Balancing of Supercapacitors
Supercapacitors and Energy

Supercapacitors (SCs) have emerged as a popular solution for those situations in which high-density back-up power is required, along with high cycle life and fast charge and discharge times. They generally operate at low voltages of about 2.7 V. To achieve higher operating voltages, it is necessary to build up a cascade of SC cells connected in series. Due to variations in capacitance and insulation resistance caused by production or aging, the voltage drop across individual capacitors may exceed the rated voltage limit. Therefore, a balancing system is required. In this issue, an article titled “Balancing of Supercapacitors” by René Kalbitz, product manager, Würth Elektronik eiSos GmbH & Co. KG, will explain the effect of unequal voltage division in such series circuits. Other topics in this issue are wide bandgap semiconductors such as GaN and SiC, Hydrogen technology, electric vehicles and advanced solutions for power production and transfer. The success of electric vehicles (EVs) depends heavily on the time required to charge the batteries. In charging systems, power MOSFETs based on silicon carbide (SiC) play a fundamental role. The search for increasingly sustainable solutions, combined with the need to contain carbon dioxide emissions by reducing the greenhouse effect, are favoring the use of renewable energy sources. The ability to produce energy from alternative sources allows for a significant reduction in environmental impact and polluting emissions compared with traditional energy sources based on fossil fuels. The overall strategy to power a climate-neutral economy includes all aspects of the energy-production system across multiple energy carriers, infrastructures, as well as the analysis of what is needed to achieve climate neutrality by 2050. In this issue, Patrick Le Fèvre provides information about the “hydrogen strategy for a climate-neutral Europe (COM/2020/301 final).” Europe is engaged in a process to develop a climate-neutral economy in which green and blue hydrogen plays a major part. These and other topics have been discussed at PCIM and APEC.

Yours Sincerely,
Maurizio Di Paolo Emilio
Editor-in-Chief, Power Electronics News
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GaN Transistors Leveraged to Develop High Performance Affordable DC/DC Converters

High-Density SiC Power Modules Meet Formula E Challenges

Saving Stand-by Power in the Smart Home
Balancing of Supercapacitors

By René Kalbitz, Product Manager, Würth Elektronik eiSos GmbH & Co. KG

Supercapacitors (SCs) generally operate at low voltages of about 2.7 V. To achieve higher operating voltages, it is necessary to build up a cascade of SC cells connected in series. Due to variations in capacitance and insulation resistance caused by production or aging, the voltage drop across individual capacitors may exceed the rated voltage limit. Therefore, a balancing system is required to prevent accelerated aging of the capacitor cell.

In the following, the effect of unequal voltage division in such series circuits will be explained in principle. For a better understanding, balancing strategies are discussed for using a series connection of two capacitors.

THE IMBALANCE OF SUPERCAPACITORS CONNECTED IN SERIES

A capacitor can be modelled by a parallel connection of an R-C element and an insulation resistor. For the moment, we can neglect the insulation resistance and consider a series connection of two capacitors with capacitances $C_1$ and $C_2$. The quantity of energy in such a case is the charge $q$ on the capacitor, i.e., on its internal interfaces. With the help of the charge conservation law

$$V_{1,2} = \frac{q}{C_{1,2}}$$

is the voltage drop across each capacitor

$$V_1 = \frac{V_g}{(C_1 + 1)}$$

and

$$V_2 = \frac{V_g}{(C_2 + 1)}$$

with

$$V_g = V_1 + V_2$$

as the total voltage. In the following, we can consider the case where $C_1$ is greater than $C_2$. In this case, the voltage drop across each capacitor is

$$V_1 = \frac{V_g}{2} - \frac{\Delta V}{2}$$

and

$$V_2 = \frac{V_g}{2} + \frac{\Delta V}{2}$$

with

$$\Delta V = \frac{V_g}{2} \frac{C_1 - C_2}{C_1 + C_2}$$

To set the voltage of each capacitor to $V_f = V_{f1} = V_{f2}$ the charge on Capacitor 1 must be increased and on Capacitor 2 decreased. Using the definition of electric current ($I = dq/dt$), the voltage can be written as

$$V_1 = \frac{V_g}{2} - \frac{\Delta t}{C_1}$$

and

$$V_2 = \frac{V_g}{2} + \frac{\Delta t}{C_2}$$

The current $I_{1,2}$ is interpreted as the electric current that must flow for a time span $\Delta t$ to balance this system. The constant current required to balance a voltage difference $\Delta V$ in a given time period $\Delta t$ is

$$I_{1,2} = \frac{\Delta V}{\Delta t} \frac{1}{C_{1,2}}$$

BALANCING STRATEGIES

The literature categorizes balancing strategies according to various characteristics such as:

- Energy-dissipative behavior
- Balancing speed
- Type of technology used
- Pricing
Therefore, when choosing the right balancing strategy, it is important to know all the parameters and constraints of the specific application to make the right choice. Here, we distinguish between active balancing and passive balancing.

Active balancing involves the use of actively controlled switches or amplifier systems. Passive balancing involves the use of shunts or voltage-dependent resistors to reduce the effects of overvoltage. Compared with passive balancing, active balancing is fast and usually energy-efficient but also relatively costly. Passive balancing, on the other hand, is relatively slow and often results in increased charge loss but is less expensive.

MEASUREMENTS

A series connection of two SCs from Würth Elektronik was tested:

- Capacitor 1: C₁ = 10 F
- Capacitor 2: C₂ = 15 F

This corresponds to deviations from a theoretical capacitor with a nominal capacitance of Cₐ = 12.5 F.

For charging, we used a charging voltage of V₁ = 5.4 V and a maximum charging current of I₁ = 2 A.

In the interest of reliable circuit design, we would like to emphasize that a combination of SCs with different nominal capacitances is not advisable. This combination was chosen for experimental purposes only.

The self-discharge behavior of each circuit over a 24-hour period was also investigated. For this purpose, we disconnected the entire balancing circuit from the primary power source after the capacitors were fully charged and balanced.

**1-KΩ RESISTOR**

For passive balancing, we used a resistor with 1 kΩ (1%) and rated for 0.6 W. The resistor was chosen to favor a short balancing time rather than low power dissipation. The measured voltages V₁ and V₂ and the resulting voltage difference V₁ − V₂, shown in Figure 1, indicates complete balancing after about 600 minutes. V₁ and V₂ asymptotically approach V₁.

The total power dissipation (calculated from effective leakage current, I Loss) after 12 hours is 2.8 mA × 5.4 V = 15 mW. For low-power applications or backup solutions, this compensation speed can be sufficiently fast and the power dissipation is acceptable. For standalone battery-powered applications, the resistance should be increased to reduce losses. To be on the safe side, it is also advisable to reduce the operating voltage to avoid overvoltage.

The half-life of the self-discharge is estimated with

\[
t_{\text{loss}} = \frac{\ln(100 \% - 50\%)}{\ln(C_{\text{stack}})} = \frac{V_g}{I_{\text{loss}}} = \frac{1}{C_{\text{stack}}}
\]

with

\[
C_{\text{stack}} = \frac{1}{C_1 + C_2^{-1}}
\]

Therefore, the following results in this example:

\[
t_{\text{loss}} \approx 0.7 \cdot \frac{5.4 V}{2.8 mA} \approx 6 F \approx 133 \text{ minutes}
\]

**ZENER DIODE BZX79-B2V7**

We used the voltage regulator diodes BZX79-B2V7 from NXP Semiconductors. The results, shown in Figure 3, show complete equalization after about 80 minutes. With the datasheet value of total power dissipation of 500 mW, the measured value roughly fits the theoretical approximation of

\[
t_{\text{b}} = 3 \cdot \left( \frac{V_g^2}{F_P} \cdot \frac{C_r}{7.3 \cdot 0.1 \cdot 0.5 W} \cdot 12.5 F \right) = 70 \text{ minutes}
\]

The total power dissipation (effective leakage current, I Loss) after 12 hours is 5 mA × 5.4 V = 27 mW. At lower voltages, the power dissipation is even lower. (The datasheet defines: I Loss (1 V) = 20 μA.)

We can estimate that the datasheet value I Loss (1 V) = 20 μA is about 10× higher in our case. With f = 10, the theoretical half-life of the self-discharge for the series connection, balanced with a Zener diode, can be estimated with

\[
t_{\text{loss}} = 0.7 \cdot \left( \frac{V_g}{I_{\text{loss}}} \cdot \frac{C_r}{6 F} \right) \approx 0.7 \cdot \frac{5.4 V}{10 \cdot 20 \mu A} \approx 1900 \text{ minutes}
\]
The results of the self-discharge measurement as shown in Figure 4 indicate that $t_{\text{loss}}$ = 1,900 minutes approximately corresponds to the actual half-life of the self-discharge.

