NEWS FOR THE ELECTRONICS INDUSTRY

Newark
AN AVNET COMPANY

eTECH JOURNAL

ISSUE 5

THE FUTURE OF POWER

MAXIMISING BATTERY POWER

GET TO THE ROOT OF BATTERY FAILURES

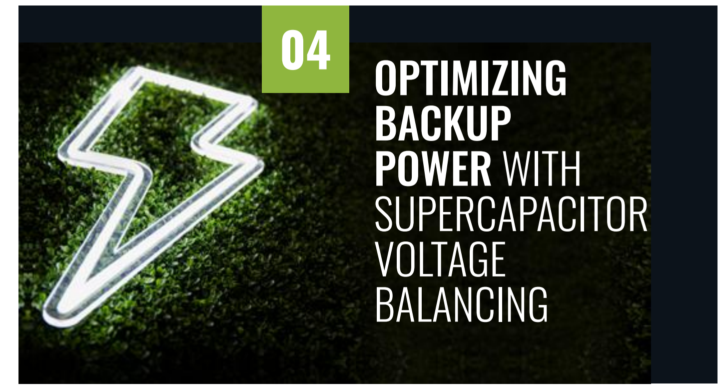
ENERGY STORAGE CIRCUIT PROTECTION

POWERFUL POSSIBILITIES WITH SIC

NEXT-LEVEL ENERGY STORAGE

\+ VOLTAGE BALANCING TECHNIQUES

CONTENTS



WELCOME

Effective Power management is critical for any modern electronic device, driven by the demands of energy efficiency and low-power operation across virtually every design. In response to these demands, the latest edition of e-TechJournal "The Future of Power," provides an in-depth look at the cutting-edge developments and emerging technologies shaping the power management landscape.

One of the featured articles from Analog Devices delves into voltage balancing techniques for optimal backup power using supercapacitors, examining the key challenges and opportunities presented by this technology. Infineon's article focuses on next-generation power density in solar and energy storage, emphasising the ability of CoolSiCMOSFETs to deliver cost-effective solutions that improve overall system efficiency.

It features an article on Microchip SiC, highlighting the technology's potential applications in electric vehicles, DC smart grids, industrial settings, and charging systems. Furthermore, the publication highlights common temperature-related battery issues and Keysightprovides guidance on how to use test instruments to build more robust, dependable battery-operated applications. An article from LittelFuse, highlights the significance of a comprehensive circuit protection strategy for Battery Energy Storage Systems (BESSs), emphasising the need for a nuanced approach that balances safety, reliability, and efficiency. Finally, the publication delves into techniques for extending battery life in low-power applications by optimising power usage with modern Op-Amps.

Ultimately, "The Future of Power" provides a wealth of knowledge and expert insights for engineers, designers, and power management professionals. This publication provides a wealth of knowledge and guidance to help you achieve your goals, whether you're looking to unlock new efficiencies, optimise your system designs, or stay ahead of emerging trends.

We hope you find this edition informative and insightful.
Happy reading!

To register for all future editions and to access all back issues of eTech Journal, scan QR code

Editor-in-chief: Cliff Ortmeyer, Managing Editor: Ankur Tomar

Cliff Ortmeyer Editor, eTech Journal
Email: editor-TJ@element14.com

OPTIMIZING BACKUP POWER WITH SUPERCAPACITOR VOLTAGE BALANCING

For applications where the supercapacitor needs to be charged to more than 2.5V or 2.7V, engineers are forced to connect multiple supercapacitors in series as the standard supercapacitor voltage is rated to 2.7V and they are of lower cost.

This article reviews the voltage balancing techniques in series supercapacitor connections for the MAX38886/MAX38888/MAX38889 backup regulators.

INTRODUCTION

The use of supercapacitors is rapidly increasing in energy storage applications such as handheld industrial equipment, portable devices with removable batteries, industrial sensors and actuators, etc. When such applications require more voltage than the normal 2.7V on supercapacitors, the option is to stack multiple supercapacitors in series. But due to capacitance tolerances, different leakage currents and ESR, the voltage across each capacitor is not distributed equally. This leads in voltage imbalance across supercapacitors since one supercapacitor voltage will have greater voltage than the other supercapacitor. As the temperature and age of supercapacitors increase, this voltage imbalance become worst and the voltage across one supercapacitor may increase to more than the rated voltage. It is very important to keep the voltages balanced across each supercapacitor to ensure long operational life.

MAX38886/MAX38888/MAX38889 4A/2A REVERSIBLE BUCK-BOOST REGULATORS FOR BACKUP POWER APPLICATIONS

The MAX38886/MAX38888/MAX38889 are storage capacitors or capacitor bank backup regulators designed to efficiently transfer power between a storage element and a system supply rail in reversible buck and boost operations using the same inductor. When the main supply is present and above the minimum system supply voltage, the regulator operates in buck mode and charges the storage element at programmed peak inductor currents. When the main supply is removed, the regulator operates in boost mode and prevents the system from dropping below the minimum operating voltage, discharging the storage element at a programmed peak inductor current.

For this study, we are considering the following test case.

System maximum voltage during normal operation, V_{SYS} = 5V.

System minimum voltage while back-up operation, V_{SYS_MIN} = 4.75V.

Supercapacitor maximum voltage while charging operation, VSC_MAX = 4.5V.

SERIES CONNECTION OF SUPERCAPACITORS FOR MAX38886/MAX38888/ MAX38889

For this application, the supercapacitor must be charged to 4.5V, and during the backup, the supercapacitor voltage is boosted and regulated to 4.75V when the actual system voltage is absent. The application circuit for this condition is depicted in Figure 1.

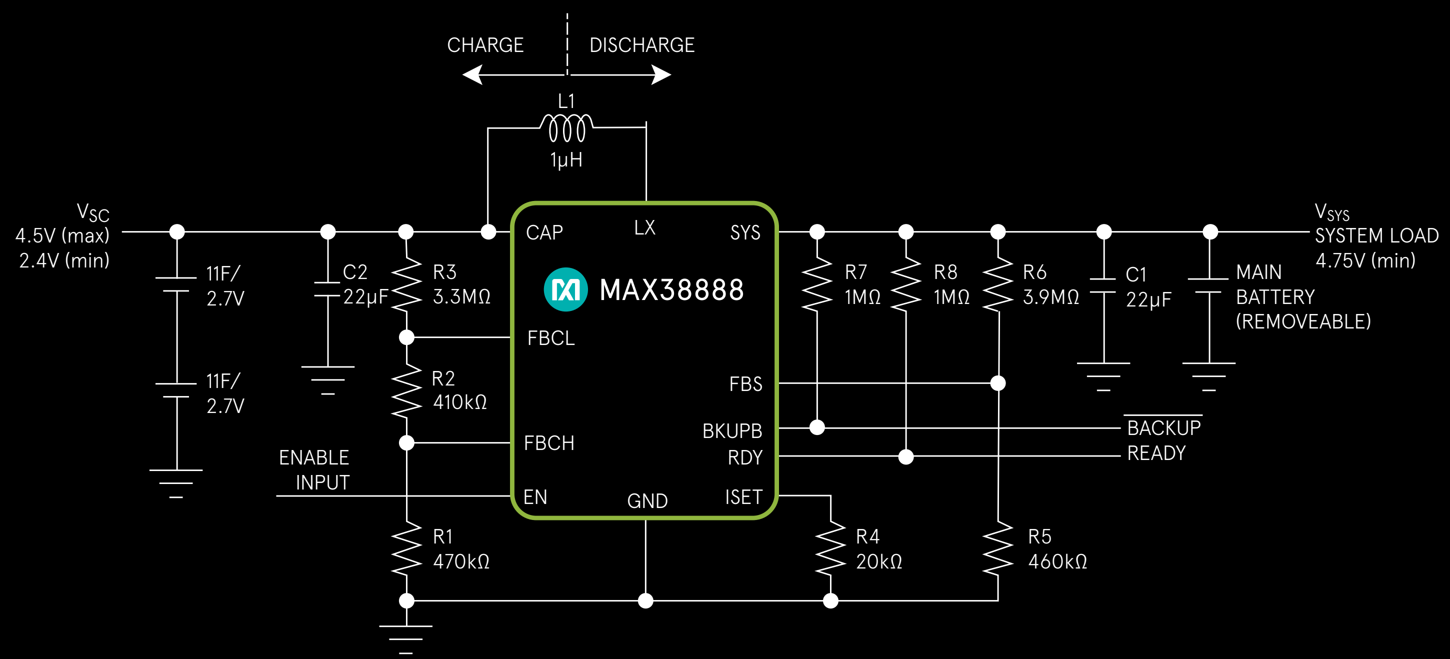


Figure 1. Application circuit of MAX38888

In the Figure 1 application circuit, the supercapacitors are rated to 2.7V, which is the standard rated voltage of supercapacitors. So, we have used two 11F supercapacitors in series to increase the voltage rating. Once the charging mode starts and the supercapacitor charges to 4.5V, the voltage across each capacitor is measured as in Table 1.

Table 1 shows that the voltage difference between the top and bottom supercapacitors is ~97mV and this reading has been taken at +25°C ambient temperature. The leakage current, capacitance, and ESR changes with temperature and age.

For example, the supercapacitor used in this application circuit has a leakage current of 6µA at +25°C ambient temperature and the leakage current increases to ~300% at +65°C temperature. These changes in the parameters of the supercapacitors may sometimes lead to an increase in voltage imbalance and one capacitor may also see a voltage greater than the rated voltage. This may also damage the supercapacitor or quickly degrade the life of the supercapacitor in the long run.

Table 1. Measured Voltages Across Each Supercapacitor

V_{SYS} (V)	V_{CAP_TOTAL} (V)	V_{CAP_TOP} (V)	V_{CAP_BOTTOM} (V)	Voltage Difference (mV)
5	4.43	2.17	2.26	97.00

There are a few methods which can be used to keep the voltages balanced across each capacitor by adding additional components. The following are a few methods that help to keep the voltages across the supercapacitor balanced.

METHODS OF VOLTAGE BALANCING

1. **Voltage balancing with balance resistors/ passive method.**
2. **Voltage balancing using an op amp circuit.**
3. **Voltage balancing using the SAB auto-balancing MOSFET arrays/active method.**

1. VOLTAGE BALANCING WITH BALANCE RESISTORS/ PASSIVE METHOD

The simple and most cost-effective way to balance the voltages across the supercapacitors is to connect resistors of equal value across each supercapacitor. As the resistor is connected permanently across supercapacitors, the power dissipation in the resistors will be continuous. The balancing resistors across the supercapacitor connection are shown in Figure 2.

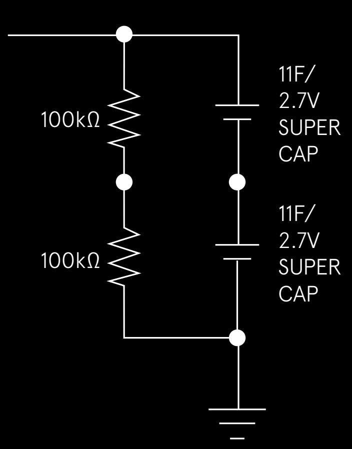


Figure 2. Voltage balancing using balancing resistors.

When 100k? resistors are used across each supercapacitor, the voltages across each supercapacitor is measured as in Table 2.

Table 2. Measured Voltages Across Each Supercapacitor with Resistor Balancing Circuits

V_{SYS} (V)	V_{CAP_TOTAL} (V)	V_{CAP_TOP} (V)	V_{CAP_BOTTOM} (V)	Voltage Difference (mV)
5	4.40	2.18	2.22	44.00

There are a few disadvantages using this method. The resistor value must be selected such that it provides significant current draw to achieve acceptable balance in the voltages. At the same time, a smaller value for resistors causes larger power consumption from the supercapacitor. As the supercapacitor temperature and age increases, the leakage current also increases which makes the circuit less and less effective with time. If the selected resistor values are very high, it takes a long time to balance the supercapacitor voltages.

2. VOLTAGE BALANCING USING AN OP-AMP CIRCUIT

The above additional circuit using balancing resistors has a continuous power dissipation and is lossy. To reduce power dissipation and to maintain balance in the voltages, the balance circuit can be implemented using an operational amplifier. This solution can contribute faster voltage balance even if high resistance values are used as the ladder network.

To reduce the power loss in the additional circuit, choose an op amp which consumes a lot less power like the MAX4470 which needs an ultra-low supply current of at least 750nA. The operating voltage of the op amp should be higher than the maximum supercapacitor voltage. A damping resistor may be needed to avoid abnormal oscillation.

The balance circuit in Figure 3 will be active when the voltage across the supercapacitor is not balanced. Once the voltages across each supercapacitor are balanced, this circuit consumes less power. Hence, this circuit is a highly energy-efficient method. We are using 2 x 2.2M? resistors across the supercapacitor to ground and the IC consumes a lot less supply current. The total power consumption is significantly less than the earlier passive method.

The voltage across each capacitor using the op-amp method is measured as in Table 3.

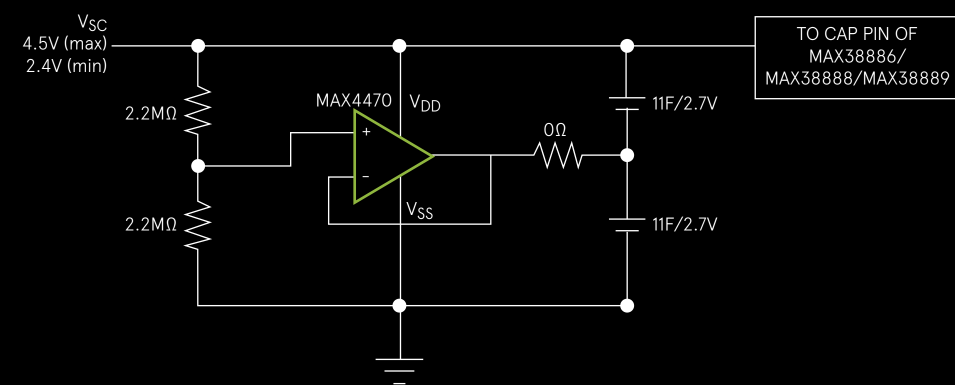


Figure 3. Voltage balancing using an op amp circuit.

Table 3. Measured Voltages Across Each Supercapacitor with an Op Amp Balancing Circuit

V_{SYS}	V_{CAP_TOTAL} (V)	V_{CAP_TOP} (V)	V_{CAP_BOTTOM} (V)	Voltage Difference (mV)
5	4.33	2.17	2.16	3.50

The waveforms in Figure 4 show the startup behavior while the supercapacitors are charging and the op amp circuit is used for voltage balancing. The waveform shows the V_{SYS} (yellow), V_{CAP_TOTAL} (blue), V_{CAP_TOP} (orange), V_{CAP_BOTTOM} (pink).

