Sustainability and Energy Harvesting | Volume 15

We get technical

How to design in SiC MOSFETs to improve EV traction inverter efficiency

Design for the energy revolution

Achieving high efficiency in telecom power supplies

Shifting product design to net-zero sustainability

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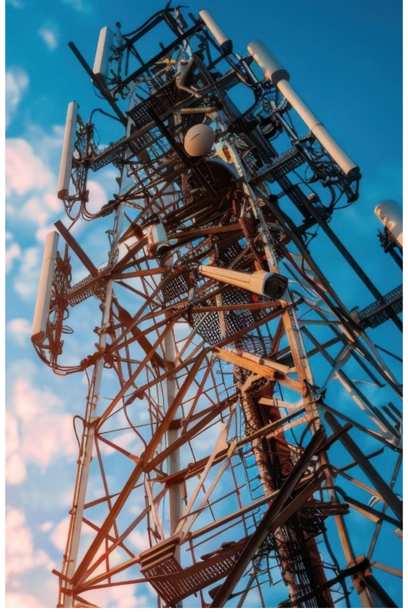


contents

Editor's note

Welcome to the *Sustainability & Energy Harvesting eMag Volume 15*, where we explore the latest advancements in technologies that are driving the transition toward a more sustainable future. This issue covers a diverse range of topics, from optimizing energy systems for green hydrogen production to improving the efficiency of electric vehicle (EV) components, all while harnessing innovative solutions that reduce energy consumption and enhance performance.

We begin by addressing a critical aspect of the green hydrogen revolution: ensuring efficient and stable DC current for hydrogen production. This article provides valuable insights into the systems that power this growing industry, emphasizing the importance of reliability and efficiency.

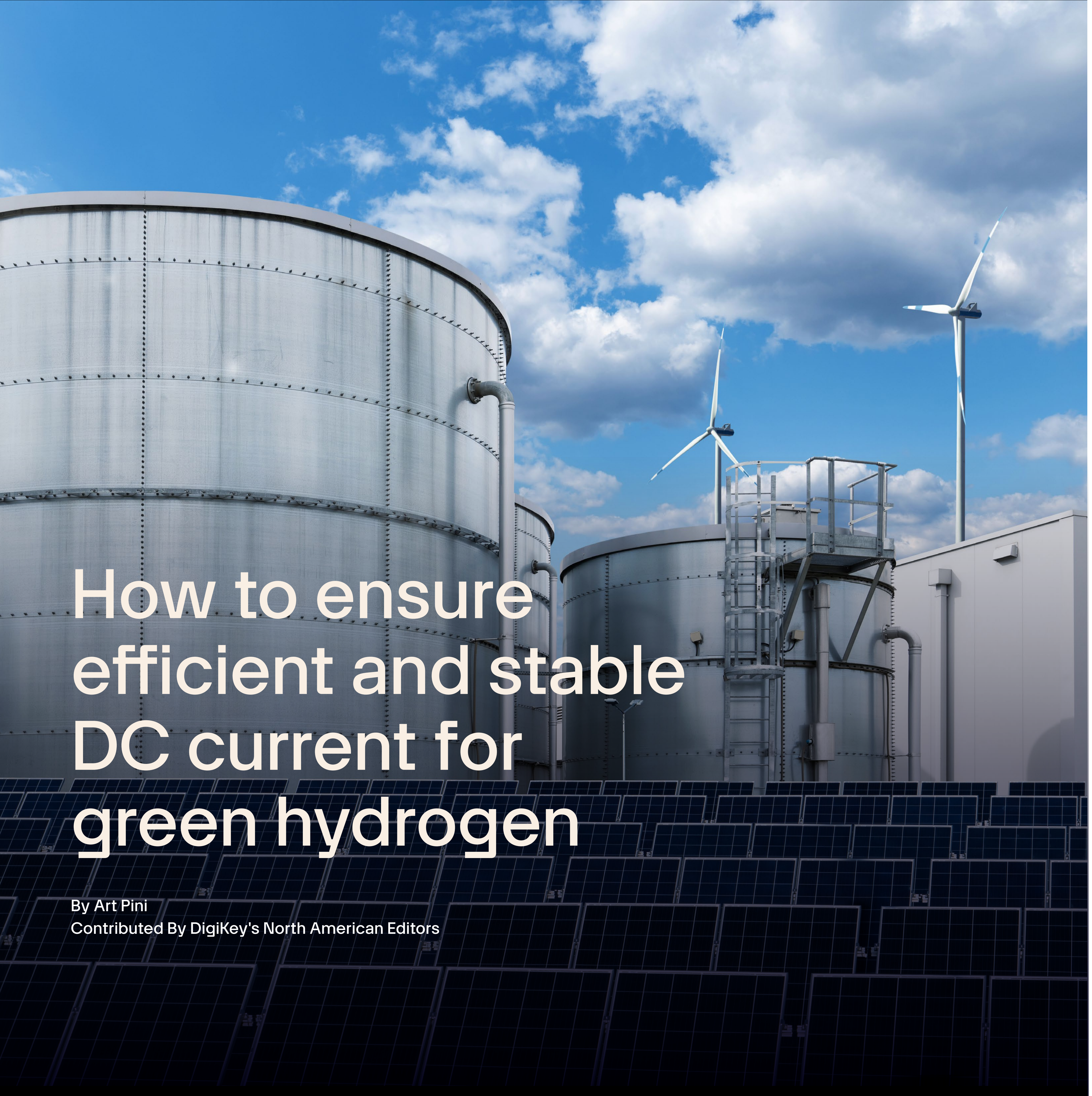
Next, we take a deep dive into the role of wide bandgap technology in LED lighting, specifically how it can maximize both efficiency and power density for high-voltage applications. These advancements are paving the way for more sustainable lighting solutions that have the potential to revolutionize industries around the world.

For those working in the electric vehicle sector, we explore how SiC MOSFETs (Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistors) can improve EV traction inverter efficiency. By enhancing power conversion and thermal management, these components are helping to make EVs more energy-efficient and cost-effective.

We also discuss adjustable speed industrial motor drives, a key technology for optimizing energy use in industrial environments. Understanding the various types of these drives can significantly contribute to reducing energy waste and improving overall operational efficiency.

Finally, we examine strategies to achieve high efficiency in telecom power supplies, which are fundamental to supporting the infrastructure needed for global communications while minimizing environmental impact.

Throughout this issue, we showcase the ingenuity and forward-thinking that are driving the sustainable energy landscape forward. Whether you're working in energy harvesting, power electronics, or green technologies, we hope the articles inspire new ideas and practical solutions to meet the challenges of our time.



How to ensure efficient and stable DC current for green hydrogen

By Art Pini
Contributed By DigiKey's North American Editors

The shift toward green hydrogen promises to reduce the level of greenhouse gases. Energy from renewable sources like hydroelectric, wind, and solar power, whether generated locally or transmitted via the power grid, must be converted efficiently to direct current (DC) to electrolyze water. For system designers, providing high and stable DC levels with low harmonic distortion, high current density, and good power factors (PFs) presents a challenge.

This article discusses the principle of green hydrogen. It then introduces power components from Infineon Technologies and shows how they can be used to convert the input from environmentally friendly energy sources into stable electrical power outputs with the characteristics required to generate green hydrogen.

Hydrogen generation by the electrolysis of water

Hydrogen can be separated from water by the process of electrolysis. The co-product of this process is oxygen. The electrolysis process requires the application of steady, high levels of DC. This process occurs in an electrolysis cell or electrolyzer that typically contains an anode (positive electrode) and a cathode (negative electrode) where the electrochemical reactions occur. A liquid or solid electrolyte encloses the electrodes and conducts the ions between them. A catalyst may be needed to increase the reaction rate depending on the process being used. The cell is powered by a steady, high-level DC source or power supply (Figure 1).

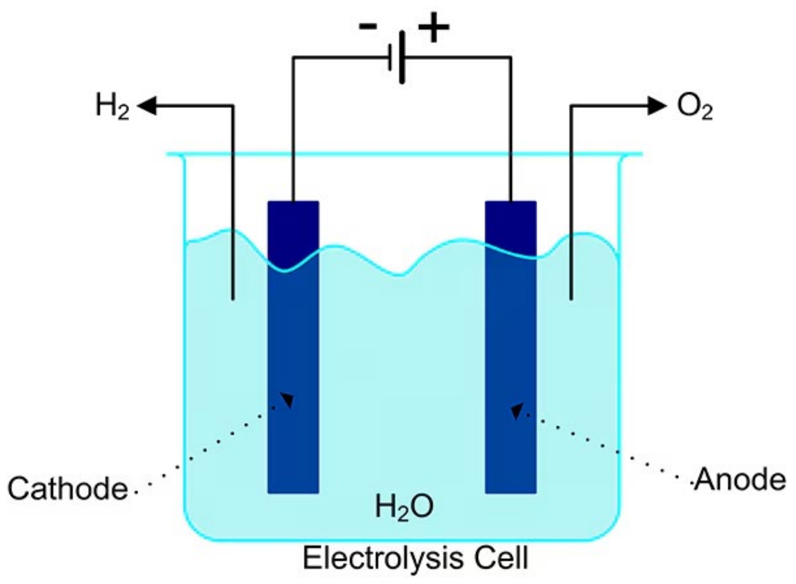


Figure 1: A basic electrolysis cell separates water's hydrogen and oxygen elements. (Image source: Art Pini)

The cell also includes a separator (not shown in this diagram) to prevent the hydrogen and oxygen produced at the electrodes from mixing.

The process requires high levels of DC. Under ideal conditions with no energy loss, a minimum of 32.9 kilowatt hours (kWh) of electrical energy is required to electrolyze enough water molecules to produce 1 kilogram (kg) of hydrogen. This will vary depending on the efficiency of the electrolysis process being used.

Three different processes are currently in use: alkaline electrolysis (AEL), proton exchange membrane (PEM), and solid oxide electrolysis.

The most established electrolyzers are AEL electrolyzers, which use an alkaline solution such as potassium hydroxide between the metal electrodes. They are less efficient than the other types of electrolyzers.

PEM electrolyzers use a solid polymer electrolyte enhanced with precious metal catalysts. They are characterized by higher efficiency, faster response times, and compact designs.

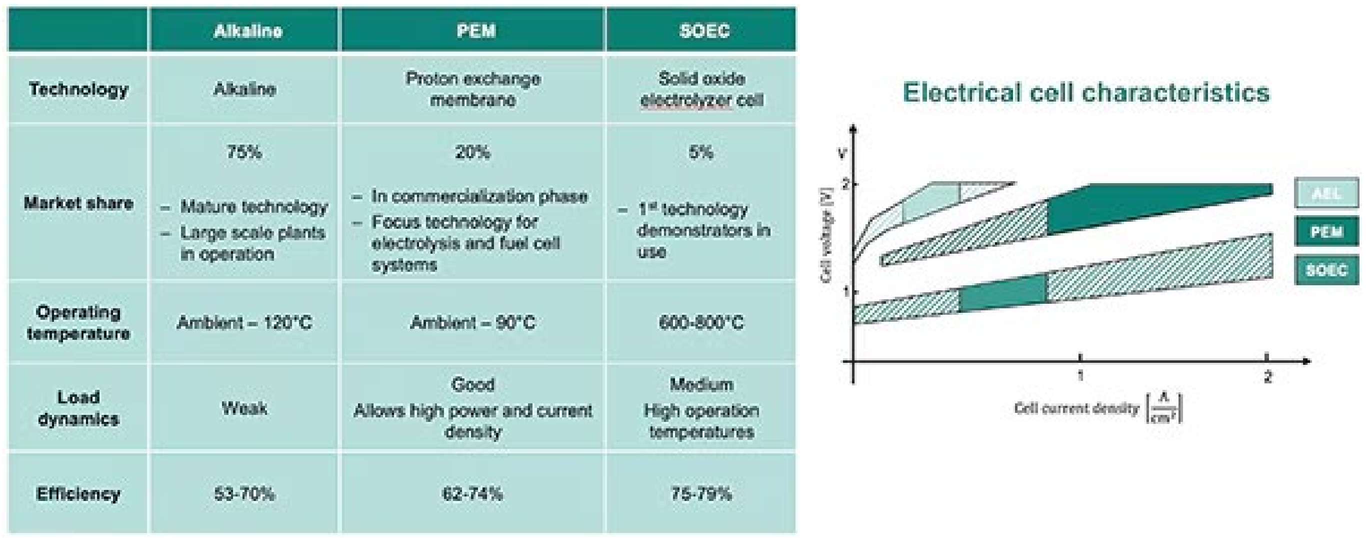
Solid oxide electrolyzer cells (SOECs) use a solid ceramic material as the electrolyte. They can be highly efficient, but they require high operating temperatures. Their response times are slower than the PEM electrolyzers.

A comparison of the characteristics of the three techniques is shown in Figure 2.

Green hydrogen generation currently costs more to produce than hydrogen from fossil fuels. This can be reversed by improving the efficiency of the discrete components, including the electrolyzers and power systems, and scaling up the conversion plants.

Power system configurations for grid and green power sources

Currently, most hydrogen-generating plants are operating off the power grid. The power source for an electrolyzer is an AC to DC rectifier fed from a line transformer.



	Alkaline	PEM	SOEC
Technology	Alkaline	Proton exchange membrane	Solid oxide electrolyzer cell
Market share	75% – Mature technology – Large scale plants in operation	20% – In commercialization phase – Focus technology for electrolysis and fuel cell systems	5% – 1st technology demonstrators in use
Operating temperature	Ambient – 120°C	Ambient – 90°C	600-800°C
Load dynamics	Weak	Good Allows high power and current density	Medium High operation temperatures
Efficiency	53-70%	62-74%	75-79%

Figure 2: A comparison of the characteristics of the AEL, PEM, and SOEC processes highlights the improving efficiencies of the newer electrolyzers. (Image source: Infineon Technologies)

Electrolysis plants powered from the grid must meet all grid standards and codes, such as achieving a unity PF and maintaining low harmonic distortion. Different power systems are required as green power sources are incorporated into the hydrogen separation process (Figure 3).

Like the power grid, wind-based power sources are AC, and powering electrolysis cells from them requires a rectifier to convert the AC into DC. Solar energy and hybrid sources using batteries rely on DC/DC converters to control the DC levels driving the electrolysis cells. The electrolysis cell may also employ a local DC/DC converter regardless of the power source. The electrolysis cell represents a constant DC load. Due to aging considerations within the electrolyzer cell, the applied voltage needs to increase over the cell's lifetime, so the power conversion system (PCS) should be able to accommodate that process. PCSs, whether mated to an AC or a DC source, will have some common specifications.

Their output voltage should be in the range of 400 VDC to 1,500 VDC). Alkaline cells have a maximum voltage range of approximately 800 V. PEM cells are not as limited and are moving toward the high end of the voltage range to lower losses and reduce costs. The output power range can be 20 kilowatts (kW) to 30 megawatts (MW). The current ripple from the PCS should be less than 5%, a specification still being studied for its effect on the cell's lifetime and efficiency. PCS rectifier designs for power grid sources, especially for higher power loads, must comply with power companies' large load and PF requirements.

Power conversion for AC sources

AC-powered hydrogen plants require a rectifier that may drive an electrolysis cell directly or may drive a DC grid attached to multiple cells.

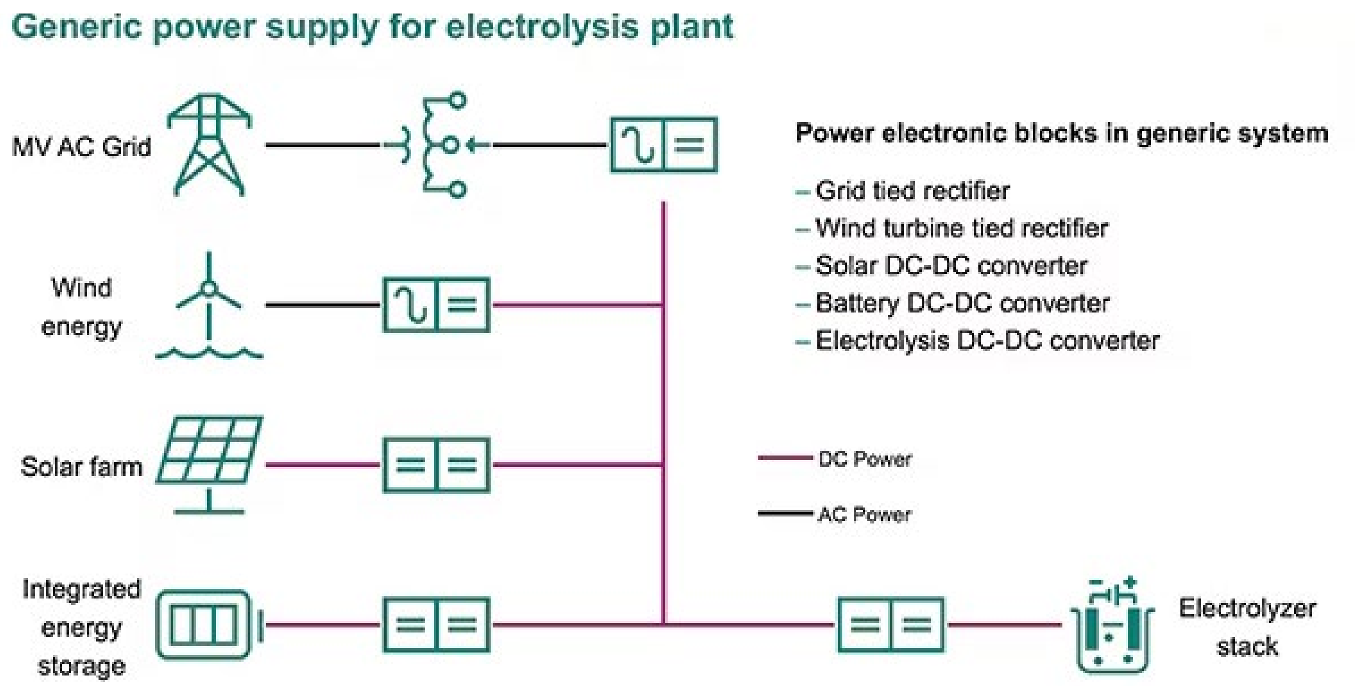


Figure 3: Electrolysis plants must convert power from the source into DC for the electrolysis cells. (Image source: Infineon Technologies)

A multi-pulse rectifier is a common choice (Figure 4). Thyristor-based, this rectifier design has high efficiency, is reliable, supports high current densities, and uses low-cost semiconductors.

Multi-pulse, thyristor-based converters are an established and well-known technology. The 12-pulse thyristor rectifier shown in Figure 4 consists of a wye-delta-wye power frequency transformer with two low-voltage secondary windings. The secondary windings drive two six-pulse thyristor rectifiers with their outputs connected in parallel. If this rectifier drives an electrolyzer directly, the thyristor firing angle controls the output voltage and the current flowing into it. The firing angle can also be used to maintain the current in the system as the electrolyzer cell ages, and the voltage required for the cell stack increases. The transformer may also include an on-load tap changer (OLTC). The OLTC changes the transformer turns ratio by switching among multiple access points or taps on one of the windings to raise or lower the voltage supplied to the rectifier.

Infineon Technologies offers a broad range of semiconductor component choices to PCS designers. Thyristor rectifiers are commonly used for these AC-source applications. For example, the T3800N18TOFVTXPSA1 is a discrete thyristor in a chassis mount TO-200AE disc package that is rated to handle 1800 V at 5970 amperes root mean square (A_{rms}) on-state current. The disc package offers increased power density due to its double-sided cooling design.

The basic rectifier design can be improved by adding buck converters as post-rectification choppers at the rectifier output. Adding the chopper stage enhances control of the process by adjusting the chopper's duty cycle rather than the thyristor's firing angle (Figure 5). This reduces the dynamic range required for the thyristor, allowing optimization of the process.

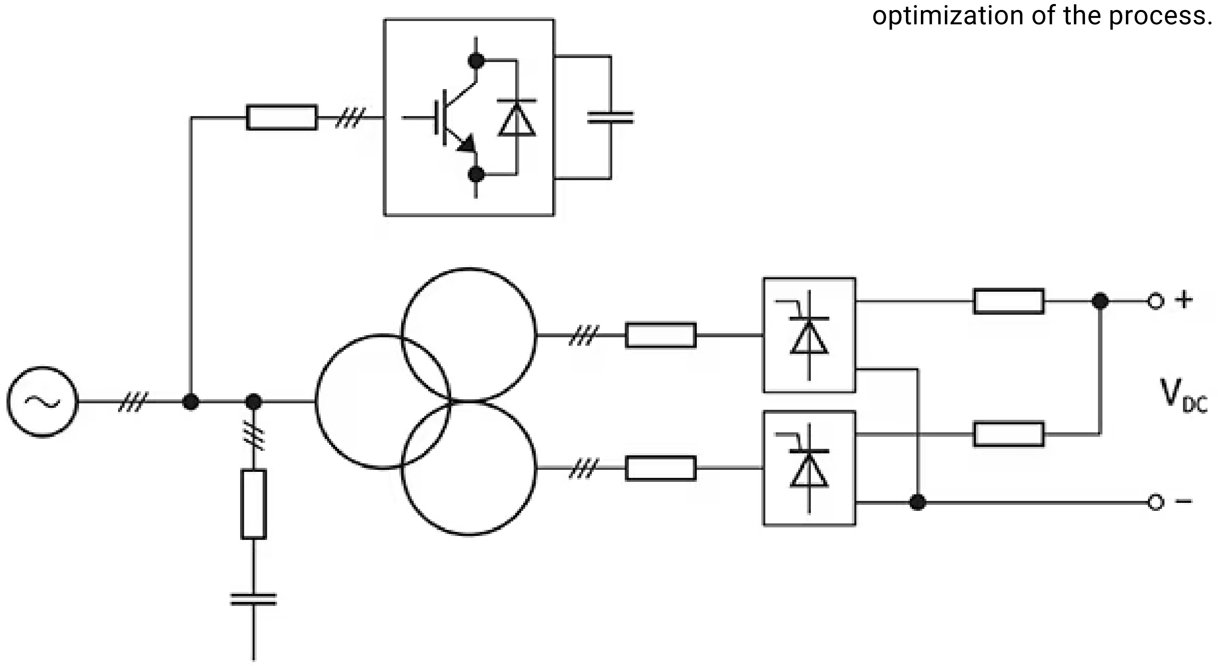
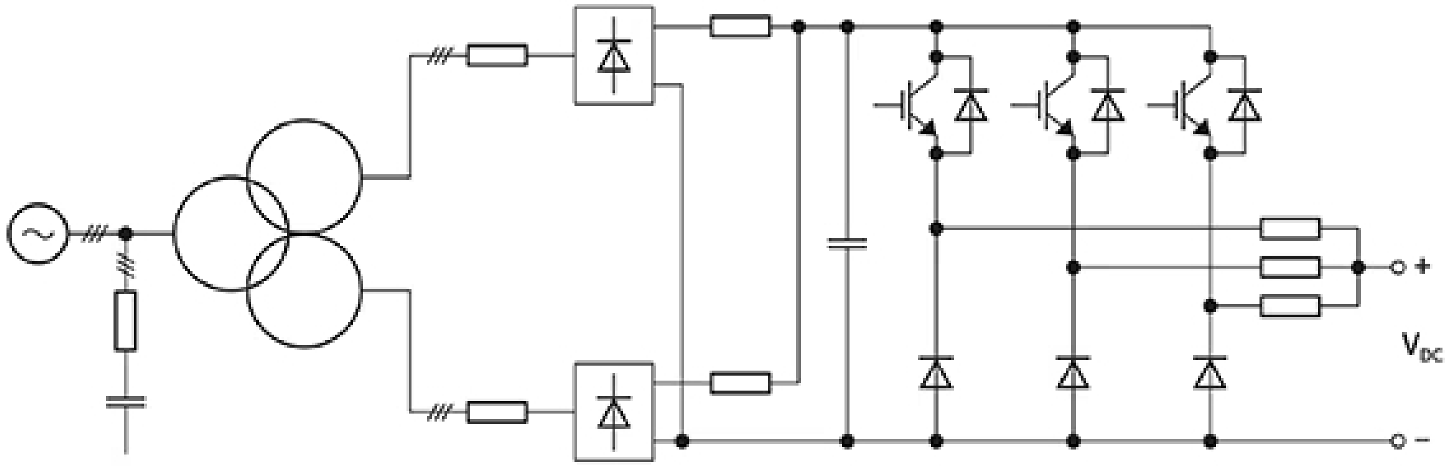


Figure 4: A multi-pulse rectifier based on thyristors has high efficiency, is reliable, supports high current densities, and uses low-cost semiconductors. Shown is a 12-pulse implementation. (Image source: Infineon Technologies)

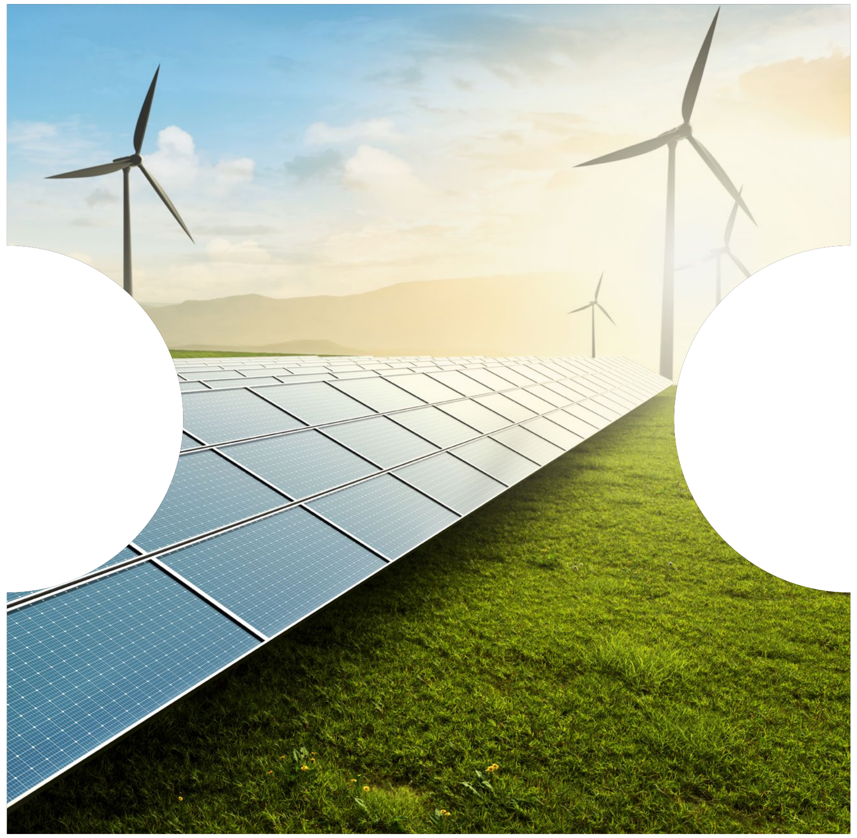
Figure 5: A post-rectification chopper reduces current distortions and improves the PF. (Image source: Infineon Technologies)



Applying the post-rectification chopper using insulated gate bipolar transistors (IGBTs) eliminates the need for the OLTC transformer, reduces current distortions, and improves the PF.

