, it requires high-pin-count power packaging, which is very expensive. Through clever integration, we managed to reduce the combination to four pins, but I wanted three. Well, everybody laughed at me because you need two pins just for the drain and source, and there is so much more to deal with. I figured out a way to use the power supply pin for feedback, compensation and auto restart using just one capacitor, which also was the supply bypass capacitor. This meant we could put the integrated high-voltage and pulse-width modulator into a simple, cost-effective three-pin transistor package. Integration also dramatically reduced the part count.

PEN: That product was TOPSwitch?

Balakrishnan: Exactly. On the back of TOPSwitch, we took the company public in 1997. It is still one of the company’s biggest-selling products and continues to evolve and do well. Recently, I visited one of the world’s top appliance companies to introduce them to InnoSwitch (more on that later), which is a truly innovative product. They listened politely and then said, “But we are still very happy with TOPSwitch.”

PEN: If TOPSwitch is an example of innovation in integration, let’s now talk about innovation in efficiency.

Balakrishnan: That would be EcoSmart — another interesting story. In the summer of ’97, a technical paper came out of the Lawrence Berkeley National Laboratory and said that 10% of electrical energy is wasted because of the power that products consume in idle mode while still plugged in. I immediately knew how to solve this problem. in only a few months, we released TinySwitch, a power supply IC with EcoSmart technology that is incredibly efficient at light loads. I was invited by President George W. Bush to give a demonstration of this technology. After that presentation, he wrote an executive order saying that all products purchased by the government had to consume no more than 1 W in standby mode. Depending on the application, the limit can be as low as 30 mW, but TinySwitch can do 2 mW. It took until around 2009 or 2010 for everyone to realize that energy efficiency and standby consumption are very important. For example, the International Energy Agency estimates that to achieve the 2050 goals laid out in carbon net-zero policies from around the globe, almost 37% of the savings has to come from energy efficiency, with another 32% from renewables. Suddenly, energy efficiency has become fashionable.

PEN: Tell us about the famous “Margarita Moment.”

Balakrishnan: Just under 10 years ago, I was concerned that we weren’t having the breakthroughs that have characterized our success. I had to attend a board meeting in the Cayman Islands, so I dragged Mike Matthews, our vice president of product development, down with me. We spent a whole week brainstorming, and it became very clear that we needed the secondary control to be more efficient and do things that couldn’t be done previously. The challenge was figuring out how to communicate across the isolation barrier between the secondary and primary sides. We were even considering using optocouplers inside our chip, but optocouplers are slow, add cost and suffer degradation over time.

On the last day, we were about to catch a flight and had an hour or so to kill. I was sitting in the Marriott reception thinking that we had spent the whole week and still couldn’t come up with anything radical. Finally, I said, “OK, you know, we might as well have a drink and forget it — we’ll do it next time.” As we were drinking margaritas, I said to Mike, “What if I could take the lead frame and use it as a one-turn coupling from one side to the other side?” Mike is very good with magnets. On the flight, we did some calculations to prove we could get enough signal with such a loose coupling. And that is how FluxLink was born. We use it today in many products, including our InnoSwitch family of power supply ICs and SCALE gate drivers.

This illustrates what I refer to as “multi-dimensional innovation.” You can’t just innovate on circuits. It has to be circuits combined with control schemes, packaging, safety isolation, magnets and systems knowledge — it’s a holistic way of thinking.

PEN: What’s your view on GaN?

Balakrishnan: It’s shocking to me that so many companies view GaN as a market in itself. GaN is not a market. It’s a technology that enables us to offer more at the system level. We are technology-agnostic. We’ll use the most appropriate switching technology — silicon, silicon carbide or gallium nitride — depending on the application. That said, GaN, especially our PowiGaN, enables
Before we wrap this up, two questions: Given that we are seeing this huge move to electrification, clean energy, sustainability and low waste, do you think power has finally become “sexy,” and, of course, what’s next?

Balakrishnan: Yes, power is sexy. Nearly 70% of the planned carbon reduction around the globe will come from energy efficiency and renewables — and we play in both of those areas. We are working on a number of products for wind and solar, which is huge. And then, of course, you have all the auxiliary products like converters and inverters as well as battery storage.

We are also working on high-voltage DC transmission, which requires gate drivers. Point-to-point high-voltage DC transmission is relatively straightforward. But if you try to do a DC grid, you have a lot of challenges, including balancing the grid, which requires innovative electronic system solutions.

We have a lot of stuff going on — so many good ideas. We look forward to talking with EE Times about several of them in the very near future.

a far superior high-voltage switch both in terms of performance and cost-effectiveness than silicon above a certain power level. The latest Yole GaN market report confirms that we are the market leader in GaN, and we have shipped the most GaN-based devices primarily in the form of InnoSwitch ICs.

You always have to consider the system. Because GaN can switch at high frequency, some people try to make power supplies that operate at a very high frequency. But the rest of the system doesn’t cope with it very well. Getting the heat out of the transformer is a big problem, and the EMI filter gets really big. It’s like when you squeeze a balloon on one side and it gets huge on the other side.

Our first GaN device was an InnoSwitch device that runs at about 60 to 80 kHz. We are really not taking advantage of the high-frequency capability of PowiGaN in that first product family. Instead, our focus was efficiency and size. We are able to replace the silicon switch with PowiGaN in the same surface-mount package and get 200 W out of it without a heatsink.