**MOSFET ALD910022 (TEST BOARD SABMB2)**
The MOSFET-based equalization circuit was implemented using the SABMB2 test board for the ALD910022 MOSFET from Advanced Linear Devices. The results in Figure 5 show complete equalization after about 300 minutes. The total power dissipation after 12 hours was 1.5 mA × 5.4 V = 8 mW, about as low as for the Zener diode.

The results of the self-discharge measurement in Figure 6 show that after 24 hours, the cell voltage has dropped to approximately 4 V. At this rate, $t_{\text{loss}}$ is on the order of several days.

**AMPLIFIER OPA2677**
For active balancing, we used the OPA2677 amplifier (Texas Instruments). The advantage of the OPA2677 is the relatively high output current of 500 mA, which enables fast balancing. The measured cell voltages in Figure 7 show immediate balancing within the charging time, which is about 3 minutes for this measurement. The damping resistance at the output should not be less than 0.4 Ω to prevent oscillation of the output voltage. The resistance of 1 Ω provides an optimum between fast equalization and damping.

The total power dissipation after 12 hours is 50 mA × 5.4 V = 270 mW. Most of the power is dissipated through the amplifier supply terminals. This relatively high power consumption shows the main drawback of this type of strategy. Although it is fast, it also has a high permanent power consumption.

The results of the self-discharge measurement in Figure 8 show a self-discharge half-life of $t_{\text{loss}}$ = 5 minutes.

Although the circuit always ensures a balanced charge, the losses through the supply channels are significant.

**BALANCING BOARD LTC3128**
The DC1887A evaluation board uses the LTC3128 buck-boost charge and balance circuit from Analog Devices. This charges the SCs with a preset voltage of 4.2 V. The board operates at a supply voltage of 5.5 V. The measurement results, which are shown in Figure 9, show complete balancing after 1.5 minutes.

The total power dissipation after 12 hours is 0.1 mA × 5.4 V = 0.5 mW.

**SUMMARY**
Balancing with the resistor is the slowest balancing strategy, but it has the advantage of low power consumption, lowest cost, and simplest circuit design.
The balancing speed of the Z-diode is moderate. It offers the advantage of relatively low power consumption, low cost, and simplest circuit design.

The MOSFET circuit also has relatively low power dissipation. The compensation speed of the given example is moderate.

Although the op-amp provides fast balancing compared with the other strategies, it exhibits the highest power dissipation.

The balancing evaluation board provided the fastest balancing and moderate power dissipation. It is overall a convenient but somewhat expensive solution. An overview of the summarized results is given in the following table:

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<th>Balancing time (min)</th>
<th>Relative costs</th>
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<td>600</td>
<td>Low</td>
</tr>
<tr>
<td>Z-diode BZX79-B2V7</td>
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<td>70</td>
<td>Low</td>
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<tr>
<td>MOSFET ALD910022</td>
<td>8</td>
<td>300</td>
<td>Moderate</td>
</tr>
<tr>
<td>Amplifier OPA2677</td>
<td>270</td>
<td>3</td>
<td>High</td>
</tr>
<tr>
<td>Evaluation board DC1887A</td>
<td>42</td>
<td>1.5</td>
<td>Moderate to high</td>
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In the end, it is the responsibility of each developer to choose and adapt the best solution for their situation.

Advanced Solutions for Power Production and Transfer

By Stefano Lovati, technical writer, EEWeb

Electronic applications involving the production and transfer of energy are of fundamental importance today. The search for increasingly sustainable solutions, combined with the need to contain carbon dioxide emissions by reducing the greenhouse effect, are favoring the use of renewable energy sources. The ability to produce energy from alternative sources such as sun, wind, wave motion, and biomass allows for a significant reduction in environmental impact and polluting emissions compared with traditional energy sources based on fossil fuels. Solar energy, for example, can help developing countries or small mountain and rural communities to equip themselves with efficient, economical, and virtually zero environmental impact plants to produce electricity. Photovoltaic (PV) panels have undergone a rapid and significant evolution in recent years, offering users increasingly efficient and reliable solutions that require reduced maintenance and are able to produce energy even in conditions of low solar radiation. At the same time, the simplicity of installation has grown, favored by the introduction of flexible panels capable of adapting to surfaces of various types. PV systems are normally combined with special units for storing the electricity produced, made with storage batteries more or less evolved according to the available budget. These batteries accumulate energy during the day and then make it available for lighting and powering different loads during the night. Not only that, they can detect blackouts, automatically becoming the primary energy source in the event of a power failure. Unlike generators, storage batteries can deliver energy without the use of fuel and in a silent way.
Of equal importance to energy production is the transfer of energy, especially if this can take place wirelessly, without requiring the use of bulky and often annoying electrical cables. The wireless electricity transfer technique, based on the principle of electromagnetic induction, has returned to the fore in recent times thanks to two applications that have become priority. The first, relating to the consumer electronics sector, concerns the charging of battery-powered mobile devices (typically smartphones), which can be recharged simply by placing them on a suitable source capable of transferring electricity by conduction. The second main application concerns the recharging of batteries in electric and plug-in hybrid vehicles, carried out by means of devices that can be placed on the floor below the car or even integrated into the road surface. In addition to not requiring the connection of electrical cables, this solution proves to be very effective from a safety point of view, as it does not expose the user to the potential risk of contact with the high powers involved.

In this article, two highly innovative applications will be presented, relating to the exploitation of solar energy as a source of electricity and the transfer of wireless energy in various types of contexts.

**FLEXIBLE SOLAR PV**

Power Roll, based in Sunderland (U.K.), has developed an innovative model of solar film capable of generating and storing energy. Lightweight and flexible, the solar film can adapt to any type of surface, producing electricity at a cost up to 20× lower than traditional PV panels. The new technology is based on a flexible film patterned with thousands of microgrooves. Each microgroove is a few microns thick, smaller than a human hair.

The advantages offered by this solution are:

- Low cost: $0.03/W for the finished product
- Low weight: 0.3 kg/m²
- Easy installation and reduction of maintenance times
- Sustainability, due to the use of fully recyclable materials and absence of rare earths
- Adaptability: The same technique can be used either on the roofs of buildings or for powering small IoT sensors
- High power density: 500 W/kg

As shown in Figure 1, the flexible film enables roll-to-roll manufacturing of capacitors using a range of dielectrics and storage materials. This capacitor technology, employed for storing energy, offers:

- Ultra-low–cost manufacturing
- Exceptional energy density
- Multiple shapes and sizes with voltage and capacitance flexibility
- Enhanced operating lifetime compared with wet electrolytic capacitors

The phases of the flexible solar film manufacturing process are outlined in Figure 1.

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“Our technology has several advantages over flexible solar technology,” said Neil Spann, managing director at Power Roll. “It is extremely easy to produce. There are fewer steps in a manufacturing process. If you look at flexible photovoltaics, we can say that it is much more expensive. So in reality, the main advantage of our technology is cost-effectiveness. In terms of efficiency, our efficiency is good. But we don’t aim to make the highest-performing solar panel in the world. There are some technologies that push the devices upward. We are looking for a compromise, a good level of performance. So our current cell performance is 11%, which is somehow comparable to other flexible solar panels like organic photovoltaics. But we plan to increase it up to 20%. And thanks to the possibility of customization, there is a wide range of applications.”

By applying different active materials to Power Roll microgroove technology, it is possible to create energy storage solutions with a range of discharge times. Today’s solar technologies are either too expensive to deploy or their rigidity and weight make them unsuitable for the job. Power Roll’s low-cost, flexible, and lightweight solar film enables the use of renewables in brand-new applications. In partnership with The Energy Resources Institute (TERI), Power Roll is installing an innovative solar mini-grid system to generate and store energy in rural villages located in Mukteshwar, in the Himalayas. The system comprises lightweight, portable solar PV to generate energy and an energy-storage capability to enable energy use at night. Each system has been designed to meet...
the bespoke needs of each village. Applications include powering water pumps to support irrigation, lights to help young people study at night, and power to run phones, enabling access to national and international knowledge and support networks. Through this project, Power Roll is also experimenting novel approaches to mounting the solar film using wire-tensioning systems, which allow the solar film to be quickly and easily moved to where it is most needed. The project is scheduled to run through to the end of 2021 and Power Roll will report on the outcomes in March 2022.