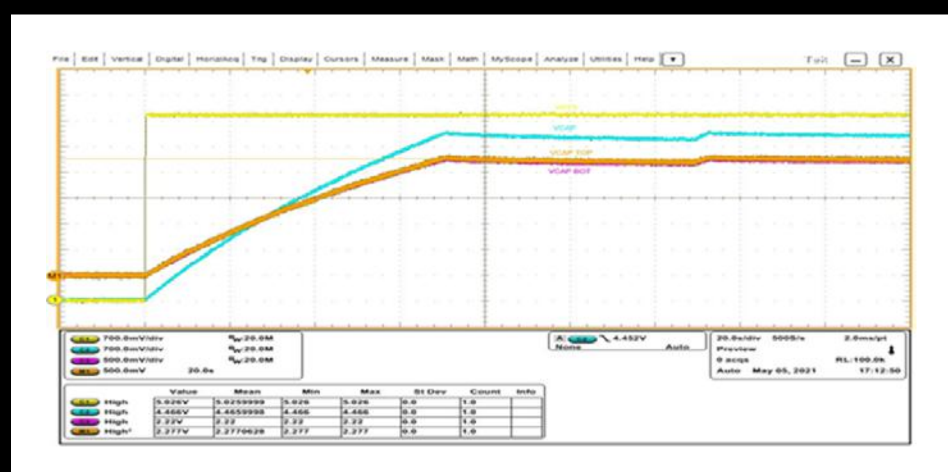


Figure 4. Startup waveform during supercapacitor charging using an op amp balancing circuit.

3. DEDICATED IC-BASED BALANCING CIRCUIT

There are few dedicated IC-based supercapacitor auto-balancing MOSFET arrays that can serve as active balancing circuits for supercapacitors. These MOSFET arrays offer self-balancing of stacked series-connected supercapacitors while dissipating near zero leakage currents, practically eliminating extra power consumption. The series-connected stack is continuously monitored and automatically controls balancing of its voltage and leakage current.

This is a special type of MOSFET that has a very tight gate threshold voltage specification. The set supercapacitor voltage should be twice that of the threshold voltage. Each capacitor will charge to the gate threshold voltage. But this will be an expensive method of voltage balancing as the cost of these dedicated ICs is more.

Comparison Between Passive, Active Methods of Voltage Balancing

Table 4 shows the overall comparison of each type of voltage balancing technique discussed.

Table 4. Overall Performance Comparison of Voltage Balancing Techniques

Parameter	Resistor Circuit	Op-Amp Circuit	Dedicated IC
Circuit cost	Low	Medium	High
Voltage balance performance	Medium	Good	Good
Power consumption	High	Less	Less
Operating voltage unit	No limit	Limited	Limited
Component count	2	4	1
Implementation	Easy	Moderate	Easy

CONCLUSION

This application note discussed why voltage balancing is required in series supercapacitor connections and reviewed different voltage balancing techniques for series super capacitor connections. The performance of each technique was compared.

To learn more about Analog Devices Supercapacitor Backup Regulator solutions please

CLICK HERE

VISIT INFINEON

BOOSTING ENERGY STORAGE WITH SILICON CARBIDE MOSFETS

Realizing the potential of CoolSiC™ MOSFETs for cost-effective power density in solar power generation and energy storage systems

The drive towards alternative, renewable energy sources is accelerating, with commitments from the major economies to move towards carbon neutrality in the relatively near future. Even the biggest emitters from east to west are now setting aggressive target dates. For example, the new administration in the US is looking to make electricity production carbon-free by 2035 with net zero emissions by 2050, and China is targeting a cut in 'CO2 intensity of GDP' by more than 65% from 2005 levels by 2030 [1]. This trend can be seen around the world, with some major countries such as Sweden already reaching more than 30% renewable electricity supply as of late 2020.

Of course, there is a range of renewable energy options, from geothermal to wind, hydro, biogas, tidal and solar. All have their challenges, whether in capital costs in hydro and wind, or pollutant emissions in biogas, or continuity of supply with wind and solar. However, photovoltaic (PV) arrays are attractive for their decreasing capital cost and ease of scalability from domestic to utility installations. If the continuity problem can be resolved with an energy storage system, then solar is a strong contender for future energy supply. Even though solar will always share the renewable energy market with other sources, growth in the industry has been strong and is predicted to increase exponentially (Figure 1).

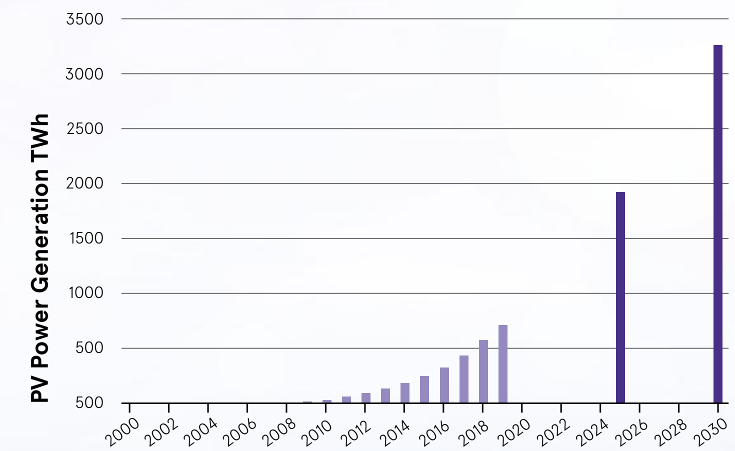


Figure 1: Solar PV power generation in the Sustainable Development Scenario, 2000-2030, source IEA, Paris. [2]

SOLAR POWER GENERATION STRUCTURES

PV installations fall into three distinct categories: residential installations with up to 10 kW power, commercial installations reaching around 5 MW power, and utility installations at higher power still. Residential installations are typically seen as a long-term investment, in addition to the existing utility grid connection. They will often have local battery storage for excess solar energy, which provides 'peak shaving' and a useful back-up if the main AC supply fails during hours of darkness.

Single or multiple PV panels, at typically 40 V to 80 V voltage, the microinverter and the battery installation can integrate as a system with increasing levels of web-connected home automation, to optimize energy use through scheduling of demand and storage. Another option is the integration of an electric car-charging system in the local network, with optional charging from solar energy or the usual AC supply grid. With bidirectional power conversion, the electric vehicle (EV) battery can form another energy storage element for domestic use or even to feed back into the utility supply for cash credit. A typical installation might look like the one shown in Figure 2.

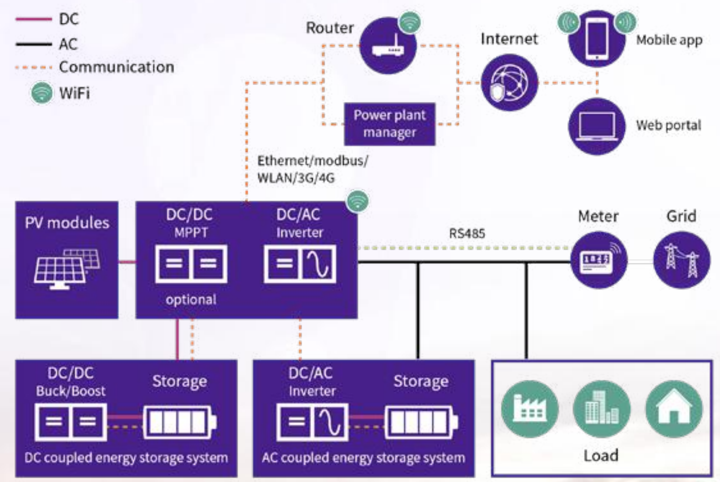


Figure 2: An example residential solar power installation with battery storage, EV integration and utility energy feed-in. Source: Infineon

Commercial solar installations, as an additional or even primary energy source for offices and factories, have similar requirements as residential installations. However, commercially, the higher energy demand implies higher equipment costs, so system efficiency and quick payback are key considerations. PV arrays will be in strings and voltages will be higher, perhaps up to 1500 V, to reduce current and consequential ohmic losses. Local battery energy storage will often be integrated to reduce peak utility demand, which attracts premium rates.

One inverter will typically be allocated to one or a few PV strings in a bigger system for fault tolerance, scalability and convenience.

Large commercial PV and utility installations can use a single, central, three-phase inverter. The central approach is used mainly for remote large-scale installations above about 10 MW, where high power can be efficiently transformed and fed directly into a transmission grid. Below 10 MW, the disadvantages of a central inverter compared with string inverters are inflexibility, higher initial capital costs and lack of incremental scalability.

A central inverter also risks supply continuity, as it is a single point of failure, so there is a trend towards distributed inverter systems with associated energy storage. Ultimately, the choice between a distributed string or central inverter arrangement is a complex decision, based on operation and maintenance costs, plant layout and design flexibility, ease of installation and access, power redundancy and much more.

A string inverter in a cabinet size with a weight of around 80 kg is seen as optimal, because it can be handled and installed or replaced by a two-person team. With this in mind, there is an intense effort to maximize the power rating of this size of cabinet by improving efficiency, and therefore, power density, without adding weight and cost. New power conversion topologies and semiconductor switch technologies are enablers for this.

PV INVERTER TOPOLOGIES – MICRO, STRING AND CENTRAL

Microinverters used for residential installations often integrate closely with the PV panel hardware and achieve moderate efficiency levels of around 96%. A microinverter may operate with a single low-voltage (<60 V) PV panel with an isolated DC-DC converter stage boosting to a high-voltage, regulated DC link, feeding a grid-compatible single-phase inverter. When multiple panels at higher power are used, it becomes necessary to use a more complex bridge circuit that combines and converts the panel voltages to a single DC-link output, feeding the inverter. Designs are targeted at low cost for a potential mass market, with switching frequencies typically in the 40 kHz–80 kHz range. The output is invariably single phase 110 V/230 VAC, and silicon MOSFET semiconductor switches are common, with IGBTs used in more basic installations if frequency is kept low. Because of the relatively low power of microinverters, the conversion topology is typically a flyback or perhaps a 'LLC' DC-DC stage with maximum power point tracking (MPPT) functionality, followed by a traditional bridge inverter for AC output. A 'cycloinverter' technique can also be used for single-stage conversion from PV DC to line AC.

In all configurations, the microinverter typically includes four to eight low-voltage switches and four highvoltage types. Energy storage can be provided by charging a battery from the inverter AC output using a bidirectional AC-DC converter allowing the battery to effectively replace the inverter output in low light conditions. The battery may also be charged from utility AC power as desired, with more complex systems allowing stored energy to be fed back into the AC line. In this way, the battery or energy storage system (ESS) can be programmed to charge from solar or utility AC when rates are low, and revert to backing up and storing solar energy when utility rates are higher.

String inverters used in residential, commercial and utility-scale installations will generate single- or alternatively three-phase AC power at higher levels. Panel voltages may be 600 V followed by a DC-DC boost converter to provide a DC link for a single-phase inverter. Alternatively, a 1000 VDC/1500 VDC system with a boost converter in a '3-level' configuration is possible for a three-phase inverter DC link.

For single-phase AC, the inverter may be a simple 2-level implementation, or one of the topologies designed for improved efficiency such as the 'HERIC', 'H6' or multilevel types.

The semiconductor switch count goes up with the topology complexity, but multilevel converters do allow use of lower voltagerated, and sometimes lower cost devices, albeit at the expense of more complex, multiple gate drives. As with microinverters, energy storage can be provided by batteries charged through a DC-DC converter off the PV panels. Because of the higher panel voltage, an isolated bidirectional converter would be used for safety reasons for less than 48 V battery. Battery charging from, or feed-in to, the utility AC supply can be implemented as needed.

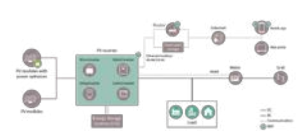
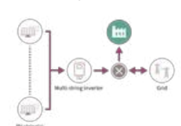
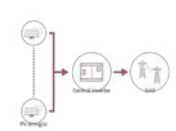
	μ inverter	String inverters	Central inverters
			
PV array voltage	40... 80 V	600 V, 1000 V & 1500 V PV array	1000 V & 1500 V PV array
Power Range Switching Freq.	200-1500 W 40 ... 80 kHz	1 ... 200 kW 20 ... 35 kHz	600... 1250 kW 2... 4 kHz
Output voltage	110V/230V (1ϕ)	110/230V (1ϕ) 360... 800V (3ϕ)	320... 690V (3ϕ)
Topology	DC/DC + DC/AC Stage DC-DC: LLC or Flyback DC-AC: 2-Level or Cyclo-converter	DC/DC + DC/AC Stage DC-DC: Single or Dual Boost 1ϕ: 2-Level, H5, H6 & HERIC 3ϕ: 3-Level: NPC1, NPC2 & ANPC	DC/AC Stage 2-Level (3ϕ Full Bridge) 3-Level: NPC1, NPC2 & ANPC
Type of Installation	Residential	Residential, Commercial & Utility Scale	Big Commercial & Utility Scale
Pros and cons	• Higher flexibility & scalability / harvesting • Moderate 96% of efficiency • Higher system cost	• Widely used / Up to 98.5% efficiency • Higher flexibility & scalability/Harvesting • Moderate system cost	• Highest efficiency upto 99% • Lower system cost • Low flexibility & scalability / Harvesting

Figure 3: Application requirements for solar inverter categories. Source: Infineon

Three-phase string inverters also vary in complexity depending on the power level, with simple 2-level, three-leg bridges used up to around 10 kW system power rating, and 3-level NPC1/NPC2/ANPC types operating into the 250-kW region. Complexity again scales with power, with the 3-level active neutral point clamped (ANPC) arrangement, for example, requiring a minimum of 18 high-voltage switches. In practice, integrated modules of multiple MOSFETs or IGBTs are typically used at the higher power levels.

Central inverters in utility-scale applications generate three-phase AC output at megawatt levels with the highest PV panel voltages and multilevel or paralleled inverters using typically IGBT modules. If local energy storage is provided, strings of batteries up to around 1000 V may be used with comprehensive battery management to ensure cell balancing and optimum service life. Feeding into the utility AC lines from the batteries provides load levelling or 'peak shaving' for the power network, independent of the solar energy generation. Figure 3 summarizes the application requirements across micro-, string and central inverters.

SIC SWITCH TECHNOLOGY

In all solar power applications, from residential to utility scale, efficiency of energy conversion is a key parameter. Every watt dissipated in equipment represents a step away from the goal of carbon neutrality and a reduction in the cost-effectiveness of the installation. Conversely, even a fraction of a percentage point saved can mean lower operating costs, smaller, lighter and cooler-running equipment, longer backup run time from batteries, and quicker capital payback.

Semiconductor switches employed in PV power conversion not only represent a significant loss contributor in themselves, but can also limit the choice of other components of the system. IGBTs for example, although they can have low static losses, cannot operate at very high frequency due to their slow switching, causing excessive dynamic losses. However, low-frequency operation generally requires larger and heavier magnetic and capacitive components. An ideal choice therefore is a switch that matches the on-state losses of an IGBT at high currents, but that can switch at higher frequency with fast edge rates. This will enable low dynamic loss and smaller passive components. Silicon MOSFETs are a contender at low power from a few kW to 10 kW, but lose out to IGBTs for static losses at high power, due to the MOSFET's finite on-resistance.

This is caused by the increase of power dissipated in a MOSFET channel resistance with the square of the current, whereas an IGBT has a near constant saturation voltage, with dissipation consequently just proportional to current.

A better proposition is a MOSFET using silicon carbide (SiC) technology, now ten years on from the launch of the first 1200 V device. SiC MOSFETs are wide band-gap semiconductors that have several advantages over silicon: critical breakdown field strength, so that the active layer is thinner at a given voltage rating and can be doped at higher level. Thus, the on-resistance is much lower for a given chip size. The smaller die dimensions also yield lower device capacitances, which allow faster switching with lower loss. Electron saturation velocity of SiC is anyway around twice the silicon value, enabling higher switching speed. Additionally, thermal conductivity of SiC is about three times better than silicon, allowing lower die temperatures for a given power dissipation and consequent lower uplift in onresistance.