We now have higher-frequency versions of PowiGaN-based InnoSwitch (InnoSwitch4) products, which overcome the frequency-related system problems through the use of our ClampZero active-clamp device to reduce transformer losses and dV/dt control of the switch to reduce EMI. This is a great example of optimizing the benefits of GaN technology through system innovations.

What about MinE-CAP?

Balakrishnan: MinE-CAP is another example of system-level innovation. MinE-CAP leverages the small size and low $R_{DS(on)}$ of our PowiGaN transistors to actively and automatically connect and disconnect segments of the bulk capacitor network depending on AC line-voltage conditions. Designers using MinE-CAP can select the smallest high-line-rated bulk capacitor required for high AC line voltages and allocate most of the energy storage to lower-voltage capacitors that are protected by the MinE-CAP device until needed at low AC line. This approach dramatically shrinks the size of input bulk capacitors without compromising EMI, output ripple and operating efficiency or requiring redesign of the transformer. It also significantly reduces in-rush current, making NTC thermistors unnecessary, increasing system efficiency and reducing heat dissipation.
Ensuring PoE-Powered Devices Will Interoperate as Advertised

By Peter Johnson, Ethernet Alliance member and vice president of engineering and co-founder of Sifos Technologies, and David Tremblay, chair of the Ethernet Alliance PoE Certification Program and system architect at Aruba Networks, Hewlett Packard Enterprise’s networking division

Rapid growth in the number and types of devices that rely on Power over Ethernet (PoE) is evident globally. PoE ports, which accounted for 30% of total ports in 2021, are “forecast to comprise nearly half of the total campus port shipments by 2026,” according to the Dell’Oro Group’s “Ethernet Switch – Campus 5-Year July 2022 Forecast Report.” The PoE market through 2030 is “anticipated to flourish at a robust compound annual growth rate of approximately 16.20% to surpass $3.2 billion,” according to a Market Research Future report released in September 2022.

Understanding the environment for standardized PoE is crucial to conceiving, designing and developing IP phones, security cameras, wireless access points, speakers, LED lighting, biometric readers, doorbells/entry systems, electricity/gas meters, point-of-sale systems, swipe-card readers, temperature sensors and a growing range of other products that run over PoE.

One of the most important challenges facing device manufacturers and users is ensuring interoperability of multi-vendor power sourcing equipment (PSEs) and powered devices (PDs). For example, merely utilizing commercial PSEs to test PDs may have grown more commonplace in the rapidly growing market, but it is an ineffective approach for ensuring interoperability. That’s because it overlooks the design flexibility written into the IEEE 802.3 PoE standards. A variety of PSE designs and configurations with widely varying tolerances of different PD traits are being made available, and a given PD’s ability to work with one or a few PSEs does not necessarily project to reliable interoperability with the hundreds of other specification-compliant PSEs and cabling networks that are deployed in the world today.

Bringing clarity and assurance to the global PoE market is at the heart of the Ethernet Alliance PoE Certification Program.

FUELING GLOBAL PoE MARKET GROWTH

Three generations of IEEE 802.3 standards undergird the global PoE market environment today:

- IEEE 802.3af, defining PDs drawing up to 13 W from Ethernet connections and PSEs furnishing at least 15.4 W
- IEEE 802.3at, defining PDs drawing up to 25.5 W and PSEs furnishing 30 W
- IEEE 802.3bt, defining PDs drawing up to 71.3 W and PSEs furnishing up to 90 W

Relying on test plans developed by many of the same individuals who helped write the IEEE 802.3 PoE standards, the Ethernet Alliance PoE Certification Program was introduced in 2017 to improve PoE end-user experience by minimizing market interoperability issues and confusion. Gen 1 EA Certified testing is based on IEEE 802.3af and IEEE 802.3at, and Gen 2 testing is based on IEEE 802.3bt.

The EA Certified program provides a publicly accessible certified product registry, easily recognizable trademarked logos and convenient options for third-party testing in authorized labs in either Asia or North America, or first-party testing via approved test equipment. For example, using the Sifos Technologies PDA-602B and PDA-604A Powered Device Analyzers and associated software, Gen 1 certification testing is fully automated, yielding test reports that can then be submitted to the Ethernet Alliance for logo certification.

The benefits that the Ethernet Alliance program offers to the global PoE community have been...
recognized, such as through the IEEE-SA Conformity Assessment Award and the Cabling Installation & Maintenance Platinum Innovators Award. The program is expressly designed to cut installation time, boost customer support at a lower cost, enhance end-user perception (and thereby adoption) of PoE, reduce overall evaluation costs and help offset other development costs.

PROMOTING BACKWARD COMPATIBILITY

When deploying EA Certified devices, end users simply check that the PSE logo class number is greater than or equal to the PD logo class to gain assurance that a PoE device will interoperate as advertised.

The IEEE 802.3 PoE standards are designed to promote backward compatibility in the space. The standards were crafted so that older PDs would be capable of being fully powered by newer PSEs and older PSEs would be able to work with newer PDs. All three generations of the standards define classification mechanisms whereby a PSE can determine a PD’s desired power demand from a PD.