Infineon Technologies' FD450R12KE4PHOSA1 is an IGBT chopper module intended for these applications. It is rated for a maximum voltage of 1200 V and a maximum collector current of 450 A, and comes in a standard 62 millimeter (mm) C-series module.

More advanced rectifier circuits include IGBT-based active rectifiers. Active rectifiers replace diodes or thyristors with IGBTs that a controller switches on and off at appropriate times via a gate driver (Figure 6).



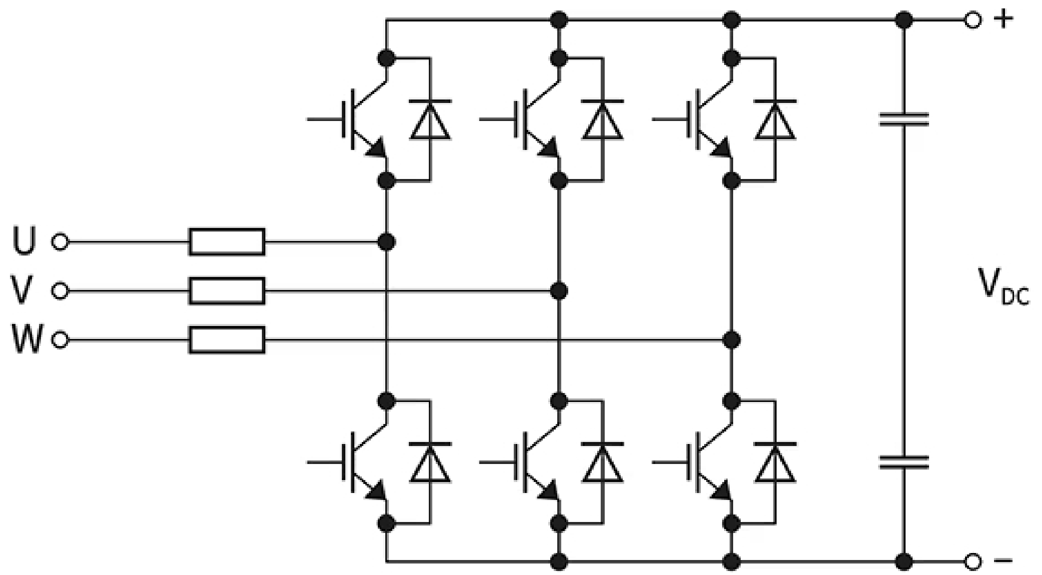


Figure 6: An active rectifier replaces the diodes or thyristors in the rectifier circuit with IGBTs, which are switched by a gate driver controller. (Image source: Infineon Technologies)

Unlike a traditional rectifier, which produces non-sinusoidal line currents, an active rectifier has an inductor in series with the IGBTs that keeps the line current sinusoidal and reduces harmonics. The impedance of the IGBT when conducting is very low, which reduces conduction losses and improves efficiency compared to a standard rectifier. An active rectifier controller maintains a unity PF, so external power factor correction (PFC) devices are unnecessary. It also operates at higher switching frequencies, resulting in smaller-sized passive components and filters.

The FF1700XTR17IE5DBPSA1 combines dual IGBTs in a half-bridge configuration in a PrimePACK 3+ modular package. It is rated to handle 1700 V with a maximum collector current of 1700 A. The circuit shown in Figure 6 would use three such modules.

An IGBT gate driver such as the 1ED3124MU12HXUMA1 turns a single IGBT pair on and off. The gate driver is galvanically isolated using coreless transformer technology. It is compatible with IGBTs having voltage ratings from 600 to 2300 V, and has a typical output current of 14 A on separate source and sink pins. The input logic pins operate on a wide input voltage range from 3 to 15 V using CMOS threshold levels to support 3.3 V microcontrollers.

Power conversion for DC sources

Separating hydrogen using DC power sources such as photovoltaic energy and battery-based hybrid systems requires DC/DC converters. As noted earlier, these converters can improve the performance of diode/thyristor rectifiers. They also permit the optimization of local DC grids for plant flexibility.

The interleaved buck converter uses half-bridge chopper modules in parallel to change the DC level from the input to the output (Figure 7).

With proper interleave control, this DC/DC converter topology significantly reduces DC ripple without increasing the inductors' size or switching frequency. Each phase of the implementation can be realized with an appropriate module. The FF800R12KE7HPSA1 is a half-bridge IGBT 62 mm module suitable for the buck topology DC/DC converter. It is rated for a maximum voltage of 1200 V and supports a maximum collector current of 800 A.

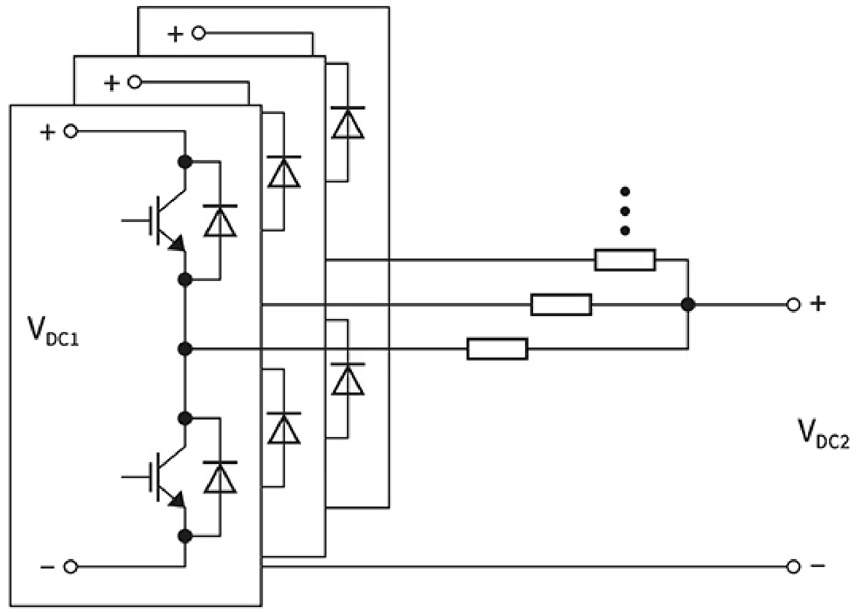


Figure 7: An interleaved buck converter reduces the input DC level, V_{DC1}, to the output level V_{DC2}. (Image source: Infineon Technologies)

The dual active bridge (DAB) converter is an alternative to the buck converter (Figure 8).

The DAB converter uses a high-frequency transformer to couple the input and output full-bridge circuits to provide galvanic isolation. Such isolation is often helpful to minimize corrosion of the tank and electrodes of the electrolyzer cell. Identical full-bridge circuits are driven with complementary square waves. The phasing of the drive signals between the primary side and the secondary determines the direction of power flow. In addition, the DAB converter minimizes switching losses by using zero-volt switching of the IGBTs. The circuit can be fabricated with half-bridge IGBT or silicon carbide (SiC) MOSFET modules.

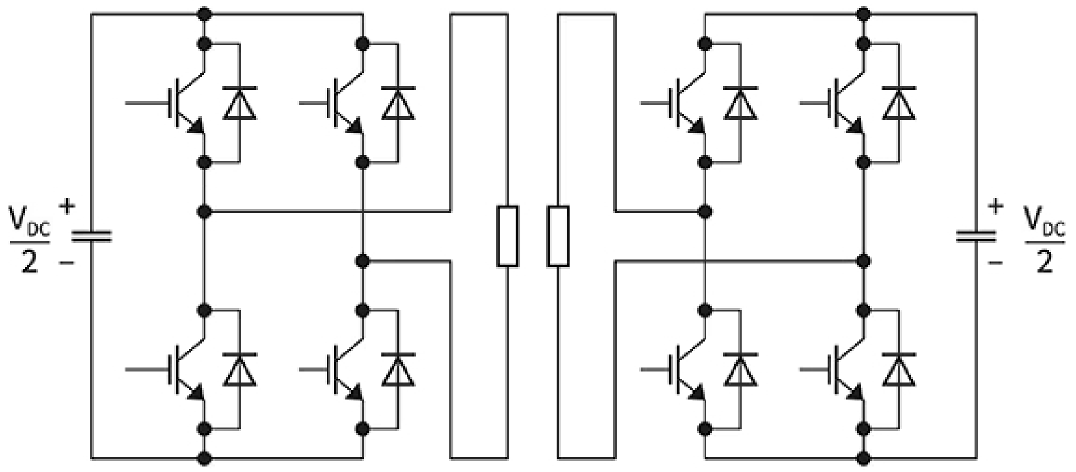


Figure 8: A DAB converter performs voltage step-down and provides galvanic isolation between input and output. (Image source: Infineon Technologies)

Conclusion

As the worldwide demand for clean energy sources continues to increase, green hydrogen separation based on renewable energy sources will grow in importance. Such sources demand efficient, reliable, and highly stable DC power. Designers can turn to Infineon Technologies' broad high voltage and current semiconductors portfolio for the necessary power conversion components.

Wide bandgap technology to maximize efficiency and power density in high-voltage LED lighting

By George Hempt

High-voltage LED lighting has proven to be a viable replacement for previous technologies such as high-intensity discharge (HID) lighting. With the adoption of high-voltage LED lighting, many manufacturers rushed to production and implementation in a variety of applications. While there was a significant increase in light quality and power density, efficiency has become an important aspect to address. Also, early applications saw failure rates that were much higher than expected. The main challenge of high-voltage LED lighting is to continue to increase power density and efficiency as well as making it reliable and more affordable for future applications.

In this article, wide bandgap (GaN) technology will be covered and how it can address the efficiency and power density challenge for high-voltage LED lighting. This discussion will show how wide bandgap technology can be used to maximize the efficiency and power density, with a focus on the buck portion of the LED driver architecture shown in Figure 1.

Wide bandgap (GaN) semiconductors can operate at higher switching frequencies compared to conventional semiconductors like silicon. Wide bandgap materials require a higher amount of energy to excite an electron to have it jump from the top of the valence band to the bottom of the conduction band where it can be used in the circuit. Increasing the bandgap, therefore, has a large impact on a device (and allows a smaller die size to do the same job). Materials like Gallium Nitride (GaN) that have a larger bandgap can withstand stronger electric fields. Critical attributes that wide bandgap materials have are high free-electron velocities and higher electron field density. These key attributes make GaN switches up to 10 times faster and significantly smaller while at the same resistance and breakdown voltage as a similar silicon component. GaN is perfect for high-voltage LED applications, as these key attributes make it ideal for implementation into future lighting applications.

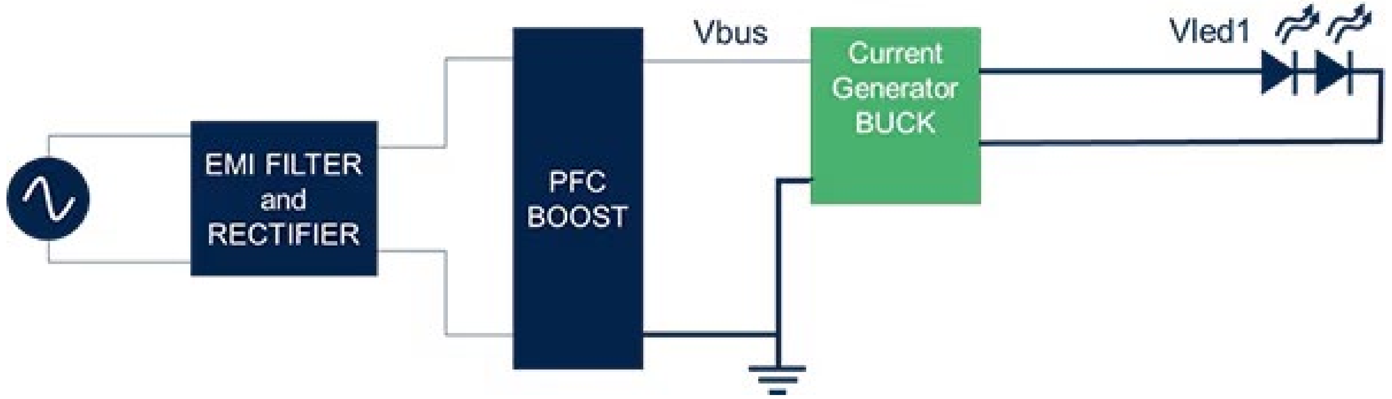


Figure 1: System architecture of a non-isolated high-power LED driver. (Image source: STMicroelectronics)

Figure 1 shows a high-level architecture of an LED lighting application that will serve as a baseline example for applying GaN wide bandgap technology. Although wide bandgap materials can be implemented across the application, the high-voltage current generator buck, highlighted in green, will be the focus to leverage wide bandgap technology for maximizing efficiency and power density. Most lighting applications require high power factor and low harmonic distortion across a wide AC input voltage range. In this case, it is preferred to implement a PFC boost to provide a clean 400 VDC input for the LED driver and meet power quality requirements. There are multiple options for a front end PFC boost converter; transition mode (TM), continuous conduction mode (CCM) as well as others. Transition mode is characterized by variable frequency operation and zero current switching at turn on of the power MOSFET. Other advantages are simple design, small inductor size, and no reverse recovery of the boost diode. The main challenges are high peak and RMS input current, which also results in a larger EMI filter as the power increases. CCM, instead, provides fixed frequency operation. The boost inductor current always has an average component, besides near zero crossing points. The inductor is designed for 20-30% ripple, resulting in a smaller EMI filter compared to TM operation. This also means a larger boost inductor and a smaller EMI filter for the same output power when compared to TM operation. The main challenges are more complex control and the need for an ultrafast soft recovery diode or SiC diode. Consequently, the CCM PFC is generally more expensive than a TM PFC. Ideally, a zero reverse recovery switch can be used in place of the rectifying diode in CCM PFCs. This makes GaN transistors very good candidates for this application.

Isolation is optional and can be introduced between the input stage and the second stage of power conversion. In this example, isolation is not used, and the input PFC stage is followed by a non-isolated inverse buck stage with CC/CV control. In the cases where isolation is needed, a resonant power converter (LLC, LCC) or a flyback converter can be used depending on the output power requirements of the application.

The PFC boost converter generates a regulated DC bus voltage on its output (higher than the peak of the input AC voltage) and passes this higher DC bus voltage to the inverted buck converter stage. The stepdown operation is quite simple. When the switch in the buck is on, the inductor voltage is the difference between the input and output voltages ($V_{IN} - V_{OUT}$). When the switch is off, the catch diode rectifies the current and the inductor voltage is the same as the output voltage.

MasterGaN system in package (SiP) for LED drivers

Along with power density and efficiency, a key challenge for high-voltage lighting applications is the complexity of the design. With the use of wide bandgap semiconductors like GaN, the power density and efficiency of the circuit can be increased. ST's MasterGaN family addresses that challenge by combining the high-voltage smart-power BCD-process gate drivers with high-voltage GaN transistors in a single package. MasterGaN allows for an easy implementation of the topology shown in Figure 1. It embeds two 650 V GaN HEMT transistors in Half-Bridge configuration as well as the gate drivers. In this example, the entire buck power stage is integrated into a single QFN 9x9 mm package requiring minimal external component count. Even the bootstrap diode, typically needed to supply the isolated high-voltage section of a dual, high-side/low-side, Half-Bridge gate driver, is embedded into the SiP. Consequently, the power density of an application that uses a MasterGAN device can be increased dramatically compared to a standard silicon solution while increasing the switching frequency or the power output. More specifically, in this LED driver application, a 30% decrease in PCB area was achieved and no heat sinks where used.

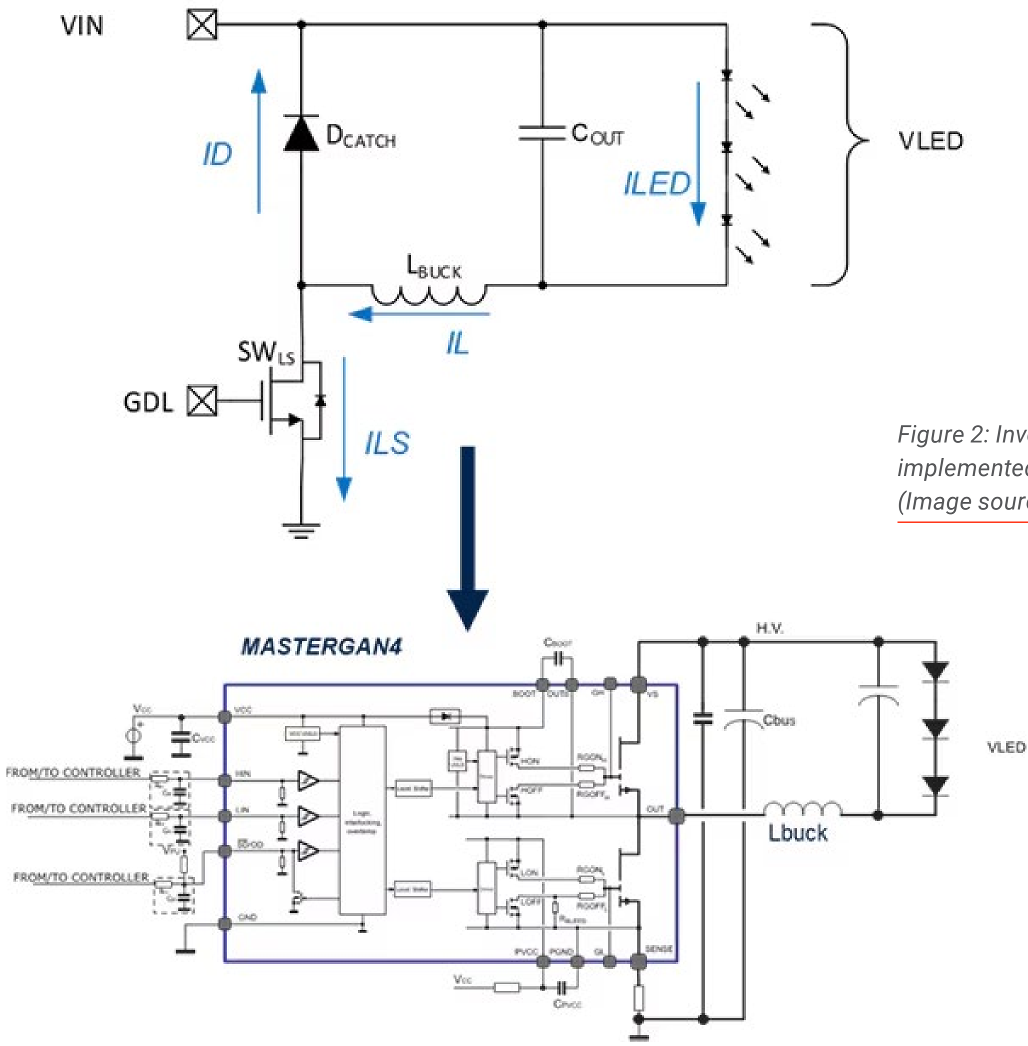


Figure 2: Inverse Buck Topology implemented with MASTERGAN4. (Image source: STMicroelectronics)

For high-power LED lighting applications, CCM is the best operating mode to use. When implementing CCM with GaN devices, there will be the high-level benefits previously discussed as well as a reduced cost. There would be no need for very low R_{DSON} to serve high power applications due to the reduced switching loss contribution to overall power losses. GaN also mitigates a major drawback of using CCM by eliminating recovery losses and reduced EMI, as GaN experiences no reverse recovery. CCM operation with Fixed Off Time control also makes the compensation of output current ripple dependency on V_{OUT} very easy. It is clear that GaN switch implementation using CCM is a great combination for high-voltage LED lighting applications, as well as many others.

The basic scheme of an Inverse Buck topology is shown in Figure 2 along with an implementation that uses the MASTERGAN4.

MASTERGAN4 embeds two 225 mΩ (typical at 25°C) 650 V GaN transistors in Half-Bridge configuration, a dedicated Half-Bridge gate driver and the bootstrap diode. This high level of integration simplifies the design and minimizes PCB area in a small 9x9 mm QFN package. The evaluation board that is shown in Figure 3, was designed with the MASTERGAN4 in an inverse buck topology has the following specifications: it accepts up to 450 V input, the output voltage of the LED string can be set between 100 V and 370 V; it operates in Fixed Off Time (FOT) CCM with a switching frequency of 70 kHz; the max output current is 1 A.

The controller in this solution, the HVLED002, is used to generate a single PWM control signal. An external circuit based on simple Schmitt Triggers is then used to generate two complementary signals to drive the low side and high side GaN transistors with a suitable dead time. Two linear regulators are also included to generate the supply voltages needed by the MASTERGAN4. The inverse buck topology implemented with MASTERGAN4 creates a solution for increased power density and efficiency, but let the results discussed below speak for themselves.