IMPLEMENTING SIC IN SOLAR TECHNOLOGY

SiC MOSFETs up to 1200 V rating can be used directly in the MPPT DC-DC boost stage at up to 1000 V PV array voltage in residential, small and medium-scale commercial installations, and in the downstream single-phase or three-phase DC-AC inverter. In large commercial/utility installation panels with up to 1500 VDC output, SiC MOSFETs can still be used in a DC-DC 3-level boost arrangement, keeping the MOSFET voltage stress below the 1200 V rating. Subsequent three-phase inverters can be multilevel types, where the voltage is shared across series switches, again allowing 1200 V SiC MOSFETs to be used.

DC-AC inverter switching frequency is not usually pushed very high; even though SiC can switch at MHz rates efficiently, inverters only have magnetic components for filtering rather than energy storage and coupling, so magnetics do not scale down as dramatically as in AC-DC or DC-DC converters, with their large transformers and storage chokes. SiC inverters switching around 100 kHz are therefore a good choice for very low dynamic and static loss, along with reasonable size filter components.

Installations with energy storage employ bidirectional DC-DC buck-boost converters for battery charging, and discharge to the local load with the battery being wall-mounted, in an EV, or both.

Useable hours of a PV installation can be extended by controlling the contributions of solar and battery energy (Figure 4). A bidirectional, AC-DC/DC-AC power factor-corrected converter similarly provides battery energy to charge from, or feed into, the utility supply. These power conversion stages require 'third quadrant' or reverse switch conduction. In this mode, current momentarily flows through the MOSFET body diode before the device channel conducts, and the recovery of the stored charge leads to dynamic power loss when the channel turns off. SiC MOSFET body diodes have much lower stored charge (QRR) than silicon types, therefore improving conversion efficiency significantly.

SiC MOSFET output capacitance and channel on-resistance is also comparatively lower than for silicon types, leading to yet more efficiency savings.

As an additional advantage, both uni- and bidirectional battery chargers boost DC-DC converters to provide DC links, while other associated power converters and power factor correction stages can all operate at higher frequency with SiC. This has the effect of reducing associated magnetic component size, weight, loss and cost dramatically. SiC MOSFETs can therefore be used to advantage in all power conversion stages in solar applications, yielding low overall losses and smaller passive components, with consequential lower energy and system costs, and longer back-up storage run-time.

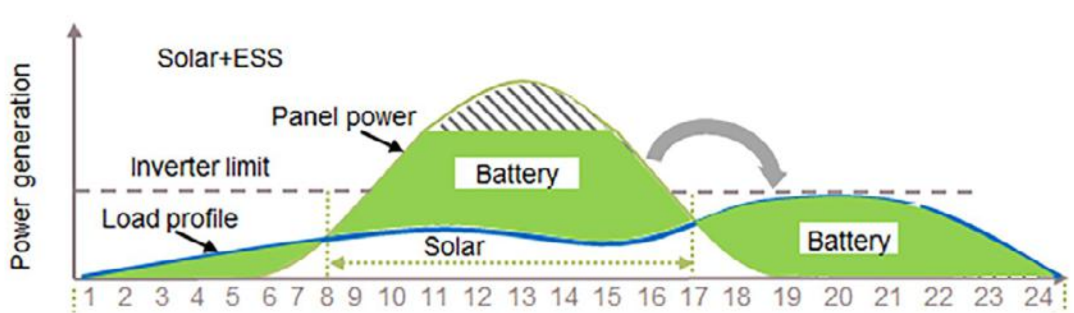


Figure 4: Over a day, solar and battery energy can fulfil load requirements. Source: Infineon

SOLUTION OFFERING FOR SOLAR AND ESS

SiC MOSFETs are available from Infineon, under their CoolSiC™ brand, in 650 V, 1200 V and 1700 V classes. As discrete devices, the range includes parts with on-resistance as low as 27 milliohms and with drain current rating up to 56 amps. Discrete packages are surface-mount TO-263 and through-hole are TO-247, both available with Kelvin source connections for optimized switching performance. For multilevel converters, CoolSiC™ modules rated at 1200 V are also offered in 3-level, dual, four-pack and sixpack configurations, with on-resistance down to 2 milliohms.

'Booster' modules include dual SiC MOSFETs and SiC Schottky diodes, along with bypass diodes, to form a two-phase boost power stage, particularly suitable for PV voltage conversion to inverter DC-link input level. Power levels exceeding 200 kW for a single bidirectional AC-DC/DC-AC converter in a 1500 VDC PV system can be achieved at an efficiency close to 99% in both directions, ideally suitable for a high efficiency string or energy storage inverter.

As with all switches, SiC MOSFETs perform best when their gate drive is accurately controlled. Gate drive ICs from Infineon in their EiceDRIVER™ family can provide isolated high-side and low-side signals with lowest propagation delays, active Miller clamps and the ability to adjust or minimize deadtime – a vital feature to optimize a SiC MOSFET's switching losses. Protection is also comprehensive with desaturation and short-circuit detection, along with common-mode transient immunity higher than 200 kV/µs across the isolation barrier, which also has pending 5.7 kVrms (1 min) safety rating.

Isolation suits 1200 V-rated switches for all common DC-link and single/three-phase converter and inverter applications.

For a complete ESS system solution, Infineon also provides components necessary for battery monitoring, protection and charge/discharge control. In energy storage systems, under-/overvoltage, inrush current, short-circuit and reverse currents can be detected and controlled while state of charge, state of health, temperature and cell balancing can be remotely indicated and controlled for optimum system lifetime and availability, all with high security through encryption and authentication processes (Figure 5).

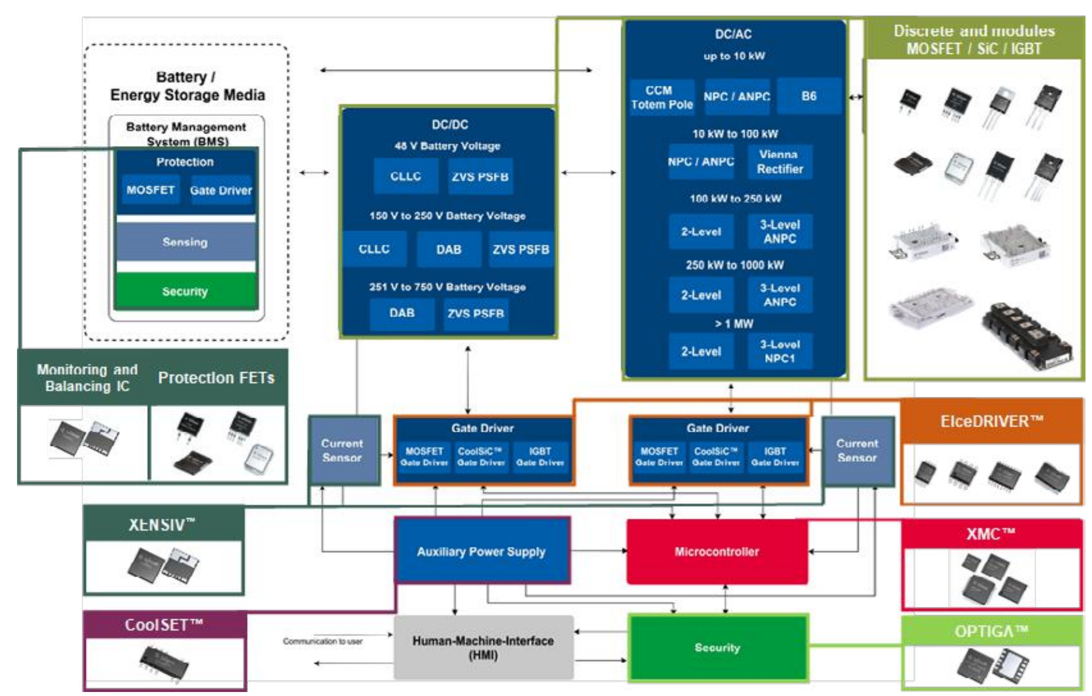


Figure 5: Infineon components provide a complete solution in energy storage and conversion systems. Source: Infineon

REFERENCE DESIGNS PROVE THE PERFORMANCE

A demonstration of the overall benefits of using SiC MOSFETs in PV string and energy storage inverters can show not only incremental savings in switch efficiency, but also wider advantages. Infineon has done this with a modular reference design for 1500 VDC systems rated up to 300 kW. The design uses a novel bidirectional 3-level ANPC topology which achieves better than 99.0% efficiency in both directions switching at up to 96 kHz. Power density is greater than 5 kW/kg for a complete solution including heatsinking and all control, allowing 300 kW throughput in the ideal 80 kg maximum cabinet weight. Energy usage and cost savings using SiC can be easily calculated from overall efficiency improvements. For example, compared with a super-junction Si MOSFET solution, 1200 V Cool SiCTM MOSFETs can lead to a halving of losses in an ESS installation, providing typically 2% extra energy and run-time.

Compared with an IGBT inverter solution, comparably sized SiC MOSFET modules can also handle more power. For example, an Infineon 950 V EasyPACKTM 3B IGBT module operating at 16 kHz can be replaced by two smaller, 1200 V CoolSiC™ 2B IGBT modules at 32 kHz, with a 27% increase in power handling to 156 kVA.

Although the SiC MOSFET unit cost is generally not yet lower than that of an IGBT for similar headline ratings, system hardware costs are lower due to maintained high efficiency at higher switching frequencies.

This allows smaller and cheaper magnetic components and heat sinks to be implemented. For example, in a 1500 V PV string inverter, around 5% to 10% cost savings per kW can be expected (Figure 6).

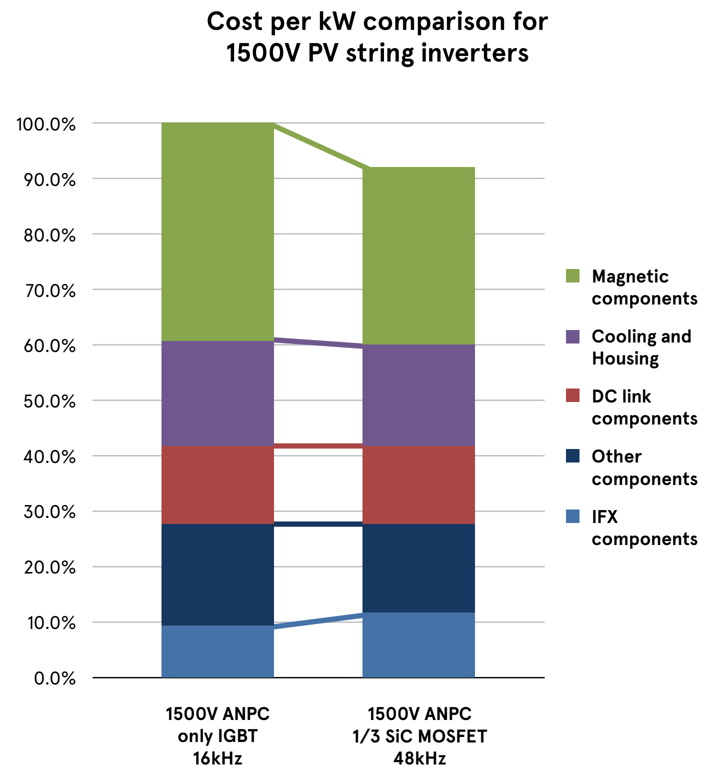


Figure 6: System costs in string inverters are significantly lower with SiC MOSFETs compared with IGBTs. Source: Infineon

CONCLUSION

SiC MOSFETs in solar and energy storage applications have clear benefits over other technologies, addressing the pressing need for energy and cost savings, particularly when bidirectional power conversion is required. Infineon offers a comprehensive range of SiC MOSFET discrete parts and modules, along with supporting drive, control and monitoring ICs for a complete system solution.

To learn more about Infineon CoolSiC™ solutions please

CLICK HERE

MICROCHIP

VISIT MICROCHIP

POWERFUL POSSIBILITIES WITH MICROCHIP SiC

For electric vehicle, DC smart grid, industrial & charging applications

PURPOSE

This application note provides design guidance for properly selecting gate-source voltages for Microchip's SiC MOSFET products, along with related device performance and behavior. This note applies to Microchip part numbers of the type MSCXXXSMAXXX.

SPECIFYING GATE DRIVE VOLTAGES FOR SIC MOSFETS

The way gate drive voltages are specified on data sheets varies by manufacturer, but most will have some form of Table 1. We begin by defining some terms:

- VGS is the applied voltage between the MOSFET's gate and source terminals.
- VGSon is the steady-state VGS applied to turn the MOSFET on.
- VGSoff is the steady-state VGS applied to turn the MOSFET off.
- VGSmax is the manufacturer's maximum allowed steady-state VGS, shown for both negative and positive extremes.
- VGS,OP is the manufacturer's recommended steady state values for VGSon and VGSoff.

Some data sheets do not specify VGSon and VGSoff; similar to silicon MOSFETs, different applications may call for different optimal values.

MICROCHIP RECOMMENDATIONS

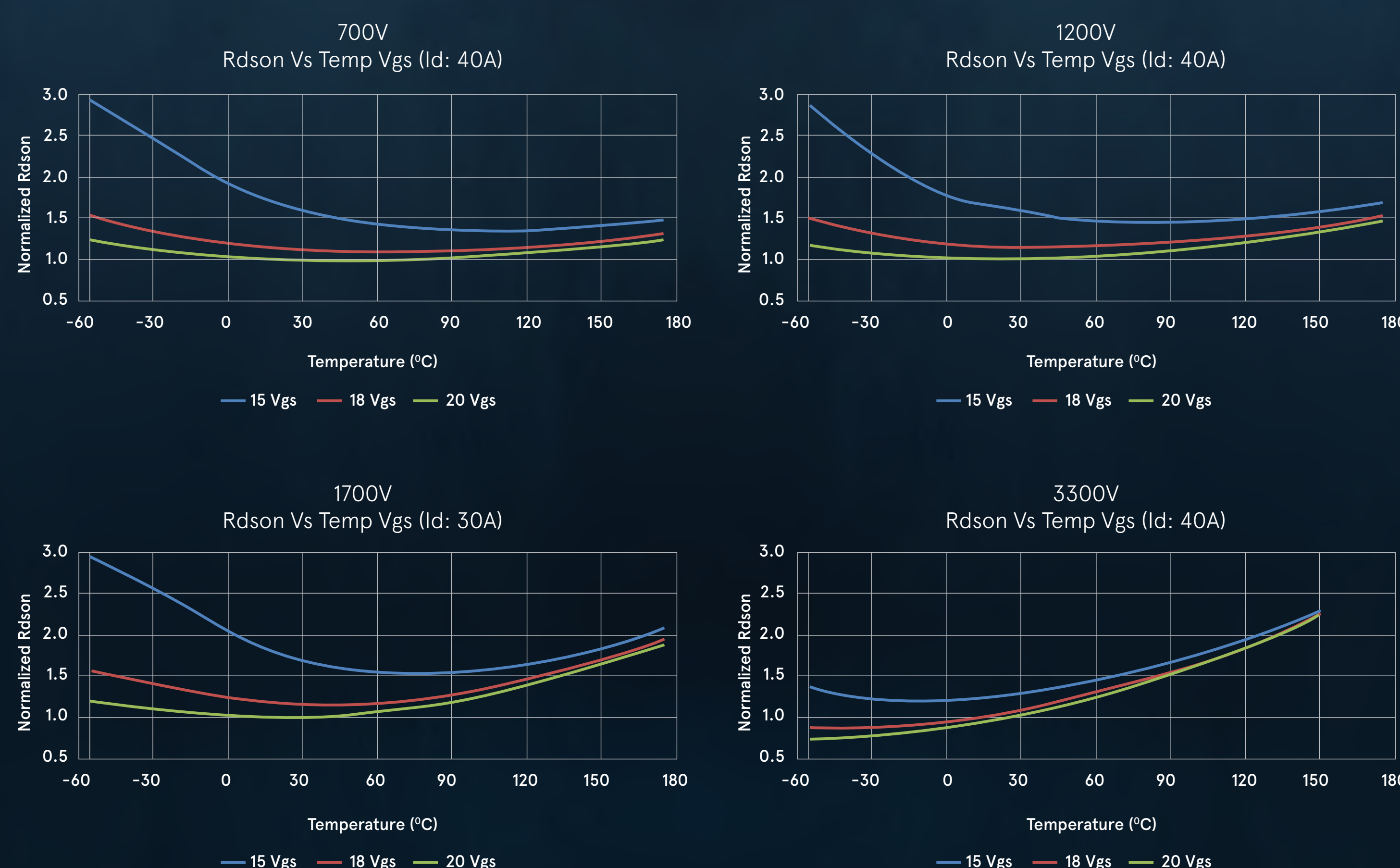
For optimal device performance and system stability, Microchip SiC MOSFETs are best driven using VGSon = +20V and VGSoff = -5V. Microchip SiC MOSFETs still perform well at lower absolute values of VGSon and VGSoff, but as with any design, the additional losses associated with sub-optimal drive conditions should be analyzed and understood. To this end, the reasoning behind optimal VGSon and VGSoff are different, and the expected trade-offs for each case are described in the following sections.