**WIRELESS POWER TRANSFER**

PowerSphyr, a company with headquarters in Danville, California, aims to revolutionize power delivery to electronic devices via its intelligent wireless power technology. PowerSphyr offers the following solutions to fit any application:

- **Magnetic resonance**, a solution that offers high power delivery and spatial freedom. It is safe for nearby metals, offers an excellent thermal management, and supports multiple devices simultaneously.
- **Qi**, the simplest and lowest-cost solution. It features limited spatial freedom, power delivery, and thermal management (metals become very hot). Moreover, this solution requires a precise alignment between transmitter and receiver.
- **Capacitive**, a solution suitable for industrial applications in which very high power is demanded.
- **RF energy harvesting**, a great solution for sensors and IoT applications. It has excellent spatial freedom (up to 40 feet), can be used to harvest existing frequencies, and supports FCC regulatory limits.

PowerSphyr’s SkyCurrent family of wireless power transmission and receiving solutions enables fast, easy-to-use, and secure wireless charging across a wide range of products and modules. Each product includes a fully developed reference design. Key markets of SkyCurrent products include automotive, consumer, and industrial. PowerSphyr designs wireless power products and modules for the automotive industry that eliminate the need for cables or precise coil alignment, enabling fast, easy-to-use, and secure charging ecosystems with elegant industrial design and flexible form factors. Figure 2 shows an automotive application that includes wireless powered sensors for control and monitoring (lights, airbags, temperature, doors, etc.) and wireless charging for occupants’ devices supporting magnetic resonant, Qi, and RF solutions.

“Vehicles today contain over 200 connectors that provide power and communication to critical features and systems,” he added. “As the electrification of vehicles continues to progress, we will see vehicles become more feature-rich and increasingly dependent on software. A new approach to connectivity will become essential. We also are seeing a massive increase in the amount of copper within vehicles. While mostly related to batteries and propulsion, it is also used to direct energy throughout the vehicle.

“Instead of using wireless power to charge a phone or tablet, we are developing wireless solutions to reduce the complexity of wire harnesses and connectors,” said Wright. “Whether it is powering seat motors, heated seats, or side mirrors and speakers, a wireless approach solves many challenges the industry has faced for years. PowerSphyr offers solutions from low power to 450 W, and we are working every year to push our technology further for our customers in the automotive and industrial space. Our primary technology is a proprietary form of magnetic resonance, which delivers power at 6.78 or 13.56 MHz, depending on the application. I cannot stress enough the importance of phenomenal electromagnetics design. Our new solutions provide both power and communication seamlessly.”

Regarding the industrial sector, PowerSphyr seamlessly supports the three primary standards for wireless charging (magnetic resonant, magnetic inductive, and AirFuel RF), able to meet middle to high power demand of industrial tools and machinery. For the consumer industry, PowerSphyr offers SkyCurrent III (shown in Figure 3), the ultimate wireless charging platform delivering its dual-mode wireless charging pad and a suite of “fast charging” battery cases.
To achieve high power densities, hybrid inductor-capacitor switching converters are used. These hybrid inductor-capacitor switches prevent transient inrush currents, which usually cause loss in the output of conventional switched capacitor converters [2-5]. Many different converter topologies can easily be hybridized and help benefit from the soft-charged action. However, Cockcroft-Walton in Figure 1 is a preferred topology, as it offers less switch and capacitor voltage stress [6].

This article will discuss three contributions. It will initially analyze the N-phase switching and split-phase switching [6-7] schemes by presenting a comparison between them and highlighting their advantages. For small loads, the N-phase scheme is more efficient, whereas split-phase is suitable for heavier loads. Secondly, CW converter is demonstrated with application of split-phase clocking [7,9]. Thirdly, a demonstration using gallium nitride FETs is made resulting in extremely large power density i.e. 483.3 kW/liter. This is accompanied by the application of gate-driver integrated circuits and high-density isolated level shift [9-11]. Please find here the original article.
In this article, both the N-phase and split-phase switching techniques will be discussed. It will also focus on discrete prototype and measured results.

**THEORY OF OPERATION**

**N-phase switching**

For an N = 5 circuit applying N-phase clocking scheme to 1:n hybrid-LC CW converter, a diagram of phase progression is shown in Figure 2. Zero current switching is experienced by each switch as a single active voltage loop passes through the inductor. To monitor the N-phases, a simplified circuit is used by placing the current-sensing hardware in series with the inductor. This reduces quiescent current draw in comparison with split-phase switching, where multiple sensors are used. This N-phase switching circuit shows sinusoidal transitions of voltage that are smooth and have no abrupt sharing of charge (Figure 3). To obtain a load of 160 ohms, an input voltage of 18 V is used with N = 5 CW converters. A voltage stress at S5, S6, and S9 can be seen by the switches in red. This shows that an increased load may increase the internal voltage ripple, producing reverse body diode turn-on. If the diode is greater in forward direction or voltages are lower, reduced efficiency may be caused by this conduction loss due to heavy diode loading.

**Split-phase switching**

The split-phase clocking scheme has an ability to achieve less ripple in output voltage with higher output powers. This is an active switching approach using diode-based charge pumps, which are loaded inductively. It is dependent on zero-current switching and timing-sensitive Zero-current switching; hence, it implies extra sensing circuitry in comparison with the N-phase switching.

A 1:5 CW converter is used to demonstrate the split-phase operation in Figure 4. To initialize the major phase, its sub-phases have to be initialized, and these are done by meeting the ZVS conditions. These conditions let switch S6 initiate Phase 1 and S5 and S9 initiate Phase 2. To engage Phase 1b, Vc3 = Vc4. Similarly, to engage Phase 2c, Vc2 = Vc4. A smooth, abrupt-free transfer is indicated by smooth voltage transitions on...
Design of prototype

Gallium nitride FETs were used to form a 1:5 CW prototype, as represented in Figure 6. A 0.8-mm PCB was used to assemble it, making up a volume of 393 mm$^3$. The $V_{IN}$ used was 20 V with a maximum offset voltage of 100 V, and the gate-driver circuit and power stage are represented in Figure 7, while the Zener diode of 5.6 V is used as a regulator for high-speed voltage.

Results

In Figures 8 and 9, it can easily be observed how N-phase and split-phase switching models may be used together in a circuit. Figures 10 and 11 show that, with similar hardware, the split-phase would give high power output while N-phase would give 30% reduced loss at lighter loads, and hence, this combination can be a preferred style of operation.
CONCLUSION

This article has demonstrated the application of the N-phase and split-phase hybrid inductor capacitor switches. The results have proved that the split-phase switching method in Cockcroft Walton topology allows a high charge density and is effective with heavy-load applications, while the N-phase scheme is highly efficient for light-load applications. It shows the success and usefulness of these two schemes while highlighting the benefits obtained by using these switching schemes in a combined manner.

For More Information

[1] A Resonant 1:5 Cockcroft-Walton Converter Utilizing GaN FET Switches with N-Phase and SplitPhase Clocking Nathan Ellis and Rajeevan Amirtharajah Department of Electrical and Computer Engineering University of California, Davis 2064 Kemper Hall, 1 Shields Avenue, Davis, CA 95616


Like Jules Verne, we have all dreamt about “green hydrogen,” but the reality today is that in practice, it’s more a case of “brown and grey” rather than “blue and green” hydrogen. Hydrogen production is almost entirely fueled from fossil sources, and more than 70% of global production comes from steam reformation of natural gas. In this process, the methane reacts with steam, causing a reaction by which hydrogen and carbon dioxide are produced. As a consequence, the worldwide production of hydrogen is responsible for CO$_2$ emissions of about 830 million tons per year, equivalent to the CO$_2$ emissions of the United Kingdom and Indonesia combined.

That has been the situation for more than a century, but things are changing and Europe is engaged in a process to develop a climate-neutral economy in which green and blue hydrogen plays a major part.

POWERING A CLIMATE-NEUTRAL ECONOMY

Part of the so-called “European Green Deal,” the EU has laid out a strategy that will contribute to transform the European Union into a fair and prosperous society in which there will be no net emission of greenhouse gases by 2050. In line with the Paris Agreement and the United Nations 2030 Agenda for sustainable development, on July 8, 2020, the European Commission issued a document (COM/2020/299 final) describing the strategy for a clean energy system integration.

Taking into consideration all aspects of the various energy sectors, the strategy aims to reduce and eliminate CO$_2$ emissions but also to diversify Europe’s sources of energy, making better, more efficient use of the energy produced within the EU.

This will require a fundamental transformation of the European energy system, which today comprises fossil fuel (solid, petroleum, gas) (72.4%), nuclear energy (12.9%), renewable (14.6%), and other (0.1%).

The overall strategy to power a climate-neutral economy includes all aspects of the energy production system across multiple energy carriers, infrastructures, and consumption sectors, as well as the analysis of what is needed to achieve climate neutrality by 2050.

In this strategy, hydrogen has been considered an important part of the ecosystem and addressed in a specific sub-project: “A hydrogen strategy for a climate-neutral Europe (COM/2020/301 final).” Making the production of hydrogen cleaner and optimizing its utilization for transportation, energy storage, and many other areas have been addressed in this sub-project.