Figure 3: Example of Inverse Buck Demo with MASTERGaN4. (Image source: STMicroelectronics)

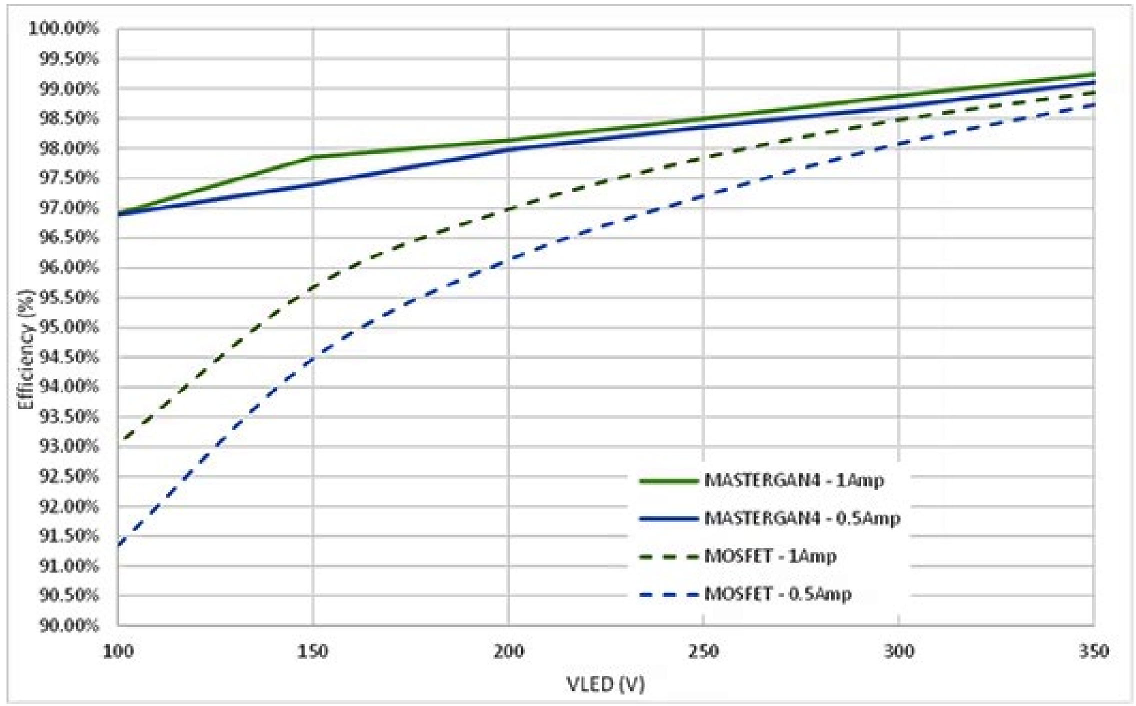


Figure 4: Efficiency vs. LED voltage for MasterGaN and Silicon MOSFET. (Image source: STMicroelectronics)

	MOS + SIC DIODE	MASTERGAN4
Power devices area	0.66 cm² Diode DPAK or TO220	0.81 cm²
Copper area for thermal management	33 cm² Copper area to have 19°C/W	19.7 cm² Copper area to have 24°C/W
Power inductor footprint	11.2 cm²	11.2 cm²
Overall Area	45.5 cm²	31.71 cm²

Table 1: Size comparison for GaN and Silicon MOSFET

Experimental Results:

The efficiency plots in Figure 4 show the advantages of the proposed solution vs. a traditional silicon solution as a function of the LED string voltage for output currents of 0.5 A and 1 A.

The efficiency of MASTERGAN4 stays at or above 96.8% across the entire LED string voltage range. It is possible to observe that across all power levels the gain in efficiency is maximized thanks to the low conduction losses as well as the minimal driving and switching losses of the GaN solution.

Table 1 compares the silicon solution with the MASTERGAN4 based solution. As can be seen, more than 30% overall PCB area reduction is shown with the GaN design implementation. The results show one path that can be taken with GaN in this inverse buck topology. Increasing the switching frequency above 70 kHz can decrease the output inductor and capacitor size at the expense of higher driving and switching losses. At a higher frequency and reduced filter size, electrolytic capacitors can be replaced with more reliable and larger ceramic capacitors. The tradeoff between filter capacitor and buck inductor size can be optimized based on the switching frequency required by the target application.

Conclusions

This article discussed the implementation of an inverse buck topology for LED lighting applications based on MASTERGAN4. The system in package configuration has 650 V, 225 mΩ GaN transistors in half-bridge configuration and dedicated gate drivers. The GaN solution vs. silicon shows higher efficiency and reduced PCB area. MasterGaN is the ideal solution for a compact, high efficiency and high-power inverse buck implementation for lighting applications.

How to design in SiC MOSFETs to improve EV traction inverter efficiency

By Steven Keeping
Contributed By DigiKey's North American Editors

Engineers face a trade-off between the performance and range of modern electric vehicles (EVs). Faster acceleration and higher cruising speeds require more frequent and time-consuming recharging stops. Alternatively, longer range comes at the cost of more sedate progress. To increase range, while also offering drivers higher performance, engineers need to design drive trains that ensure as much battery energy as possible gets transferred to the driven wheels. Just as important is the need to keep drive trains small enough to fit within the constraints of the vehicle. These twin demands require both high-efficiency and high-energy-density components.

The key component in an EV drive train is the three-phase voltage source inverter (or “traction inverter”) which converts the batteries’ DC voltage into the AC required for the vehicle’s electric motor(s). Building an efficient traction inverter is critical to lowering the trade-off between performance and range, and one of the key routes to improving efficiency is proper use of wide bandgap (WBG), silicon carbide (SiC) semiconductor devices.

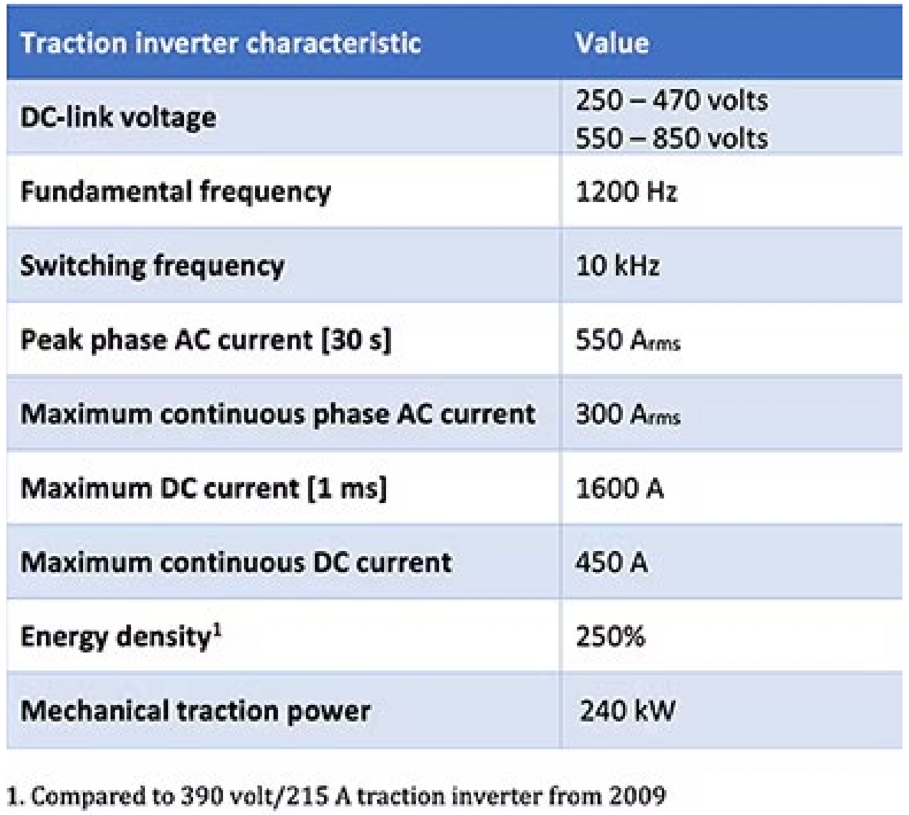
This article describes the role of the EV traction inverter. It then explains how designing the unit with SiC power metal oxide semiconductor field-effect transistors (MOSFETs) can yield a more efficient EV drive train than one using insulated-gate bipolar transistors (IGBTs). The article concludes with an example of a SiC MOSFET-based traction inverter, and design tips on how to maximize the unit's efficiency.

What is a traction inverter?

An EV's traction inverter converts the DC-current provided by the vehicle's high-voltage (HV) batteries into the AC-current required by the electric motor to produce the torque required to move the vehicle. The electrical performance of the traction inverter has a significant impact on the vehicle acceleration and driving range.

Contemporary traction inverters are driven by HV battery systems of 400-volts, or more recently, 800-volt designs. With traction inverter currents of 300 amperes (A) or greater, a device powered by an 800-volt battery system is capable of delivering over 200 kilowatts (kW) of power. As the power has climbed, the size of the inverters has shrunk, significantly increasing the power density.

EV's with 400-volt battery systems require traction inverters with power semiconductor devices rated in the 600 to 750-volt range, while 800-volt vehicles require semiconductor devices rated in the range of 900 to 1200 volts. The power components used in the traction inverters must also be able to handle peak AC currents of over 500 A for 30 seconds (s) and a maximum AC current of 1600 A for 1 millisecond (ms). In addition, the switching transistors and gate drivers used for the device must be capable of handling these large loads while maintaining high traction inverter efficiency (Table 1).



Traction inverter characteristic	Value
DC-link voltage	250 – 470 volts 550 – 850 volts
Fundamental frequency	1200 Hz
Switching frequency	10 kHz
Peak phase AC current [30 s]	550 A_{rms}
Maximum continuous phase AC current	300 A_{rms}
Maximum DC current [1 ms]	1600 A
Maximum continuous DC current	450 A
Energy density[1]	250%
Mechanical traction power	240 kW

1. Compared to 390 volt/215 A traction inverter from 2009

Table 1: Typical 2021 traction inverter requirements; energy density shows a 250% increase, compared to 2009. (Image source: Steven Keeping)

A traction inverter typically comprises three half-bridge elements (high-side plus low-side switches), one for each motor phase, with gate drivers controlling the low-side switching of each transistor. The entire assembly must be galvanically isolated from the low-voltage (LV) circuits powering the rest of the vehicle's systems (Figure 1).

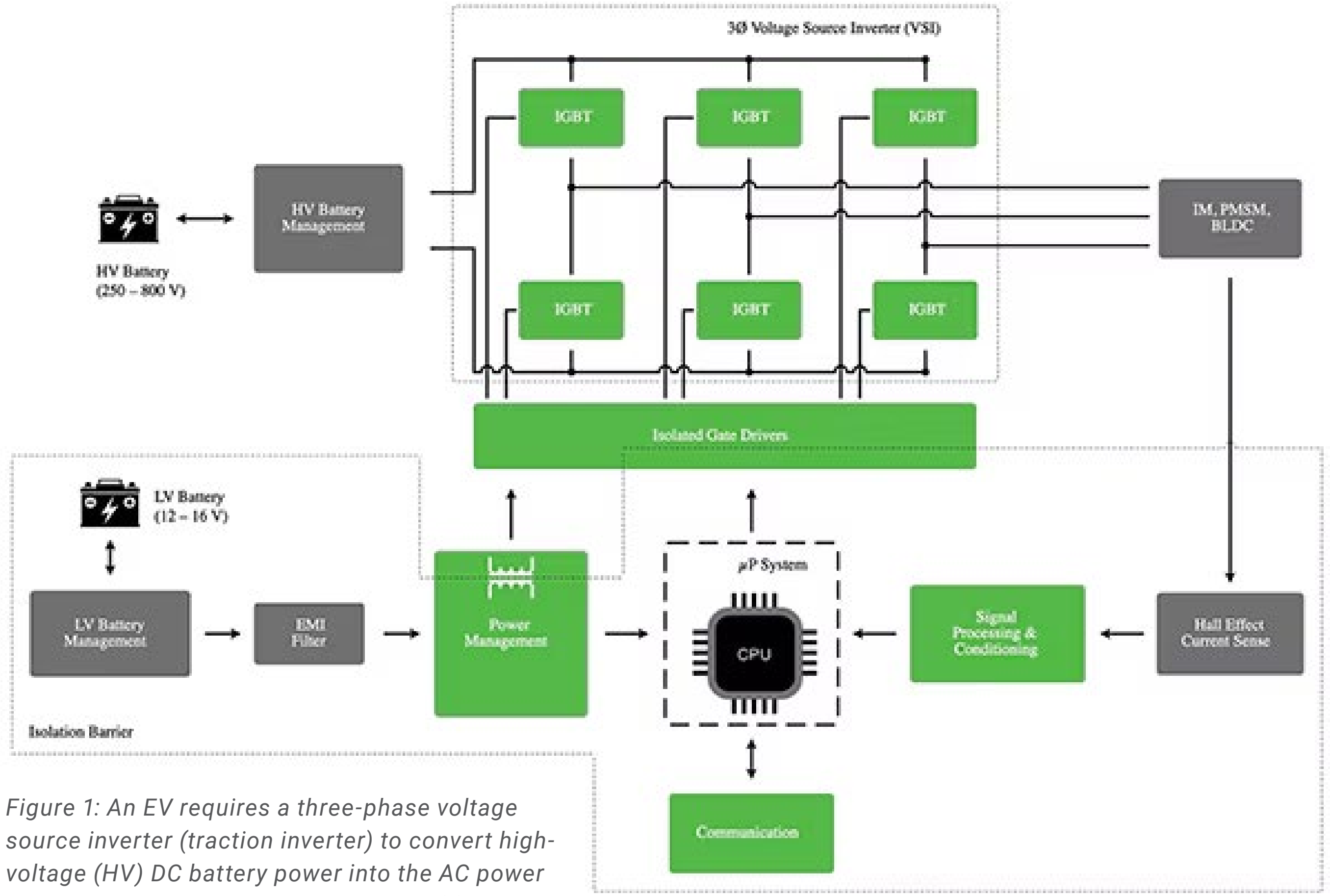


Figure 1: An EV requires a three-phase voltage source inverter (traction inverter) to convert high-voltage (HV) DC battery power into the AC power required by the vehicle's electric motor(s). The HV system, including the traction inverter, is isolated from the vehicle's conventional 12-volt system. (Image source: ON Semiconductor)

The switches in the example shown in Figure 1 are IGBTs. These have been a popular choice for a traction inverter because they are capable of handling high voltages, switch rapidly, offer good efficiency, and are relatively inexpensive. However, as the cost of SiC power MOSFETs has fallen and they have become more commercially available, engineers are turning to these components because of their notable advantages over IGBTs.

Advantage of SiC MOSFETs for high-efficiency gate drivers

The key performance advantages of SiC power MOSFETs over conventional silicon (Si) MOSFETs and IGBTs derive from the devices' WBG semiconductor substrate. Si MOSFETs have a bandgap energy of 1.12 electron-volts (eV) compared to SiC MOSFETs' 3.26 eV. That means the WBG transistor can withstand much higher breakdown voltages than Si devices, as well as a resultant breakdown field voltage about ten times greater than Si. The high breakdown field voltage allows a reduction in device thickness for a given voltage, lowering the "on" resistance ($R_{DS(ON)}$) and thus reducing switching losses and enhancing current-carrying capability.

Another key advantage of SiC is its thermal conductivity, which is about three times higher than Si. Higher thermal conductivity results in a smaller junction temperature (T_j) rise for a given power dissipation. SiC MOSFETs can also tolerate a higher maximum junction temperature ($T_{j(max)}$) than Si. A typical $T_{j(max)}$ value for a Si MOSFET is 150˚C; SiC devices can withstand a $T_{j(max)}$ of up 600˚C, although commercial devices are typically rated at 175 to 200˚C. Table 2 provides a comparison of properties between Si and 4H-SiC (the crystalline form of SiC commonly used to manufacture MOSFETs).

The high breakdown voltage, low $R_{DS(ON)}$, high thermal conductivity, and high $T_{j(max)}$ allow a SiC MOSFET to handle much higher current and voltage than a similarly-sized Si MOSFET.

IGBTs are also capable of handling high voltages and currents and tend to be less expensive than SiC MOSFETs – a key reason for them finding favor in traction inverter designs. The downside of IGBTs, particularly when the developer is looking to maximize energy density, is a restriction on the maximum operating frequency due to their “tailing current” and relatively slow turn-off. In contrast, a SiC MOSFET is able to handle high-frequency switching on par with a Si MOSFET, but with the voltage and current handling capability of an IGBT.

Properties	Si	4H-SiC	GaN
Bandgap Energy (eV)	1.12	3.26	3.50
Electron Mobility (cm^2/Vs)	1400	900	1250
Hole Mobility (cm^2/Vs)	600	100	200
Breakdown Field (MV/cm)	0.3	3.0	3.0
Thermal Conductivity (W/cm°C)	1.5	4.9	1.3
Maximum Junction Temperature (°C)	150	600	400

Table 2: A SiC MOSFET's breakdown field, thermal conductivity, and maximum junction temperature make it a better choice than Si for high-current and high-voltage switching applications. (Image source: ON Semiconductor)

Wider availability of SiC MOSFETs

Until recently, the relatively high price of SiC MOSFETs has seen their use limited to traction inverters for luxury EVs, but falling prices have seen SiC MOSFETs become an option for a wider variety.

Two examples of this new generation of SiC power MOSFETS come from ON Semiconductor: the NTBG020N090SC1 and the NTBG020N120SC1. The major difference between the devices is that the former has a maximum drain-to-source breakdown voltage ($V_{(BR)DSS}$) of 900 volts, with a gate-to-source voltage (V_{GS}) of 0 volts and a continuous drain current (I_D) of 1 milliamp (mA), while the latter has a maximum $V_{(BR)DSS}$ of 1200 volts (under the same conditions). The maximum T_j for both devices is 175˚C. Both devices are single N-channel MOSFETs in a D2PAK-7L package (Figure 2).

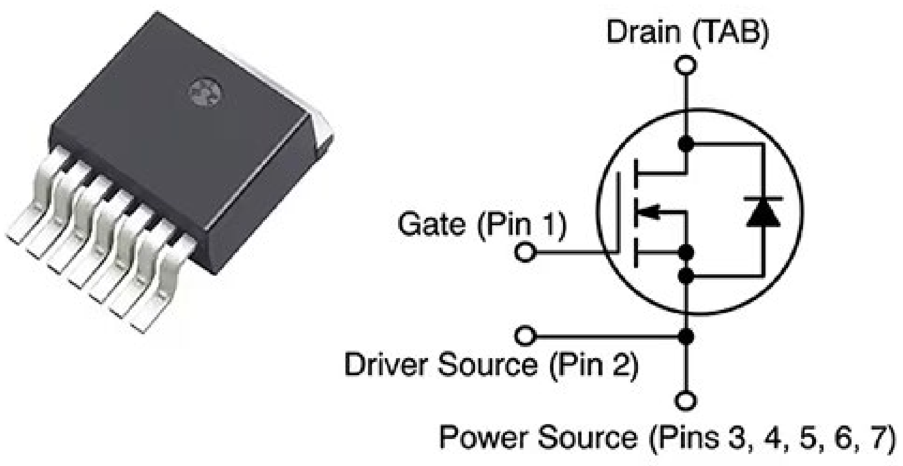


Figure 2: The NTBG020N090SC1 and NTBG020N120SC1 N-channel SiC power MOSFETs both come in a D2PAK-7L package and differ primarily in their $V_{(BR)DSS}$ values of 900 and 1200 volts, respectively. (Image source: Steven Keeping, using material from ON Semiconductor)

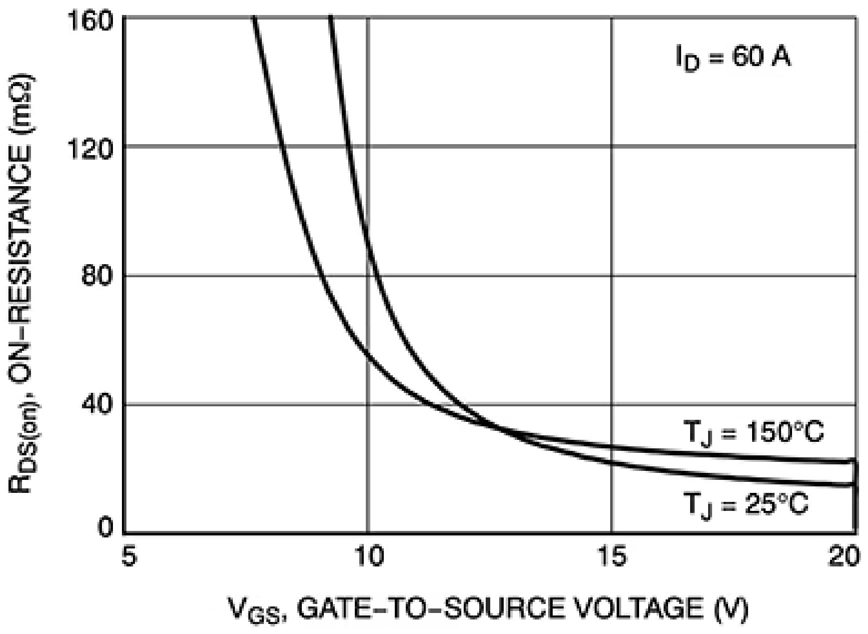


Figure 3: For the NTBG020N090SC1 SiC MOSFET, a high V_{GS} is required to avoid thermal stress from high $R_{DS(ON)}$. (Image source: ON Semiconductor)

The NTBG020N090SC1 has an $R_{DS(ON)}$ of 20 milliohms (mΩ) with a V_{GS} of 15 volts (I_D = 60 A, T_j = 25˚C), and an $R_{DS(ON)}$ of 16 mΩ with a V_{GS} of 18 volts (I_D = 60 A, T_j = 25˚C). Maximum continuous drain-source diode forward current (I_{SD}) is 148 A (V_{GS} = −5 volts, T_j = 25˚C), and maximum pulsed drain–source diode forward current (I_{SDM}) is 448 A (V_{GS} = −5 volts, T_j = 25˚C). The NTBG020N120SC1 has an $R_{DS(ON)}$ of 28 mΩ at a V_{GS} of 20 volts (I_D = 60 A, T_j = 25˚C). Maximum I_{SD} is 46 A (V_{GS} = −5 volts, T_j = 25˚C), and maximum I_{SDM} is 392 A (V_{GS} = −5 volts, T_j = 25˚C).

Designing with SiC MOSFETs

Despite their advantages, designers looking to incorporate SiC MOSFETs into their traction inverter designs should be aware of a significant complication; the transistors have tricky gate drive requirements. Some of these challenges arise from the fact that compared to Si MOSFETs, SiC MOSFETs exhibit lower transconductance, higher internal gate resistance, and the gate turn–on threshold can be less than 2 volts. As a result, the gate must be pulled below ground (typically to −5 volts) during the off–state to ensure proper switching.

However, the key gate drive challenge arises from the fact that a large V_{GS} (up to 20 volts) must be applied to ensure a low $R_{DS(ON)}$. Operating a SiC MOSFET at a V_{GS} that is too low can result in thermal stress or even failure due to power dissipation (Figure 3).

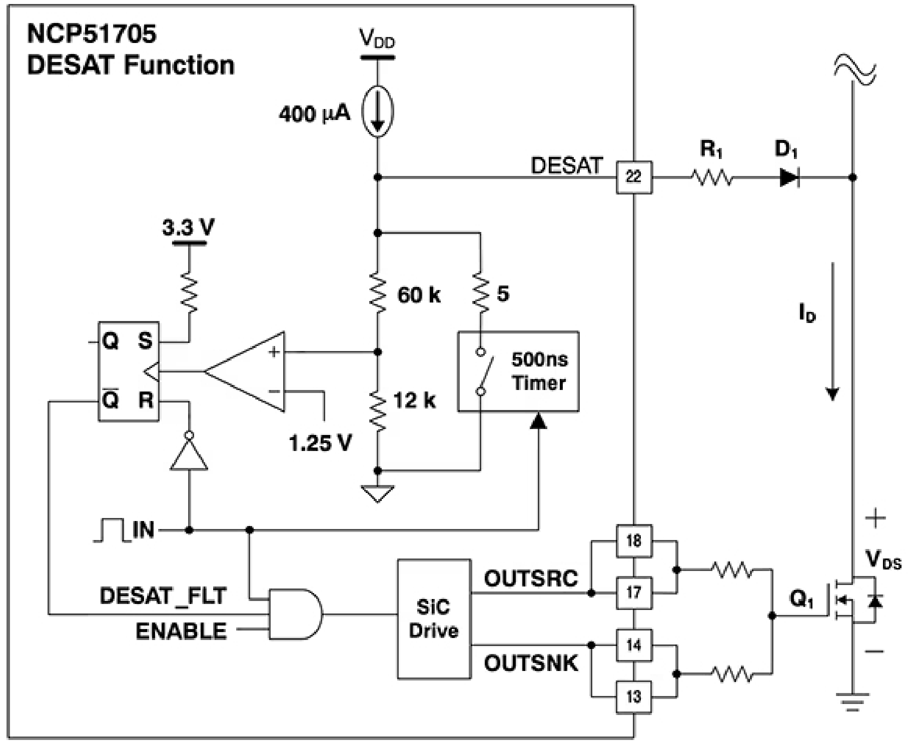
Moreover, because a SiC MOSFET is a low-gain device, the designer must take into account the impact this has on several other important dynamic characteristics when designing a gate drive circuit. These characteristics include the gate charge Miller plateau and the requirement for overcurrent protection.