ON STATE GATE DRIVE VOLTAGE, VGSon

Driving Microchip SiC MOSFETs with a lower VGSon will exhibit:

- Increased on-state resistance, resulting in higher conduction loss
- Reduced peak (saturation) current capability
- Longer short circuit withstand time
- Extended gate oxide lifetime
- Increased switching loss under the same gate resistance.

Figure 1: Temperature Dependency of RDSon Under Different Gate Voltage of Different Voltage Families.



ON STATE RESISTANCE, RDSon

The four curves in Figure 1 show how the normalized RDSon (normalized to RDSon at 25°C and 20V gate voltage) increases with junction temperature, Tj. Data is shown for Microchip's largest SiC MOSFET die at each of four voltage classes: 700V, 15 mΩ; 1200V, 17 mΩ; 1700V, 35 mΩ; and 3300V, 25 mΩ. Some general observations include:

- The increase of RDSon for SiC MOSFETs with temperature is much lower than that of silicon MOSFETs.
- Microchip SiC MOSFETs show a lower increase of RDSon at elevated Tj than other SiC MOSFET suppliers.
- At VGSon = 18V, RDSon shows a minor shift which gets even smaller at higher Tj.
- At VGSon = 15V, the increase of RDSon is more substantial, particularly at lower Tj.

DESIGNING FOR VGSon < 20V

Due to SiC's wide band gap, a higher electric field is required to invert the semiconductor of a MOS-gated transistor than is required for silicon. The electric field can be increased either by raising the applied VGSon or by reducing the thickness of the gate oxide. Raising VGSon may call for a new gate driver design, while reducing the oxide thickness could make the device more susceptible to failure. A third way to get more current is to increase die size, but this increases cost. Clearly the best technical and commercial choice is a new gate driver design, but what compromises are made if the ideal VGSon = 20V is impossible to achieve?

EFFECT ON RDSon

Due to SiC's wide band gap, a higher electric field is required to invert the semiconductor of a MOS-gated transistor than is required for silicon. The electric field can be increased either by raising the applied VGSon or by reducing the thickness of the gate oxide. Raising VGSon may call for a new gate driver design, while reducing the oxide thickness could make the device more susceptible to failure. A third way to get more current is to increase die size, but this increases cost. Clearly the best technical and commercial choice is a new gate driver design, but what compromises are made if the ideal VGSon = 20V is impossible to achieve?

EFFECT ON RDSon

When driving at lower values of VGSon, designers should analyze how RDSon changes across the junction temperature range of interest. If the RDSon across relevant Tj is consistently within a close range of the RDSon at VGSon = 20V, the final design can accommodate these small differences and be extremely robust. For Microchip SiC MOSFETs, production measurement of RDSon shows VGSon = 20V is an excellent predictor of RDSon at VGSon = 18V; in the case of a 1200V SiC MOSFET at Tj = 175°C, RDSon at VGS = 18V is only 4% higher than RDSon at VGS = 20V.

In contrast, the comparison of RDSon at VGSon = 20V and VGSon = 15V requires careful consideration. The variance is approximately 4x higher for VGSon = 15V and dependent upon device threshold voltage, VGS(th). For this reason, Microchip does not recommend driving SiC MOSFETs of type MSCXXXSMAXXX at VGSon = 15V. If they must be driven with 15V, a sufficient design margin for RDSon should be considered. Contact your local Microchip sales office for support.

PARALLEL-CONNECTED SIC MOSFETS

There is a final point to be made about parallel-connected SiC MOSFETs and VGSon < 20V. One can observe from the charts that the temperature coefficient of RDSon may not be positive across the entire range of relevant Tj. In an extreme example, consider the 700V SiC MOSFET at VGSon = 15V. This gate drive situation results in a SiC MOSFET with a negative temperature coefficient up to Tj = 80–100°C. Ensuring that paralleled devices will evenly share current is a risk against which the design should be safeguarded. However, much as in the previous paragraphs, using VGSon = 18V is the simplest solution and is well-suited for most applications.

PEAK CURRENT CAPABILITY

When driving with a lower VGSon, the MOSFET channel is not fully enhanced, and the maximum current is reduced.

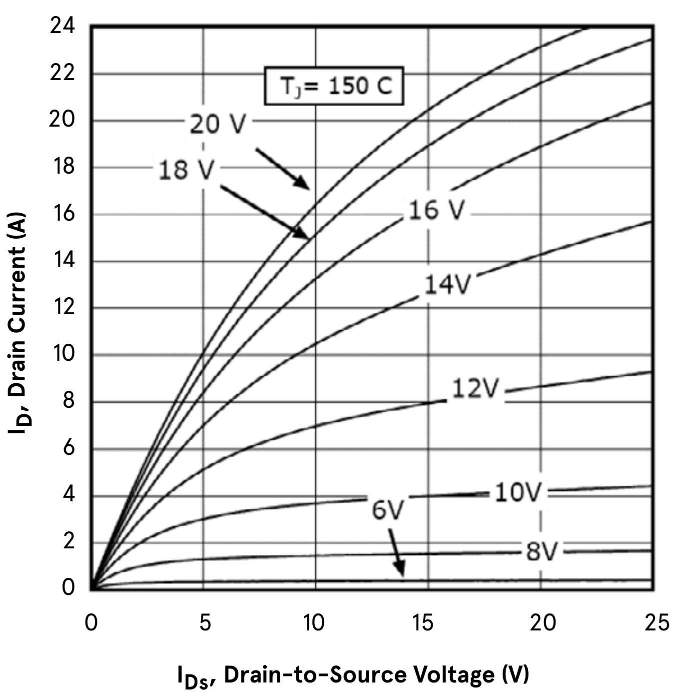


Figure 2: I-V Curve of MSC360SMA120B Under Different Driving Voltages at Tj = 150°C.

Figure 2 shows the I-V curve of MSC360SMA120B under different driving voltages at Tj = 150°C. Note the small separation between the RDSon curves at VGSon = 20V and VGSon = 18V, and compare this to the bigger differences in RDSon as VGSon drops increasingly below 16V. Some important considerations include:

- An over-current protection scheme based upon the maximum current may fail to trigger. Designers should account for the higher variability of RDSon at lower VGSon.
- The small-signal transconductance, gm, is higher at lower VGSon. This effect can lead to switching instability, since VGS may be in a middle range in the presence of high drain-source voltage – resulting in a short circuit event. (The peak short circuit current will be governed by the precise value and duration of VGSon. See the next subsection.)

SHORT CIRCUIT WITHSTAND TIME

When driving with lower VGSon, the maximum current will be lower under short circuit conditions, which can lead to a longer short circuit withstand time.

The following plot shows the short circuit withstand time (SCWT) in relation to gate and drain voltage for MSC035SMA070B measured with VDS = 350V, 470V and 560V and VGSon = 20V, 18V and 15V. It can be seen that the drain voltage is the most significant factor affecting SCWT, followed by VGS.

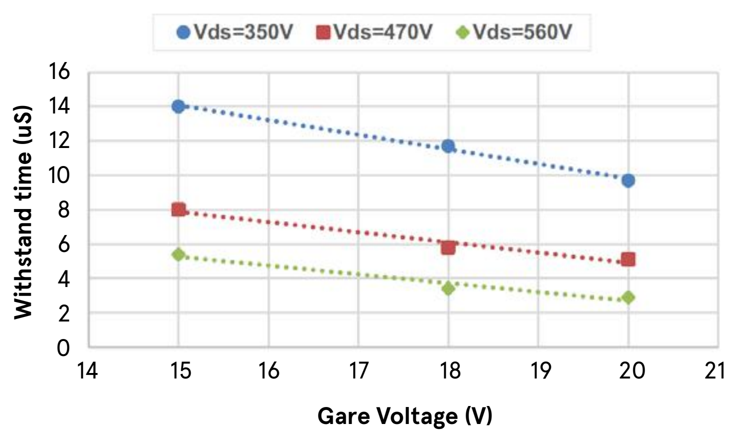


Figure 3: Short Circuit Withstand Time of MSC035SMA070B.

In applications where short circuits may occur, the following considerations should be made:

- The SCWT specified in the data sheet is the typical time to failure, as defined by the device no longer exhibiting proper electrical function. In reality, the failure occurs after the device is switched off, when the latent heat generated causes irreversible damage. In essence, the delay does not happen when the measurement says it happens. Because of this delay, data sheet's SCWT can only be seen as a typical number.
- A more reasonable requirement would be that a specified number of devices are still operational after a specified number of short circuit events.
- Short circuit withstand time can be extended by increasing the device size or using multiple devices designed to drive at a reduced current level with source degeneration.

For additional guidance and insight, please contact your local Microchip sales team.

PROJECTED LIFETIME

The below graph indicates that for every 2.5V increase in VGSon, the projected lifetime of the gate oxide is reduced by an order of magnitude. This relationship applies over a wide range. It is a wear out mechanism due to accumulated damage over time.

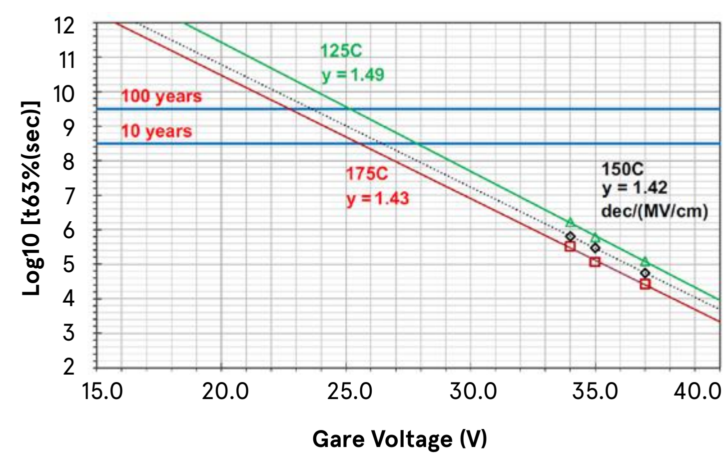


Figure 4: Projected Device Lifetime Under Different Gate Voltage.

The lifetime of the gate oxide is mostly determined by the steady state gate ON drive voltage. The +23V maximum rating on the gate is a recommendation for steady state gate voltage based on the projected lifetime of the device. Transient overshoots in VGSon do not materially affect the device lifetime because of their brief duration. As an example, assume a rectangular overshoot for 20 ns at 25V with a nominal gate voltage of 20V. Per the oxide lifetime graph, the rate of degradation of the oxide during the pulse is 80 times higher. However, with a switching frequency of 100 kHz, the duty factor is 20/100,000 = 0.002. The relative stress, then, is only 80 × 0.002 = 16%.

It should be noted that transient VGS is not observable at the package pins. The gate and source lead inductances make it difficult to measure the actual gate voltage overshoot. Due to the high capacitance of the gate, the gate drive is normally over-dampened, and overshoot is rarely a problem. This is easiest to determine in simulations.

SUMMARY OF VGSon

Microchip SiC MOSFETs can operate at +18V drive voltage with little loss in performance compared with the recommended +20V drive voltage. As can be seen in the above graphs, the increase in RDSon is much larger at 25°C than at 100°C-150°C. A system generally is penalized less by conduction loss than would be implied by the difference at 25°C if the die is hot. While the switching losses may be slightly higher under the same gate resistance, and saturation current will be lower, the positive trade-off is a longer short circuit withstand time.

Operation at VGSon < 18V gate drive comes with elements of risk and should only be used if there is sufficient margin in RDSon. Current sharing between paralleled devices can be problematic at colder junction temperatures. If VGSon < 18V is needed, please contact your Microchip team for design support.

OFF STATE DRIVING VOLTAGE, VGSoff

Microchip SiC MOSFETs are normally OFF power transistors. A negative VGSoff is not required to keep the switch OFF during steady state. Rather, it is used to minimize switching loss and enhance switching stability.

- The presence of source inductance can slow the device turn-off process. A negative VGSoff is used to overcome this effect.
- A negative VGSoff provides more margin to avoid false turn on (also called shoot-through or cross conduction) during switching transients.
- A negative VGSoff has been used for decades with silicon IGBTs. Negative gate drive is not unique to SiC.
- More complex modules with distributed transistors need a higher (more negative) VGSoff to avoid instability. Single transistor discrete designs can get by with very little negative VGSoff.

Third Quadrant Conduction Performance Unlike a silicon IGBT, SiC MOSFETs can conduct current in both directions. The figure below shows the so-called "third quadrant" performance of Microchip's MSC360SMA120B; simply put, this is the drain current when the drain voltage is reversed. The body diode carries reverse drain current if the MOSFET's channel is turned OFF. In the case of VGSoff = -5V, all current flows through the body diode. As VGS is increased, the channel begins to form but maintains a substantial voltage drop even at VGS = 0V, meaning the body diode still carries most of the reverse current. Following the switching transient, the channel can be turned ON to also conduct the reverse current to further improve conduction losses in a technique known as synchronous rectification.