IEEE 802.3at and IEEE 802.3bt went further to introduce classification mechanisms so that a PD could determine the power that the PSE could provide when initially powering the PD. For example, any interoperable IEEE 802.3at or IEEE 802.3bt PD that requires more than 13 W must be sensitive to the power allocated initially via classification and designed to not draw more than that level of power. Furthermore, that IEEE 802.3at or IEEE 802.3bt PD also must be able to communicate to the PSE (via PoE LLDP) the maximum PD power demand with resolution of 0.1 W, and the PSE can withhold requested power until the PD communicates that power demand. In such an instance where a PD is initially allocated less than its power demand, it is considered to be “power demoted.” Proper handling of power demotion in these ways is key to ensure safe backward compatibility in standardized PoE.

DESIGNING FOR CONFORMANCE AND INTEROPERABILITY

Sifos Technologies, an Ethernet Alliance member and approved provider of test equipment for the program, offers an insightful application note stressing the importance and peculiarities of designing for IEEE 802.3–standardized PoE conformance and interoperability.

For example, the application note raises key points about where using IEEE 802.3–compliant PD controllers can and cannot help in achieving an interoperable product. Whereas manufacturers of integrated PD controllers and PD interface modules may claim that their solutions have been fully tested for IEEE 802.3 PoE conformance (and might even have test data to prove such), the application note shows how there could be more to the story in terms of true PSE-PD interoperability. PD controllers impact only a subset of the conformance properties; indeed, the heavy lifting of achieving interoperability with all of the standardized PSEs in all of the PoE connection environments globally falls outside the PD controller’s scope and role.
SiC Power Module Packaging Solutions for MV Grid Applications

By Sonu Daryanani, contributing writer for Power Electronics News

Some of the power-electronics applications in medium-voltage (MV) power-distribution and conversion applications in the range of 1–35 kV include grid-tied inverters and DC/DC converters for renewable energy systems like solar, power management and interruption devices, such as solid-state circuit breakers, DC/DC converters for DC microgrids and battery-storage systems needing bidirectional inverters.

These applications have traditionally relied on silicon (Si)-based devices like insulated-gate bipolar transistors (IGBTs). Due to their material advantages, including a wider bandgap, lower intrinsic carrier density, higher thermal conductivity and higher saturation velocity, silicon carbide (SiC) power devices offer a number of advantages over Si. These include a lower specific on-resistance ($R_{DS(on)}$) for a given voltage rating, a higher voltage rating than that available with Si (e.g., up to 15 kV for SiC MOSFETs, versus 6.5 kV for Si IGBTs) and much lower capacitances due to smaller die sizes for a given $R_{DS(on)}$. Combining the benefits of lower conduction and switching losses, higher switching frequencies and simpler cooling requirements can translate to lower power-conversion loss, improved efficiency, simpler converter topologies and significantly improved high-temperature ratings and performance, as well as reduced size, weight and system costs.

The packaging of these high-voltage (HV, >3.3-kV–rated) SiC devices and modules for use in these MV grid applications poses several challenges. This article summarizes work done by Professor Christina DiMarino and her group at the Virginia Tech Center for Power Electronics Systems (CPES) on high-density, high-speed 10-kV SiC power module packaging. CPES focuses on research and development dedicated to improving electrical power-processing and -distribution systems, including power-conversion architectures, power-electronics components, modeling, power quality and high-density integration.

CHALLENGES IN HV SiC DEVICE/MODULE PACKAGING

- Due to their faster switching speeds, SiC devices are more sensitive to parasitic inductances from the packaging. These can resonate with the device capacitances, causing undesirable electromagnetic interference. During high-speed current transients (di/dt), large overvoltages can be created across the device, which can degrade device reliability or cause catastrophic fails.

- Parallel devices are often used to achieve module current ratings. Imbalances in parasitic inductances/capacitances or static device parameters like the threshold voltage can result in varying transient voltage overshoots across the paralleled die. Die with higher overshoots will see greater switching losses and thus higher temperatures. This can reduce module lifetimes. External gate resistors are commonly added to control overshoots; however, these increase switching times and hence losses. Low-inductance wire-bondless interconnect schemes have been proposed, for example, with metal-post-interconnected parallel plates. Decoupling capacitors can be used to mitigate the impact of parasitic inductance. One approach places the capacitors above the power device, creating a vertical power loop that keeps the horizontal module footprint unchanged.

- Traditional power modules include a parasitic capacitance across the insulating ceramic substrate (such as direct-bonded copper, or DBC) to the heatsink, which is generally at ground potential. Under higher-voltage transients (dV/dt), this capacitance becomes a path for common-mode (CM) current to flow through the system ground. Filters and chokes can mitigate this; however, they add cost and complexity. A screen layer can be added with the use of multilayer ceramic substrates, which returns the CM current back to the die while also reducing high-frequency noise.

- The high electric field created in these HV devices can exceed the breakdown strength of dielectric materials in the packaging. This can create partial discharge (PD), which can damage the insulating ceramic substrate. Reducing the electric field, and thereby increasing the PD inception voltage (PDIV), near the insulating substrate is key, as this is typically where the PD occurs.
To address these challenges, DiMarino’s group at CPES has proposed an innovative package solution for a 10-kV, 350-mΩ SiC power module with high switching speed, improved HV performance and lower CM current. Experimental validation has also been done on the key aspects of this proposed package. Figure 2 shows the schematic and 3D model of the half-bridge module.