These design complications demand a specialized gate driver with the following attributes:

- An ability to provide a VGS drive of -5 to 20 volts to take full advantage of the SiC MOSFET performance benefits. To provide adequate overhead to meet this requirement, the gate drive circuit should be able to withstand VDD = 25 volts and VEE = −10 volts.
- VGS must have fast rise and fall edges, of the order of a few nanoseconds (ns).
- The gate drive must be able to source high peak gate current on the order of several amperes, across the entire MOSFET Miller plateau region.
- The sink current rating should exceed that which would be required to just discharge the input capacitance of the SiC MOSFET. A minimum peak sink current rating on the order of 10 A should be considered for high-performance, half-bridge power topologies.
- Low parasitic inductance for high−speed switching.
- Small driver package able to be located as close as possible to the SiC MOSFET and to boost energy density.
- A desaturation (DESAT) function capable of detection, fault reporting, and protection for long-term reliable operation.
- A VDD undervoltage lockout (UVLO) level that is matched to the requirement that VGS > 16 volts before switching begins.
- VEE UVLO monitoring capability to assure the negative voltage rail is within an acceptable range.

ON Semiconductor has introduced a gate driver designed to meet these requirements in traction inverter designs. The NCP51705MNTXG SiC MOSFET gate driver features a high level of integration making it compatible with not only their SiC MOSFETs but also those from a wide range of manufacturers. The device includes many basic functions common to general purpose gate drivers, but also features the specialized requirements necessary for designing a reliable SiC MOSFET gate drive circuit using minimal external components.

Figure 4: The NCP51705MNTXG's DESAT function measures V_{DS} for anomalous behavior during periods of maximum I_D and implements overcurrent protection. (Image source: ON Semiconductor)



For example, the NCP51705MNTXG incorporates a DESAT function that can be implemented using just two external components. DESAT is a form of overcurrent protection for IGBTs and MOSFETs to monitor a fault whereby V_{DS} can rise at maximum I_D. This can affect efficiency and, in a worst-case scenario, possibly damage the MOSFET. Figure 4 shows how the NCP51750MNTXG monitors V_{DS} of the MOSFET (Q1) via the DESAT pin through R1 and D1.

The NCP51705MNTXG gate driver also features programmable UVLO. This is an important feature when driving SiC MOSFETs because the switching component's output should be disabled until VDD is above a known threshold. Allowing the driver to switch the MOSFET at low VDD can damage the device. The NCP51705MNTXG's programmable UVLO not only protects the load but verifies to the controller that the applied VDD is above the turn-on threshold. The UVLO turn-on threshold is set with a single resistor between UVSET and SGND (Figure 5).

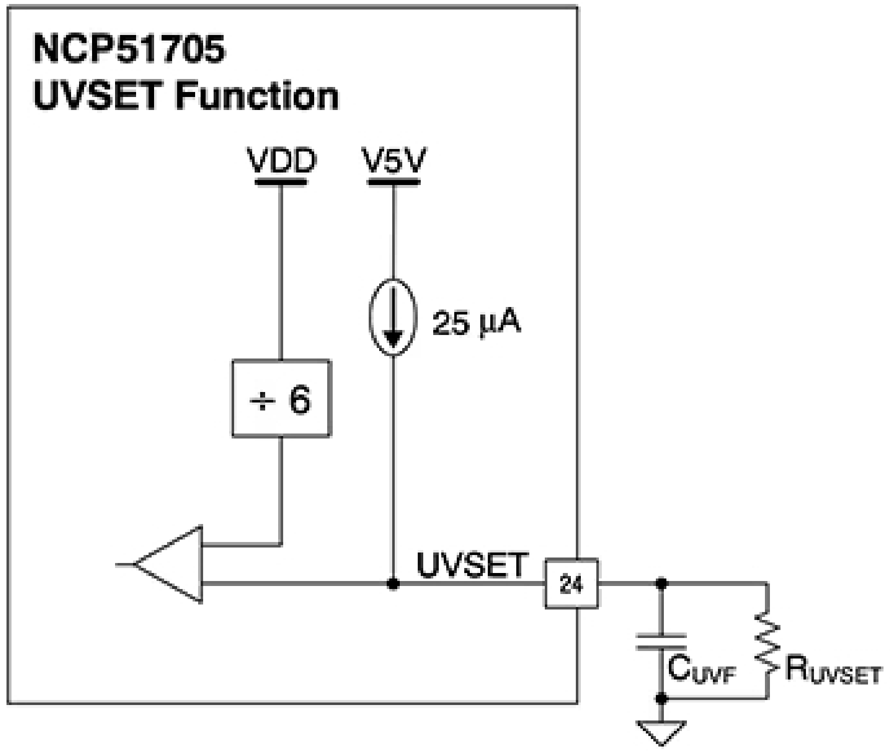


Figure 5: The UVLO turn−on threshold for the NCP51705MNTXG SiC MOSFET is set by the UVSET resistor, R_{UVSET}, which is chosen according to a desired UVLO turn−on voltage, V_{ON}. (Image source: ON Semiconductor)

Digital isolation for traction inverters

To complete a traction inverter design, the engineer must ensure that the LV side of the vehicle's electronics are isolated from the high voltages and currents passing through the inverter (Figure 2 above). However, because the microprocessor controlling the HV gate drivers is on the LV side, any isolation must allow for the passage of digital signals from the microprocessor to the gate drivers. ON Semiconductor also offers a component for this function, the NCID9211R2, a high-speed, dual-channel, bidirectional ceramic digital isolator.

The NCID9211R2 is a galvanically isolated, full-duplex digital isolator that allows digital signals to pass between systems without conducting ground loops or hazardous voltages. The device features a maximum working insulation of 2000 volt$_{speak}$, 100 kilovolts/millisecond (kV/ms) common-mode rejection, and a 50 megabit per second (Mbit/s) data throughput.

Off-chip ceramic capacitors form the isolation barrier as shown in Figure 6.

The digital signals are transmitted across the isolation barrier using an ON-OFF keying (OOK) modulation. On the transmitter side, the V_{IN} input logic state is modulated with a high-frequency carrier signal. The resulting signal is amplified and transmitted to the isolation barrier. The receiver side detects the barrier signal and demodulates it using an envelope detection technique (Figure 7). The output signal determines the V_O output logic state when the output enable control EN is high. V_O defaults to a high-impedance low state when the transmitter power supply is off, or V_{IN} input is disconnected.

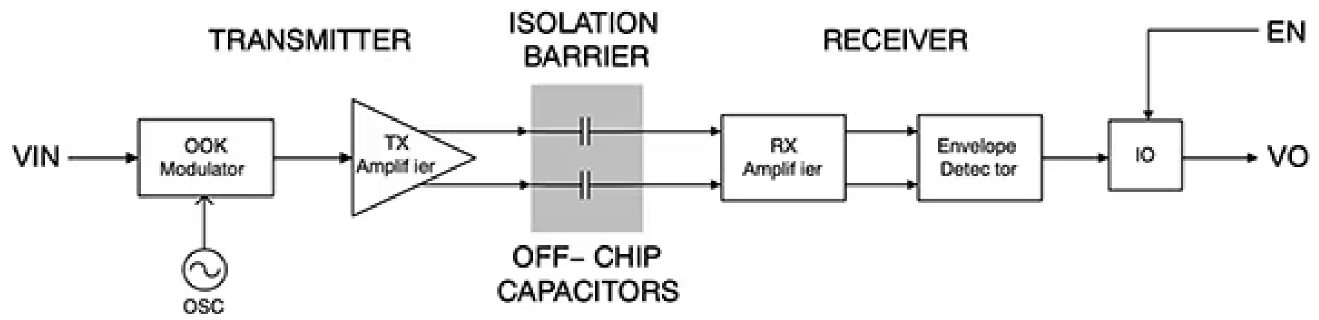


Figure 6: Block diagram illustrating a single channel of the NCID9211R2 digital isolator. Off-chip capacitors form the isolation barrier. (Image source: ON Semiconductor)

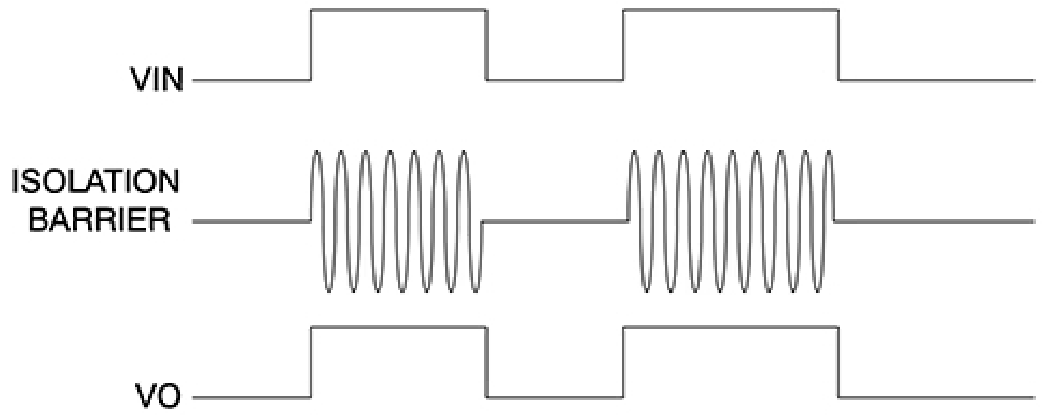
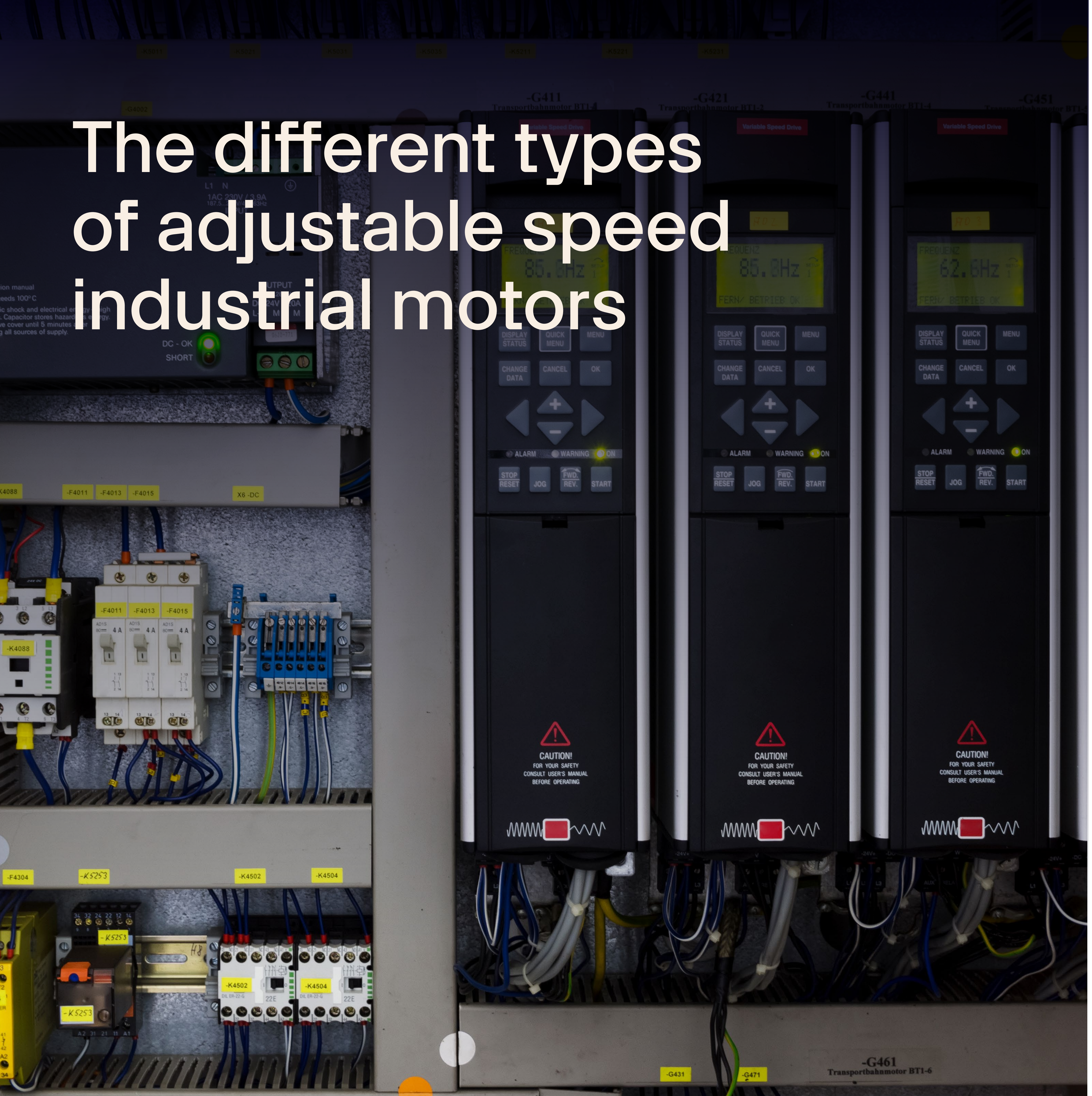


Figure 7: The NCID9211 digital isolator uses OOK modulation to transmit digital information across the isolation barrier. (Image source: ON Semiconductor)

Conclusion

SiC power MOSFETs are a good option for high-efficiency and high-power-density traction inverters for EVs, but their electrical characteristics bring unique design challenges with respect to gate drivers and device protection. Adding to the design challenges, engineers must also ensure that their traction inverter design offers high-level isolation from the vehicle's sensitive LV electronics.

As shown, to ease engineering development, ON Semiconductor offers a range of SiC MOSFETs, specialized gate drivers, and digital isolators to meet the demands of traction inverters, and strike a better balance between long-range and high performance for modern EVs.



The different types of adjustable speed industrial motors

By Jeff Shepard
Contributed By DigiKey's North American Editors

International Electrotechnical Commission (IEC) standard 61800 recognizes two types of adjustable speed electrical power drive systems (PDS) for industrial applications. 61800-1 applies to direct current (DC) PDS, and 61800-2 applies to alternating current (AC) PDS. The term PDS applies to the entire system of drive plus motor.

Other sections of 61800 discuss test methods, safety requirements related to thermal and energy conditions, functional safety, electrical and environmental requirements for encoders, electrical interfaces, and performance measurements. The newest part, IEC 61800-9, covers ecodesign for motor systems, including energy efficiency determination and classification.

While IEC 61800 defines adjustable speed AC and DC PDS, there are also general definitions for variable speed drives (VSDs) and variable frequency drives (VFDs) in industrial applications. IEC 61800 applies to mains-powered PDS connected to up to 1.5 kV_{AC} 50 Hz or 60 Hz. It also applies to DC input voltages for battery-powered systems like industrial autonomous mobile robots (AMRs) that use adjustable speed drives. Traction and electric vehicle drives are excluded from IEC 61800.

This article briefly presents the common definitions of VSDs and VFDs and looks at why VFDs are widely used. It then reviews the efficiency classes defined in IEC 61800-9 for AC drives and, considers exemplary mains-powered VFDs from Delta Electronics, Siemens, Schneider Electric, Omron Automation, and closes by looking at the use of VFDs in AMRs and other battery-powered systems using an example system from MEAN WELL.

The standard definition of a VFD is a drive that uses changes in frequency to control motor speed, making them useful with AC motors. At the same time, a VSD varies the voltage to control the motor, making it useful for both AC and DC motors.

But it's not quite that simple. Both types of drives can be used to control the speed of motors. As a result, sometimes, the term VSD is applied to VFDs. VFDs can be used with brushless DC motors (BLDCs); strictly speaking, they are not limited to AC motors. VFDs are suitable for use with a variety of motors like:

- Induction (IM), or asynchronous AC motors, are widely used in industrial applications since they are self-starting, reliable, and economical.

- Permanent magnet synchronous motors (PMSM) are highly efficient AC motors and can enable precise control of torque and speed in high-performance applications that demand high energy efficiency.
- BLDCs are also used in applications that require high efficiency and precise control and typically have long operating lives.
- Servo motors can be AC or DC and support rapid, high-precision responses. VFDs with specialized control algorithms can be used with servo motors in robots, computer numerically controlled (CNC) machines, and similar applications.
- Synchronous AC motors (SMs) are suited for applications that require constant speed and precise synchronization. While VFDs can control the speed of SMs, other (lower cost) drive options can support constant speed operation.

There's a variety of control algorithms used with VFDs that increase their versatility. For example, there are four primary types of VFD control algorithms just for induction motors: volts-per-Hertz (V/f), V/f with encoder, open-loop vector, and closed-loop vector. All use pulse-width modulation and provide different levels of control over speed and torque.

The importance of VFDs in a wide range of industrial applications is evidenced by the development of IEC 61800-9, which is focused on the efficiency and ecodesign of VFDs and related motor drive systems.

BDM, CDM, and PDS

There are two sections of IEC 61800-9 related to VFDs. Part 1 delineates the methodology for determining an application's energy efficiency index or reference. Part 2 details methods for evaluating efficiency based on a series of classifications.

While the efficiency of VFDs, called basic drive modules (BDMs) in IEC 61800-9, is important, it's not the primary focus of the standard. The standard is more broadly based and considers complete drive modules (CDMs) that consist of a frequency inverter (the VFD), a feeding section, and input and output auxiliaries (like filters and chokes) and on the power drive system (PDS) that consists of the CDM plus the motor (Figure 1).

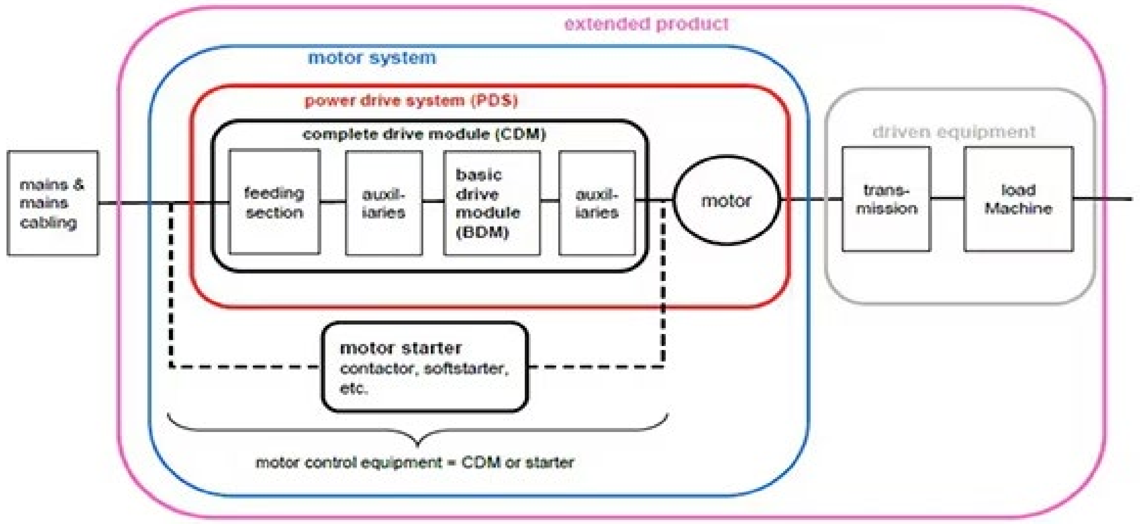


Figure 1: IEC 61800-9 efficiency classes apply to the CDM (black section) and PDS (red section) in VFD systems. (Image source: Schneider Electric)

CDM efficiency classes

CDM international efficiency (IE) classes are defined from IE0 to IE2. They are determined by comparing the total loss of the CDM with the performance of a reference CDM (RCDM). IE classes for CDMs are defined relative to the 90, 100 operating point using 90% motor stator frequency and 100% torque current to avoid overmodulation and ensure comparability of the performance measurements of drives from different makers.

The performance of the RCDM is defined as IE1. A CDM with greater than 25% lower losses than the RCDM is classified as IE2, and a CDM with greater than 25% higher losses than the RCDM is classified as IE0. The RCDM also enables the comparison of the energy consumption with an average technology CDM at eight pre-defined operating points (0, 25), (0, 50), (0, 100), (50, 25), (50, 50), (50, 100), (90, 50) and (90, 100) (Figure 2).

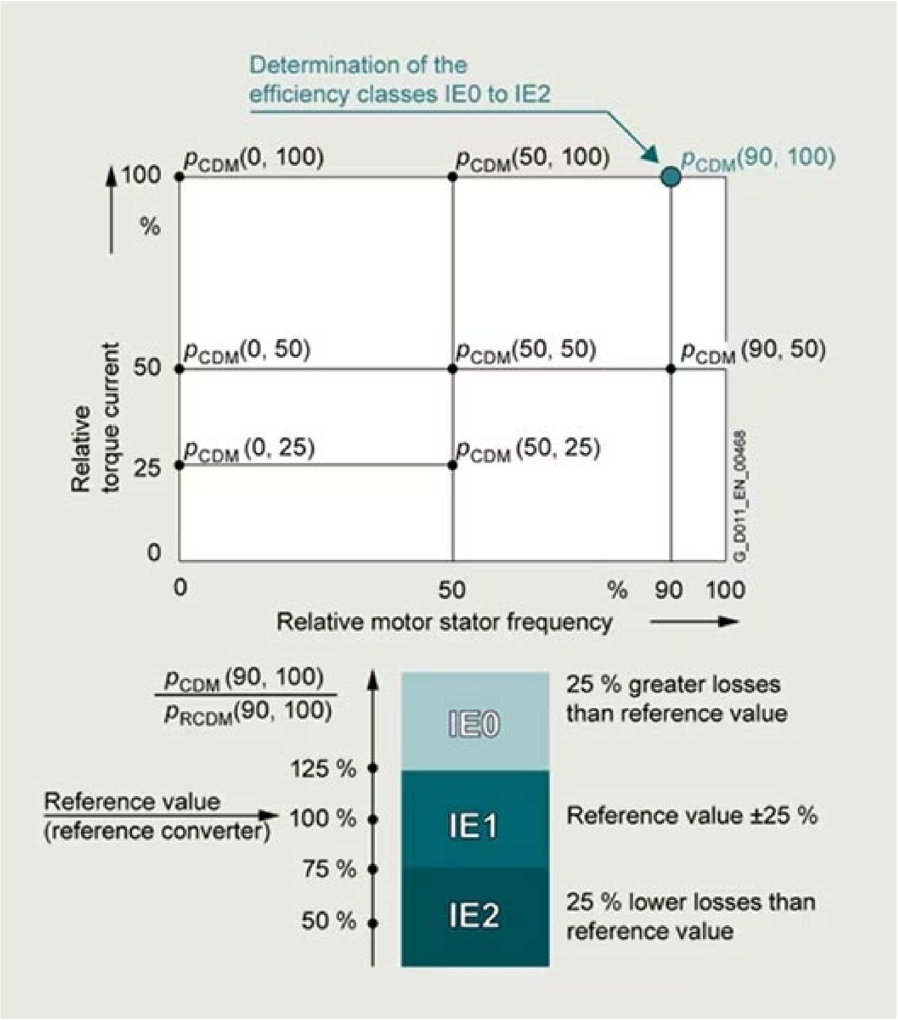


Figure 2: IEC 61800-9 CDM operating points and efficiency classes. (Image source: Siemens)

PDS efficiency classes

PDS international efficiency system (IES) classes are like the CDM IE classes and are defined as IES0 to IES2. They are based on a reference PDS (RPDS) and reflect the efficiency of the complete drive module plus the motor.