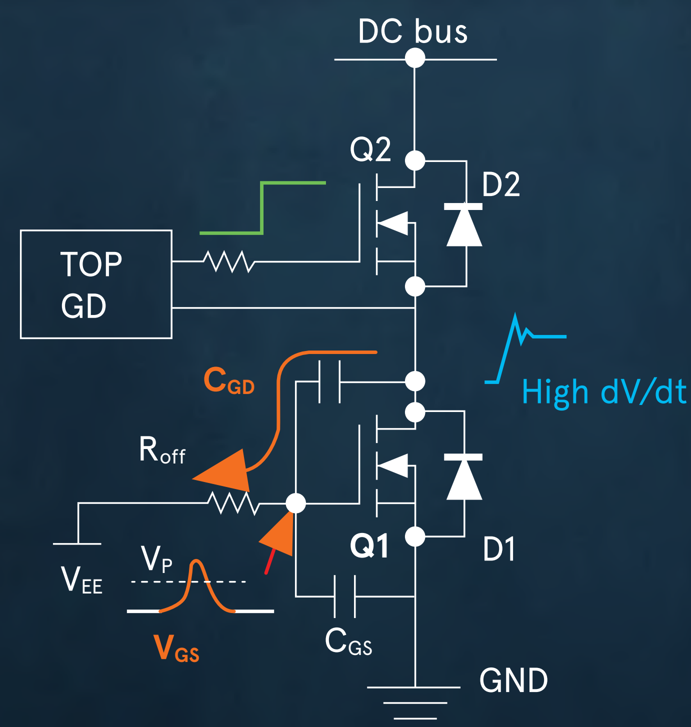


FIGURE 6: Switching Induced False Turn ON in a Half Bridge Configuration.

SUMMARY OF VGSoff

Due to the previous discussion, Microchip does not recommend the use of VGSoff = 0V. For single-ended topologies with no danger of shoot-though (e.g., flyback, buck, or boost topologies), it is possible to use VGSoff = 0V. Should VGSoff = 0V be absolutely required, attention should be given to proper gate-source loop design.

Specifically, designers should try to minimize three things: (i) parasitic drain-gate capacitance, (ii) gate-source loop inductance, and (iii) shared inductance between the gate-source loop and main current commutation loop.

CONCLUSION

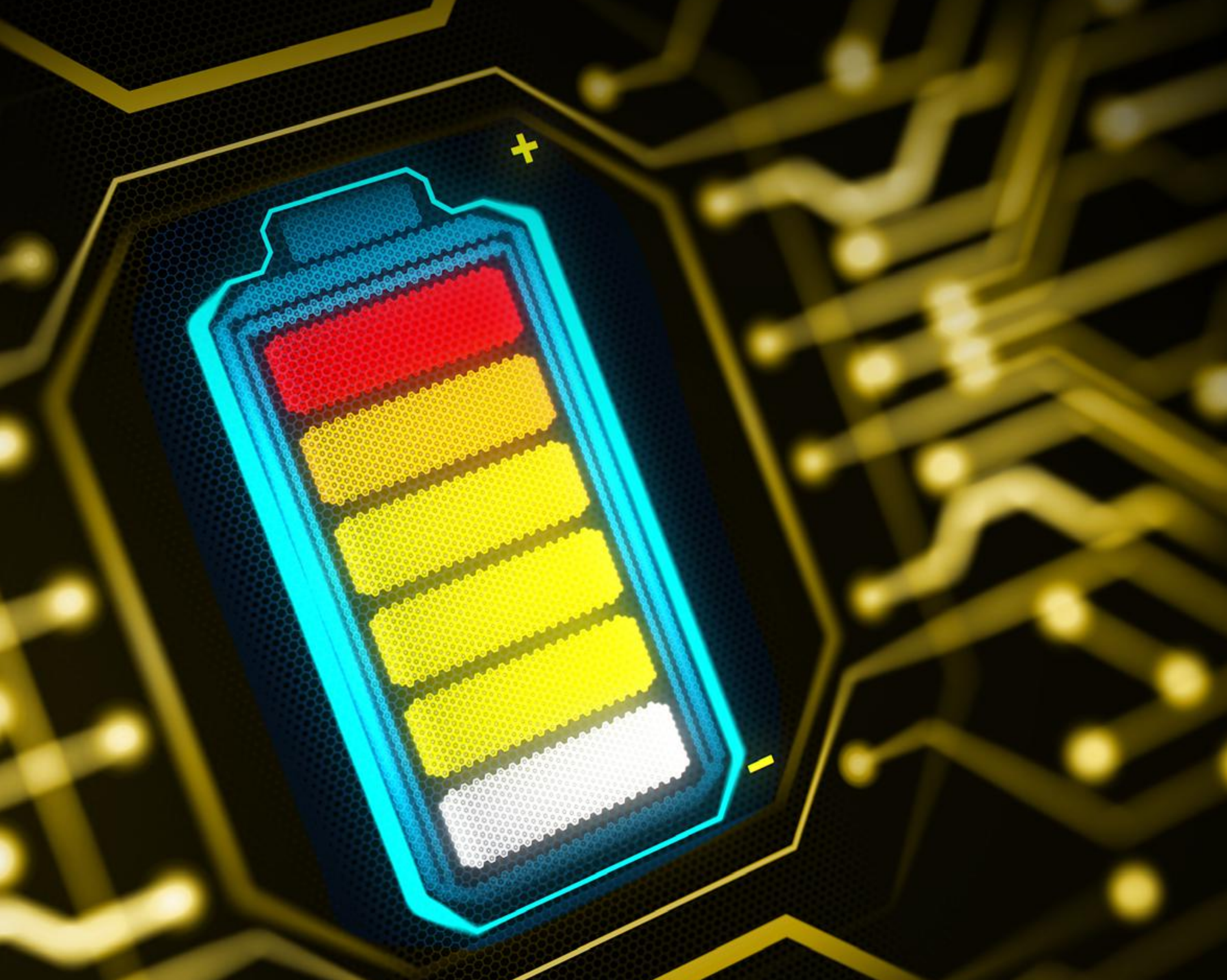
This application note provides guidance on Microchip SiC MOSFET gate-source voltage specifications and design considerations for making the most effective gate driver circuit. The following are key takeaways.

1. For the best possible switching and conduction performance, Microchip recommends driving with VGSon = +20V and VGSoff = -5V.
2. It is permissible to deviate from these recommendations. Microchip SiC MOSFETs can operate at +18V with slight reductions in current capability and turn-on efficiency, but comes with the benefit of longer short circuit withstand time.
3. Driving current-generation Microchip SiC MOSFETs using VGSon = 15V is not recommended. If this situation cannot be avoided, please contact icrochip for design assistance.
4. Microchip guarantees turn-off with VGS = 0V at Tj = 175°C. That said, using a negative VGSoff provides greater margin around Vp, which enhances switching stability and is the most certain way to prevent false turn-on.

To learn more about Microchip SiC solutions please

CLICK HERE

PROTECTING BESSs WITH COMPREHENSIVE STRATEGY



Battery Energy Storage Systems (BESSs) demand a comprehensive circuit protection strategy

INTRODUCTION

Recent growth in renewable energy generation has triggered a corresponding demand for battery energy storage systems (BESSs). The energy storage industry is poised to expand dramatically, with some forecasts predicting that the global energy storage market will exceed 300 gigawatt-hours and 125 gigawatts of capacity by 2030. Those same forecasts estimate that investments in energy storage will grow to $103 billion over that period. At the same time, the cost per kilowatt-hour of utility-scale battery systems is likely to drop to less than half of today's cost, making controlling system costs critical.

Today's battery systems aren't just designed to serve as local power backups, such as the systems used to power critical facilities including hospitals, data centers when the normal power source fails. BESSs also offer other benefits and ancillary services, including load-leveling, spinning and regulation reserves, T&D deferral, and frequency regulation, which when captured as a value stack maximizes this as a valued asset to utilities. Today's BESSs are increasingly designed to feed local micro-grids to supply power to the local area when the demand rises. They store electrical energy produced by solar or wind power generators, then inject that energy back into the grid when needed.

BESS CIRCUIT PROTECTION

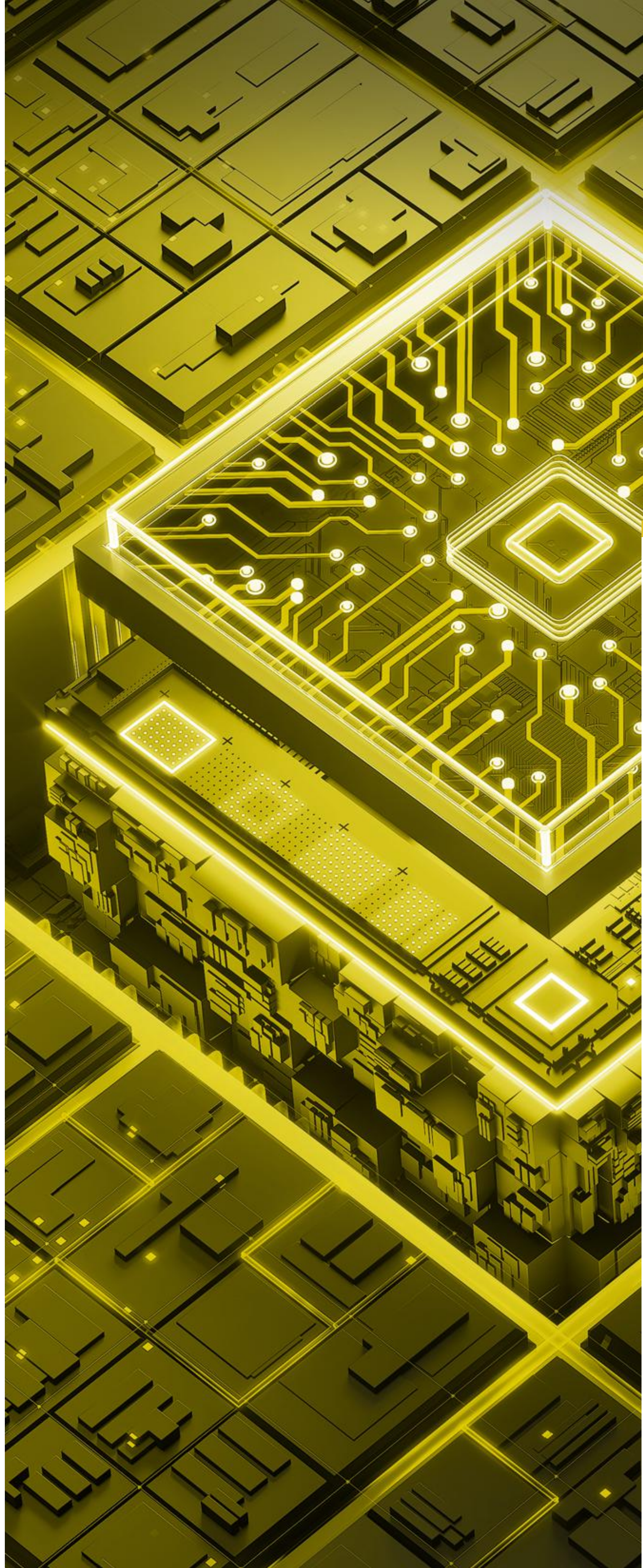
As the power density of modern lithium-ion batteries grows, BESS integrators are striving to offer their customers more power in a smaller footprint. However, with higher power levels, circuit protection becomes increasingly important.

Renewable energy providers are incorporating new generations of high-efficiency power semiconductor devices into their systems to control power in inverters and converters. Because these are sensitive electronic devices, they require robust protection against energy surges. The design of BESSs can still be considered to be in its infancy, given that the technologies that go into them are evolving rapidly. As a result, many of the electrical engineers integrating those solutions are seeking guidance in selecting and implementing appropriate circuit protection strategies.

A comprehensive circuit protection strategy is crucial to meeting BESS integrators' most critical objectives:

- To prevent costly service interruptions to end-users with critical uptime requirements, such as hospitals, industrial processing plants and data centers. For example, the cost of data center downtime is in the range of $8000 per minute.
- To prevent revenue losses for renewable energy suppliers.
- To prevent power disruptions to the local area.
- To protect the workers who will install and maintain the BESSs that the integrators will design.
- To prevent damage to the BESS equipment itself, which would jeopardize the sizable investment that the end-users or renewable energy suppliers have made.
- To provide grid stability as generation is additionally from renewable sources.

Electrical faults within a BESS can pose significant hazards to workers, including the risk of electric shocks, chemical/electrolyte burns from the batteries, and the release of toxic or explosive gas. The three main areas of concern are protection against electrical overcurrents, ground faults and arc-flash hazards.



OVERCURRENT PROTECTION

Inverter protection is one of the most important facets of BESS circuit protection. Inverters are typically—although not always—located outside of the trailer or other enclosure in which the banks of batteries are housed. A DC/AC inverter converts DC output from batteries into a utility frequency alternating current (AC) that can be fed into a commercial electrical grid. However, a BESS also allows storing the DC current generated by renewable energy sources to a bank of batteries. Later, when there's a demand for that stored power, a DC/AC inverter converts the DC battery power into AC power that can be exported to the grid.

In order to provide the longest possible battery discharge times, BESS designers are building in larger and larger battery banks. Each of those batteries represents an energy source. Any fault in the system can lead to dumping a massive amount of energy all at once, and all the dangers to people and equipment that could pose.

A wide range of fuses are available to handle a variety of current overload applications. High-speed fuses are the usual choice for these DC ESS applications because they are much smaller, faster and less expensive than DC circuit breakers. The maximum interrupting rating for circuit breakers tops out at about 25,000 to 30,000 amps. In contrast, the latest generation of high-speed fuses (such as Littelfuse PSR Series High-Speed Square-Body Fuses) (Figure 1) can interrupt up to 150 kA of DC current (or 200 kA AC) in a much smaller footprint than a DC circuit breaker.

High-speed fuses are designed to operate about 24 times faster than conventional fuses in order to protect sensitive power semiconductor devices (such as diodes, triacs, IGBTs, SCRs, MOSFETs and other solid-state devices) that are built into inverters, UPSs, battery management devices, and other systems by reducing peak let-through current and let-through energy (I2t).

Figure 1. Littelfuse PSR Series High-Speed Square-Body Fuses are frequently used for overcurrent protection of inverters because of their compact design, fast response to short circuit fault currents, and high interrupting ratings.

These fuses are also invaluable for protecting a BESS's DC batteries. Each battery is protected by DC fuses at the positive and negative terminals to isolate the battery during any internal short-circuit condition. DC combiners, where the outputs from multiple battery racks are combined to feed the inverter, are critical locations that are susceptible to high DC overcurrent faults. Typically at this location, output strings from batteries are protected by DC fuses with the highest possible DC interrupting rating.

GROUND FAULTS

A variety of factors can contribute to the development of ground faults. These factors include insulation or component degradation over time (often as a result of overvoltage or overtemperature), humidity/moisture, rodents, dust accumulation between live parts of the system, and human error. Unless an appropriate ground-fault device is used, low-current ground faults can often go unrecognized.

BESSs are typically ungrounded systems. The system may remain in operation after the first ground fault, resulting in higher voltage on the unfaulted bus with reference to ground but with no current flow. However, subsequent ground fault on the opposite bus can have catastrophic consequences from both an equipment-protection and worker-safety perspective. A second ground fault on an ungrounded system may constitute a phase-to-phase fault that can result in arcing, fires and severe damage or injuries. Most electrical faults, including arc flashes, begin as ground faults and so detecting these faults early is essential so they can be addressed before serious damage or injury occurs.

For ungrounded BESS systems, designers can choose from three options for ground-fault detection for the DC side:

1. Active insulation monitoring. This approach involves injecting a low-level signal that seeks the lowest-resistance path back to the relay through ground. The leakage current returning to the relay is directly proportional to the insulation of the system to ground. This method is attractive, but has some significant challenges, including difficulty in locating the exact fault location, susceptibility to system capacitance and interference of the active signal with other components of the electrical system.