Some of its main design and assembly characteristics are discussed below:

- The half-bridge module has three 10-kV SiC MOSFETs per leg. No external anti-parallel diodes will be used. Significant improvements in the SiC MOSFET body diode enable symmetric reverse conduction with low recovery losses. The module footprint is 74 × 49 × 11 mm without the housing, which gives a power density of 13 W/mm². The added housing and integrated cooler result in a net power density of 4 W/mm².
- In power modules, the electric field concentrates at the intersection of the ceramic, metal and encapsulation, known as the triple point. Stacking DBC substrates can reduce electric field within the bulk ceramic and at the critical triple points. The worst-case field is produced when the low-side switch is conducting. Simulations of the electric field under this condition concluded that in the stacked ceramic approach, the middle metal layer should be connected to half the DC bus voltage, i.e., 5 kV in this case. The peak electric field is reduced by 58% compared with the single substrate case, and it’s uniformly distributed within the two bulk ceramic substrates. The implementation of creating the half bus is done with a pair of 5-kV ceramic decoupling capacitors, as shown in Figure 2(c). The midpoint 5-kV connections of the capacitors are done with metal posts and vias, as shown in Figure 2(d), and connected to the middle metal layer of the bottom DBA stack. The proposed module has a planar sandwich structure. Four substrates were used, as shown in Figure 2(d), with two (DBA1, DBA2) beneath the die and two (DBA3, DBA4) above. The stacked substrate approach effectively increases the PDIV. A pressure-assisted silver (Ag) sintering process was developed for bonding the 50 × 50-mm bottom and the 35 × 75-mm top stacked substrates. Ag sintering has advantages of low void content, higher thermal conductivity and reliability than solder and the ability to undergo multiple sintering cycles without affecting previously sintered joints. After the printed paste is applied and dried, 1 MPa of pressure was applied in a hydraulic press, with the temperature increased to 260°C for sintering. The substrates are cooled under uniform pressure to prevent the CTE mismatch between the aluminum (Al) and aluminum nitride (AlN) from bending or cracking. Line thermal resistance of 0.11–0.14 K/W was measured, which indicates good uniformity.
- Metal posts made of molybdenum (Mo) are used to increase the distance and thereby reduce the electric field between the die and the top substrate. Mo is chosen for its low CTE. Pressure-less and pressure-assisted Ag sintering methods were tried for the post attachment, yielding similar results for bonding strength. The optimal post height is a tradeoff between electromagnetic and electrostatic performance, with a shorter post reducing parasitic inductance and resistance but increasing electric field strength. The field needs to be below the breakdown strength of the encapsulation material. Simulations of the electric field distribution show significant reduction in the field when the post height was increased from 1 to 2 mm; hence, a 2-mm height was chosen.
- The S1D2 node shown in Figure 2(a) experiences high dv/dt as it switches between D1 and S2. To divert the resultant current seen at the system ground back to the DC bus, the intermediate metal layer in a stacked DBC arrangement can be tied to either the positive or negative bus. The amount of current diverted back will depend on the high-frequency impedance of the connection back to the DC bus; hence, the implementation of this CM screen is critical. Connecting the middle metal layer to the midpoint of the decoupling capacitors...
creates a low-inductance path for the CM current flow, balances and reduces the power-loop inductances for the MOSFET switch pairs and reduces the peak electric field at the triple point.

- The resulting module has a power-loop inductance of 4.4 nH/MOSFET pair, which is one of the lowest reported for 10-kV SiC power modules to date.

- The housing has a significant impact on the overall size, thermal resistance and voltage rating. Figure 3 shows the housing design. The external bus bar is mounted on top and pressure applied through mounting screws. The pressure compresses the springs until the bus bar contacts the protrusions in the housing lid. Because the springs are not exposed, creepage and clearance restrictions do not apply. The protrusions create defined air gaps between the housing lid and the bus bar, which can be adjusted to trade off the PDIV and parasitic inductance/resistance from the added connection distance. A larger gap will increase PDIV as well as the parasitics. A 1-mm protrusion height was chosen. Even with this, as shown in the electric field simulation in Figure 4(a), the field strength exceeds the 3-kV/mm breakdown in air. Hence, field-control plates within the bus bar, and serve to shift the peak electric field from air to the solid insulation within the bus bar, as shown in Figure 4(b).

- Baseplate and thermal grease for cooling can increase net thermal resistance and create bending stress on the ceramic substrates. In the proposed package, the bottom DBA is scaled to the housing and a targeted jet-impinged cooling system is used, which injects coolant directly onto the lower surface of the substrate.

- Ag sintering was chosen for the die attach due to its lower thermal impedance and thermal cycling capability compared with solder. Because the 10-kV SiC MOSFET die have gold (Au) backside metallization, and Ag diffuses faster than Au, a sintering profile is needed to limit Ag diffusion and prevent void formation. Hence, 230°C at 90 minutes was used in this study. Average shear strength of 15 MPa was achieved. Applying pressure can improve this to about 25 MPa but adds complexity when sintering multiple die simultaneously.

A prototype module was built in which the springs used had a continuous current rating of 10 A. The housing and integrated jet-impingement cooler was 3D-printed out of high-temperature resin. A Si gel with low viscosity was chosen for the encapsulation due to its simple processing and good reliability with fewer air pockets.

Table 1 lists the process steps and materials selected for the module prototype.