Matching the combined motor and CDM to the specific application requirements provides greater potential for overall efficiency optimization. That efficiency optimization is reflected in a higher IES classification. Like the RCDM, the RPDS enables the comparison of energy consumption with an average technology PDS at eight pre-defined operating points.

The operating points are based on a percentage of torque and a percentage of speed, and the IES value is calculated based on 100% torque and 100% speed, which is the (100, 100) operating point.

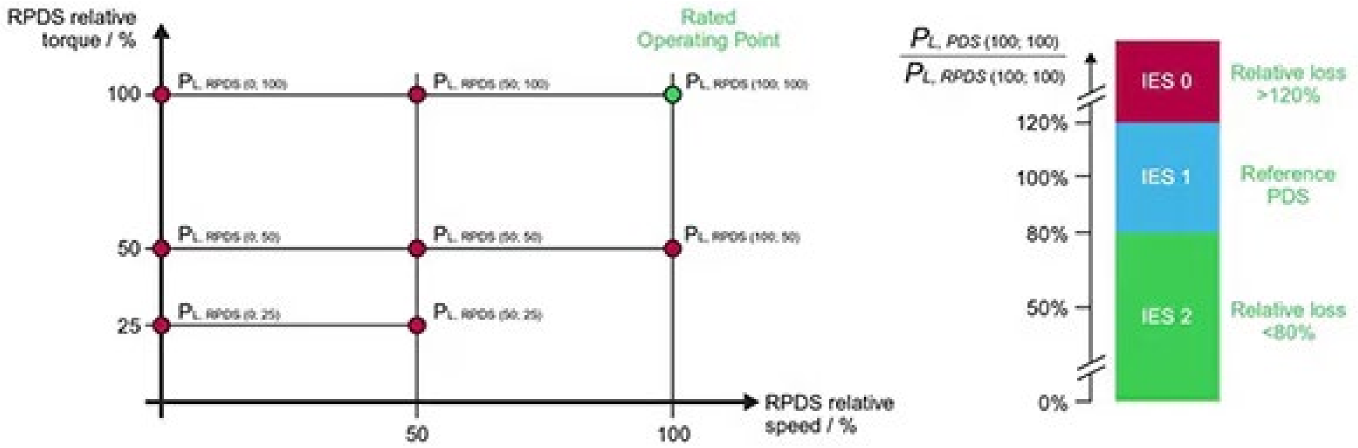


Figure 3: IEC 61800-9 PDS operating points and efficiency classes. (Image source: Schneider Electric)

Instead of using the 25% changes of the IE classes, IES classes are based on 20% changes. A PDS with an efficiency class IES2 has greater than 20% lower losses, and a class IES0 PDS has greater than 20% higher losses than the RPDS performance defined as IES1 (Figure 3).

VFD examples

VFD makers don't always report efficiency based on 61800-9. That's because the simplest efficiency measurement using IEC 61800-9 is for the CDM, which consists of the VFD (frequency inverter) plus numerous additional components, including the feeding section and input and output auxiliary devices. The use of specific additional components is beyond the control of VFD makers, and 61800-9 doesn't apply directly to VFDs.

Some VFD makers have adapted the 61800-9 methodology. When IE2 compliance is claimed, the data is reported in various formats, including charts, tables, and Excel files.

For example, Siemens uses the IEC 61800-9 methodology with its SINAMICS V20 drives and reports them as efficiency class IE2 (Figure 4). These drives are offered in nine frame sizes, ranging from 0.16 to 40 horsepower (hp). These drives have been optimized for basic drive systems in manufacturing and process applications like pumps, fans, compressors, and conveyors. Numerous optional components include input filters, input and output reactors, braking resistors, and so on.

Delta Electronics has also adapted the 61800-9 methodology and reports IE2 efficiency for its 1.7, 3.0, 4.2, 6.6, 9.9, and 12.2 kVA MS300 Series compact drives. The data is detailed in a tabular format rather than as a chart. The MS300 series includes drives from 0.2 to 22 kW (Figure 5). These drives feature several built-in features, including a programmable logic controller (PLC) function for programming, MODBUS communication, a communication slot that can support additional protocols, and a USB port for uploading and downloading data.

Omron reports its "variable speed drives with three phases input," like the MX2 Series VFDs, meet the requirements of IE2 efficiency. The company provides the test data as an Excel file. MX2 drives are available with ratings from 0.1 to 2.2 kW for 200 V single-phase input, 0.1 to 15.0 kW for 200 V three-phase input, and 0.4 to 15.0 kW for 400 V three-phase input. These drives are designed for IM and PM motors and support smooth control down to zero speed with 200% starting torque at 0.5 Hz.

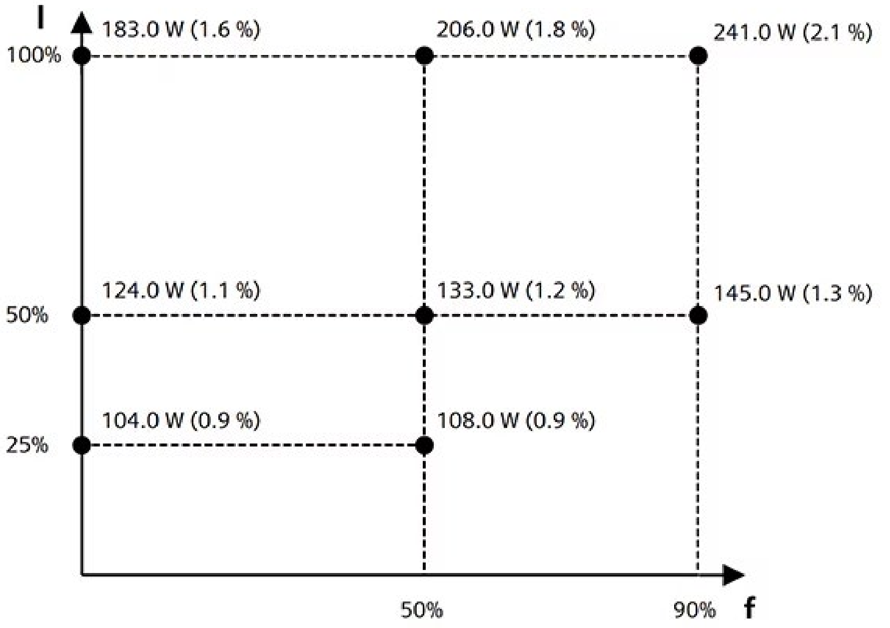


Figure 4: Efficiency class IE2 7.5 kW CDM that has 36.1% lower losses compared with the reference converter (90% / 100%). The percentages show the losses in relation to the rated power of the basic drive without optional components. (Image source: Siemens)

Figure 5: Delta Electronics' MS300 series includes 0.2 to 22 kW drives. (Image source: Delta Electronics)

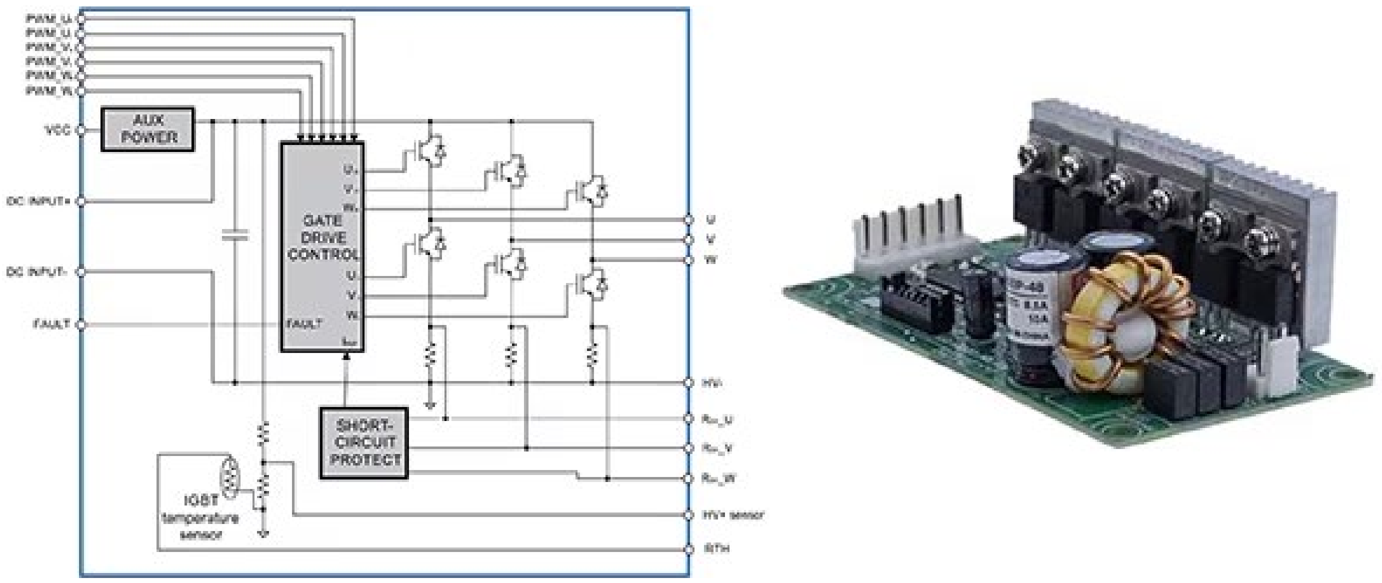


Figure 6: Block diagram of a VFD drive power section (left) and the power section ready for installation in an AMR (right). (Image source: MEAN WELL)

While other VFD makers focus on sections 1 and 2 of IEC 61800-9, Schneider Electric takes a more holistic approach and describes how to integrate its drives with the appropriate motor to meet the ecodesign directive and section 3 of IEC 61800-9 that delineates a quantitative ecodesign approach by means of eco balancing including product category regulations and related environmental declarations.

The company's Altivar Machine ATV320 drive family includes IP20 and IP6x rated VFDs from 0.18 to 15 kW (0.25 to 20 hp) for three-phase synchronous, asynchronous, PM and BLDC motors in open loop control and includes functions like:

- Low-speed torque and speed accuracy and high dynamic performance using flux vector control without a sensor
- Support for high-frequency motors
- Integrated functions for compliance with functional safety standards

What about AMRs?

AMRs use VFDs, but a different type of VFD. The VFD Series of industrial BLDC motor drives from MEAN WELL are a good example. They comply with the relevant sections of IEC 61800, such as 61800-5-1 safety requirements and 61800-3 electromagnetic compatibility (EMC) requirements. However, these VFDs are not packaged drives, so the efficiency categories of 61800-9 don't apply.

The VFD Series includes eight models with DC and AC input versions ranging from 150 to 750 W. The model VFD-350P-48 operates with an input of 48 V_{DC} for battery-power applications like AMRs and can supply up to 350 W and 20 A of output current. This 350 W BLCD driver is packaged on a 4"x 2" circuit card, and the fanless design can support 200% peak loads for 5 seconds (Figure 6). All the models in the VFD Series include only the power drive section and require an external control card. MEAN WELL also offers an optional control card.

Conclusion

Various adjustable speed drive designs are available for industrial applications, including machine controls and AMRs. They can support both AC and DC motors and have varying levels of compliance with sections of IEC 61800. In addition, since the performance of individual VFDs is not a focus of IEC 61800-9, there are several different approaches to reporting performance relative to those efficiency standards. Some VFD makers focus on sections 1 and 2 and report VFD efficiency levels like IE2. In contrast, others focus on section 3, which is related to overall ecodesign considerations, including product category regulations and related environmental declarations.

From kerosene to kilowatts: The story of rural electrification

By David Ray
Cyber City Circuits

A nation divided

America in the early 20th century was a nation divided.

Not by war, not by politics, but by light.

In the cities, electricity illuminated streets, powered factories, and fueled the Second Industrial Revolution. While in rural farm areas, darkness persisted. Electricity is taken for granted today, as it should be, but that was not the case a hundred years ago.

The story of rural America’s emergence from the darkness is one of ingenuity, determination, and the people's collective will to bring electricity to every corner of the nation. It’s the story of rural electrification, beginning in the dim glow of the 19th century.

The lights of the city

Electricity, a new technology, grew by leaps and bounds in the late 1800s. The Centennial Exposition of 1876 attracted inventors, mechanics, and engineers from all around the world to Philadelphia. This exposition featured gadgets and gizmos a plenty, including the first demonstration of the telephone, all sorts of arc lamps, and fancy new telegraph equipment lined the rows for months. There were steam powered engines on one side, gas powered engines on the other. This really was the golden age of innovation.

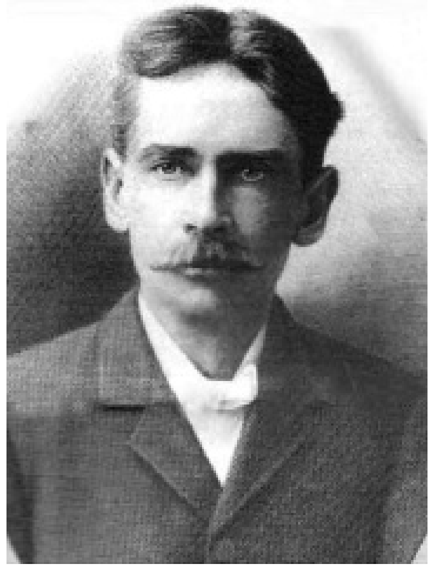
Thomas Edison founded Edison Electric Light Company in 1878, and by 1882, he had opened the first commercial power plant, Pearl Street Station, in New York City.Within thirty years, the city would have over thirty-five thousand streetlights. Cities hummed with industrial factories running around the clock, demonstrating the transformative potential of this new technology. Urban centers were already buzzing with the inventions of Edison, Westinghouse, Brush, Bell, and others. Their pioneering work laid the foundation for modern electrical networks. However, these systems had one major flaw: they were not built for distance.

During this time, Frank Sprague had recently left Edison, where he was instrumental in defining the mathematics needed to develop power grids. Learn more in the RetroElectro article 'Frank J. Sprague and the Richmond Union Passenger Railway.' (https://www.digikey.com/en/emedia/emagazine/2024/transportation?page=9)

The long-distance power transformer

Enter William Stanley Jr. (of Stanley Cup (not hockey) fame), who introduced the first practical power transformer in 1886 while working for George Westinghouse. This groundbreaking device allowed electrical currents to travel long distances with minimal loss, a stark contrast to Edison's direct current methods.

The major issue when transmitting power over long distances is that the impedance of the transmission lines create a lot of loss. Using his alternating current power transformer, Stanley substantially increased the line's voltages and reduced them when it reached the end user, paving the way for power grids extending beyond city limits.



William Stanley Jr

With this new 'power transformer,' poles were planted, and wire was strung along railroad tracks and telegraph lines across the country, powering up small communities along the way. Despite this breakthrough, the countryside remained in the dark. Investor-Owned Utilities (IOUs) focused on cities where customers were plentiful, and profits were high. This left rural areas in a perpetual state of economic disparity as opportunities clustered around the cities and people left the farms. Rural isolation deepened, with limited access to technology, education, and communication, further widening the gap between rural and urban life. Rural areas were deemed by the accountants and bean counters to be unmanageable and unprofitable due to their low population density and the vast distances.

Barriers to progress

Life in rural America at the turn of the century was difficult. Farming relied on manual labor and animal power. Candles and kerosene lamps provided meager light at night. Homes lacked the conveniences that urban residents of the day took for granted, like hot running water, electric heat, broadcast radio, etc. Yet, many rural families resisted the idea of electrification. The risks were high, the costs seemed exorbitant, and the benefits could not be comprehended by those who had never experienced them.

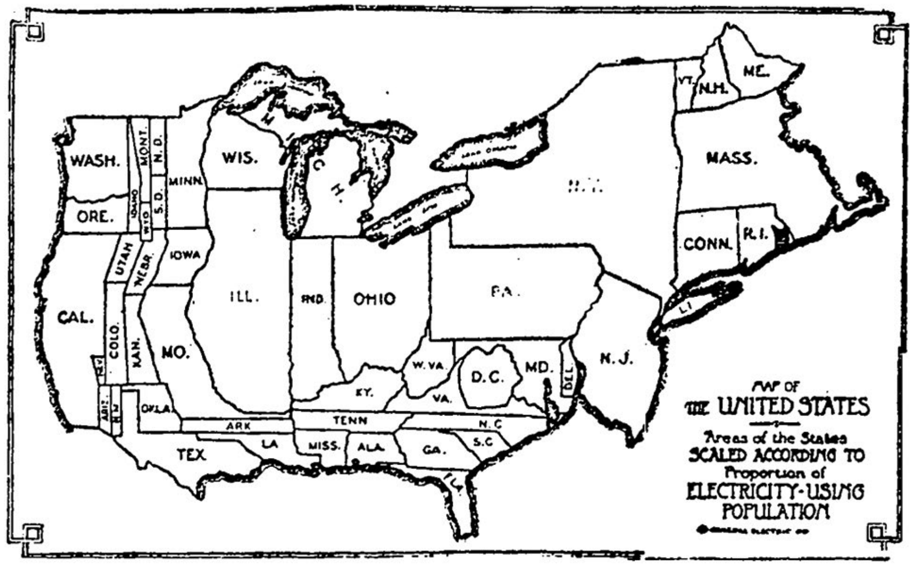
Adding to the challenge was the outright opposition from IOUs. These companies refused to extend their lines into rural areas and actively lobbied against efforts to bring power to the countryside. Whenever a community tried to manage power generation on its own, it was often sabotaged by utility companies. For them, rural electrification threatened their utility monopolies and profit margins.

The breaking point – the Great Depression

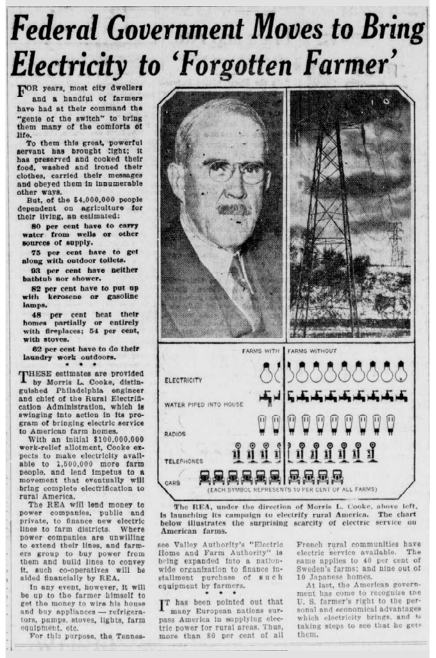
Soon after the stock market crash of 1929 devastated America, the early 1930s suffered a historic drought (The Dust Bowl). Many farming communities struggled to survive. As crop prices plummeted, many people left the farms to seek work in the city, leaving farmers and sharecroppers with even less help than before. For many, the lack of electricity symbolized their isolation and economic disadvantage, while urban centers thrived with the conveniences of modern technology. Farmers petitioned to get power to their community from the city, but they were rejected by the IOUs, who did not want to pay for it.

By the 1930s, the divide between urban and rural America had become impossible to ignore. The Great Depression hit farmers particularly hard. Farmers who could afford electricity on their farms could outproduce their neighbors. Many farmers used horses and mules to operate a grinding mill, while wealthier farmers could produce much more in the same amount of time simply by flicking a switch to run a motorized mill.

Side Note: During this time, out west in the Gold Rush, mining companies independently electrified nearby towns to establish the infrastructure needed for powering the mines. This was a particularly savvy business move because many of the mining companies were extracting coal, which was used to generate electricity.



A cartogram of electricity usage in 1921 by General Electric.



Federal Government Moves to Bring Electricity to 'Forgotten Farmer'

FOR years, most city dwellers and a handful of farmers have had at their command the "genie of the switch" to bring them many of the comforts of life.

To them this great, powerful servant has brought light; it has preserved and cooked their food, washed and ironed their clothes, carried their messages and obeyed them in innumerable other ways.

But, of the 54,000,000 people dependent on agriculture for their living, an estimated:

80 per cent have to carry water from wells or other sources of supply.

75 per cent have to get along with outdoor toilets.

93 per cent have neither bathtub nor shower.

82 per cent have to put up with kerosene or gasoline lamps.

48 per cent heat their homes partially or entirely with fireplaces; 54 per cent, with stoves.

62 per cent have to do their laundry work outdoors.

• • •

THESE estimates are provided by Morris L. Cooke, distinguished Philadelphia engineer and chief of the Rural Electrification Administration, which is swinging into action in its program of bringing electric service to American farm homes.

With an initial $100,000,000 work-relief allotment, Cooke expects to make electricity available to 1,500,000 more farm people, and lend impetus to a movement that eventually will bring complete electrification to rural America.

The REA will lend money to power companies, public and private, to finance new electric lines to farm districts. Where power companies are unwilling to extend their lines, and farmers group to buy power from them and build lines to convey it, such co-operatives will be aided financially by REA.

In any event, however, it will be up to the farmer himself to get the money to wire his house and buy appliances — refrigerators, pumps, stoves, lights, farm equipment, etc.

For this purpose, the Tennessee Valley Authority's "Electric Home and Farm Authority" is being expanded into a nation-wide organization to finance installment purchase of such equipment by farmers.

• • •

IT has been pointed out that many European nations surpass America in supplying electric power for rural areas. Thus, more than 80 per cent of all French rural communities have electric service available. The same applies to 40 per cent of Sweden's farms; and nine out of 10 Japanese homes.

At last, the American government has come to recognize the U. S. farmer's right to the personal and economical advantages which electricity brings, and is taking steps to see that he gets them.

The REA, under the direction of Morris L. Cooke, above left, is launching its campaign to electrify rural America. The chart below illustrates the surprising scarcity of electric service on American farms.

In 1935, President Franklin D. Roosevelt's New Deal introduced the Rural Electrification Administration (REA), a cornerstone of a broader vision that included projects like the Tennessee Valley Authority and the Civilian Conservation Corps. These projects aimed to modernize infrastructure and uplift rural communities. With federal loans and support, communities could form cooperatives to build power lines and bring electricity to their homes and farms.

The electric cooperative

Each city would have its own 'R.E.A. Man' who would visit different farm communities to explain how they could establish their electrical power grid. They would hold town hall meetings to answer community questions, conduct classes on safety, and teach how to install power poles, but that was about it. Their real influence lay in the government-backed loans they provided to farmers, enabling them to start their own electric cooperatives.

Electric cooperatives are community-driven, nonprofit utility companies. They are called cooperatives because everyone in the town had to work together to achieve the mission. Farmers would spend two or three days a week digging holes for poles and working on their farms the rest of the week. Initially, they began their efforts to bring electricity to rural areas that investor-owned utilities (IOUs) wouldn't serve. Often, they did not generate their own power but bought power from the existing IOUs at bulk rates while maintaining their own infrastructure.

Initially, the profits they earned were used to repay the loan from the REA, but afterward, they often used any profits they made to fund community development. Not only did they run electric poles and manage electric service, but they also paved roads, built schools, and constructed dams. Most rural areas didn't have schools for children beyond age 12, and then school was only a month or two each year. The co-op made it possible for rural areas to receive an education similar to that of city folk, increasing literacy rates nationwide. In many ways, the modernization of rural America was directly due to the local electric co-op.

> "It wasn't just about light. It was about life," recalls one cooperative organizer, "When that first light bulb flickered on in the barn, we knew everything was about to change."

These cooperatives became a lifeline. Neighbors worked together to string power lines across fields and through forests, often overcoming treacherous terrain and technical challenges. When the REA started, ten percent of America's countryside had electricity. By the end of the 1930s, around twenty-five percent of rural households had electricity.

War

At the beginning of World War II, the United States mainly supplied the Allied nations with food, metals, weapons, and various other goods. The U.S. would not begin its substantial military involvement until after the attack on Pearl Harbor in late 1941, but once that happened, the nation moved full speed ahead against the Axis powers. Of the eighteen million U.S. servicemen enlisted at the time, nearly two-thirds were drafted and yanked from their homes to fight in the Pacific and European theaters.