2. Passive voltage monitoring with respect to ground. This method does not inject an active signal; instead, it monitors the voltage of each side of the DC bus (or each phase of the AC bus) with respect to ground. The advantage is that there is no active signal to cause any interference, but fault location is a challenge with this method as well.

3. Passive current monitoring through use of a ground neutral ground reference. The Littelfuse SE-601 Series DC Ground-Fault Monitor (Figure 2) can provide such a reference. This approach creates a neutralground point in between the DC bus voltages and looks for leakage current to or from ground. The advantages of this system are that the fault location (positive or negative DC bus) can be determined, there are no active signals to cause interference, and the reference module usually serves to limit fault currents to a safe value. The disadvantage of this method is that a symmetrical fault (a fault of equal resistance to ground on both buses simultaneously) might not be detected.

Figure 2. The SE-601 DC Ground-Fault Monitor provides sensitive, fast ground-fault protection with nuisance tripping. Ground-fault current is sensed using an SE-GRM Series Ground-Reference Module—a resistor network that limits ground-fault current to 25 mA. The SE-GRM allows an SE-601 to be connected to systems up to 1200 Vdc and potentially higher.

Any current running through to ground requires attention. Sensitive ground fault-relays will pick up leakage currents at 10 mA or even lower. The latest ground-fault relays can pick up levels of fault current as low as 30 milliamps. Typically, a ground reference module is installed between the negative and positive portions of a DC system, the reference model is connected to the relay, and the relay is connected to the ground.

Figure 3. The SE-704 Earth-Leakage Monitor provides both feeder-level protection or individual-load protection.

Although most BESSs are ungrounded, grounded BESSs do exist but require different methods of ground-fault detection. Designers need to weigh the relative merits of an AC ground-fault relay vs. an AC insulation monitor. An AC ground-fault relay, such as the SE-704 Earth-Leakage Relay (Figure 3), offers very sensitive ground-fault detection and can be used on systems with significant harmonic content. The output contacts can be connected for use in protective tripping circuits or in alarm indication circuits. The analog output can be used with a PLC or a meter. In contrast, an AC insulation monitor such as the PGR-3200 Series Insulation Monitor (Figure 4) which operates on one- or three-phase ungrounded systems up to 6 kV, can also be used on grounded systems to monitor the insulation for damage when the system is de-energized.

Figure 4. The Littelfuse POWR-GARD® PGR-3200 Insulation Monitor can be used with both ungrounded and grounded BESSs.

Many designers choose to use a breaker between each battery bank and the combiner box to simplify performing inspection or maintenance on each bank individually. An ungrounded DC ground-fault monitor, such as the Littelfuse SE-601 Series, can be used to monitor the status of the battery banks. It can be used in combination with the EL3100 Ground-Fault and Phase-Voltage Indicator (Figure 5) for 3-phase systems. It meets both the NEC and CE Code requirements for ground detectors for ungrounded AC systems.

Figure 5. EL3100 Ground-Fault and Phase-Voltage Indicator can be used in conjunction with an SE-601 Series DC Ground-Fault Monitoring for monitoring the status of a BESS's battery banks.

ARC-FLASH PROTECTION

According to OSHA, arc-flash events are responsible for approximately 80 percent of electrically related accidents and fatalities among qualified electrical workers. Even when there are no injuries to workers, an arc flash can destroy equipment, requiring costly replacement and system downtime.

The high levels of DC power that feed into inverters from the combined output of the banks of DC batteries creates the potential for arc-flash incidents. When the outputs of multiple daisy-chained batteries are brought together in a combiner box, they can also produce sufficient DC voltage to initiate an arc. Unlike with sinusoidal AC power, where the zero crossing helps AC arcs extinguish themselves, there's less chance that DC arcs from batteries will be self-extinguishing.

Arc flashes present a number of hazards. The heat can be more intense than the temperature on the surface of the sun, and the accompanying explosion may hurl debris at the speed of a bullet. The threat to both maintenance personnel and nearby equipment is obvious. To mitigate these hazards, arc-flash relays are designed to detect the light from an emerging arc flash and trip an upstream circuit breaker as quickly as possible. For example, the PGR-8800 Series Arc-Flash Relay (Figure 6a) can detect and send a trip signal in less than 1 millisecond, preventing an arc from growing into a potentially catastrophic incident. The trip time for a typical AF0100 Series Arc-Flash Relay (Figure 6b) configuration is less than 5 milliseconds.

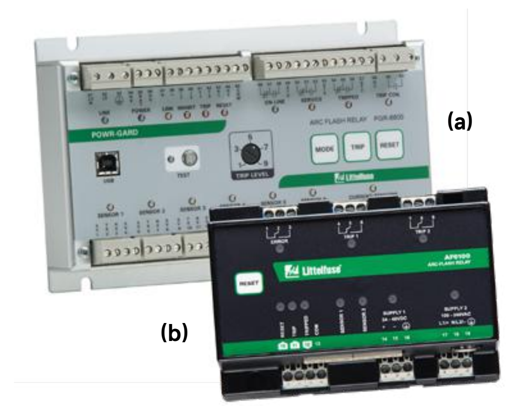


Figure 6. The PGR-8800 Series Arc-Flash Relay (a) detects developing arc-flash incidents by looking for a combination of excess light and current. An optical sensor and adjustable trip level reduce the chance of nuisance tripping by setting a threshold for ambient light. The AF0100 Series Arc-Flash Relay (b) reduces arc-fault damage by detecting the light from an arc flash and rapidly tripping. Two remote light sensors can be connected to one relay and multiple AF0100 and/or AF0500 (not pictured) relays can be connected to monitor additional sensors.

Installing an arc-flash relay system involves placing light sensors around the interior of the enclosure that houses the inverter and the associated bus bars most likely to be the origin of an arc. The power semiconductor device inside the inverter usually fails safe, but it is possible that it or its connectors could fail to ground and cause an arc flash.

ARC-FLASH CONSIDERATIONS FOR DC AND ENERGY STORAGE APPLICATIONS

Allow calculating the arc flash potential for to develop the calculations for arc-flash incident energy on, particularly the development of IEEE 1584 (Guide for Performing Arc-Flash Hazard Calculations). A revision is forthcoming based on further testing with AC systems. However, DC arc flash has been less studied and is less understood. The DC fault currents can be released rapidly on almost all types of BESSs, but those employing Lithium-Ion batteries can release very large amounts of current very rapidly.

The purpose of arc-flash calculations is to determine the largest possible incident energy. However, a few factors that may not be intuitively obvious can result in higher incident energy levels than would be anticipated if only an overcurrent protective device were used:

- **Battery age:** As batteries age, their internal impedance increases. This can result in lower arc-flash current, which can in fact lead to higher energy because the overcurrent protection device takes longer to operate.
- **State of charge:** A partially depleted battery bank may not produce full arcing or short-circuit current. Using an arc-flash relay instead of relying on overcurrent protection devices alone for arc-flash protection can help designers realize a consistently low incident energy throughout the lifetime of the BESS.

It's also important to keep in mind for incident energy calculations that battery cabinets tend to direct the energy out of the cabinet door. Large-scale BESS enclosures can expose personnel to even more energy during an arc flash, both by containing the fault and by making it more difficult for workers to self-rescue within a typical two-second window.

The battery banks themselves represent an arc-flash protection challenge in a BESS. An arc flash on one battery bank will be fed from other parallel battery banks. This can be resolved by monitoring the battery bank and disconnecting from the bus on a fault. At this point, the arc fault is only fed from the faulted bank, reducing its total energy by a factor proportional to the total number of parallel battery banks. The remaining battery banks continue supplying or being supplied with energy. Although disconnecting a faulted bank has a significant impact on operations and reducing incident energy, a fault local to the battery bank is more difficult to address. One option is to provide the means to disconnect/ de-couple sections of the battery bank physically, further reducing the voltage of each remaining section and reducing the hazard and available incident energy while maintenance is being performed.

To learn more about LittelFuse Supercapacitor Backup Regulator Solutions please

CLICK HERE

GET TO THE ROOT OF **BATTERY FAILURES**

KEYSIGHT TECHNOLOGIES

VISIT KEYSIGHT TECHNOLOGIES

Modern product applications running on rechargeable batteries typically have built-in sensors and battery management system (BMS) circuitries.

A BMS monitors a rechargeable battery system's voltage, current, and temperature, whether a single cell, a module (a group of cells), or a battery pack (a group of modules). Monitoring the voltage and current flowing from the batteries is usually not enough to determine battery health.

Monitoring battery temperature can warn you of potential defects and quickly isolate fault locations. A BMS monitors battery packs to keep operating temperatures within an optimal range. A battery that is too hot will degrade or malfunction. But a battery that is too cold will perform sluggishly due to slower internal electrochemical reactions, reducing its capabilities.

This white paper highlights common temperature-related battery issues and will show you how test instruments can help you build better battery-operated applications.

COMMON CHALLENGES IN MONITORING BATTERY TEMPERATURE

Thermal imbalance, battery-pack hotspots, low performance, and capacity are areas that you need to keep an eye on when monitoring battery temperature.

WHEN USAGE CAUSES THERMAL IMBALANCE

Large-scale applications typically use battery packs with modules wired in series and parallel connections. Thermal sensors placed strategically across a battery pack detect temperature variations. Large battery-pack thermal imbalance usually starts with the non-uniformities of battery cells affecting their charging and discharging voltages. Over time, the non-uniformity variation accelerates, with some cells overcharging or over-discharging, causing the batteries to overheat disproportionately.

You can minimize thermal imbalance by using a BMS to cell balance, equalize voltages, and state of charge (SOC) among the cells at a full charge. Battery manufacturers can also select batches of battery cells with very close open-circuit voltage to build battery packs and minimize SOC variations.

Product application design can also cause thermal imbalance. For example, the cooling system of battery packs is not effective enough for certain external harsh environments.

BATTERY-PACK HOTSPOTS

Monitoring battery temperatures helps you detect hotspots. Depending on how critical the battery application is, sometimes having just a few sensors strategically located across a battery pack is sufficient. However, in applications that require critical performance such as electric vehicles, you can place a temperature sensor on each battery-pack module.

Hotspots tend to occur on weak battery cells in a battery pack. Weak battery cells are susceptible to overstress and gradually degrade. As a result, they grow hotter during operation versus normal, good cells because they struggle to keep up with the performance of good cells.

Hotspots can also warn you about potential damage to battery cells or modules. A physical impact on the battery pack can puncture or deform the battery cell's internal structure, such as the electrodes or polymer separator. If that happens and no intervention occurs, the battery cell damage can degrade and potentially cause a thermal runaway. Fire and explosion may result, so it is important to detect hotspots, locate the faulty cells, and replace them quickly.

Other causes of hotspots include poor terminal connections, heat dissipation component defects, and external cable shorts.

LOW BATTERY PERFORMANCE AND USAGE CAPACITY

Monitoring battery temperatures represents a proactive, closed-loop process to keep battery packs operating in the optimal charging and discharging temperature ranges.

Frigid temperatures cause sluggish battery performance because of slower electrochemical reactions. As a result, battery usage capacity will drop significantly, and the battery may even stop operating.

A bigger concern is when the battery system operates at temperatures above the manufacturer's specification. Battery life will degrade and weaker batteries may deviate more from the good performing ones. At this point, thermal imbalance and hotspots start to show up.

INDEPENDENT TEST EQUIPMENT MONITORS BATTERY TEMPERATURE

Many commercial battery management systems are available for all kinds of applications, from Internet of Things (IoT) devices to high-voltage automotive applications. Essential features include overcurrent protection, overvoltage protection, overcharge protection, overtemperature protection, undervoltage protection, cell balancing, SOC, and state of health.

However, there are many good reasons to acquire independent test equipment to monitor battery temperature in your applications.

BENEFITS OF AN INDEPENDENT TEST VALIDATION SYSTEM

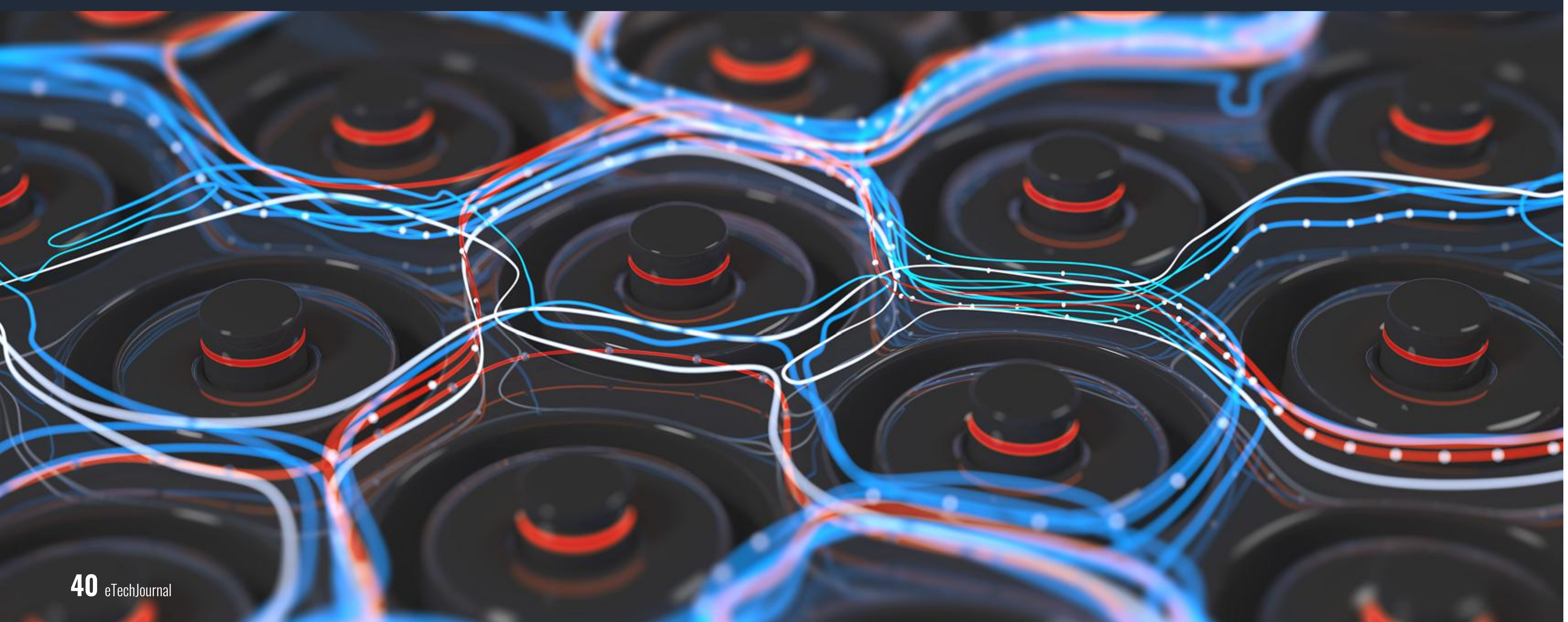
Having an independent test validation system, such as a modular data acquisition (DAQ) system, helps validate that your BMS is performing properly. It also helps validate the overall integrated system of your application. An independent DAQ system can do the following:

Measure more accurately with many types of temperature sensors, such as thermocouples, thermistors, and resistance temperature detectors (RTDs). Using thermistors or RTDs, you can achieve temperature accuracies of ≤ 0.1 °C.