THE EUROPEAN HYDROGEN STRATEGY

Clearly too broad a subject to cover all aspects that it involves, in summary, the EU hydrogen strategy is aiming to use renewable hydrogen in industrial processes and heavy-duty road and rail trans-
port, in synthetic fuel production from renewable electricity in aviation and maritime transport, or in biomass in those sectors where it has biggest added value.

Hydrogen ‘in colors’

To begin, hydrogen is not a raw fuel, and its production requires a certain chemical reaction that can result in significant CO$_2$ emissions. It is important to differentiate the different methods of production and their environmental impact. To make it easier to understand that relationship, a de facto definition has been used within the industry, and four main categories have been defined (Figure 1). The long-term goal is to use only green hydrogen, though in the short and midterm, blue hydrogen is needed to support the deployment of hydrogen in Europe, implying efficient carbon capture and storage technology to reduce greenhouse emissions.

Making green hydrogen a reality

As shown in Figure 2, the EU strategy to develop renewable hydrogen is based on three phases with reasonable targets and goals. By 2050, the renewable hydrogen technologies are expected to have reached maturity and deployed on a large scale to contribute to decarbonize sectors in which other alternatives are not feasible or of prohibitive cost. To reach this goal and to produce renewable hydrogen in volume will require a great amount of investment and strong cooperation between the different sectors, from research to end user.

Due to the massive use of coal, the iron and steel industry is responsible for about 4% of anthropogenic CO$_2$ emissions in Europe and 9% worldwide. Replacing coal with hydrogen generated from renewable energy would make it possible to largely decarbonize this industry. The project H2FUTURE developed best practices to use the excess electricity from renewable sources to produce hydrogen from electrolysis. The hydrogen can be stored and used for fuel cells to deliver power when needed. The project has focused particularly on deploying a large-scale electrolysis system operated for steel manufacturing. One outcome from this project is the demonstration of the increasing power of electrolyzers, highlighting their suitability for energy-intensive heavy industries.

Pilot case

Engaged in a process to reduce its carbon footprint, Austrian steel manufacturer Voestalpine set a goal to reduce its CO$_2$ emissions by 80%. A large part of this reduction required them to change their way of working when manufacturing steel. The company research team investigated the practicality of using a hybrid technology to bridge the gap between the existing coke-/coal-based blast furnace route and electric arc furnaces powered by green electricity partly generated using green hydrogen. It was obvious that hydrogen would make the deal and here started one of the European flagship projects for hydrogen.

Under Horizon 2020, after receiving EU agreement and a funding of €12 million, on Jan. 1, the H2FUTURE project began. As defined in the project, under the coordination of Verbund (energy supplier), Voestalpine (steel manufacturer), and Siemens (proton exchange membrane, or PEM, electrolyzer manufacturer), the goal was to install and demonstrate the ability of a 6-MW electrolysis power system to deliver hydrogen to the Voestalpine Linz plant. The project also included competences from Austrian Power Grid and research partners K1-MET and Energieonderzoek Centrum Nederland (ECN).
Connecting such an installation to the grid presented many challenges. One important step has been to test PEM electrolysis technology on an industrial scale (6 MW) and to simulate rapid load changes in electricity generated from renewable energy sources and from electric arc furnace steelmaking (grid balancing). This has been successfully completed, and in November 2019, the kickoff of the largest green hydrogen facility took place (Figure 3).

With a capacity of 6 MW and a production of 1,200 m³ of green hydrogen per hour, H2FUTURE has proven the ability of that technology, contributing to the European goal of becoming climate-neutral by 2050. H2FUTURE is one of many projects initiated under Horizon 2020, setting the foundations for hydrogen to become an intrinsic part of the European Union's integrated energy system. The EU hydrogen strategy Phase ONE is just the beginning of a long journey of technical innovations to make Jules Verne's vision a reality.

Verifying, Calibrating, and Certifying DC Current Meters for EV Charging and Microgrid Applications to a Very High Accuracy

By Loic Moreau, vice president of marketing, Danisense, and Patrick Fuchs, business development manager, Zes Zimmer

A 2020 report by Deloitte forecasts total EV sales growing from 2.5 million in 2020 to 11.2 million in 2025, then reaching 31.1 million by 2030, representing a compound annual growth rate of 29% over the decade. This means that EVs would secure nearly one-third of the total market share for new car sales. This will require a huge investment in charging stations, and consumers will demand that the accuracy and reliability of the DC measurement — which will regulate the amount they have to pay — is tightly regulated and controlled. Zes Zimmer, a leading German power instrumentation company, is working in partnership with Danish current-sense transducer company Danisense to deliver precision DC metering solutions.
EV charging stations are proliferating as the uptake in EVs progresses. In Germany, there are many charging stations in cities and towns and increasingly also at workplaces. There are already charging stations available that can provide up to 350 kW. Customers need to be able to rely on the accuracy of the measurement of the DC energy transferred because there is a direct link between the energy consumed and the billing.

At the beginning of 2020, Zes Zimmer, one of the technical leaders in the field of power analysis, was approached by German standards organization VDE, which was working to ensure the proper verification, calibration, and certification of DC meters used in EV charging stations. Zes Zimmer already provides instrumentation that accurately measures up to 32 A, but for larger installations ranging into hundreds of kilowatts, the requirement is to measure much greater currents, in the region of a few hundred amps. This requires the use of external current sensors.

Figure 1 shows the measurement setup with a Zes Zimmer LMG641 power analyzer and an external DS600 current-sense transducer from Danisense. To calibrate the DC meter, the energy supply is generated by a precision PSU and fed both into the energy meter and the reference power analyzer, in parallel. In addition, the energy meter’s pulse output is connected to the LMG600’s external cycle input, allowing the analyzer to synchronize its measuring cycle for voltage, current, power, and energy to the meter’s pulses. Because the external cycle input is sampled with more than 5 MHz, the pulses will be captured reliably and precisely. Once the pulse intervals are synchronized to the measuring cycle of the power analyzer, their length can be recorded. In combination with the use of a highly stable and accurate DC source, this permits the accuracy of the intervals and thus the energy counted to be simply verified. Zes Zimmer’s LMG600 power analyzers allow the GUI to be customized to mimic a specific application. This GUI can be fed with values from the built-in Script Editor and displays only those parameters that are relevant to the application. An example is shown in Figure 2.

On its own, the LMG600 series provides accurate DC measurement across a current input range of 500 μA to 32 Arms. To extend this current input range, Zes Zimmer is partnering with Danisense. Based on the zero-flux principle, Danisense current transducers deliver a measurement accuracy down to 1 ppm, and the combination of Zes Zimmer LMG600 power analyzer and Danisense DS600 results in a highly accurate yet simple-to-use calibration test system.

There are many different types of current-measurement technologies, from basic shunt and Hall-effect devices to more complex systems. The determining factor is usually the accuracy required, and simple devices cannot deliver at high accuracies. Danisense proprietary fluxgate is a closed-loop compensated technology with fixed excitation frequency and second-harmonic zero-flux detection (Figure 3). It combines complex magnetic performance with advanced signal processing, and by using second harmonics, signals can be extracted to provide a measurement of the current in the conductors and its DC current value to extremely high levels, very repeatably. Furthermore, Danisense employs a dual-balanced fluxgate structure, which deploys two magnetic cores in opposition, similar in concept to a Wheatstone bridge. This provides natural compensation, eliminating the effect of any drift due to environmental conditions such as temperature. This is important if a DC current of a few hundred amps is driven for some while the sensor heats up. Therefore, temperature stability is essential.

Zes Zimmer supplies a cable with in-built intelligence to facilitate simple setup of Danisense current transducers, such as the DS600 shown in Figure 4 and marketed by Zes Zimmer as Plug’n’Measure PCT600, which enables automatic identification of the sensor type connected and configuration of the LMG600 current input. Every important parameter, such as the precise scaling factor, delay compensation variable, last calibration date, and sensor type, will be read and used automatically by the power analyzer. Moreover, the sensors are actively powered via the LMG600, so separate power supplies are not required. Danisense offers a range of products that enable the current measurement to be extended up to 2,000 Arms (3,000 A peak or DC) and even higher.
Zes Zimmer power analyzers in combination with the Danisense sensors are being used in the field by institutions like the VDE to test the accuracy of the DC meters installed at EV charging stations to standards such as Eichrecht conformity resp. E-VDE-AR-E 2418-3-100. They are also being used by manufacturers of DC meters to do pre-compliance tests before they send them off for independent certification to ensure that they will get a positive result. So the fact that no additional equipment is required and all the setup is simplified and matched through the partnership between Zes Zimmer and Danisense is very useful.