World War II saw a profound shift in who worked the farms. With so many young men leaving to serve in the military, women took on a greater role in ensuring food production met the demands of the nation and its allies. Electricity became their partner, powering tools and machinery that lightened their load and made the work more efficient. Tasks that had once required brute strength could now be managed with the push of a button, enabling farms to maintain productivity in the absence of much of their traditional labor force.

Electrification at war

World War II marked a turning point not just for America but for the rural electrification movement. Electrified farms didn't just feed the nation—they fed the war effort. Beyond agricultural output, electricity-powered equipment that processed and preserved food, allowing supplies to be shipped efficiently to troops overseas. It also bolstered rural factories repurposed for wartime production, contributing to the arsenal of democracy that defined the Allied victory.

At the same time, the U.S. Department of Agriculture reorganized to meet ambitious wartime food production goals. Electricity was no longer a luxury; it was critical for national security. Wartime propaganda even celebrated the role of electrification with slogans like "Powering victory from coast to coast."

Post-war developments

After the war, the momentum of rural electrification continued. Advances in technology made electricity more reliable and affordable, enabling the grid to reach the most remote areas. The REA provided ongoing support for grid modernization, ensuring that rural communities could maintain and expand their systems. By the 1950s, most rural households had electricity, transforming not just the economy but also the daily lives of millions.

The fight against monopolies

In the 1950s and 1960s, the REA adopted creative strategies to engage rural communities and expand participation in cooperatives. Film strips and promotional materials often targeted farmers' wives, recognizing their influential role in decision-making. These campaigns highlighted the conveniences electricity could bring to the home, from running water to electric stoves, persuading families to join cooperatives and electrify their homes.

As rural cooperatives grew in number and power, they faced continued opposition from IOUs. The most significant battle was Otter Tail Power Co. v. United States (1973). In this landmark case, the Supreme Court ruled against Otter Tail Power Company for blocking rural municipalities from developing their own electric systems. Not only did the IOUs need to allow the cooperatives to operate, but in many cases, they were required to help the cooperatives.

This decision reinforced antitrust laws and was used as a precedent against telephone companies, like AT&T, during a similar situation with long-distance carriers in the 1980s and 1990s.

Legacy and lessons

The Rural Electrification Administration effectively ended in 1985 after fifty years. Today, it's easy to overlook the poles and wires stretching out beyond the horizon, but they tell a remarkable story. Electrification didn't just bring light to rural homes; it brought opportunity. It connected communities, enabled industry, and reshaped the American landscape.

Rural electrification's legacy lives on, not just in the glowing bulbs of farmhouses but in the spirit of cooperation and progress it represents. As we look to the future of renewable energy and smarter grids, the story of rural electrification serves as a reminder that when there are large changes in the technological landscape, government appropriation is sometimes necessary to make sure the nation is not left behind.

1876

The Centennial Exposition in Philadelphia showcases early electrical technologies, drawing inventors like Edison and Bell into the spotlight.

1878

Thomas Edison establishes the Edison Electric Light Company to develop and commercialize electric lighting.

1882

Edison opens the Pearl Street Station in New York City, the first commercial power plant, powering the area with direct current (DC).

1886

William Stanley Jr., working with George Westinghouse, introduces the first practical power transformer, enabling long-distance transmission of alternating current (AC).

1890s

Power begins to extend along railroads and telegraph lines, serving small communities, but rural areas remain largely without electricity.

1929

The stock market crash devastates the U.S. economy, plunging rural farmers into financial despair.

1930s

The Dust Bowl intensifies challenges for farmers, highlighting their isolation and economic disadvantage due to a lack of electricity.

1935

President Franklin D. Roosevelt's New Deal establishes the Rural Electrification Administration (REA) to provide loans and support for electrifying rural America.

1941 - 1945

World War II accelerates the need for electrified farms to support increased agricultural production and wartime manufacturing.

1950s

The rural electrification movement reaches most American farms, transforming rural life and modernizing agriculture.

1985

The Rural Electrification Administration concludes its active role after 50 years, having successfully electrified rural America.

BESS: A solution to manage energy proactively

By Andrey Solovev

The expansion of renewables and a global tendency towards efficient energy consumption have boosted interest in energy storage solutions and, particularly, battery energy storage systems. Reading this article will help in understanding what these systems are about and the benefits of using them.

A BESS:What stands behind it?

A battery energy storage system (BESS) is a complex solution that makes use of rechargeable batteries to store energy and release it at a later time. BESS types correlate with electrochemistry or the battery they employ—the systems can be based on lithium-ion, lead-acid, nickel-cadmium, sodium-sulfur, and flow batteries. An energy storage system (ESS) is a broader term and it may rest on a variety of technologies other than batteries, for example, hydropower, flywheels, compressed air, and others.

To understand what a BESS is and how it works, it will help to look at its structure and core elements:

Battery

Electrical energy supplied from different sources, such as solar, wind, or power stations, converts to chemical energy during the battery charging process. The energy released from the battery during discharging can power homes, vehicles, commercial buildings, and grids. Batteries are made up of cells and can be arranged in modules, packs, and containers.

Battery Management System (BMS)

A BMS provides for the safe and correct operation of the battery. Every battery type has certain charging and discharging conditions. A BMS makes sure the battery stays within the required current, voltage, and temperature range. By monitoring the parameters and estimating the state-of-charge (SOC) and state-of-health (SOH) of the battery, a BMS ensures its reliable and long-lasting performance.

Power Conversion System (PCS)

Through the use of a power conversion system, a BESS converts direct current (DC) into alternating current (AC) and vice versa. AC flows from a power source and converts to DC during battery charging. When the battery is discharged, it produces DC, which is converted back to the AC necessary to power BESS applications.

Energy Management System (EMS)

An EMS is a control unit of a battery energy storage system. It manages the power available in a BESS—namely, when, why, and in which amounts to accumulate or release the energy. An EMS puts the elements of a BESS together and optimizes its overall performance.

SAFETY SYSTEMS

There can be an array of safety systems, each responsible for a specific task. For example, an HVAC system enables a BESS to maintain the desired temperature and humidity through heating, ventilation, and air conditioning. A fire protection system can detect smoke and prevent fire incidents.

What can a BESS do?

Every year, battery energy storage systems supply power to thousands of homes, businesses, plants, and communities worldwide. They vary in scale and storage capacity.

For example, having 13.5 kWh of usable capacity, the Tesla Powerwall is a compact device that can serve as a source of uninterrupted power for a single household. While with its total capacity of 1,600 MWh, the Vistra Moss Landing Energy Storage Facility—the world's largest BESS—can provide energy to 300,000 homes.

However, despite the difference in size and capacity, BESS can fulfill similar functions and address similar problems. Let's consider the cases when battery energy storage can come into play.

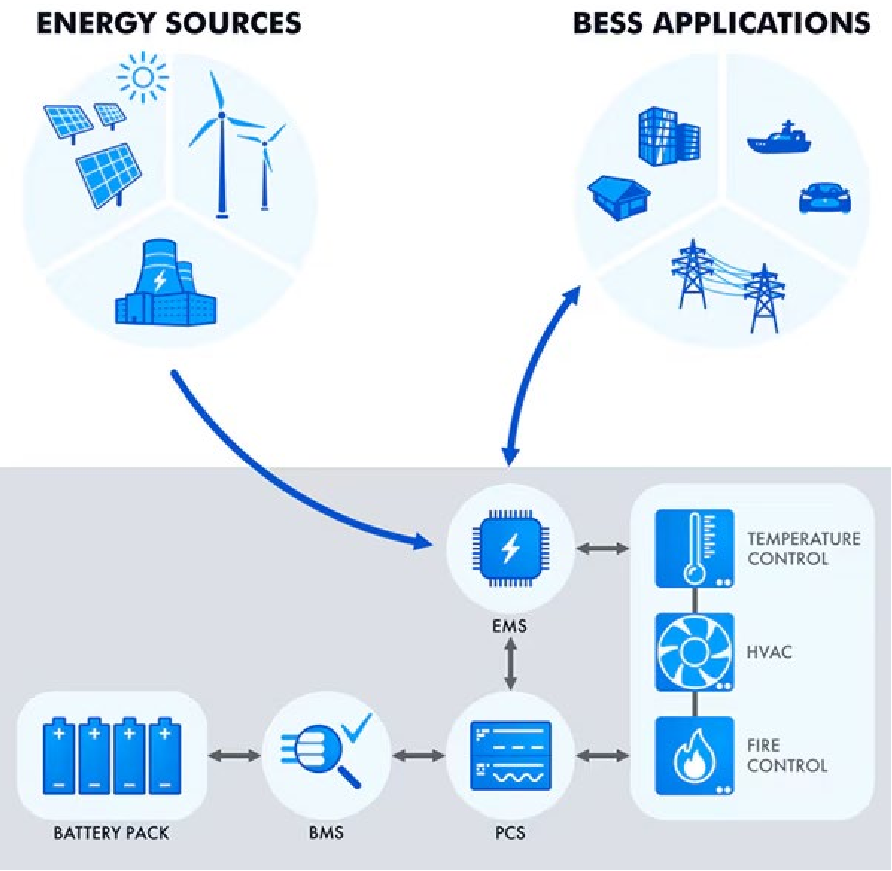


Figure 1: A typical BESS structure. (Image source: Integra Sources LLC)

Figure 2: Battery energy storage systems are widely used in solar and wind farms. (Image source: Integra Sources LLC)

Renewable energy integration

BESS can utilize solar and wind power efficiently at all times and in all weathers. Rechargeable batteries can store excess energy generated by intermittent renewables. Later, this energy can be dispatched according to the users' needs.

When integrated with battery storage solutions, renewable energy sources can replace fossil fuels, offering cheap and clean energy to a diversity of applications. Renewable integration is widely adopted in:

- solar and wind farms
- off-grid and isolated communities (islands and hard-to-reach areas)
- home energy storage devices coupled with solar panels (such as Powerwall)
- Apart from off-grid systems, a BESS can significantly support on-grid and hybrid solutions for residential, commercial, and industrial use.

Energy arbitrage

There is a positive correlation between the demand for electricity and its cost. The energy price increases during peak demand periods and decreases when the demand drops. Energy arbitrage, alias time-shifting, is what consumers can apply using a battery storage system.

By charging the battery at off-peak times, consumers can buy cheap energy and store it with their BESS. Then, they can wait until the electricity price rises and discharge the battery to either use low-cost energy or sell it to the grid.

Thus, households and businesses can effectively manage energy resources, cutting down on their costs.

Load management

Energy is consumed differently throughout the day and based on the season—there are on-peak and off-peak times. A BESS allows users to navigate between these periods, adjust energy consumption, and save on electricity costs.

Peak shaving is one of the most popular BESS use cases in load management. This is about reducing power consumption during peak periods. Along with that, consumers can cut their expenses just like with energy arbitrage.

A battery storage solution can help avoid peak loads on an electricity grid and, consequently, blackouts and other emergencies. By discharging the stored energy, a BESS takes the load off the grid and supplies power without interruption.

Black start

A BESS can help power stations and electricity grids restore quickly after power outages.

Instead of using a diesel generator, consumers can take to a battery storage system—a cheaper and greener black start solution. A BESS can work independently of the grid's transmission line and supply energy for the time required—from minutes to hours.

Power backup

A BESS can provide energy to homes, businesses, and other facilities, ensuring their continuous operation. This is of vital importance for healthcare institutions and other organizations that deliver services connected with people's health and safety. Depending on the storage capacity, a BESS can supply backup power as long as it takes, even in the case of a severe grid failure.

Frequency and Voltage Control

Frequency and voltage can go outside their operating limits if the power supply is out of sync with its actual demand. This may lead to the loss of power and blackouts. A BESS can ensure the stability of an electricity grid or power system through voltage and frequency regulation. Because of its fast response time, a battery energy storage system becomes an efficient grid balancing solution.

Microgrids

These are small electric grids that can supply electricity to commercial buildings, manufacturing plants, or neighborhoods when connected to a larger grid. Autonomous

Figure 3: A microgrid can act as a resilient power system for remote areas and communities, such as islands. (Image source: Integra Sources LLC)

microgrids can power remote areas and communities, such as islands. When combined with a BESS and integrated with renewable energy, a microgrid can act as a resilient power system for multiple users.

Transmission and distribution deferral

Transmission and distribution (T&D) lines are prone to aging and depreciation because of peak loads and congestions. A battery storage solution can solve this problem by taking on the role of T&D assets. A BESS can offer additional storage capacity and balance loads, thus deferring the upgrade of the existing T&D lines and construction of new infrastructure. This means saving heaps of money.

Where can a BESS be used best?

BESSs rely on affordable technologies, for example, the price for lithium-ion batteries has fallen by nearly 90% over the past 10 years and is going to drop further. Battery storage solutions have a broad range of configurations, including storage capacity and size, so they can fit many industries and applications.

These applications can be divided into **front-of-the-meter (FTM)** or utility-scale systems (the energy consumed is measured by an electric meter) and **behind-the-meter (BTM)** or on-site solutions (the energy consumed cannot be connected to a grid and thus measured by an electric meter). Here's a list of FTM and BTM BESS applications (which is definitely not complete).

Front-of-the-meter applications

Battery energy storage systems can contribute heavily to the operation and maintenance of utility-scale facilities and equipment. A BESS can offer reserve capacity and black-start services, provide voltage and frequency stability, and save money through deferred maintenance. FTM BESS applications include:

- Utility grids
- Substations
- Transmission and distribution lines
- Power stations

Behind-the-meter applications

BTM systems can supply power to consumers, bypassing an electricity grid. Along with green energy sources, a BESS can ceaselessly support standalone power systems or microgrids. Manufacturers can use battery storage for power backup to avoid downtime at production facilities. By using BESSs, companies and families can significantly reduce electricity tariffs with energy time-shifting. BTM battery energy storage systems can be found in:

- Industrial and manufacturing facilities
- Businesses
- Households
- Electric vehicles
- Marine systems

Does it make sense to build a BESS?

The short answer is yes, it does. The longer answer needs some clarification.

Without a doubt, buying a ready-made BESS saves lots of time and, sometimes, money. If there are no special requirements for the system, an out-of-the-box solution can be chosen from plenty of energy storage products available on the market. That said, there are some reasons that could hold a consumer back from the purchase, for example:

- specific customer requirements, including business niche demands and operating conditions
- lack of desired features or needless features that add to the system's cost
- system incompleteness and lack of supporting equipment
- low-quality software
- absence of warranty and post-warranty maintenance

Building a battery energy storage system can be a tedious process that takes time, money, and expertise. But this gives an opportunity to create a highly customized solution that fully meets all the requirements of an end-user.

A bespoke BESS can offer improved functionality, usability, safety, and cybersecurity. Implementing advanced BMS algorithms will allow users to enhance the performance of the battery and extend its lifetime. Developing a custom solution optimizes technical support, customer care, and other services that may be needed as either an end-user or a BESS provider.

To design a high-quality BESS requires a team of professionals well-versed in battery technologies, power electronics, embedded software, and hardware development. It's essential to organize and harmonize each stage of creating the product from design to certification and manufacturing. Hiring engineers with relevant expertise and experience can help build a full-fledged battery storage system that anticipates consumer expectations.

For all that, a custom product is not a silver bullet. Making a custom BESS should be considered on a case-by-case basis and for some projects, a turnkey solution would work best. To learn more about tailor-made versus off-the-shelf BESSs, read a larger article about battery energy storage systems on the Integra Sources LLC blog page. Here, readers can also learn about various battery technologies and characteristics, major BESS manufacturers, alternative energy storage systems, and other related details.

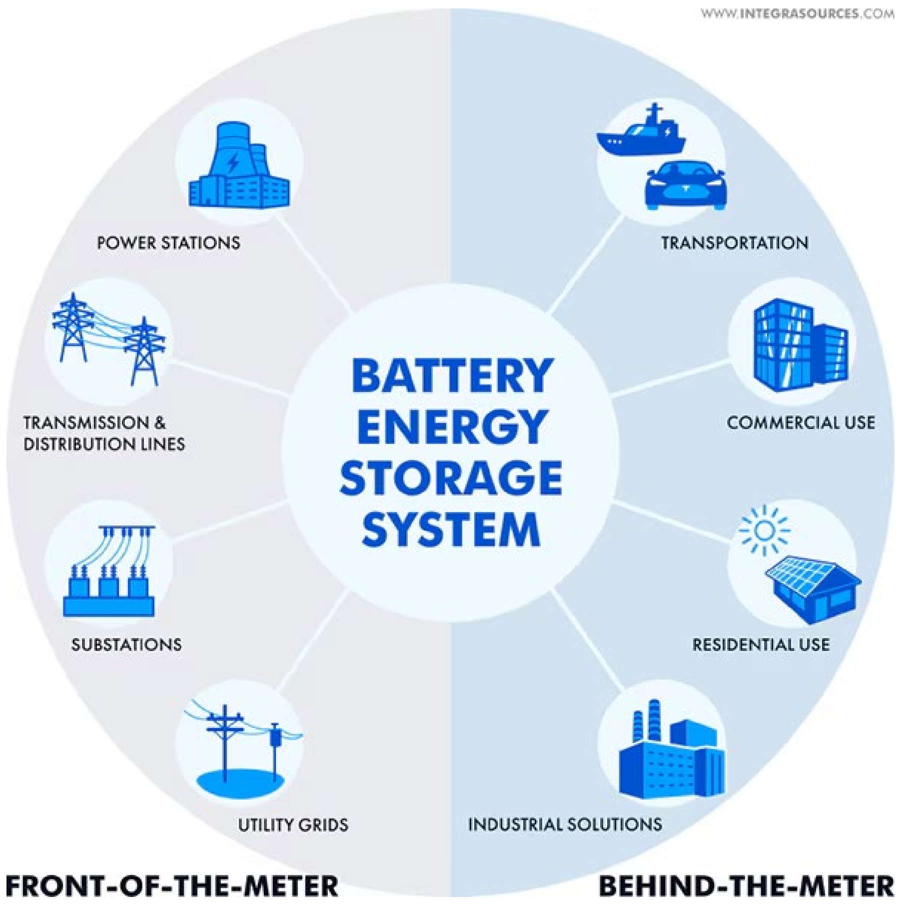


Figure 4: BESS applications. (Image source: Integra Sources LLC)

Design for the energy revolution

By Art Pini

Phoenix Contact aims to help designers minimize environmental impact and prepare for the renewable energy revolution by reducing emissions while supplying the world with sustainable, on-demand energy. They have made this their goal for the next decade with a concept called the “All Electric Society.” In their vision, renewable energy is generated and utilized efficiently through intelligent and networked systems created using electrification, networking, and automation technology.

Clean and sustainable energy comes from photovoltaic, hydroelectric, wind, and geothermal sources. Energy storage systems like batteries or green hydrogen systems complement the generation process and guarantee that energy is always available. Combined with networking and automation for control, they enable the electrification of all aspects of our lives. Phoenix Contact supplies many components for energy generation, storage, and automation in the All Electric Society.

Wind turbine generators

Wind turbine generators produce about ten percent of the electricity in the United States. These generators are complex structures where machine diagnostics monitor system health to reduce damage and minimize downtime. For example, intelligent turbine blade monitoring includes sensors to check ice, lightning, load, and structural health (Figure 1).

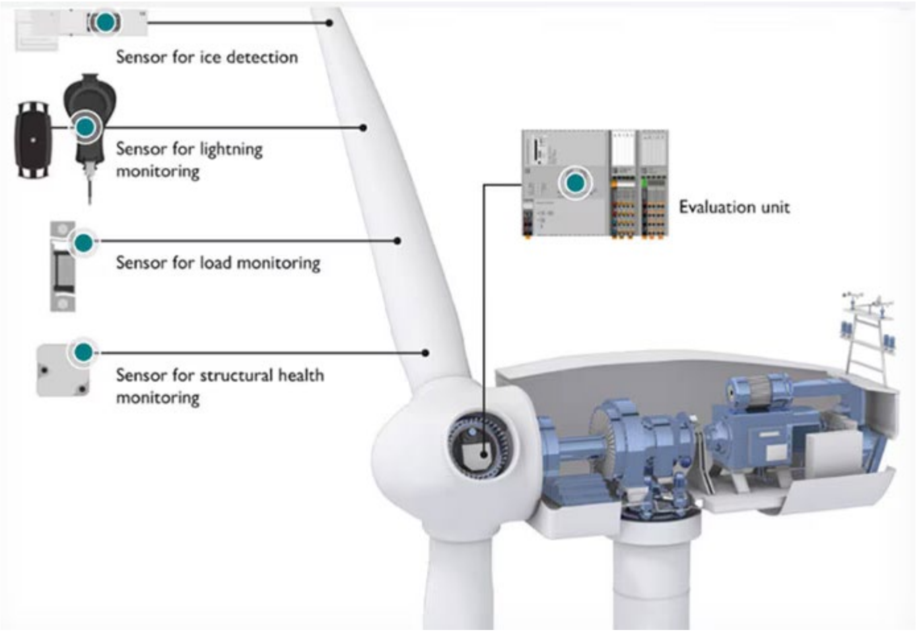


Figure 1: Intelligent turbine blade monitoring includes sensors to check ice, lightning, load, and structural health to detect and prevent damage. (Image source: Phoenix Contact)

The Phoenix Contact 1183803 rotor blade load sensor mounted near the blade's interior base uses strain gages to monitor turbine blade loading. Combined with data from other sensors, the measurement-evaluation controller monitors the blade load, permitting the turbine to be controlled to optimize performance with minimal blade loading.

Photovoltaic power generation

Solar power generation requires system-wide monitoring to ensure that solar panels in the field are operating with peak efficiency. Solar cells are connected in series, described as a photovoltaic (PV) string, to achieve a prescribed voltage. Monitoring current and voltage in the individual strings of panels allows users to pinpoint power losses due to damaged solar panels or poor electrical connections (Figure 2). Sensor modules are multiplexed through multichannel communications modules to a coordinating controller.

In Figure 2, voltage and current sensors monitor twenty PV string currents and the common voltage using only two communications modules. Communications modules send the data to a compact controller via a Modbus interface.