Measure temperature ranges from -150 °C to 1,820 °C. This allows you to monitor both the internal battery system and external environmental temperatures at the same time.

Measure more points than the BMS implementation in your application to validate that your BMS is not missing out on any key locations.

Measure in much shorter intervals without taxing your BMS and the application's hardware resources. Shorter intervals help you find the best interval setting for your BMS monitoring system.



GAIN EXTERNAL REDUNDANCY FOR MISSION-CRITICAL APPLICATIONS

A key reason for having an independent test system is to provide redundancy for mission-critical applications.
For example, medical devices that monitor and control vital organ functions cannot afford unscheduled power interruptions during operations. Another example is large energy storage systems that power essential building functions such as IT, telecommunications, and medical equipment.

An independent DAQ system can do the following:

- Provide an independent alarm and emergency secondary switch-off to prevent a battery system meltdown or fire.
- Provide a backup monitoring and control system if the primary system malfunctions or loses communication.

The highly versatile DAQ system is the best option for independent test equipment to monitor temperatures. Plus, it is flexible enough to accommodate large-scale projects.

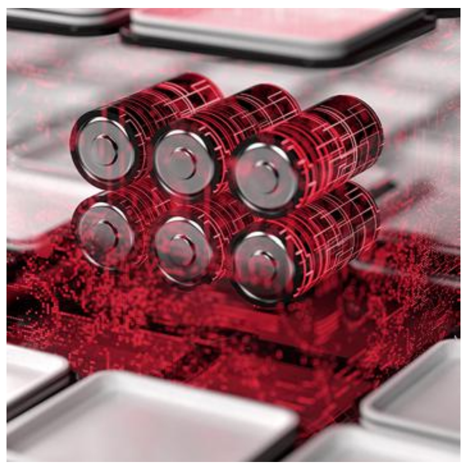
Many modern DAQ systems have built-in high-resolution, 6.5-digit multimeter instruments. They also come with various solid-state, armature, and reed-switching multiplexer modules to monitor more than 100 channels of temperature points. In addition, since the DAQ has a built-in digital multimeter (DMM), it can measure other signals besides temperature, such as AC / DC voltage and current, resistance, and capacitance.

The DAQ system that appears in Figure 1 is modular and allows for the expansion of channels for temperature monitoring. The system allows you to add modules to scale up accordingly when your project expands. This means you do not have to invest in new systems and can save precious development time.

Figure 1. Keysight 34980A data acquisition switch / measure unit (SMU)

TEST EQUIPMENT TO HELP BUILD BETTER BATTERY-OPERATED APPLICATIONS

Once you understand the sources of battery failures, you can use battery emulation software to predict drops in battery capacity.



BATTERY FAILURE MECHANISMS AND CONCERNS

You can analyze the root cause of battery failures by physically cross-sectioning them. However, electrical measurements offer signs that can help predict failures before they happen.

One source of failure comes from lithium plating or dendrite growth on the anode electrode.[1] This growth is typically due to overcharging batteries through many cycles, causing lithium deposits on the anode. Over time, this may cause an electrical short across the two battery electrodes. It is difficult to monitor such an electrical short because it happens quickly — within milliseconds of a voltage drop.

Another source of failure is degradation of the electrode. In this case, the electrode shows oxide buildup or microcracks from charge and discharge cycle fatigue and repetitive chemical reactions of the electrolyte.

Internal battery separator failure can also occur causing an electrical short.[3] A separator failure can come from a physical impact or puncture of a battery or exposure to very high temperatures. In addition, a material defect during manufacturing can also cause failure.

Aging and a drop in battery capacity are not serious failures requiring immediate intervention. However, these factors are concerning to battery application users. Open-circuit voltage measurement itself is not a good indicator of battery capacity. The internal resistance of aging batteries increases over time, but you cannot take a snapshot of resistance measurement and make an immediate capacity degradation conclusion. Temperature, SOC, and discharge rate affect internal battery resistance. Figure 2 shows a few key battery failure mechanisms that can occur in a battery cell over time.

Battery failures are complex because of electrochemical reactions and batteries' exposure to physical variables such as temperature and mechanical stress. The battery charging method is another factor. For example, if a battery is subjected to fast charging very often, it gets heated up much higher temperature than normal charging and degrades faster over time.

There is no single battery test instrument that can provide a definitive diagnostic solution for battery failures. However, there are test equipment solutions available to meet your needs depending on your application, power usage requirements, capacity, and production cycle (R&D, compliance testing, or production). See the "Learn More" section for links to test equipment to meet your diagnostic needs.

Now we will explore test equipment tools to help you better substantiate battery life and the effects of temperature on it.

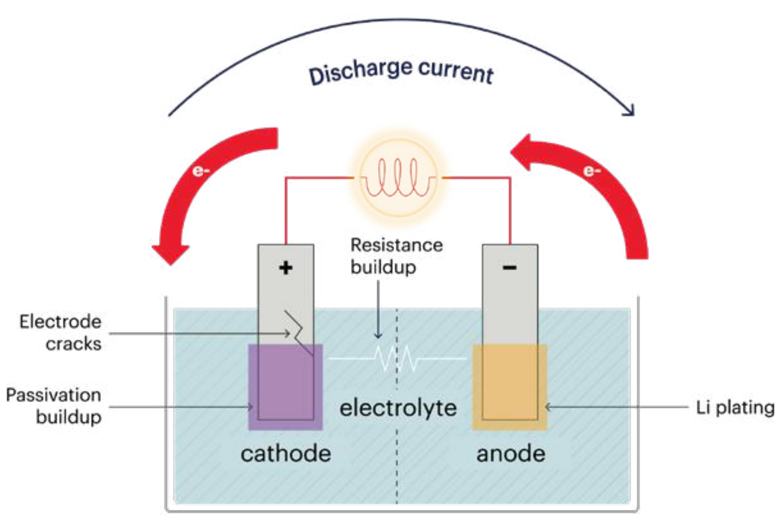


Figure 2. Internal battery failure mechanisms over time.

BATTERY EMULATION TO VALIDATE BATTERY PERFORMANCE, INCLUDING EFFECTS OF TEMPERATURE

You can use battery emulation software to better understand and predict drops in battery capacity over time. In addition, battery emulation software can predict the impact of temperature on battery life.

Before you emulate a battery, you must first profile it. You need to understand the amount of energy the battery can store and supply as a battery discharges over time. The open-circuit voltage and internal resistance vary as the battery discharges.

Therefore, it is crucial to map these out so that battery profiles accurately reflect the real-world performance of the battery. Figure 3 is an example of a typical plot. An engineer can obtain a battery profile by using battery modeling software or receiving a profile from a battery supplier. Modeling software creates a profile that reflects the current consumption for a specific device; it is more accurate than a battery supplier's generic profile. The battery profile is the basis for the software to emulate the battery.

It is critical to consider the effect of temperature on battery life. Figure 4 shows how temperature can affect the capacity curves of a battery. Generating profiles at different temperature values enables you to better predict the impact of temperature on battery life.

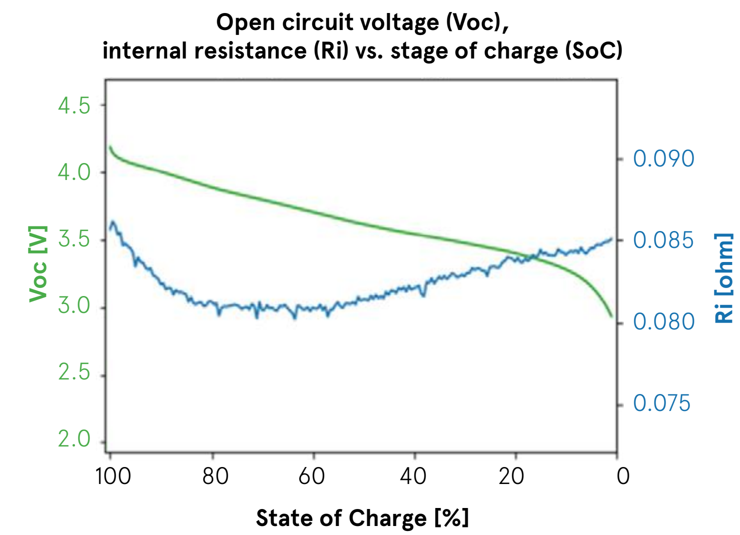


Figure 3. Battery profile created with Keysight BV9210B / 11B PathWave BenchVue advanced battery test and emulation software.

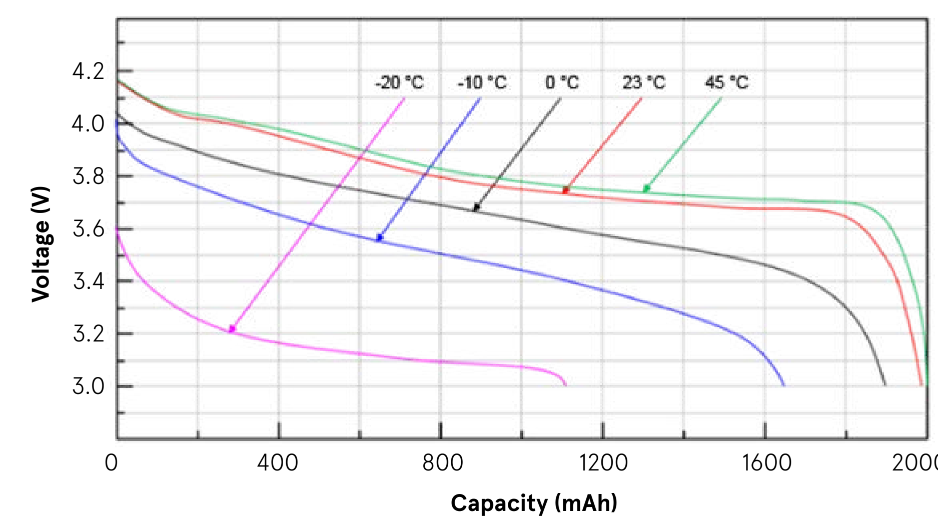


Figure 4. 1,000 mAh Li-ion cell, 3 V cutoff voltage — temperature variation

Once you develop battery profiles, you can use battery emulation software to cycle batteries to determine loss of capacity and battery life reduction. Battery performance can decline significantly over a lifetime of charging and discharging which is why it is vital to simulate battery cycling. Battery test and emulation software offers an easy solution to accomplish this. It is important that the software support arbitrary waveform generation (AWG) and data logging. In addition, it is valuable to have the ability to create various charging and discharging waveforms for a battery.

Engineers can combine multiple disparate charging and discharging sequences to simulate complex cycling profiles. They can then confirm how a battery's performance degrades over time. Emulation software solutions enable engineers to make, for example, up to 1,000 cycle operations to determine the battery's age effect and reliability under sequence test conditions (see Figure 5).

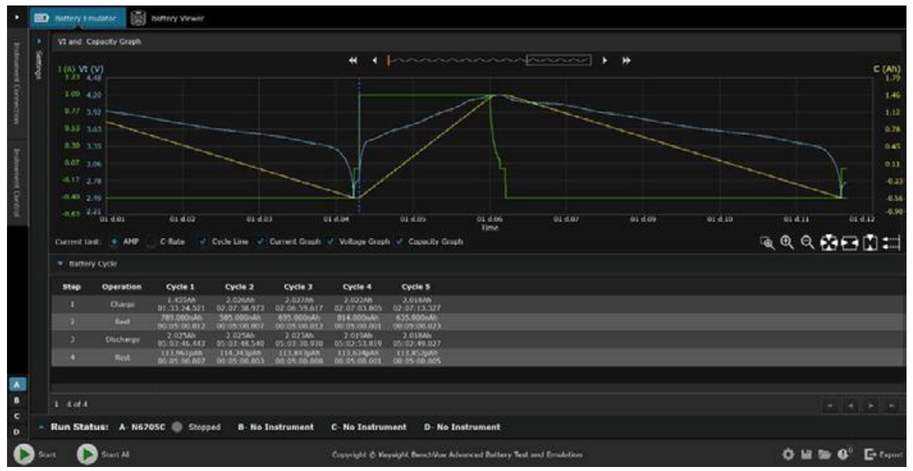
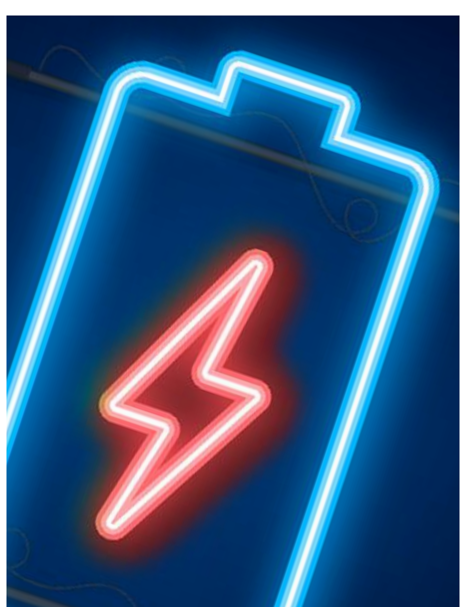


Figure 5. Battery cycling testing results using Keysight's BV9210B / 11B software

Keysight's BV9210B / 11B PathWave BenchVue advanced battery test and emulation software, along with the N6705C DC power analyzer and the N6781A or N6785A source measure unit (SMU) modules, can perform battery profiling, battery emulation, current drain analysis, and battery cycle testing.



SUMMARY AND RESOURCES

Having an independent test system to monitor battery health and temperature is indispensable. An independent test system enables you to detect potential issues such as thermal imbalance, hotspots, and changes in ambient temperatures that can affect the overall performance of your battery system even if you already have a BMS.

An independent battery test system can serve as a test validation system and an external redundancy safety system; it expands to meet all your battery test system needs. Further, the system helps in troubleshooting battery failures. And with a few additional setups and battery software applications, you can use the system as a battery emulator to help build better battery-operated applications.

CLICK HERE

MAXIMIZING BATTERY LIFE WITH MODERN OP-AMPS

Modern operational amplifiers (op-amps) find use in various battery-powered applications. Examples include portable medical devices, fitness trackers, mobile phones, tablets, and condition monitoring sensors.

To extend battery runtime between battery replacement or charging, the system can turn off active components whilst in sleep mode. Depending upon the applications, when the system comes out of sleep via a timer or a triggering event, the system needs to be up and running quickly to allow for signal conditioning and event logging.

Consider the discharge curve of a battery illustrated in Figure 1. Discharge cycles of batteries are typically similar to this curve. The terminal voltage will gradually decrease as the battery discharges with time.
As the battery comes to the end of its charge, the terminal voltage of the battery will rapidly decrease.

If the op-amp circuit is designed to operate at a voltage near the nominal voltage of the battery, such as V1, the operating time of the circuit t1 will be short. However, using an op-amp capable of functioning at a slightly lower voltage, such as V2, significantly increases the operating runtime of the battery t2.
The key to designing a battery-operated system that is efficient is to optimise battery runtime by minimising the current drawn by the circuit.