**DC MICROGRID**

Another application that calls for a similar approach is 1,500-V DC microgrids. In applications in which power is being generated by wind or solar power, for example, why convert to AC? Why not use the DC power directly? It is predicted that the house of the future will run on DC, resulting in significant efficiency benefits. This could be especially valuable if a vehicle is being charged in the garage overnight. This leads to a system called a DC microgrid. The high-voltage AC grid will still exist, but alongside it, a DC box connects to the DC generators, mostly renewable energy generators, and consumer products. Again, testing, calibration, and certification of such systems will call for highly accurate, stable DC current measurement.

It is vital to build customer trust and confidence that DC meters used in EV charging stations and other energy systems are highly accurate and regularly calibrated. The combination of Zes Zimmer power analyzers and Danisense current-sense transducers provides a precise, stable measurement that is repeatable and simple to facilitate. This is why renowned institutions such as VDE are using this approach.
Other forms of alternative energy sources are being developed. One of the most promising is using hydrogen in fuel cells, which converts the energy stored in the hydrogen to electrical energy. This use will lead to fuel-cell EVs (FCEVs). While the energy is stored differently in BEVs and FCEVs, both produce electrical energy used to power a motor. Yet another technology being developed involves using supercapacitors to store electrical energy. A supercapacitor is similar to a battery in that it can be charged and discharged repeatedly, but internally, the differences are significant. Supercapacitors can be charged and discharged quickly, which means they are capable of higher power delivery than batteries, but the total energy stored is less.

Each of these technologies has its limitations. Batteries take time to recharge, fuel cells are slow to release their energy, and supercapacitors have low energy storage capacity. But they all generate electricity, the essential “fuel” needed by EVs. Perhaps in the near future, the term “hybrid” may evolve to describe vehicles that combine all three technologies to deliver the right user experience.

Range and rapid recharging are cited as reasons why consumers are reluctant to make a move to full electric. The automotive industry and the public sector must overcome that reluctance, without a doubt. By using batteries, fuel cells, and supercapacitors together, each technology has the potential to deliver energy when and where it is needed. For example, range concerns could be addressed by fuel-cell technology combined with fast-charging supercapacitors to provide good acceleration.

There are no known examples of this potential new hybrid class today. Still, it is one direction the industry could pursue in the future and is grounded in technology that currently exists.

GOING WIRELESS IN AUTOMOTIVE

Energy storage isn’t the only area of innovation within the automotive industry. Vehicles are becoming more connected, both with the general infrastructure and their on-board systems. In general, the amount of data generated by a vehicle is increasing exponentially. Wireless technology avoids the proportional increase in wiring required to support that connectivity.

Wires are costly, heavy, and bulky. On the other hand, wireless connections are effectively weightless, but they do require careful design, and the antenna is one of the most critical aspects of the system. As vehicle manufacturers adopt more wireless connectivity types, at frequencies ranging from low megahertz to high gigahertz, antenna design and location are becoming more crucial. These design considerations will be more important as 5G connectivity finds its way into the vehicle, to provide mission-critical connectivity such as V2X and autonomous driving. The data infrastructure needed to support full autonomy will rely heavily on wireless technologies, including Wi-Fi and 5G.

Going wireless presents challenges, not least because vehicles are still predominantly made using large pressed-metal panels. It would be hard to replace metal entirely, but it is happening. Both glass and plastic are used more in automotive design and manufacture. Most types of glass and many plastics are transparent to radio waves. This transparency is excellent news for engineers developing electronic systems that use wireless connectivity. It also allows vehicle designers to explore new concepts. Entire glass roofs are becoming more common, for example. This design feature provides the option to mount antennas in the roof space that have clear access to the glass aperture.

Figure 1: Going wireless in automotive

Figure 2: Think automotive.
As the need for wireless connectivity increases, it may promote a new era of design that utilizes glass and plastic more. Of course, this also needs to be balanced with the need to design more affordable, maintainable, and recyclable vehicles.

In general terms, EVs are mechanically simpler than ICE-powered vehicles. This simplicity means they could be designed to last longer, be more easily serviced and maintained, and be highly recyclable. However, the electronic systems in EVs will be more diverse and, in the case of autonomy, more complex. The balance between power consumption, between the motive force and the electronic systems, will evolve, and this may also have implications on the types of energy storage systems employed.

THINK AUTONOMOUS, THINK UP

Another major trend shaping the future of vehicle design, ownership, and utilization is autonomy. There is a growing correlation between ownership and autonomy; many believe that the first fully autonomous vehicles will be taxis and ride-sharing schemes. The economics support this theory; an autonomous EV will be expensive to buy but cheap to run, so to see a return, the owner will need a high utilization rate.

Most privately owned vehicles spend the majority of their time parked somewhere. It means the per-mile cost is high. Taxis and other service vehicles, on the other hand, spend most of their time being operated. Usage drives the cost per mile down and, if that cost has a markup, as is the case with a taxi, it moves into a positive return on investment.

One exciting area of research here is the autonomous flying electric taxi. It may sound like science fiction, but it is happening. There are good reasons why it makes sense, not least because many journeys are short and within congested cities. Flying through cityscapes would reduce the congestion at the road level. Several pilot projects are already in operation, and millions of research dollars have been spent making it a reality. In terms of autonomous operation, moving into the third dimension makes a lot of sense. There are no roads, buildings, or pedestrians in the sky, even at low altitudes. The sky gives autonomous vehicles a lot of freedom, with the only obstacles being other flying vehicles.

Moving into the third dimension will elevate the need for reliable wireless connectivity. Wireless technology is, by default, omnidirectional. Modern systems are more discriminative, using phased-array antennas and multiple in, multiple out to direct the RF energy and maximize the available bandwidth. Range may also be a consideration. Land-based transceivers in an urban area may never be very far from a 5G base station or equivalent, but air-based vehicles will be more distributed and dispersed. With fewer obstacles, the wireless signal should propagate further and suffer from less interference and multipath distortion. Air-based vehicles will also influence the way the systems are designed.

FOR MORE INFORMATION

▶ Kemet

▶ Automotive Electronics Reliability Testing Starts and Ends with the Mission Profile
Gallium nitride (GaN) is a “wide bandgap” material because it offers an electron bandgap that is 3× larger than silicon, which means GaN can handle 10× stronger electric fields and deliver high power with dramatically smaller chips. With much smaller transistors and shorter current paths, ultra-low resistance ($R_{DS(on)}$) and capacitance ($Q_{GD}$, $C_{OSS}$, zero $T_J$) are achieved, enabling up to 100× faster switching speeds. To deliver actual performance to match GaN’s promise, GaN power ICs’ monolithically integrate GaN power (FET) and drive to control and protect the GaN power switch at high speeds.

Three new topologies are presented: 50-W pulsed ACF, 300-W CrCM totem-pole PFC, and 1-kW half-bridge LLC.

**PULSED ACF: ELECTROLYTIC BULK-CAPACITOR ELIMINATION**

Bulk capacitor reduction — or complete removal — has been an elusive topology for many years, with little to no success. Bulk capacitor rating (µF) is determined by the required output power, AC line voltage, and AC line frequency. The rating is a balancing act between charging the capacitor each AC line cycle and discharging it to provide the necessary output power, all while maintaining a minimum DC hold-up voltage level (~400 V) necessary for providing a constant DC output voltage. Increasing the switching frequency of the power conversion stage itself has no effect on the size of the bulk capacitor, so it does not benefit from the same frequency-to-size reduction that we get with magnetics. Even if the switching frequency is increased high enough such that the magnetics shrink down to PCB-based “air cores,” the bulk capacitor voltage must still be replenished by the AC line voltage at the ultra-low AC line frequency (50/60 Hz) so the rating — and physical size — remains unchanged.

However, if we change the output requirements of the converter from, say, a tightly regulated DC voltage to a rectified AC voltage, then we can change the rules of the game. With a pulsed output, we can have a rectified AC bulk capacitor voltage, which allows for the bulk capacitor capacitance value to be greatly reduced and the DC bus voltage can follow the rectified AC line voltage directly. For smartphone fast chargers, a pulsed current is acceptable, especially if the phone’s battery-charging algorithms are slightly modified to accept the pulsed voltage waveform.