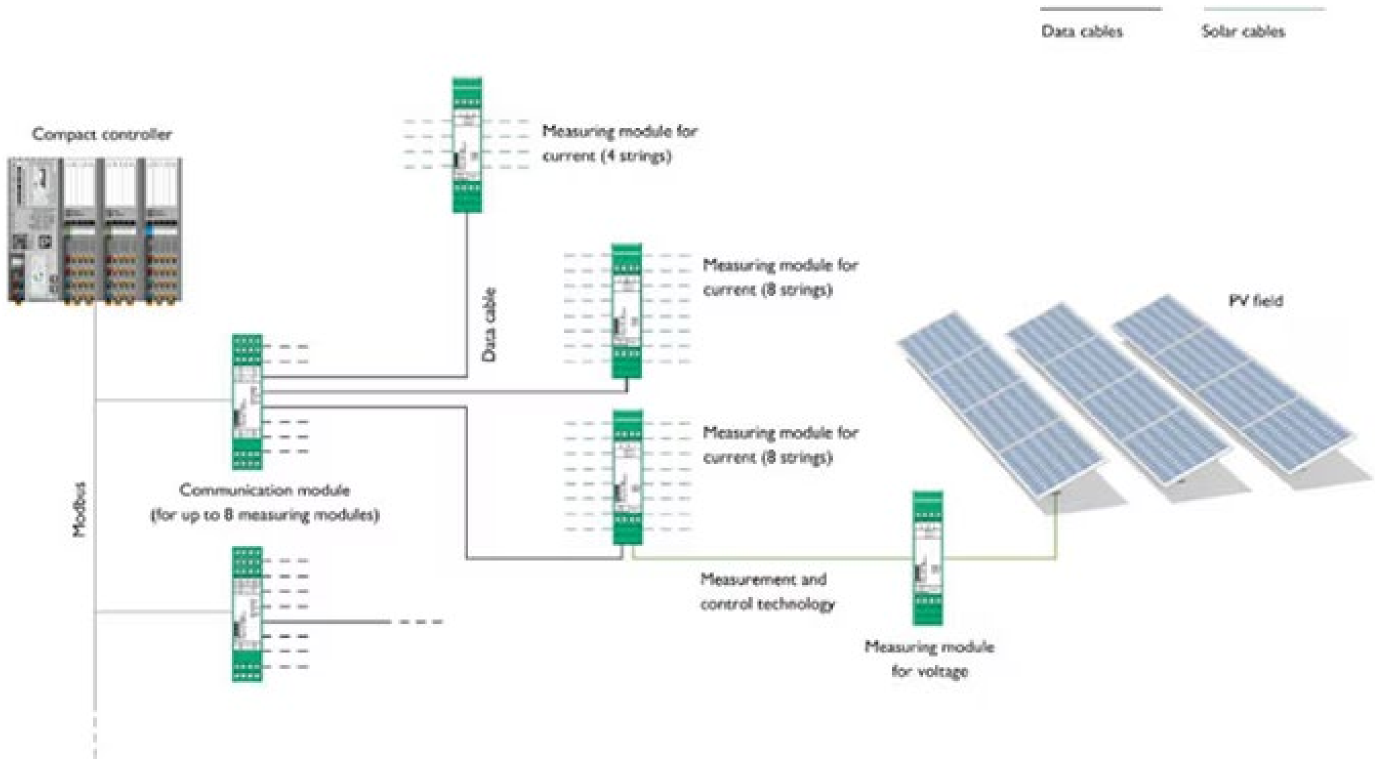


Figure 2: Monitoring PV string current and voltage in the individual strings of panels allows users to pinpoint power losses due to damaged solar panels or poor electrical connections. (Image source: Phoenix Contact)

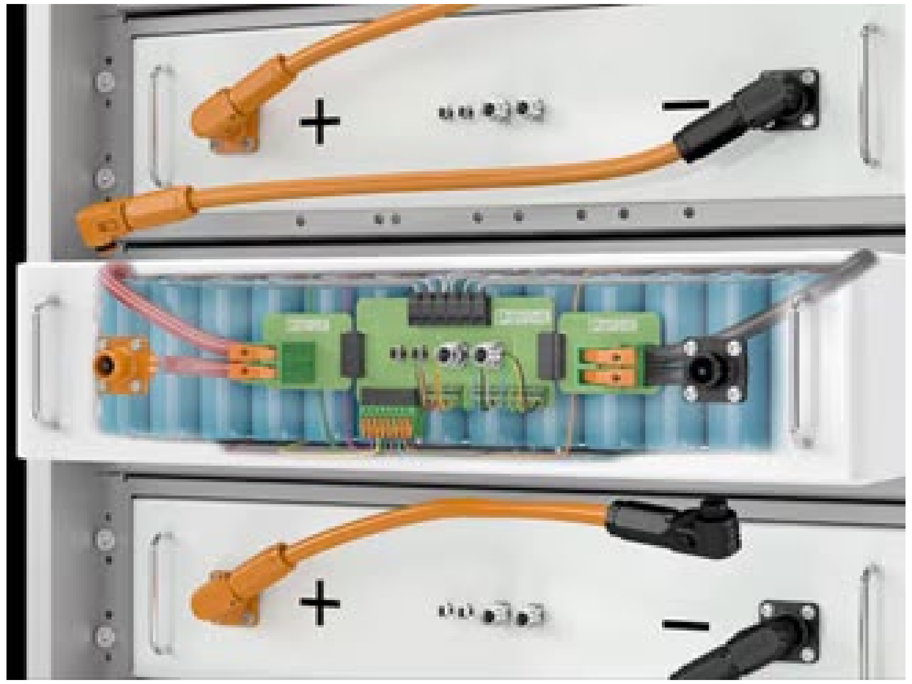


Figure 3: Shown is an energy storage cabinet with the front panel removed, exposing three battery modules composed of individual battery cells (blue) with their associated control electronics. (Image source: Phoenix Contact)

The Phoenix Contact 2903591 is an example of a sensor module that can measure a single voltage up to 1500 volts. The output data is an analog voltage in the 2 to 10 volt DC (VDC) range, proportional to the measured input. The 2903591 sensor is a 35 millimeter (mm) DIN rail module powered by a 24 VDC source.

Energy storage

Since energy demand is constant, designers must be able to store generated power from renewable energy sources such as the sun and wind. The common approach is to rely on batteries for energy storage. The smallest energy storage unit is the battery cell, but multiple cells can be combined into a battery module to increase the available storage capacity. The power from the individual cells must be balanced to ensure that they are charged or discharged at a similar rate. Safety concerns require monitoring the battery module temperature to detect thermal runaway. Multiple modules are combined into a storage cabinet under the control of a power control unit (PCU) (Figure 3).

Phoenix Contact supplies the connectors used to join these modules. For example, the polarized connectors can link modules with the 1106306 as the positive contact and the 1106307 as the negative contact. These battery pole connectors are mechanically coded to prevent accidental polarity reversal or touching, and can be rotated a full 360˚ for wiring flexibility.

Conclusion

Phoenix Contact offers a wide range of products intended for the All Electric Society, from connectors to sensors to control elements. It also supplies software and controllers for the automation and control of industrial systems. In addition to its products, Phoenix Contact is committed to operating sustainably by reducing CO2 emissions in its facilities and daily operations.

Achieving high efficiency in telecom power supplies

By Rolf Horn
Contributed By DigiKey's
North American Editors

The telecommunications sector has become an important element of modern society and instantaneous global communication. Whether for a phone call, text message, or web command, telecom equipment ensures reliable connections. The power supply operating behind the scenes is an essential component that is rarely acknowledged.

This article focuses on the Analog Devices MAX15258, which is designed to accommodate up to two MOSFET drivers and four external MOSFETs in single-phase or dual-phase boost/inverting-buck-boost configurations. It is possible to combine two devices for triple-phase or quad-phase operation, achieving higher output power and efficiency levels.

Meeting the need of increased power demand

The power demand within the telecommunications industry has grown over time, driven by developments in technology, heightened network traffic, and the expansion of telecommunications infrastructure. The transition from third generation (3G) to fourth generation (4G) and fifth generation (5G) networks has led to advanced and high power equipment.

The deployment of 5G technology has had a significant impact on the power requirements of base stations and cell towers. Base stations, particularly those in urban areas, require higher power levels to support the increased number of antennas and radio units needed for massive MIMO (Multiple Input, Multiple Output) configurations and beamforming.

Redundancy is another crucial factor. Power supplies must be designed with redundancy in mind, often including backup power sources like batteries or generators to ensure uninterrupted operation in case of power outages.

Compared to previous generations of wireless networks, the deployment of 5G mobile technology introduces several changes to power device requirements. For 5G to deliver on its promise of reliable, high speed, and low latency communication, some criteria must be addressed.

Power amplifier requirements

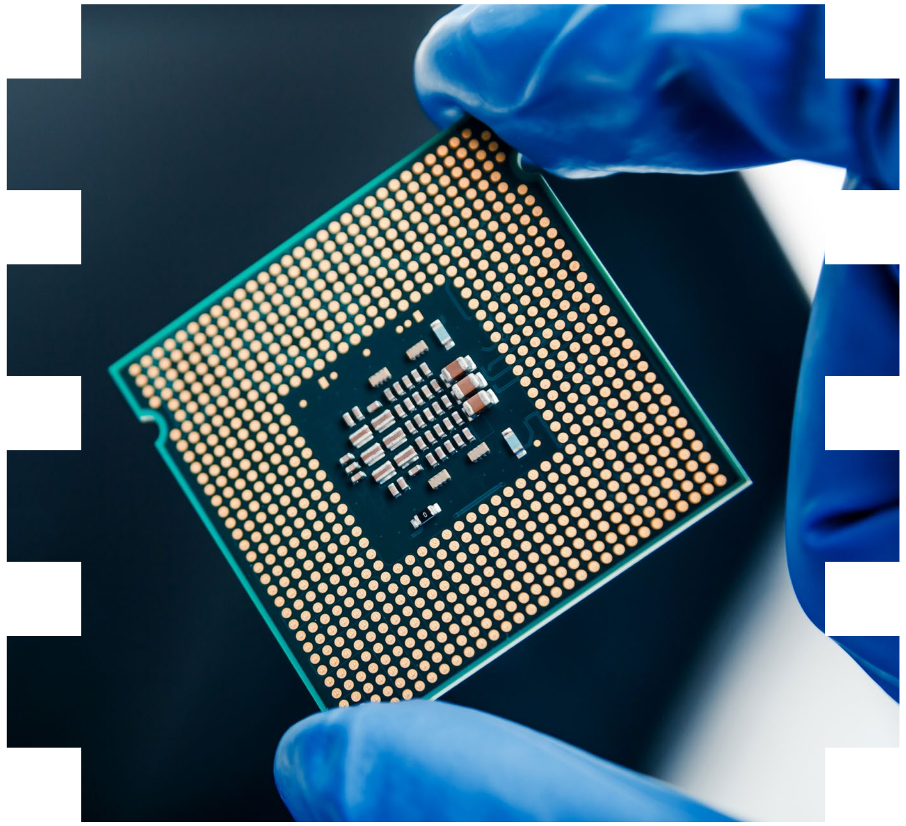
- Support a broad spectrum of frequency bands, including sub-6 GHz and mmWave (millimeter wave) frequencies, which present unique challenges for signal propagation.
- Accommodate wider signal bandwidths and higher power levels, as well as providing linear amplification to prevent distortion of high-data-rate signals.
- Operate efficiently to minimize power consumption and heat generation, especially for battery-powered devices and remote small cells.
- Include a lightweight, compact form factor that can fit into small enclosures, such as small cell sites and user equipment.
- Incorporate advanced materials and technologies such as semiconductor devices made of Gallium Nitride (GaN) and Silicon Carbide (SiC) to provide increased power density, enhanced performance, and increased operating frequencies.

Power conversion requirements

For historical, practical, and technical reasons, telecom systems typically utilize a -48 V_{DC} power supply. In the event of a grid malfunction or other emergency, telecommunications networks require dependable backup power sources. Commonly used for reserve power, lead-acid batteries can also operate at -48 V_{DC}. Using the same voltage for both primary and backup power makes it easier to design and maintain backup systems. Additionally, lower voltages such as -48 V_{DC} are safer for personnel working with telecom equipment, reducing the risk of electrical shock and injury.

Power supplies for telecommunications equipment must meet specific operational requirements to ensure reliability and efficiency. Here are some important specifications:

- Input voltage range: The power supply should be designed to tolerate a broad input voltage range.
- Voltage regulation: The power supply must provide a stable and regulated output voltage per the requirements of the telecom equipment.
- High efficiency: Power supplies should be highly efficient to reduce power loss and energy consumption. Efficiencies of at least 90% are typical.
- Redundancy: To ensure uninterrupted operation, power supplies frequently include redundancy features such as N+1 where an additional power supply is used. If one fails, the other can assume the burden.



- Hot-swappable: In mission-critical installations, power supplies should be hot-swappable, assuring minimal downtime during replacement or maintenance.
- High reliability: The power supply should be equipped with protection mechanisms to avert damage caused by adverse operating conditions, such as overcurrent, overvoltage, and short-circuits.

The active clamp forward converter

The active-clamp forward converter (ACFC) is a DC/DC converter configuration common in power supply systems, and it is primarily utilized for converting -48 V_{DC} to positive voltage levels. The ACFC is a voltage conversion circuit that integrates characteristics from the forward converter and the active-clamp circuit to enhance efficiency.

This technology is prevalent in power supply systems for telecommunications and data center apparatus.

The central element of the ACFC is a transformer (Figure 1). The main winding of the transformer receives the input voltage, resulting in the induction of a voltage in the secondary winding. The output voltage of the transformer is determined by its turn ratio.

The active-clamp circuit, which incorporates supplementary semiconductor switches and a capacitor, regulates and governs the energy contained inside the leakage inductance of the transformer. When the primary switch is off, the energy stored in the leakage inductance is redirected to the clamp capacitor, thereby preventing voltage spikes. This practice mitigates the strain on the primary switch and enhances operational effectiveness. The voltage from the transformer's secondary winding is rectified by a diode, and the output voltage is smoothed by an output filter capacitor. Finally, ACFC operates with soft switching, meaning that switching transitions are smoother and produce less noise. This results in reduced electromagnetic interference (EMI) and lower switching losses.

The ACFC circuit reduces voltage spikes and stress on components, leading to improved efficiency, especially at high input-to-output voltage ratios. Moreover, it can handle a wide range of input voltages, making it suitable for telecom and data center applications with varying input voltages.

Disadvantages of the active clamp circuit include the following:

- If not constrained to a maximum value, an increased duty cycle can result in transformer saturation or additional voltage stress on the main switch, necessitating the precise sizing of the clamp capacitor.
- ACFC is a single-stage DC-to-DC converter. As the power level rises, the advantages of a multiphase design for power intensive applications such as telecom will increase.

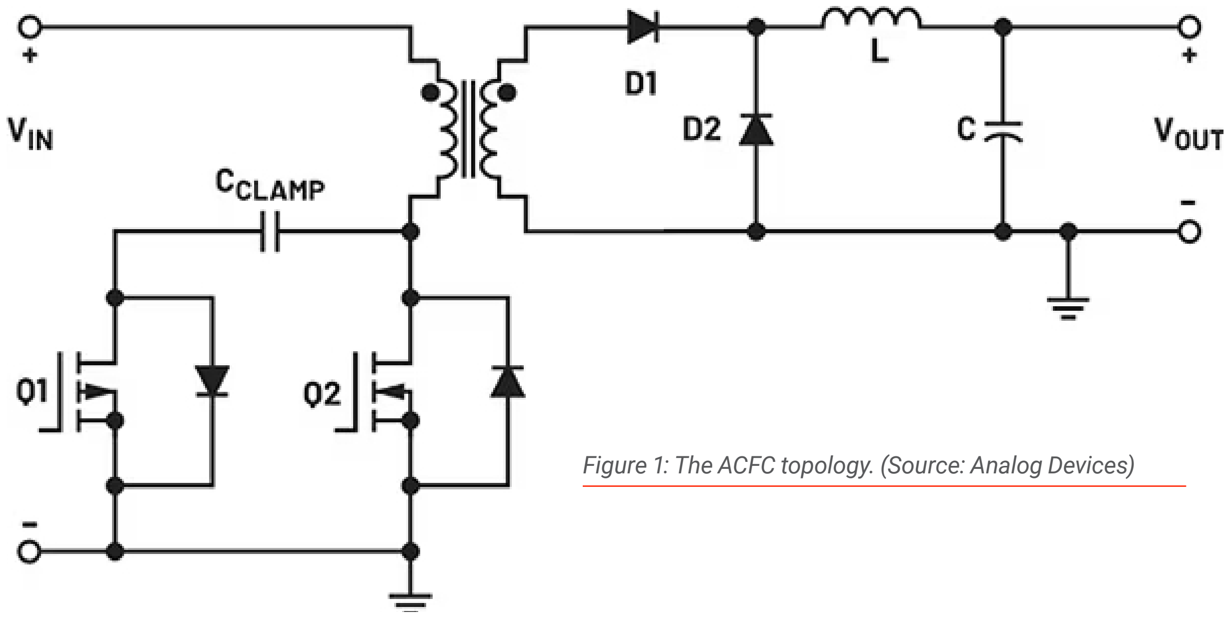


Figure 1: The ACFC topology. (Source: Analog Devices)

- An active clamp forward design cannot be scaled to higher output power and maintain similar performance.

Overcoming ACFC's limits

Analog Devices' MAX15258 is a high-voltage multi-phase boost controller with an I²C digital interface designed for telecom and industrial applications. The device features a wide input voltage range of 8 V to 76 V for boost configuration and -8 V to -76 V for inverting buck/boost configuration. The output voltage range, from 3.3 V to 60 V, covers the requirements of various applications, including telecom devices.

A typical application of this versatile IC is the power supply for a 5G macrocell or femtocell shown in Figure 2. The hot-swap feature is ensured by a negative voltage hot-swap controller, such as ADI's ADM1073, powered by -48 V_{DC}. The same voltage supplies the MAX15258 buck/boost converter, which is capable of providing up to 800 W of output power.

The MAX15258 is designed to support up to two MOSFET drivers and four external MOSFETs in boost/inverting-buck-boost single-phase or dual-phase configurations. It also combines two devices for triple-phase or quad-phase operation. It has an internal high-voltage FB level shifter for differentially sensing the output voltage when configured as an inverting-buck-boost converter. Through a dedicated reference input pin or via an I2C digital interface, the output voltage can be set dynamically.

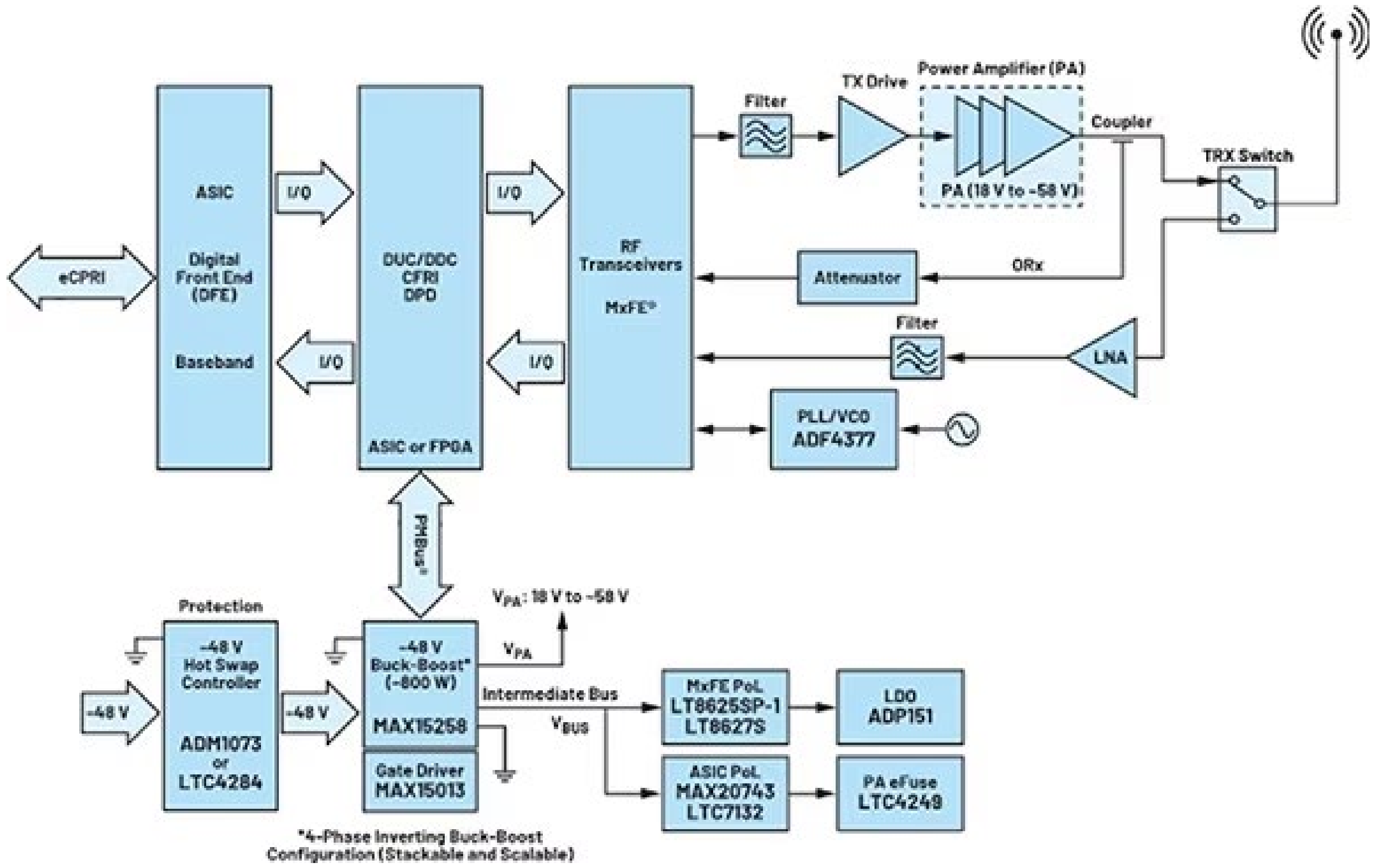


Figure 2: Block diagram of a power supply stage for 5G applications. (Source: Analog Devices)

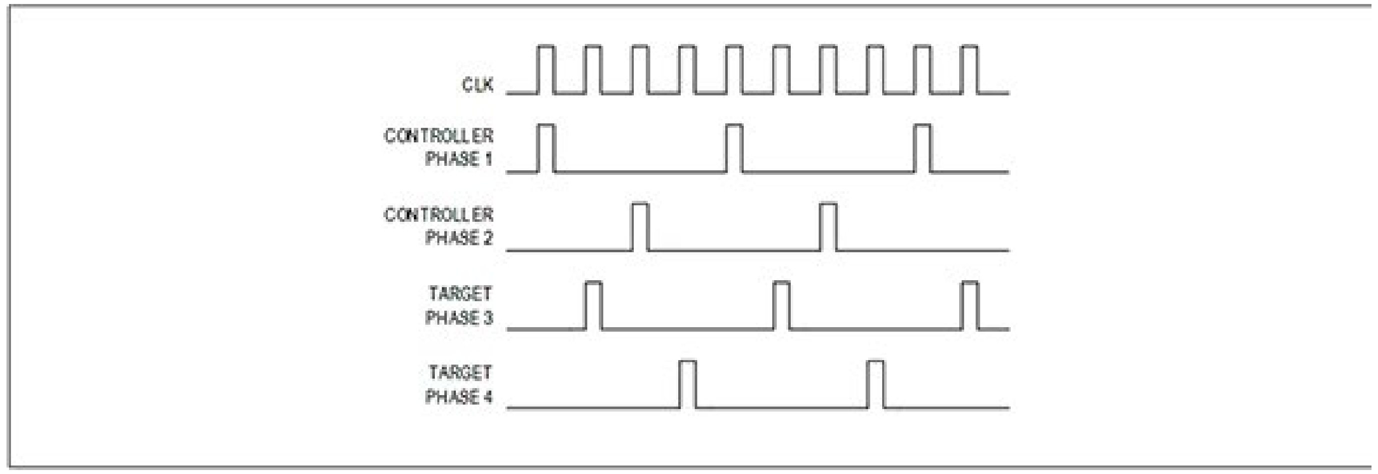


Figure 3: Quad-phase configuration - controller and target waveforms. (Source: Analog Devices)

An external resistor can be used to adjust the internal oscillator, or the regulator can be synchronized with an external clock to maintain a constant switching frequency. Switching frequencies from 120 kHz to 1 MHz are supported. The controller is also protected against overcurrent, output overvoltage, input undervoltage, and thermal shutdown.

The resistor at the OVP pin designates the number of phases to the controller. This identification is used to determine how the controller responds to the primary phase's multiphase clock signal. In a quad-phase converter, the two phases of the MAX15258 controller or the target are interleaved by 180°, whereas the phase shift between the controller and target is 90° (Figure 3).

In multiphase operations, the MAX15258 monitors the low-side MOSFET current for active phase current balancing. As feedback, the current imbalance is applied to the cycle-by-cycle current sensing circuitry to help regulate the load current. Doing so ensures equitable distribution between the two phases. Unlike forward converter designs, designers do not need to account for a possible 15% to 20% phase imbalance during the design calculation stages when using this IC.

In triple-phase or quad-phase operation, the average per-chip current is transmitted between the controller and target via dedicated differential connections. The current-mode controller and target devices regulate their respective currents so that all phases equitably share the load current.