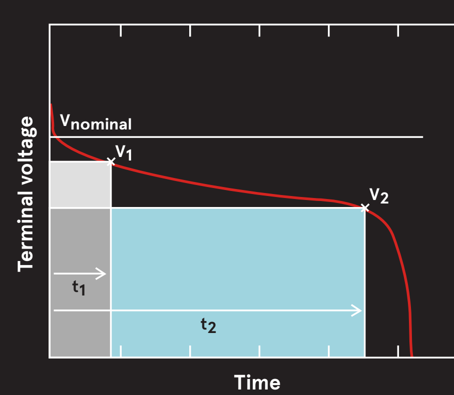


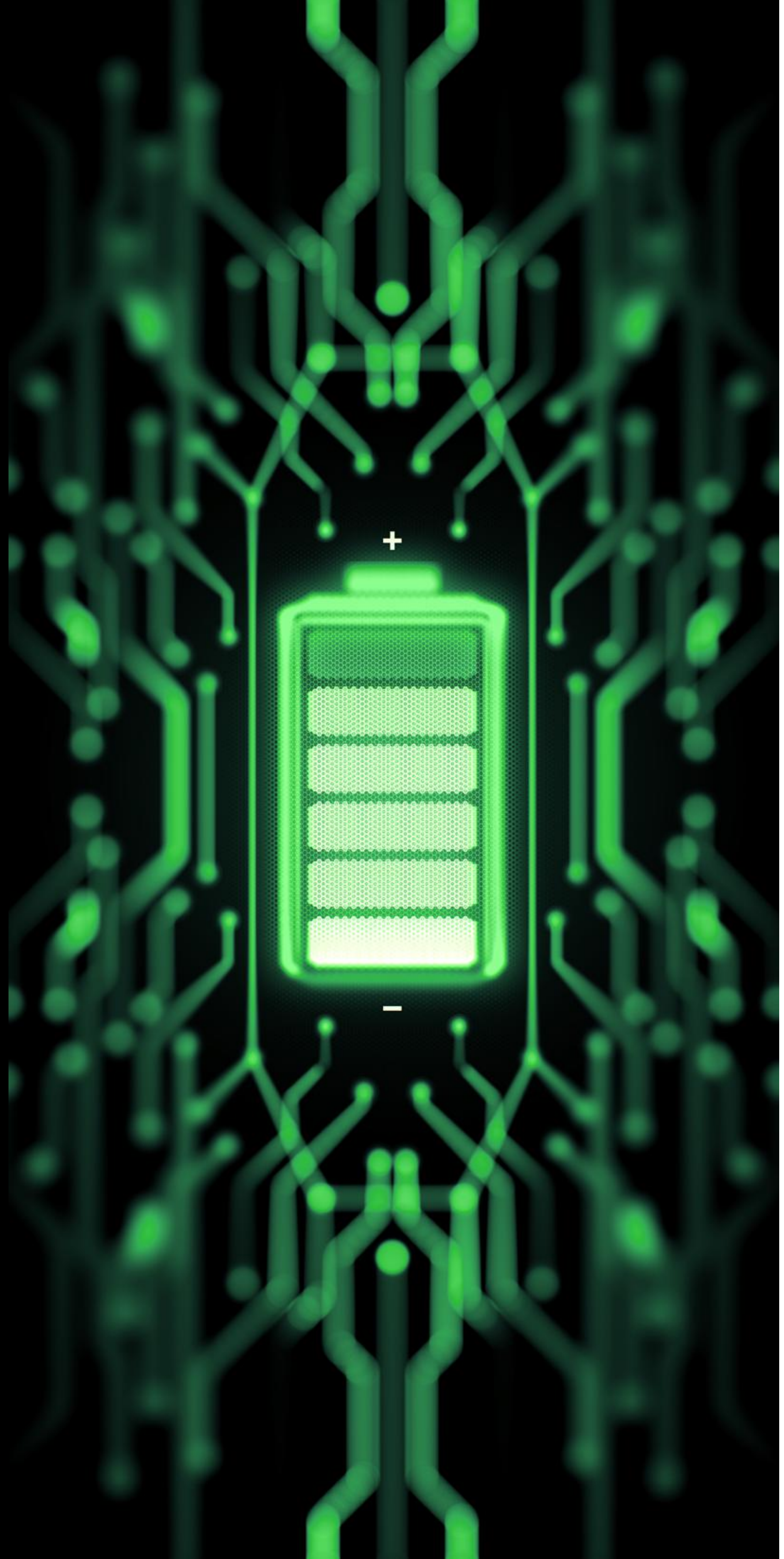
Figure 1: Battery discharge plot

BY CONSIDERING LOWER THE QUIESCENT CURRENT (IQ) SUPPORTS LONGER BATTERY RUNTIME:

Quiescent current refers to a circuit's quiet state when it is not driving any load and its inputs are not cycling. It is typically nominal; however, it has a significant impact on battery runtime, especially in wearables, hearables, and internet of things (IoT) sensor nodes. The most straightforward strategy for lowering overall power consumption is to select an operational amplifier with a low IQ.

Devices with a lower IQ often have lesser bandwidth, more noise, and maybe more difficult to stabilise. Power consumption in an op-amp circuit consists of various factors: quiescent power, op-amp output power, and load power. The quiescent power, PQuiescent, is the power needed to keep the amplifier turned on and consists of the op amp's IQ. POutput is the power dissipated in the output stage of the op-amp to drive the load. Finally, load power, PLoad, is the power dissipated by the load itself.

These types of products are typically designed to wake periodically to perform some action. After then, they return to standby mode. Battery runtime is calculated based upon active, sleep, and hibernate currents of the central controlling unit, such as a microcontroller. Active current consumption is vital in increasing battery runtime; ultimately, the runtime is influenced by how much time is spent in each power mode. As a result, the standby current of each component becomes increasingly crucial as sleep and hibernate modes occupy longer periods of time in a device. In such instances, the power supply's quiescent current is the biggest contribution to the system's standby power consumption. An op-amp with a low quiescent current can generate considerable energy savings for a device that spends a long time in idle mode.



USE CASE: REVOLUTIONISE ELECTROCHEMICAL SENSOR USING A 1V OP-AMP

The amperometric gas sensor generates a current proportional to the volumetric fraction of the gas. It is a three-electrode device that measures ethanol at the working (or sensing) electrode (WE). The counter electrode (CE) completes the circuit, whilst the reference electrode (RE) provides a stable electrochemical potential in the electrolyte, which is not exposed to the ethanol. In the instance of the SPEC sensor, a bias voltage of +600mV is applied to RE. Figure 2 depicts a typical architecture for biasing the sensor and measuring ethanol concentration in a battery-powered sensor system.

The sensor can operate at 0.9V, however, the signal conditioning and MCU require 1.8V. This voltage is generated by a boost converter, such as the nanoPower MAX1722x series. The MCU, with its integrated ADC, is only active to make measurements in such a system, whilst the boost converter and signal conditioning (op-amp) circuits are always active since they are used to generate the bias potential required at RE.

With the Maxim Integrated MAX40108 1V op-amp, it is possible to power the signal conditioning directly from the battery as seen in Figure 3. The MAX40108 is a low-power, high-precision op-amp that operates with a power supply voltage as low as 0.9V to 3.6V.

The MAX40108 features rail-to-rail CMOS inputs and outputs, a 168 kHz GBW, with low 25.5μA (typ) quiescent current and 1μV (typ) zero-drift input offset voltage over time and temperature.

Since the sensor and the signal chain are always active, powering them directly from the battery reduces the output current of the nanoPower boost and thus, the current requirements of the entire system. The MCU will still be powered by the boost regulator, but it is only active to make measurements. Otherwise, it is mostly on standby. The traditional sensor circuit consumes 150.8μA of standby current and 164.4μA of average current. Replacing the signal conditioning circuit with the MAX40108 reduces the standby current down to 81.9μA, a reduction of 45% and the average current down to 95.7μA, a reduction of 41.79%. As a result, the battery runtime of the system using the MAX40108 1V op-amp is almost longer than that of the traditional system.

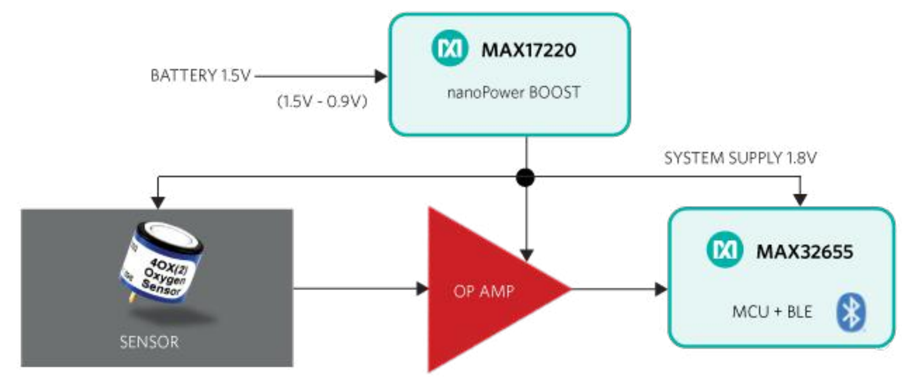


Figure 2: Traditional architecture of battery-powered sensor system

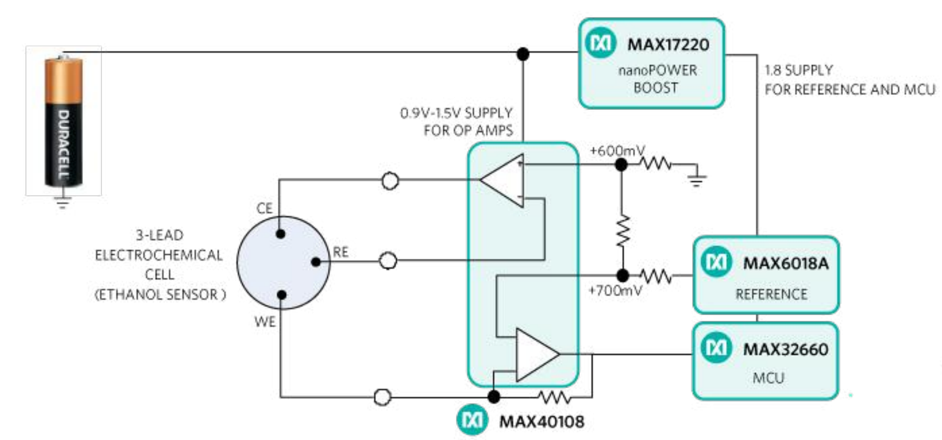
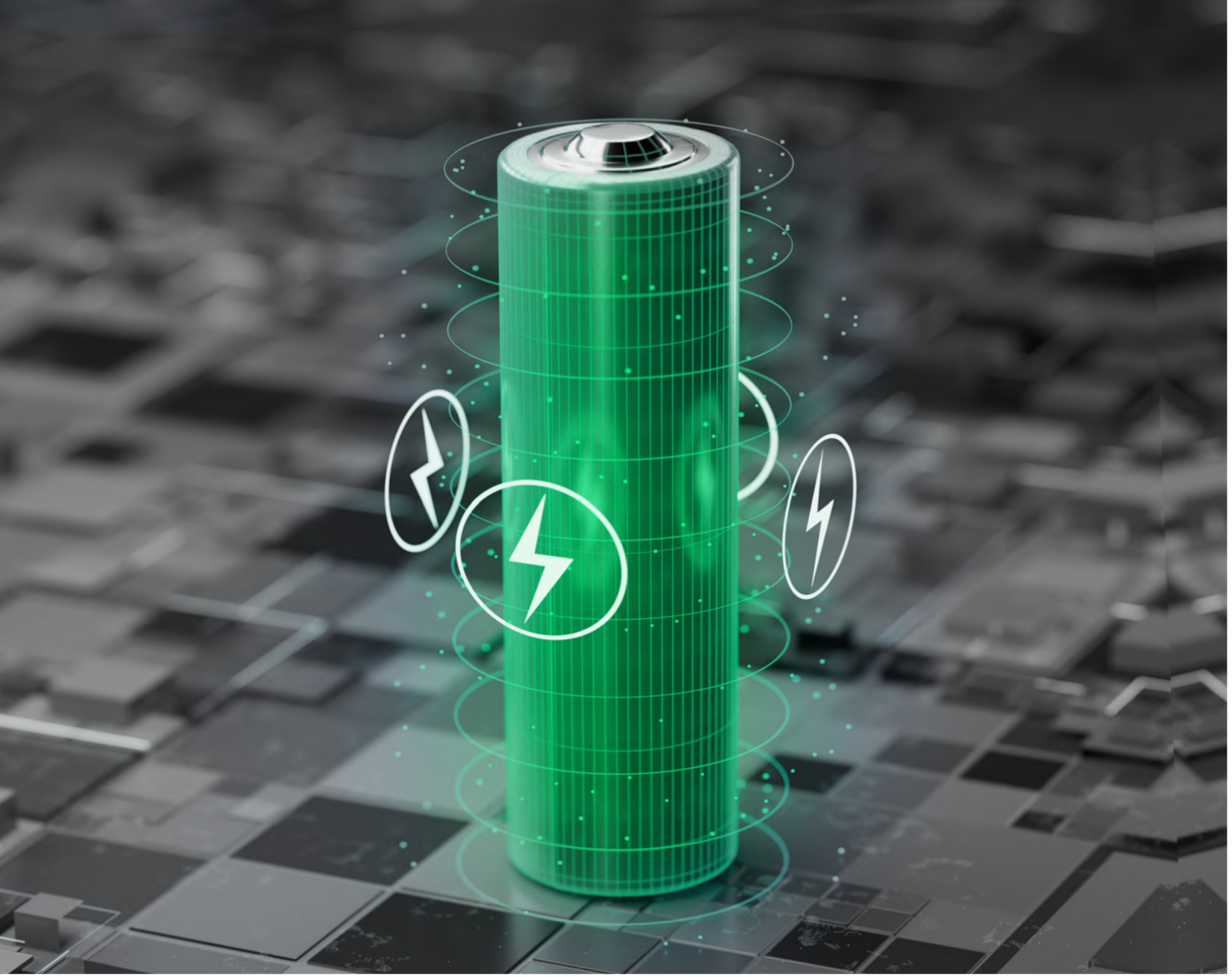


Figure 3: Block diagram of battery-powered electrochemical sensing system with 1V op-amp



FEATURED PRODUCT:

MAX40108 1V, Low-Power, Precision Operational Amplifier

A compact, high-precision op amp with low power consumption and zero-drift feature. Ideal for various consumer, medical, and industrial applications.

BUY NOW

CONCLUSION

In low-power battery-operated devices, minimizing power consumption is crucial for extending battery life. By selecting an operational amplifier with a low quiescent current, it is possible to reduce the overall power consumption of the circuit. This is especially important for devices that operate in sleep and hibernate modes for extended periods, where quiescent current becomes the most significant contribution to standby power consumption. The MAX40108 1V op-amp from Maxim Integrated is an excellent option for these applications, as it features low quiescent current, high precision, and operates on a power supply voltage as low as 0.9V. Using this op-amp can significantly increase battery life in battery-powered sensor systems, as demonstrated in the article's use case.

Discover Analog Devices' complete range of power management solutions,

CLICK HERE

TECHNICAL RESOURCES CENTRE

Learn innovations,
Stay informed,
Be inspired

A comprehensive selection of products framed into design situations, latest news and trends, design tools and resources to enable you to move from block diagram concept to solution for your vertical segment applications.

LEARN MORE

Explore our expanding library of:

Whitepapers

Articles

How To's

Webinars

Podcast