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### Table 1: Packaging processes and materials selected for the 10-kV SiC module

<table>
<thead>
<tr>
<th>Component</th>
<th>Process</th>
<th>Material</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Direct-bonded aluminum (DBA)</td>
<td>Ag-plated 1-mm AlN</td>
<td>High thermal conductivity, voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with vias</td>
<td>isolation, and reliability</td>
</tr>
<tr>
<td>Substrate attach</td>
<td>Pressure-assisted sintering</td>
<td>Nano-Ag paste</td>
<td>Low voiding and high thermal</td>
</tr>
<tr>
<td>Die attach</td>
<td>Pressure-assisted sintering</td>
<td>Nano-Ag paste</td>
<td>conductivity, low thermal</td>
</tr>
<tr>
<td>Intermodule</td>
<td>Pressure-assisted sintering</td>
<td>Detail nano-Ag paste</td>
<td>Low voiding and high temperature,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>thermal conductivity, and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>reliability</td>
</tr>
<tr>
<td>Terminals</td>
<td>Pressure contact</td>
<td>Acrylic springs</td>
<td>Round geometry, easy connection,</td>
</tr>
<tr>
<td></td>
<td>Terminal and connector</td>
<td>Soldering</td>
<td>good reliability</td>
</tr>
<tr>
<td></td>
<td>Soldering</td>
<td>Soldering</td>
<td>Thick line, compliant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Low voiding and high thermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>conductivity</td>
</tr>
</tbody>
</table>

Figure 5 shows the switching performance of the module using a double-pulse test with two SiC 10-kV MOSFETs. The tests were done at 5 kV and 20 A with turn-on and turn-off gate resistors of 0.33 and 0.17 Ω. Table 2 lists the transient parameters from this test. Negligible overshoot and ringing were observed, indicating low gate-loop and source-loop inductances. These results are some of the fastest switching speeds reported for similarly rated SiC MOSFETs and IGBTs.

The effectiveness of the CM screen was measured using an RF current transformer in the ground path with a bandwidth of 200 MHz. Figure 6 shows the turn-off waveforms with three MOSFETs in parallel. The dv/dt is 25 V/ns at a 2-kV bus voltage. As shown, the CM screen lowers the ground-current overshoots from 2 A to 0.2 A, validating its effectiveness.
PD tests were conducted using a 50-kV, 60-Hz AC excitation source and a PD sensor. These tests were completed on both the internal stacked substrates as well as the PCB bus bar with internal field grading. A patterned, 1-mm–thick AlN-DBA substrate with 2-mm spacing between metal traces was used to compare the single substrate with the stacked substrates, in which the middle metal is at half the applied voltage.

As shown in Table 3, the PDIV on the stack when the middle metal is connected to half the applied voltage shows an increase of 53% in air and >40% with encapsulation when compared with the single substrate case. The PCB bus bar with internal field-grading plates was also verified using PD tests. As shown in Table 3, the bus bar demonstrated a PDIV of 12.4 kV in air and 11.6 kV in air with a PD dummy module mounted to the bus bar.

Thermal characterization of the prototype module showed a lowest junction-to-ambient specific thermal resistance of 26 mm²·K/W (0.38 K/W).

In conclusion, DiMarino said, “At CPES, we have proposed a high-density, high-speed module package for 10-kV SiC MOSFETs that could be used in a variety of MV power-conversion and -distribution applications. Our package approach focuses on low parasitics, reducing CM current, achieving high PD voltages and lowering thermal resistance. With this, we can truly take advantage of the superior SiC material characteristics and create highly efficient solutions in this voltage space.”

**References**

The Energy Ecosystem: Technologies Driving the Future of E-Mobility

By Hwee Yng Yeo, e-mobility solutions lead at Keysight Technologies

Climate concerns and evolving consumer preferences are driving technology innovations for electric vehicles as a means toward a greener transportation future.

Innovations for this expanding e-mobility market range from smart inverters, which help to integrate solar energy and other distributed energy resources into the electric grid, to ultra-fast–charging EV supply equipment (EVSE) and increasingly potent battery cells. These technologies also help to provide range assurance and drive the adoption of EVs.

EV sales surged by 160% in the first half of 2021 from a year earlier, to 2.6 million units globally, despite the global pandemic. Technological innovations including better design and test methods across the electronic microcosms of power devices, converters, batteries and chargers are just some of the developments helping to fuel the overall growth of the e-mobility ecosystem. Let’s explore some recent automotive innovations and test methods that are enabling the rolling chassis.
DPT FOR SiC AND GaN POWER DEVICES

Within the EV power ecosystem are power semiconductors — these tiny chips help to convert power among the different systems — such as the power steering and braking, infotainment system, lighting, air-conditioning and, of course, electric powertrain. Increasingly, designers are switching to wide-bandgap (WBG) SiC and GaN power devices to leverage faster switching frequencies, as well as higher voltage and thermal operation ranges.

While WBG devices improve functional efficiency and help reduce both design size and cost, they also suffer from higher switching losses due to the extremely fast oscillations, resulting in reduced efficiency of the power converter.

Power-converter designers are turning to a relatively new method called the double-pulse test (DPT) technique to make repeatable and reliable measurements for determining these switching losses. DPTs can help designers ensure their end products conform to industry standards, such as those set by JEDEC, a global leader in developing open standards and publications for the microelectronics industry.