Figure 1: How high frequency drives smaller passive components, 50-W fast-charger example: ~100-kHz traditional bobbin (22 mm high) (left) and ~500-kHz planar transformer (8 mm) (right)
To achieve the new pulsed output voltage requirement, the ACF topology can efficiently convert the rectified AC bus voltage into a pulsed DC output voltage. Traditional QR flyback is simple and low-cost but “hard switches” during high-line conditions. Resonant LLC topologies deliver ZVS operation over the entire load range but depend on a limited-range DC bus voltage. The ACF topology offers the best of both worlds by enabling ZVS operation over the entire line and wide load and voltage range. Compared with the traditional QR flyback, the ACF topology includes an additional high-side switch and capacitor to slew the switched-node voltage ($V_{SW}$) to the opposite rail during the deadtime and achieve ZVS. Megahertz ACF using GaN power ICs was demonstrated academically in 2016 and available for industry since the 2018 introduction of TI’s UCC2878x ACF PWM controller. GaN enables high-frequency ACF operation and results in a dramatic size reduction of the transformer; for example, from a 22-mm–high RM10 bobbin-based transformer at 50 kHz to an 8-mm–thin EI25 planar transformer at 500 kHz, as shown in Figure 1.

Size reduction by increased frequency and pulsed operation (bulk capacitor elimination) led to the introduction of Oppo’s ultra-thin 50-W “Cookie” GaN-power-IC–based fast charger in 2020. This was a perfect example of combining GaN with some novel system partitioning to reduce the converter size and profile and ultimately creating a new and unique out-of-the-box user experience.

**HIGH-FREQUENCY PFC, WITHOUT THE BRIDGE**

Conventional PFC topologies for mid-power (100 to 500 W) applications include an input bridge rectifier followed by a traditional boost converter. As the boost switch is turned on and off at a given switching frequency, the switch on and off times are controlled such that the AC line input current follows the same shape and phase as the AC line voltage and the DC bus output voltage is maintained at a constant level. During $90-V_{ac}$ input and full-load conditions, this circuit can reach efficiencies of about 96%. The boost converter itself can be made very efficient, but the AC input-bridge losses are very high, causing severe thermal extremes and poor overall efficiency.

Enter the “bridgeless totem-pole” PFC topology.

In conventional PFC circuits with a standard AC rectifier, at any point in time, two diodes of the input bridge are always conducting and generate >50% of the total PFC circuit losses. Many bridgeless PFC circuits have been investigated over the past few decades in attempts to eliminate the input bridge rectifier and boost system efficiency, but few have made it out of the lab and into the mainstream market, mainly due to higher complexity and cost. These topologies include classic bridgeless, semi-bridgeless, bidirectional bridgeless, and bridgeless totem pole. Each of these topologies has its own set of pros and cons, but none of them are the perfect solution. While microcontroller-based designs have been implemented for multi-kilowatt datacenter SMPS, standby losses have been too high to meet consumer market requirements like DoE Level IV and Euro CoC Tier 2.

With the emergence of new controllers in 2021, the high-frequency CrCM bridgeless totem pole is emerging as a popular topology due to low EMI, plus simplified voltage and current sensing by the controller. Switching speeds can be increased up to 10×, from fixed-frequency 50-kHz CCM to 200–500 kHz for CrCM totem-pole operation, and GaN’s low output capacitance ($C_{oss}$) delivers a cool, high-efficiency result.

**HIGH-FREQUENCY DC/DC: 6× THE POWER WITH GaN**

For fixed-output voltage converters in the 100- to 3,000-W power range, the downstream DC/DC converter choice is typically an LLC resonant stage with ~400-VDC input. The 400-V bus can come from an upstream PFC stage within an encased AC/DC SMPS or can be the main distribution rail in a HVDC installation.

The LLC topology has several benefits that include ZVS operation, high efficiency, and high-power density, and the ZVS operation makes this converter an ideal platform for increasing the switching
frequency and reducing the size of the magnetics using a high-speed powertrain.

In the industry-standard (DOSA) quarter-brick form factor, best-in-class silicon-based designs reach 150 W. By using GaN power ICs and increasing the DC/DC switching frequency 3× from 275 kHz to 830 kHz, the power rating can be increased up to 6× to 1 kW.

**HIGH-SPEED GaN ENABLES HIGH-FREQUENCY APPLICATIONS**

These are only a few of the vast opportunities in power electronics to be revolutionized by GaN power ICs. As operating frequencies are increased and magnetic sizes decreased, the entire ecosystem will continue to evolve, including upgraded magnetic materials, new planar transformer designs, smaller capacitor technologies, new circuit topologies, and improved thermal materials. The results are higher efficiencies, improved robustness, new power-adapter form factors, and, ultimately, lower costs.

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**For More Information**


3. Gallium nitride (GaN) overview.


STMicroelectronics is already producing STPOWER SiC MOSFETs in high volume, helping to propel the adoption of electric vehicles (EVs) and sparking an era of massive electrification. It is also conceivable that this leads eventually to autonomous driving for a sustainable mobility.

Another revolution involving high-voltage (that is, above 200 V) silicon power transistors happened at the turn of the century, when superjunction MOSFETs emerged. Up until the end of the 1990s, designers had to accept the “axiom” that for a planar transistor, the figure of merit (defined as on-resistance multiplied by the chip area) is proportional to the breakdown voltage (BV) raised to 2.5. This axiom implied that the only solution to reach lower values of on-resistance by a given voltage was to increase the die area. This made the use of devices with small-outline packages increasingly difficult. Superjunction technology came to the rescue for high-voltage MOSFETs by making the above relationship close to linear. ST dubbed the technology MDmesh and made it part of the STPOWER sub-brand.

**THE PRINCIPLE OF SUPERJUNCTION TRANSISTORS**

The working mechanism of a superjunction transistor makes use of one of Maxwell’s equations, simplified for a one-dimensional case — say, the vertical axis, y. It states that the slope of the electric field along that axis is equal to the charge density \( r \) divided by permittivity \( e \). In symbols, \( \frac{dE}{dy} = \frac{r}{e} \). The other equation relates the voltage \( V \) to the component of the electric field \( E \) along \( y \); that is, \( E = -\frac{dV}{dy} \). Said differently, the voltage \( V \) is the integral of \( E \), or in geometric terms, the area under the \( E \) curve as a function of \( y \). We can see how it works by comparing the vertical structure of a standard planar MOSFET versus its superjunction counterpart of similar size. The superjunction is essentially an extension of the p-body of the basic transistor inside the vertical drain through the realization of a p-type pillar.

In a planar structure (see Figure 1, left) starting from the surface along the y-axis, we encounter the p-body, and therefore, the slope is positive until we reach Point A. From A to B, we have the drain with opposite polarity, and therefore, the slope reverses to negative. From B to the substrate, the polarity gets even more negative (n–), and therefore, the slope increases. The green area in the graph represents the voltage that can be sustained in the off state. In the superjunction diagram shown on the right, the addition of the p-type region pillar changes the electric field distribution. In fact, from C to A, the electric field distribution stays constant (body and pillar have the same polarity), and then the slope is reversed as in the planar structure due to the drain and substrate. As a result, the area below the electric field is larger, so the voltage \( V_2 \) is sustained. Here, the pillar has performed its magic. Now, at a given voltage, we can reduce drain resistivity and can decrease on-resistance.

**TECHNOLOGY EVOLUTION**

Since their first appearance, MDmesh transistors have relentlessly been improved and refined, and a large spectrum of power-conversion applications are still benefiting from their use. The process techniques for creating the vertical pillars have been greatly optimized for better manufacturing yields and device ruggedness. Depending on the target circuit topology and application, different dedicated product series are now available. This technological versatility and flexibility allow system designers to choose from a variety of options. The general-purpose M2 series has the best cost/performance in the 400- to 650-V range, and there are the application-specific variants separately addressing PFC, soft-switching LLC, and bridge topologies, with voltage capability extending to 1,700 V.

**Figure 1:** Planar (left) and superjunction MDmesh (right) MOSFETs

**Figure 2:** Compressor inverter's efficiency curves of fast-diode MDmesh MOSFET vs. IGBT in a DPAK package. Test condition: 0.23 Nm (load), 220 V/50 Hz (input voltage)
On top of that, lifetime-killing techniques such as platinum-ion implantation are being used to enhance the performance of the integral body diode for reduced reverse-recovery time $t_{rr}$, as well as reverse-recovery charge $Q_{rr}$ plus improved $dV/dt$ (DM series). These features are ideal in bridge and high-power phase-shift circuits. A fast-diode version can even compete with IGBTs in low-power motor drives, which eliminates the need for a co-packaged diode. In terms of efficiency, a typical example is represented by a 150-W inverter for a refrigerator compressor, as shown in Figure 2.

It's no surprise that the ubiquitous MDmesh transistors have been produced in the billions!

In Figure 3, by comparing the features achieved with the latest M6 series optimized for resonant converters, we see how diligent ST designers have been with respect to improving the early M2 version.

The underlaying superjunction technique coupled with the most advanced process steps has yielded a high-performance high-voltage MOSFET with special focus on key switching parameters such as $dI/dt$ and $dV/dt$, as the safe-operating diagram in Figure 4 proves. Thanks to such improvements, the DM6 MDmesh series fits well in solar inverters, charging stations, and EV on-board chargers (OBCs) to name just a few applications.