The quad-phase interleaved inverting buck-boost power supply shown in Figure 4 is suitable for applications requiring large amounts of power. The CSIO+ and CSIO− signals connect the

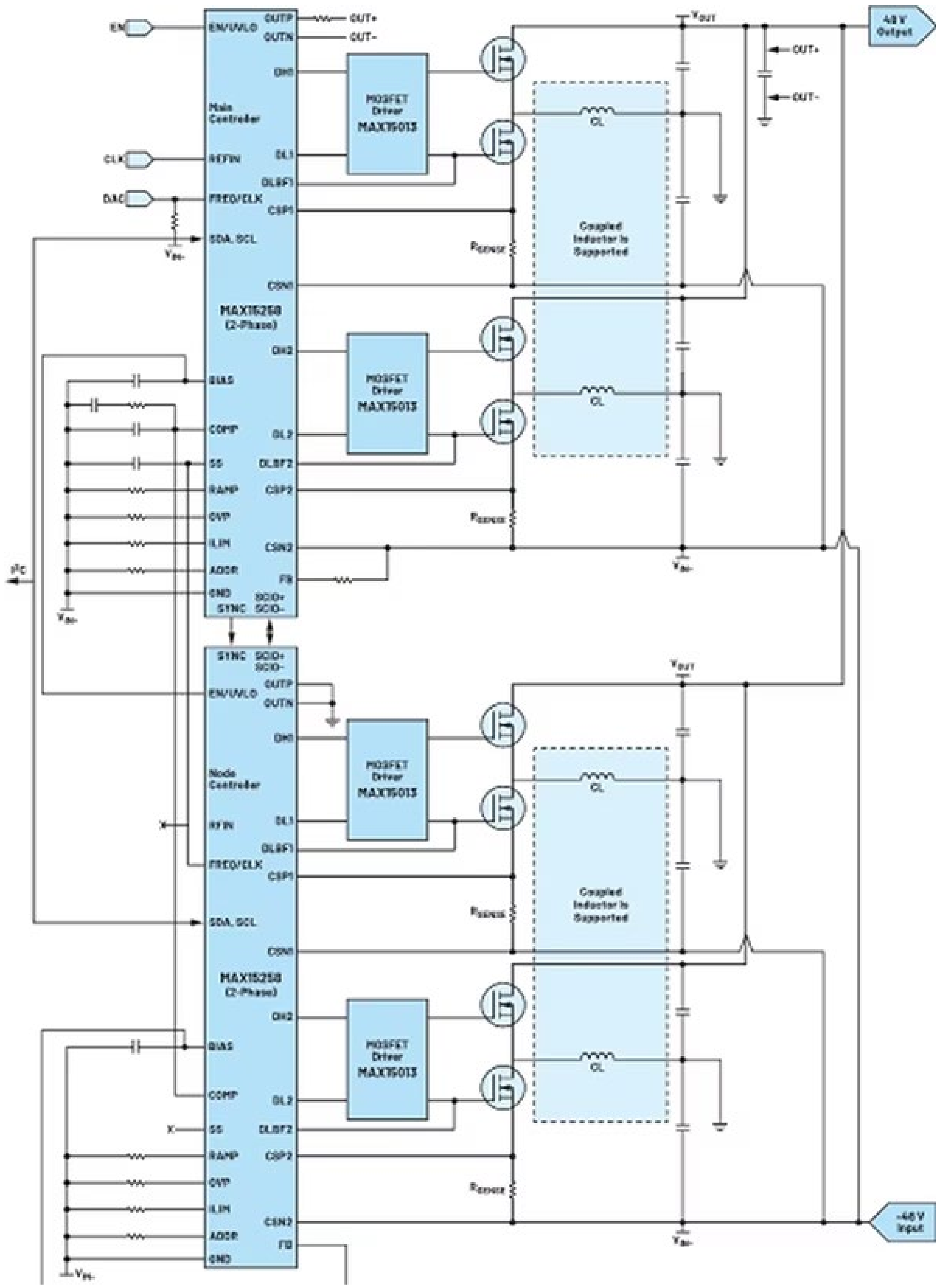


Figure 4: Quad-phase inverting buck-boost -48 V_{IN} to +48 V_{OUT} 800 W power supply. (Source: Analog Devices)

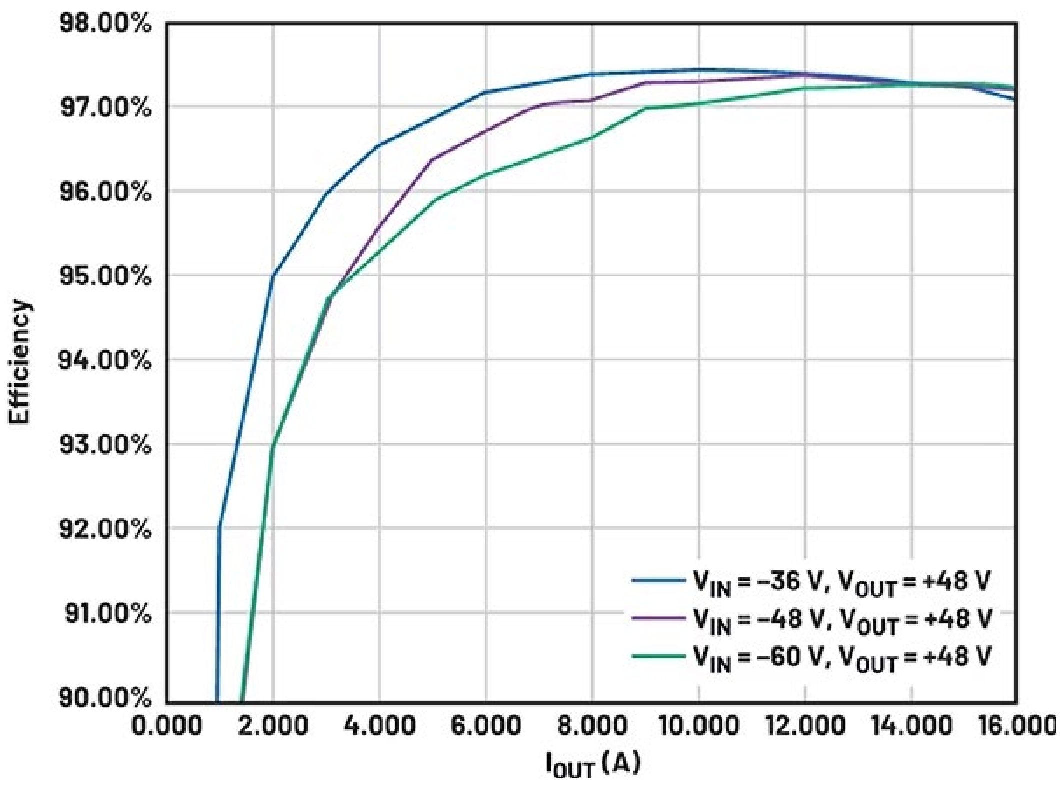


Figure 5: Efficiency vs. output load current of a MAX15258 CL 800 W reference design. (Source: Analog Devices)

two controllers, and the SYNC pins are connected to assure clock synchronization for the phase interleaving scheme with coordinated phases.

The MAX15258 is a low-frequency boost converter. This reduces the converters' primary source of power loss—switching losses. Because each converter operates in its low-loss area at low frequency, this offers high output power at a high equivalent total frequency. This makes it the go-to device for converting -48 V_{DC}.

Operating with a stable duty cycle, it obtains a high output power with extremely high efficiency. Figure 5 shows the efficiency curves of a coupled inductor-based MAX15258 800 W reference design for various combinations of V_{IN} and V_{OUT}. As a result of reduced conduction losses, the plots plainly display efficiency figures more than 98%.

Conclusion

Power supplies play an important role in the telecommunications industry. Due to their ability to attain high efficiency and minimize power losses, active clamp forward converters (ACFCs) are favored in telecom power supply designs. However, inherent limitations can hinder their efficacy in specific circumstances. To overcome the limitations of active clamp forward converters, a new generation of power supply technologies has emerged, offering enhanced efficiency, increased power density, and simplified control mechanisms. In the telecom industry, these novel solutions pave the way for more advanced and optimized power supplies.

Shifting product design to net-zero sustainability

By Pete Bartolik
Contributed By DigiKey's North American Editors

Major forces are aligning to ensure a significant business requirement for sustainability over the next few decades. Around the globe, governments, businesses, and people are rallying to support a net-zero carbon emissions goal for 2050. Product designers would be well advised to factor net-zero sustainability into their future product plans or risk losing business to competitors better able to respond to intense market pressures.

The National Association of Manufacturers (NAM) reported at the end of 2022 that 58% of surveyed manufacturer executives believe sustainability is essential to future competitiveness, substantially higher than for a similar survey in 2019.[i] Sustainability, in the case of manufacturers and producers, refers to the ability to continue processes and practices over time without depleting resources such as the energy, materials, and water on which they depend.

The term net zero was codified in 2015 under the auspices of the United Nations when 196 countries adopted the Paris Agreement, an international, legally binding treaty.[ii] Subsequently, in 2017, a UN Intergovernmental Panel set 2050 as the target for achieving net-zero goals for emissions of carbon dioxide (CO2) and deep reductions of non-CO$_2$ emissions. Despite the lack of any universal enforcement mandate, the net-zero target is increasingly being adopted by governments and businesses:

- Thirty countries, including the U.S., have pledged to meet a net-zero goal for their government operations by 2050 and to reduce emissions by 65% by 2030.
- Half of the world's 2,000 publicly listed companies have set net-zero targets, representing 66% of the annual revenue for that top 2000 category.[iii]
- 45% of those polled by NAM say their companies have set formal net-zero goals, and 30% plan to achieve that by 2030.[iv]

Commercial implications of net zero

The business ramifications of net-zero sustainability are enormous.

U.S. defense agencies spent an estimated $210 billion on products in 2022, while civilian agencies spent $49 billion.[v] The European Commission, in proposing a net-zero technology products manufacturing ecosystem, projects that the global market for mass-manufactured net-zero technologies will amount to EUR 600 billion annually by 2030.[vi]

Manufacturers will be expected to produce goods for electric vehicles and infrastructure, modernized power grids, building controllers, and heat pumps, among others. In addition, investment in carbon capture technology will drive the need for new product designs and solutions to retrofit existing manufacturing plants.

The shift to net zero will require a massive reallocation of capital, likely adding up to hundreds of trillions in U.S. dollars and equivalents by 2050. This will require a massive transformation in how those in the manufacturing sector do business, from how they power their plants and tools to adoption of lighter and stronger materials.

Entire manufacturing supply chains will be impacted. Manufacturers measuring their progress to net zero will have to calculate their overall carbon footprint, including the net zero progress of their suppaliers. Companies that want to profit from non-zero business opportunities will need to demonstrate they are moving to achieve net-zero goals.

Companies will have to calculate the carbon impact of the entire product life cycle, from materials sourcing to end-of-life management. Designers must learn new skills, adapt or replace existing processes, and revamp operations to make sustainability a core design concept. Key best practices areas include:

- Adopting circular economy practices that reduce materials use and recapture waste products to be used in manufacturing new materials and products.
- Optimizing processes to decarbonize product development, including minimizing materials consumption and resource usage during the manufacture of products.
- Innovating in new design concepts and investing in new tools and technologies to achieve more energy-efficient products and processes.
- Fostering a net-zero mindset by focusing on change management issues, including elevating sustainability champions in the organization, addressing worker fears and resistance, and reskilling and bringing in new skills necessary to achieve net-zero goals.
- Extending the usefulness of mechanical systems with digitized services that deliver new features and functions as needed.

Leveraging supplier advances

Analog Devices, Inc. (ADI) is a $12 billion (FY2023) global semiconductor leader that combines analog, digital, and software technologies to bridge physical and digital worlds. Its products help drive advancements in digitized factories, building automation, mobility, and digital healthcare. It is committed to achieving net zero by 2050 or sooner, cutting Scope 1 and 2 carbon emissions by 50% by 2030, and diverting 100% of waste from ADI manufacturing facilities by 2030.

ADI aims to reduce energy consumption, extend asset lifetime, and reduce raw material usage through power-efficient motion control, precision low-power asset health monitoring, and adaptive intelligent sensing, actuation, and controls.

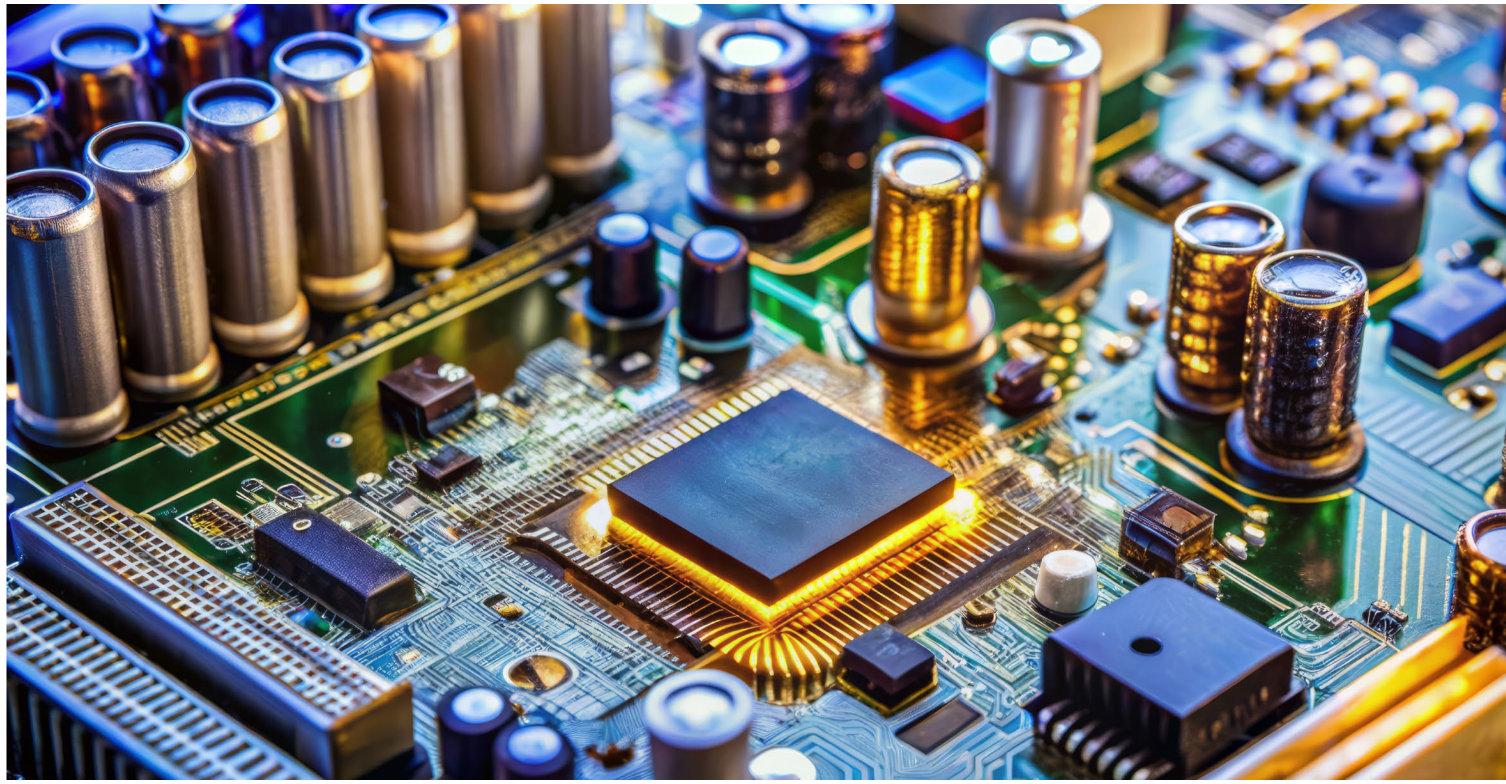
With an extensive portfolio, ADI provides product designers with a wide range of components aimed at improving energy efficiency in industrial automation and intelligent building applications:

Variable speed drives: It's estimated that electric motors account for about 65% of industrial electricity use.[vii] Historically, most of those motors are fixed rotation devices, and equipping all with variable speed drives could reduce global energy usage by up to 10%.[viii] ADI's variable speed drive solutions incorporate high-performance current and voltage sensing, robust isolation, high-density power management, and seamless connectivity.

High voltage, high bandwidth current-sense amplifiers, such as the AD8410A and AD8411A, perform bidirectional current measurements across a shunt resistor to deliver feedback that can enhance drive performance and determine bandwidth and response time of motors, ensuring the motor is operating at peak efficiency. Power management in smaller enclosures is a key design consideration. ADI offers flyback switching regulator integrated circuits like the MAX17692 that sense the isolated output voltage directly from the primary-side flyback wave-form during secondary-side rectifier conduction. Without the need for a secondary-side error amplifier and optocoupler, designers can save up to 20% of printed circuit board (PCB) space compared to a traditional flyback converter.[ix]

Position encoders: High-efficiency servo-driven motors with precise position and torque control can optimize energy usage by enabling faster machining of complex components. ADI precision signal conditioning and conversion technology accurately measures small-magnitude signals in noisy industrial environments. ADI's offerings help in developing high performance position encoder solutions that provide advanced control loop performance, high efficiency, and highly integrated power management technology that can reduce the energy consumption required in the machining process and drive factory throughput.

ADI technologies can help accelerate time to market in delivering high performance position encoder solutions. The company offers encoder signal chain solutions for sensor types such as optical, magnetic, resolvers, and linear variable differential transformers. The ADP320 triple-output low dropout (LDO) features low quiescent current, low dropout voltage, and wide input voltage range to power all components in optical and magnetic encoder signal chains.



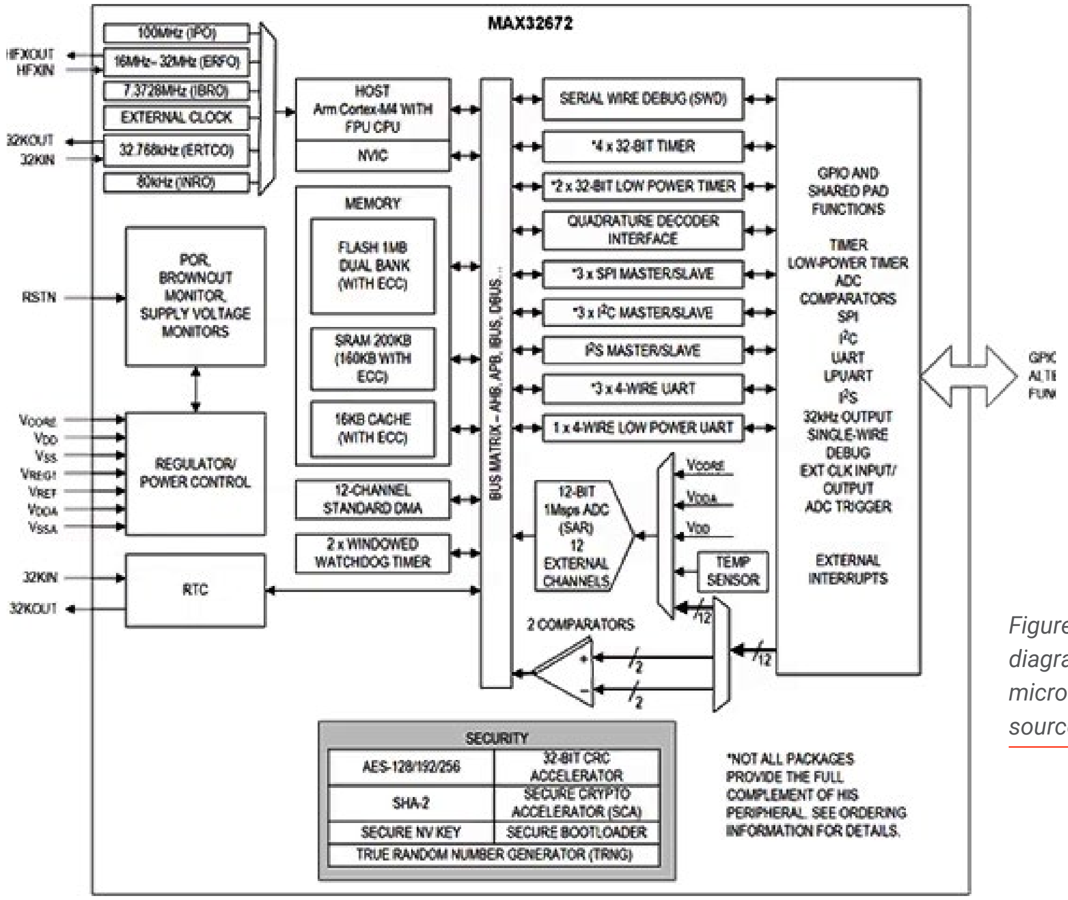


Figure 1: Simplified block diagram of the MAX32672 microcontroller. (Image source: Analog Devices, Inc.)

A simplified block diagram of ADI's MAX32672 is shown in Figure 1. It is a tiny, ultra-low-power, highly integrated, and reliable 32-bit microcontroller, enabling designs with complex sensor processing without compromising battery life, and can provide an easy, cost-optimal path from 8- or 16-bit microcontrollers of legacy designs.

Designers incorporating encoders on motors to support advanced manufacturing capabilities will benefit from reduced encoder form factors.

Integrated power management: ADI provides highly integrated micropower management solutions in compact footprint ICs, including low-noise regulators like the LT3029, for applications such as general-purpose linear regulators, battery-powered systems and microprocessor core/logic supplies, as well as the LT3024, that is suited for cell phones, wireless modems, and frequency synthesizers.

Dependable connectivity: ADI offers half and full duplex RS-485 transceivers for reliable data transmission at high data rates. The ADM3066E and ADM3067E, for example, deliver high-speed, 50 Mbps, bidirectional data communication on multipoint bus transmission lines and feature a 1/4 unit load input impedance that allows up to 128 transceivers on a bus. Designers can take advantage of several evaluation boards, like the EVAL-ADM3066EEBZ (Figure 2), to help assess and demonstrate capabilities of these transceivers.

Building controllers: Making new and existing buildings more sustainable requires measurement, connectivity, and processing technologies to control HVAC and lighting, sense occupancy, and monitor environmental conditions. This will drive demand for intelligent edge devices to enable the digitalization of building systems.

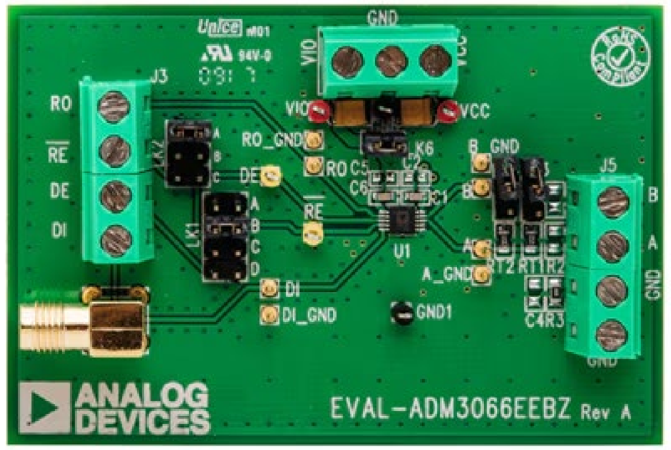


Figure 2: ADI's EVAL-ADM3066EEBZ evaluation board has a footprint for the ADM3066EBRMZ half-duplex RS-485 transceiver in a 10-lead MSOP package. (Image source: Analog Devices, Inc.)

Building automation systems typically incorporate multiple controllers and disparate nodes, each requiring reliable connectivity. The ADIN1110 is a low-power single-port transceiver with an integrated media access control (MAC) interface that requires lower overall system-level power consumption, and has integrated voltage supply monitoring and power-on reset circuitry to improve system-level robustness.

Intelligent buildings need efficient management of power at the edge. ADI's LTC4296-1 enables Single-pair Power over Ethernet (SPoE) power sourcing for 10Base-T1L controllers and switches, with transmission of up to 52 W of power plus data over a single twisted-pair Ethernet cable. The LTC9111 is an IEEE 802.3cg-compliant SPoE power device controller particularly suited for classification-based systems in building and factory automation.

Conclusion

The growing demand for net-zero sustainability by 2050 represents an enormous opportunity for products that support manufacturing innovation, retooling, and advancing new technologies. While 2050 may seem far in the distance, data cited in this article underscores that governmental, business, and societal pressures are already causing many companies to build 2050 net-zero and 2030 carbon-neutral goals into their current strategies. Every supplier ultimately will likely need to show progress toward those goals. Product designers who proactively incorporate those goals into their planning, processes, and component supplies stand to benefit from one of the largest industrial transformations ever.

Resources

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