TESTING AND SAVING WITH REGENERATIVE POWER

Power conversion occurs throughout the EV. Power levels range from ~50 kW up to and over 180 kW. Most of the components in the EV support bidirectional power flow. Besides the modest 12-V battery that powers the vehicle windows and lights, today’s EVs sport batteries from 280 V to 800 V.

Testing at high power is not a simple extension of low-power testing carried out for conventional combustion-engine cars. Working with hundreds of volts, the automaker must prioritize the safety of both human and devices under test. High-power testing also generates tremendous amounts of heat, which add to air-conditioning operation costs.

An increasingly popular cost-down solution is to use commercially available regenerative-power systems that provide bidirectional, regenerative DC or AC power. The regenerative capabilities of these power supplies allow the energy consumed to be put back onto the grid cleanly instead of being dissipated as heat, thus saving costs from energy consumption and cooling.

UNDERSTANDING CELL SELF-DISCHARGE TO MAKE LONGER-LASTING BATTERIES

EV batteries have improved vastly since the early 2010s, when they supplied only 50–60 miles per full charge. These days, the average EV battery offers 250 miles per full charge, enough to assuage the range anxiety of most drivers.

Creating better batteries starts from understanding cell chemistry. A complaint of cell designers is the phenomenon of abnormally fast self-discharge in lithium-ion cells. Cell self-discharge is the reduction of the stored charge of the battery even when it is not connected to any device. Self-discharge decreases the shelf life of Li-ion cells and causes them to initially have less than a full charge when used.

To detect abnormal self-discharge in Li-ion cells, developers and manufacturers have traditionally relied on measuring the drop of a cell’s open-circuit voltage over a period of several weeks or even months to obtain good validation results. Having to wait this long during development results in lost opportunities by being late to the market with new designs. This is further compounded if self-discharge testing must be repeated. In manufacturing, storing large quantities of cells for a long time to screen them for self-discharge presents major expense, logistics and safety problems.

EV & EVSE: ENSURING INTEROPERABILITY

The EV is connected to the grid via an increasingly sophisticated network of EVSE. According to a Reuters report, there are more than 300 EV charging companies globally. Combine that with over 500 EV models, different charging modes and charging standards around the globe, and we can see why charging EVs at different charging stations is not as simple as filling up the gas tank.

To address this interoperability challenge and accelerate time to market, many EV and EVSE manufacturers are investing in simulation solutions that can save them time and money.

These design verifications use machines that can simulate both EVs or charging stations, solving the challenges of uniquely testing a new product under different EV or EVSE models.

CREATING A SUSTAINABLE ENERGY ECOSYSTEM

The automotive industry will face evolving consumer demands, such as whether the product meets environment, social and governance (ESG) goals. New test technology will need to evolve in tandem to help develop better electronic microcosms like power devices, converters, cells, batteries and drivetrains. At the macrocosm level, we will see smarter grids harnessing renewable energy to power the growing fleets of EVs and meet our ESG goals as a civilization.
Power Steering with GaN ePower ICs

By Marco Palma, director of motor drive systems and applications at Efficient Power Conversion (EPC)

In modern cars, the increased weight and the wider front tires make unassisted steering impractical because of increased resistance to the operator; thus, several years ago, power steering was adopted. In the beginning, the assistance to the driver was accomplished with hydraulic systems, and always-operating pumps were used to provide the necessary pressure to the liquid used in the circuit. However, the governments’ call to reduce emissions required car manufacturers to shift to electric power steering (EPS).

With EPS, the hydraulic system is replaced with an electric motor that aids the driver only when needed. Its digital assistance control can be modified online to adapt to driving conditions. There are, however, several design constraints to consider. One is that the driver does not want to lack the haptic feedback from the tires, especially when a vehicle is large, such as a truck. Other constraints are determined by safety regulations, particularly for automatic guided vehicles. These constraints require adopting an efficient, accurate and redundant system. Gallium nitride technology helps the designers in all these areas.

DIFFERENT TYPES OF EPS

EPS reduces energy consumption because it assists only when the driver actuates the steering wheel. A downside to EPS is the challenge to mimic the tactile feel of “traditional” hydraulic power steering. The working principle of EPS is simple: There are sensors at the steering column to detect the steering angle and torque, an electronic control unit (ECU) that analyzes the signals and determines the amount of assistance needed and an electric motor mounted at the steering column or rack that actuates the assistance force according to the instruction from the ECU. Depending on the actuating mechanism, several types of EPS are widely used in production cars. In this article, we will take a look at some of them.

Column-type EPS (Figure 1) is widely used in small economical vehicles. In column EPS, the motor is mounted at the steering column and drives the steering shaft directly. Its advantage is simple construction and low cost. Because the motor is located inside the dashboard, it is not subjected to water and extreme temperatures; thus, the production cost could be lowered further. The motor is mounted at the top of the steering shaft, increasing inertia and friction, but eliminates the haptic feedback for the driver.

Parallel-axis EPS (Figure 2) has the motor mounted in the rack between the tires. The construction method determines the cost and the driver’s “feeling” while driving.

Figure 1: Column-type EPS. The assistance motor is inside the red box.

Figure 2: Parallel-axis EPS. The motor shaft is parallel to the rack inside the red box.
Parallel-axis EPS is more expensive, but it is also more accurate and has been adopted by cars that offer automatic driving assistance.