APPLICATION AREAS

ST's MDmesh transistors are used in numerous applications, and this allows us to show their merits in a small but representative selection.

One of the highest-volume applications is smartphone adaptors. Figure 5 shows a 120-W version.

Figure 6 shows how a "tailored" M5 series can improve efficiency in a 1.5-kW PFC at higher power with respect to the "basic" M2 series. The two MOSFETs used exhibit similar on-resistance (37- and 39-mΩ on-resistance for M5 and M2, respectively) and voltage-blocking capability (650 V).

Another interesting example is shown in Figure 7: a 3-kW half-bridge LLC circuit for an automotive OBC comparing the latest DM6 (STWA75N65DM6) versus the best competition at $V_{in} = 380–420$ V, $V_{out} = 48$ V, switching frequency $f = 250$ Hz to 140 kHz.

Figure 3: From M2 to M6 — improving gate charge, threshold voltage, and output capacitance

Figure 4: $dI/dt$ vs. $dV/dt$ safe operating areas

Figure 5: MDmesh in smartphone adaptor

Figure 6: How M5 series (in blue) can improve PFC efficiency at higher power

Figure 7: 3-kW full-bridge LLC — off-energy and delta efficiency vs. $P_{out}$
Figure 8 illustrates the split of losses, showing that the key to reaching the lowest level of losses and highest efficiency is through an optimal mix of conduction and switching losses.

Fast-growing 5G technologies also benefit from the MDmesh innovation. With 5G systems’ high level of cell densification and ever-decreasing size of base stations (from microcells to picocells), MDmesh is the perfect match to equip the repeaters’ power supplies due to its efficiency, very high-volume production capability, competitiveness, and performance.

In order for 5G systems to operate above 98% efficiency, PFC and DC/DC converter stages need to be 99% efficient individually. A solution for the PFC can be a three-channel interleaved bridgeless totem-pole in triangular current mode (TCM) operation with MCU digital control. The TCM system enables the converter to operate at zero-voltage switching to reduce switching losses significantly. Overall, the results are a flat efficiency curve and a good value of efficiency at low load on top of a size reduction of inductors, EMI filters, and output capacitor.

MDmesh transistors pave the way for the rollout of 5G wireless systems.

DIFFUSION SOLDERING AND PACKAGING

Another interesting innovation being incorporated into MDmesh’s next iterations is the diffusion soldering process.

In a standard soldering process (soft soldering), the build-up of an intermetallic phase (IMP) is the basis for bond formation. It consists of thin intermetallic layers at the interface and unreacted solder material in between. Failure mechanism analyses of standard soft solder joints after thermal cycling reveals fatigue crack growth within the unreacted solder volume.

Two important properties of all intermetallic compounds are the hardness and embrittlement, which is a decrease of ductility. The latter can notoriously cause a device’s failure during thermo-mechanical stress, thereby worsening electronic equipment reliability.

Furthermore, the solder layer contains voids of different size that may not only deteriorate the thermal connection between the chip and the lead frame but can also generate “hotspots”; that is, microscopic volumes reaching very high local temperatures. Another effect to consider is the temperature dependence of MOSFET parameters such as on-resistance that increases, whereas the threshold voltage decreases as temperature goes up. While the former trend has a stabilizing effect, the latter can be harmful, especially during on/off transitions.

To overcome such issues, a new process known as isothermal diffusion soldering is being developed, which associates the features of standard soldering to diffusion bonding.

This is obtained essentially by a reaction between a material possessing low melting point (e.g., Sn-Cu solder paste) and one exhibiting high melting point (e.g., Cu from substrate) through IMP growth at the interfaces.

In contrast to conventional soldering, the joint is formed by isothermal solidification during the soldering process itself, not only after cooling.

This advantage of the formation of phases with very high melting points also relates to superior mechanical robustness. As junction temperatures reach 200°C in power packages, the diffusion soldering technology improves the chip-to-substrate interconnect, ensuring operating temperatures do not exceed the joining process temperatures that would lead to pre-mature failure.

The soldering process’s improved thermal performance removes some of the negatives of the soft solder, and this translates into better electrical behavior as well. It therefore weds perfectly with new packaging concepts such as the TO lead-less (TO-LL), which, among surface-mount device (SMD) packages, has the best ratio of board space area to thermal resistance. It is also equipped with a Kelvin pin that makes turn-off even more efficient and therefore can address hard-switch topologies with M6 or bridge circuits, with the MD6 series delivering even lower on-resistance.
Design

To complete this packaging overview, the innovative ACEPACK SMIT (Surface Mounted Isolated Top-side cooling) “discrete” power module is shown in Figure 9. This molded, lead-frame package contains a direct bonded copper (DBC) substrate and can house separate chips for realizing various topologies. The ACEPACK SMIT has an impressively low thermal resistance, 0.2°C/W, and the back-side ceramic ensures an insulation voltage of 3,400 V_{RMS} minimum (UL-recognized).

WHAT COMES NEXT

After more than 20 years, STPOWER MDmesh technology keeps evolving and, along with ST’s most innovative WBG semiconductors, continues to offer the widest range of power transistors in the market. Figure 12 depicts specific on-resistance versus breakdown voltage of the successive MDmesh versions benchmarked to standard technology and to its theoretical physical limit: M9 and K6 are now in full production. For the sake of clarity, K5 and K6 represent the very high-voltage (from 800 V to 1,700 V) technology subsets.

In order to appreciate the efforts devoted to the many iterations of MDmesh developed to address the requirements of distinct applications, have a look at the succession of images in Figure 13, from the first-generation MOSFET to the latest TrenchFET.

And what’s the next big step? After the introduction of MD6, the aim is to apply the benefits of the trench structure to the super junction. This feat will enable another step forward for the MDmesh and extend it to future breakthrough technologies like SiC. This WBG technology is expected to enjoy, with due adaptation and optimization, the performance improvements implemented and debugged extensively on existing silicon technologies. The journey never ceases to surprise!

For More Information

▶ STMicroelectronics
▶ Wide-bandgap semiconductors
SiC MOSFETs Replace IGBTs in EV Bidirectional Chargers

By Maurizio Di Paolo Emilio, Editor-in-Chief of Power Electronics News and EEWeb

The success of electric vehicles (EVs) and, more generally, of electric mobility, depends heavily on the time required to charge the batteries. Long considered one of the weak points of EVs, the charging time has progressively reduced, with advanced solutions such as fast charging that take only a few minutes. On-board charging systems (OBCs), connected directly to the AC mains, normally require at least four hours for each charge. Conversely, fast-charging systems operating in direct current can reduce the charging time to less than 30 minutes. In charging systems, power MOSFETs based on silicon carbide (SiC) play a fundamental role. SiC is a wide-bandgap semiconductor that, compared with silicon, offers advantages such as high efficiency and power density, high reliability, and durability, reducing both the cost and size of the solution.

As shown in Figure 1, despite having different power requirements and technical specifications, both charging systems can benefit from the use of SiC MOSFETs, which can manage the wide voltage range (typically between 200 V and 800 V) of the batteries installed in EVs, reducing power losses by up to 40%, increasing power density by 50%, halving the number of active components, and reducing the overall cost of the solution. Wolfspeed’s 1.2-kV SiC MOSFET series not only meets these requirements but manages the bidirectional charge/discharge process, replacing the IGBT transistors used in current charging circuit topologies.

THE SiC-BASED TWO-LEVEL AFE BLOCK

To handle the wide voltage range of EV batteries and bidirectional charge/discharge, Wolfspeed has developed a 22-kW active front end (AFE) and flexible DC/DC converter that can be adapted to both OBC charging systems and DC fast chargers. The proposed solution, based on 1,200-V SiC MOSFETs with $R_{DS(on)} = 32 \, \text{m}\Omega$ (Figure 2), provides a very high power density (4.6 kW/L) and efficiency (>98.5%) at a lower cost.

Unlike other standard topologies, such as the six-switch IGBT-based design (a simple but much less efficient and power-dense solution) and the T-type converter (a more complex and costly solution), the SiC AFE offers a simple control and driver interface, supporting bidirectional operation with a lower part count. The C3M0032120K, a 1.2-kV 32-mΩ SiC MOSFET with Kelvin-source package, helps to reduce switching loss and crosstalk while allowing for an easy driving voltage of –3- to 15-V Vgs. The AFE design has been optimized for the use of magnetics, achieving a high switching frequency (45 kHz) with lower power loss on both the core and winding. The AFE design has been optimized for the use of magnetics, achieving a high switching frequency (45 kHz) with lower power loss on both the core and winding.