The torque and position sensors are in the steering wheel, as well as in the rack. The motor is coupled directly to the rack by a belt and a recirculating ball gearbox that offers a conversion ratio of 4:1. For safety reasons, also depending on the vehicle size, the motor windings and the inverter are made redundant, to have the assistance available even in case of partial system failure. Because this system is used in automatic driving systems, motor control precision is essential.

The steer-by-wire system (Figure 3) can eliminate the steering column and the mechanical connection between the steering wheel and the steering gear. A sensor on the vehicle’s steering wheel senses each rotary movement. As in parallel-axis EPS, an electric motor on the rack’s steering gear generates forces transmitted to the tie rods. Another electric motor on the steering wheel generates the haptic feedback familiar to the driver from conventional steering systems. This steering system can be adapted to suit the driver’s preferences electronically. And it has become essential in large vehicles, such as agricultural machines and trucks.

**EPS INVERTER DESCRIPTION**

The electronic part controlling the motor attached to the rack in the EPS comprises at least two inverters that provide for redundancy. The motor has three, six or nine phases, depending on the vehicle, and for every three phases, there is an inverter. In the case of a single three-phase motor, there are at least two inverters. In state-of-the-art systems, the motor is controlled without sensors using the conventional field-oriented-control (FOC) technique. In advanced driver-assistance systems, precise torque control at zero speed is needed, and it is obtained through high-frequency-injection (HFI) algorithms. The block diagram for one inverter is shown in Figure 4.

A similar system without redundancy, as shown in Figure 4, is used at the steering wheel for haptic feedback in the steer-by-wire–ready systems.

In all of these cases, GaN technology helps increase efficiency, reduces size and ensures high control accuracy over traditional silicon devices, offering improved performance and a safer driving experience.

**GaN FETs AND ICs BENEFIT THE INVERTER AND MOTOR**

GaN devices are the leading innovation in power conversion. The benefits and technical advantages of GaN-based inverters are becoming more evident in motor drive applications. GaN FETs can switch faster while wasting less switching energy than their silicon MOSFET counterparts. Moreover, a GaN FET has a lower on-state resistance per square millimeter of area, and this helps shrink the die size and increase power density in converters.

Using GaN monolithic integrated circuits (ICs) for power conversion introduces further advantages compared with their discrete equivalent. Gate-loop inductance is substantially eliminated because the gate driver and power device are integrated on the same die. The short path between the power devices also reduces the common source inductance of the high-side device. Moreover, thanks to chip-scale packaging, power-loop inductance is minimized. The overall dimensions of the circuits are reduced, as...
no external gate drivers are needed. Using LGA and QFN packaging eases connecting the devices to a heatsink, enhancing the thermal resistance from the junction to ambient temperature.

Recently, EPC introduced its ePower stage EPC23102, which combines all the features previously described. EPC23102 is rated at 100 V maximum bus and can deliver 35-A continuous current at 1-MHz switching frequency into a load; the integrated power FETs have a typical on-resistance of 6.6 mΩ. An external 5-V supply biases the internal circuits, and the input logic is compatible with 3.3-V and 5-V CMOS technology. External resistors tune the switching transition so the designer can define the best compromise between rise and fall times and overvoltage spikes and ringing. Internal circuitries include level shifting and synchronous bootstrap for high-side device power. The block diagram of EPC23102 is shown in Figure 5.

In motor drive applications, a GaN inverter can switch at hundreds of kilohertz and reduce the dead time to tens of nanoseconds. The designer can choose the transition voltage slope (dV/dt) applied to the motor windings by trading off EMI, power consumption and winding insulation requirements. A slope of 5 V/ns is commonly used in these applications. Increasing the pulse-width–modulation (PWM) frequency and reducing the deadtime allows for the input filter reduction and the use of only ceramic capacitors. It also improves motor efficiency because the lower total harmonic distortion of the applied voltage generates an applied torque with fewer harmonics. The harmonics in the torque cause undesired vibrations that only contribute to mechanical loss. Another essential effect of PWM frequency increase is shown in Figure 6, where the same motor, operated at a high temperature near saturation at 100 kHz, shows a better current control with less ripple than when controlled at 20 kHz.

The ability to increase the PWM frequency up to 100 kHz is also beneficial to the HFI algorithm for accurate motor control at zero and very low speeds. Under these conditions, traditional sensorless FOC algorithms based on indirect back-EMF sensing do not work. They need to be upgraded with the HFI of modulating signals (in the range of a few kilohertz) to determine the rotor magnet position. The accuracy of the rotor position detection depends on the ratio between the PWM frequency and the injected frequency. The higher the ratio, the higher the accuracy in the position detection and hence the precision in the motor control.

**EPC MOTOR DRIVE REFERENCE DESIGNS**

IC-based motor drive applications allow for smaller boards and easier design. EPC released two reference design boards for motor drive inverters using ICs.

EPC9173 is a 1.5-kW motor drive board including six EPC23101 ICs. The excellent thermal performance of the PQFN makes the inverter able to deliver 20-A_{peak} current to the motor without a heatsink and 25-A_{peak} current with a heatsink, keeping the temperature increase of the die with respect to ambient below 50˚C for switching frequencies up to 100 kHz.

EPC9176 is a 400-W motor drive inverter using three EPC23102 ICs with a wide input voltage range of 14–65 V. It can deliver 15-A_{peak} current to the motor without a heatsink and 20-A_{peak} current with a heatsink, and natural convection cooling keeps the temperature increase of the die with respect to ambient below 60˚C for switching frequencies up to 100 kHz.

The EPC9173 and other equivalent motor drive reference designs (such as the EPC9167HC) can be used as a starting point to develop and test GaN technology for the motor in the gearbox. The EPC9176 can be used for the haptic feedback motor in the steering wheel for agricultural machines and trucks. All EPC motor reference designs come with a standard connector from the power board to the motion controller, so the designer can use their preferred controller without having to design a power board at the initial development stage. The EPC9173 reference design board and a zoomed detail of the switching cell are shown in Figure 7.

![Figure 7: EPC9173 reference design with EPC23101 GaN IC in QFN package](image-url)
Motor Control

for current measurement, phase voltage sensing, DC bus voltage sensing, Hall/encoder interface for sensored control and protection circuits like overcurrent protection and undervoltage lockout.

GaN devices introduce several advantages in motor drive applications with respect to silicon MOSFET–based inverters, whose switching frequency is typically limited to 40 kHz by the switching losses and deadtime is usually in the range of 200–500 ns. GaN-based inverters operate at hundreds of kilohertz and with a deadtime of tens of nanoseconds, eliminating the harmonics in the torque, reducing vibrations and increasing the motor efficiency. The higher PWM frequency allows better precision in the motor control at low speeds when the HFI algorithm is used in conjunction with sensorless FOC.

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Onsemi and VW Group announce strategic collaboration on SiC technology for next-gen EVs

Onsemi recently announced that it had reached a strategic partnership with Volkswagen AG (VW) to supply power modules and chips for a full electric vehicle (EV) traction inverter solution for VW’s next generation platform family. The chips are a component of a larger system optimization and offer a solution for the VW models’ front and rear traction inverters.

New All-in-One Hybrid Power Drive Module Solution from Microchip is Designed for Electric Aviation Applications

Aircraft manufacturers designing More Electric Aircraft (MEA) are looking to convert the flight control systems from hydraulic to electric to reduce weight and design complexities. To meet the needs for an integrated and configurable power solution for aviation applications, Microchip Technology has announced a new comprehensive hybrid...

New Rare Earth Minerals Deposit in Sweden

LKAB has identified more than one million tonnes of rare earth oxides in the Kiruna area which is located in the far north of Sweden. A Swedish state owned mining company, LKAB, announced last week that it had found Europe’s largest known deposit of rare earth elements. This discovery could reduce the continent’s reliance on China for this critical resource.

Design Higher Density and Lower Cost Lidar Systems with New 80 V, 15 A GaN eToF™ Laser Driver IC

Efficient Power Conversion (EPC) introduces EPC21701, an 80 V laser driver IC capable of 15 A pulsed current for time-of-flight (ToF) lidar applications including vacuum cleaners, robotics, 3D security cameras and 3D sensing. EPC announces the release of the EPC21701, a laser driver that monolithically integrates an 80 V, 40 A FET with gate driver and 3.3 V logic level input into a single chip...

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This Electronica 2022 presentation discusses...

Electronica 2022: Interview with Alex Lidow, CEO of EPC

In this interview, Lidow will talk about technology during these 50 years of EE Times, the next challenges for our industry, and the growth of GaN.

Panel Discussion about Technical Trends with Power Conversion

Innovative power management devices improve power-factor correction and lower standby power consumption to offer energy-efficient solutions across all industrial, consumer, and automotive applications.

Sensors in Industry 4.0: vibration monitoring

Industry 4.0, also known as the fourth industrial revolution, is a term used to describe the current trend of automation and data exchange in manufacturing technologies, including the Internet of Things (IoT) and artificial...

The diverging worlds of SiC and GaN semiconductors

Gallium nitride (GaN) and silicon carbide (SiC) semiconductors are now in mass production and rapidly gaining market share. According to market research firm Yole, by the end of 2027, GaN and SiC devices will...

Motor Control Design Trends

In this podcast with Jose Quinones, Staff Applications Engineer at Qorvo’s Programmable Power Management Group, we will analyze the fundamental concepts every designer, maker, or student must master to face a motor control application.

Energous Expands Wireless Power Network Ecosystem

The Internet of Things (IoT) ecosystem is rapidly and incessantly expanding, with an ever-increasing number of connected devices thanks to the diffusion of smart technologies, the transformation...
Next-Generation Battery Management System Architectures
Switching battery architecture from 2×400 V to 800 V: one more step forward to greener mobility. This white paper explores the rapid roll-out of EV HVBMS technologies as well as challenges of giving the best of both worlds: 2×400 V/800 V to OEMs.

How to Overcome the Limits of Boost Converters
This article will explain the inherent limitations of the boost topology and how to overcome them. When designing and evaluating boost converters, sometimes the intended output voltage is not realized. Instead, it has a lower value than desired.

GaN and SiC, Devices and Technology – Download our eBook
Improved energy efficiency and growing demand for longer battery life are prompting the power electronics community to take yet another hard look at the tradeoffs presented by wide-bandgap semiconductor technology operating at higher voltages, temperatures, and frequencies.

Noise Reduction Network for Adjustable Low Dropout Regulators
Noise is a parameter that is extremely important to designers of high-performance analog circuits.

The Power Electronics News & Know-how e-mail newsletter informs about Products, Technologies, Applications and technical Trends about Power Supplies, Power Components, Thermal Management and more.