The AFE also uses a digital control circuit capable of supporting both three-phase and single-phase PWM schemes, balancing switching losses and optimizing thermal performance, efficiency, and reliability. Furthermore, variable DC-link voltage control enables high system efficiency by varying the...
DC bus output voltage based on sensed battery voltage and ensuring the CLLC runs close to resonant frequency. Figure 3 (top) shows the single-phase mode waveforms when charging (totem-pole operation) and discharging (interleaved operation). The waveforms in Figure 3 (bottom), which have a total harmonic distortion of less than 5%, refer instead to a three-phase leg AFE configuration.

Compared with a traditional solution based on an IGBT (whose maximum efficiency is 96%), the SiC MOSFET reaches an efficiency of 98.5%, reducing power losses by up to 38%. In addition, SiC allows for lower operating temperatures and therefore better thermal management. Under maximum power conditions (22 kW), it was measured 89.4°C at the case, 112.4°C (calculated) at the junction, and 65°C for the baseplate. Figure 4 shows the efficiency curves relating to the results obtained with the tests.

**FULL-BRIDGE CLLC DC/DC CONVERTER WITH 1.2-KV SiC MOSFETS**

Another interesting application scheme is the full-bridge CLLC DC/DC converter, in which the 1.2-kV SiC MOSFETs can be used in a single, two-level high-efficiency converter scheme (Figure 5), reducing both part counts and system cost. The operating currents on the DC link side (900 V) reach 22.6 A<sub>RMS</sub>, while on the battery side (800 V), they reach up to 28.5 A<sub>RMS</sub>.

Combined with SiC AFE block, the full-bridge DC/DC design benefits from the variable DC bus voltage provided by the AFE based upon the sensed battery voltage to be charged. This allows the CLLC to run close to resonant frequency, achieving high system efficiency. When battery voltage becomes low, control will switch to phase-shift mode, reducing circuit gain without running inefficiently outside of the resonant frequency range. At lower output voltages (just above 400 V), CLLC primary is run as a half-bridge, further reducing system gain and maintaining the resonant converter in an efficient operating zone. The half-bridge mode has some limitations in total power range but provides a strong peak efficiency of 98%, even for low-voltage batteries.

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**Figure 3:** (top) test result AC/DC waveforms for single-phase AC and (bottom) test result AC/DC waveforms for three-phase AC.

**Figure 4:** AFE efficiency plots for single-phase charging/discharging and three-phase charging modes.

**Figure 5:** SiC-based single two-level converter.
Figure 6 shows the waveforms, both for charging and discharging, relating to the full-bridge configuration. By examining them, it is possible to observe the regularity of the commutation (low overshoot), combined with zero-voltage turn-on and low-current turn-off, which results in higher efficiency.

The efficiency of the DC/DC converter during charging reaches the maximum value of 98.5% and remains above 97% until it enters the half-bridge mode (Figure 7). Note how, for lower values of the output voltage during charging, the half-bridge mode limits both the efficiency and the output power. Similar curves are obtained during the discharge process.

The highest loss and temperatures were recorded with the CLLC MOSFET in the 480-V DC@17.28-kW test, with a calculated power loss of 42 W, case temperature of 97.8˚C, and calculated junction temperature of 116.7˚C.

CONCLUSION

Wolfspeed’s 22-kW AC/DC and DC/DC converters demonstrate high performance of Gen SiC MOSFETs for automotive on-board chargers, fast chargers, and energy storage applications. Innovative control methods such as variable DC bus control, combination of frequency modulation and phase shift, and half-bridge/full-bridge topologies can be combined to achieve top-level efficiency and power density.

Wolfspeed offers many other reference designs and additional support tools, including design schematic and layout files, BOMs, info on preferred magnetics, application notes, training presentations, and some firmware upon request. Additionally, the SpeedFit simulator program helps to quickly calculate losses and estimate junction temperature for power devices based on lab data for common topologies ranging from simple buck and boost converters to a fully bidirectional totem-pole PFC with a resonant DC/DC converter.

For More Information

▶ More details on Wolfspeed’s evaluation platforms for automotive applications can be obtained by visiting Richardson RFPD’s DC fast charging site.

▶ Modeling of Energy Storage Devices for EVs
AspenCore Guide to Gallium Nitride
A New Era for Power Electronics

As silicon reaches its theoretical performance limits for power electronics, industry is shifting toward wide-bandgap materials like gallium nitride (GaN), whose properties provide clear benefits in power converters for consumer and industrial electronics. This book delves into GaN technology and its importance for power electronics professionals engaged with its implementation in power devices.

Foreword: Alex Lidow, CEO of Efficient Power Conversion (EPC)

Market Overview: Yole Développement

Technology Analysis: Elena Barbarini, System Plus Consulting; Filippo Di Giovanni, STMicroelectronics; Alex Lidow, EPC; Chris Lee, Power Integrations; Dildar Chowdhury, Nexperia; Stephen Oliver and Dan Kinzer, Navitas Semiconductor; Stefano Lovati and Davide Di Gesualdo, EEWeb; Paul Wiener, GaN Systems; and Professor Alex Q. Huang, Tianxiang Chen, and Ruiyang Yu, University of Texas at Austin. In addition, there are reports from Jens Tybo Jensen, Jun Honda, and Pawan Garg, Infineon Technologies; Max Zafra, EPC Space; Kasyap Patel, Wolfspeed, a Cree Company; Andrea Vinci, Tektronix; and Gerald Deboy, Infineon Technologies.

Tech papers: Keysight, ON Semiconductor, Cadence, United Monolithic Semiconductors, Transphorm, Nexperia, and CEA-Leti

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ONLINE BOOKSTORE: www.eetimes.com/shop
TOLG for Improved TCoB Robustness and TOLT for Improved Thermal Performance

Applications such as e-scooters, e-forklifts and other light electric vehicles (LEVs), as well as power tools and battery management systems, demand high current rating, ruggedness and extended lifetime. Infineon Technologies addresses these requirements by offering more choices to power system designers to meet diverse design needs and achieve maximum performance in the smallest space.

Expanded SL Series Programmable DC Power Supplies to 10 kW in 1U with 18 New Models

Magna-Power expanded its SL Series programmable DC power supply product line with the introduction of 18 new models at 10 kW rated output power, while maintaining the product line’s 1U (1.75” high) rack-mount form factor. The SL Series continues to lead 1U rack-mount programmable DC power supply power density, enabling extremely power dense rack-mount integrations.

FOR MORE INFORMATION >

An Alternative to Lead-Acid Battery Backup Systems

ZincFive has announced its entry into Mexico with its UPStealth 2 products, designed to provide uninterruptible, reliable, and eco-friendly power to the country’s traffic intersections.

“We are excited to now be able to offer our game-changing UPStealth 2 products to municipalities across Mexico,” said Jeff McAleen, Vice President of Sales for Transportation, ZincFive.

FOR MORE INFORMATION >

GaN Transistors Leveraged to Develop High Performance Affordable DC/DC Converters

With its new VALUE DC-DC product line, BrightLoop Converters is aiming to democratize access to performance and offer a range of converters dedicated to off-highway and commercial vehicles. The French player in power electronics is teaming up with Efficient Power Conversion (EPC) to deliver the upcoming VALUE product line.

FOR MORE INFORMATION >

Live Coverage of APEC 2021

APEC is going to be digital from 14 – 17 June 2021. During the “APEC digital days” exhibitors and speakers can network and exchange views on product innovations and research findings with visitors and participants.

FOR MORE INFORMATION >

High-Density SiC Power Modules Meet Formula E Challenges

Formula E, an electric-powered race car championship that began in 2014 and is currently known as “ABB FIA Formula E Championship” after ABB sponsorship in 2018.

FOR MORE INFORMATION >

Saving Stand-by Power in the Smart Home

With IoT, connectivity becomes increasingly important as it allows maintaining proper communication and, as a result, standby consumption is turning into a real challenge.

FOR MORE INFORMATION >
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Electrochemical Impedance Spectroscopy (EIS) for Batteries
This circuit note describes an electrochemical impedance spectroscopy (EIS) measurement system for characterizing lithium ion (Li-Ion) and other types of batteries. EIS is a safe perturbation technique used to examine processes occurring inside electrochemical systems.

Power saving methods for LTE-M and NB-IoT
LTE-M and NB-IoT require long battery lifetime to ensure IoT services and minimize maintenance costs in the future. This technical white paper describes the possible power saving methods that can be applied to LTE-M and NB-IoT devices.

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

Can You Really Get ppm Accuracies from Op Amps?
Commercially available ppm-accurate amplifiers are difficult, if not impossible, to find. This article presents op amp accuracy limitations and how to choose the few op amps that have a chance of 1 ppm accuracy. It will also discuss a few application improvements to existing op amp limitations.

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