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System Solution Guide

Solid-State Circuit Breaker

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A circuit breaker is a device used to protect electrical circuits from damage caused by overcurrent, overland and short circuits. It is not used to protect people against electric shocks. A device called residual-current device or ground fault circuit interrupter is used to protect against these electric shocks. It detects leakage currents and interrupts the circuit.

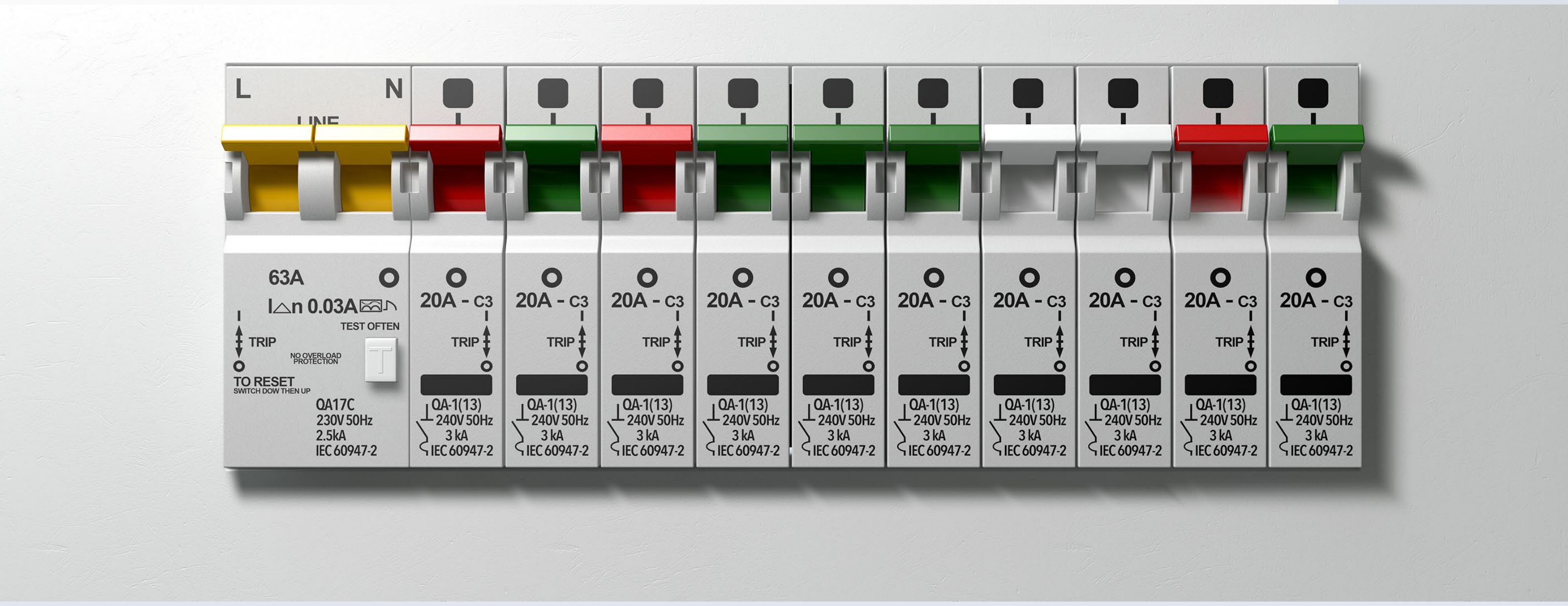
Electromechanical variants of circuit breakers, whose design can be traced back to the 1920s, are still widely used. Circuit breakers have the advantage over previous fuse designs in that they can be used repeatedly. These previous designs must be replaced after usage.

Nowadays, with advancements in the wide-bandgap semiconductor technology, solid-state variants are taking bigger market share. Wide-bandgap semiconductor switches have lower on-state losses and higher efficiency during normal operation compared to silicon-based semiconductors.

Solid-state circuit breakers (or circuit e-breakers) do not contain mechanical parts as their switch is a semiconductor. They use electronic components to detect and interrupt fault conditions to ensure safety and reliability of electrical systems of electrical systems.

Solid-state circuit breakers are faster, can be dynamically adjusted and can be connected to the intelligent network and monitored remotely.

They can be used in various applications, including residential, commercial and industrial AC systems. Solid-state circuit breakers can also be used in HV DC systems, e.g., as a disconnect switch for HV battery in electric vehicle.



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Circuit Breakers

Circuit breakers are used in residential, commercial, and industrial settings to ensure the safe operation of electrical systems. They can be found in homes, offices, factories, data centers and power plants, playing a crucial role in maintaining electrical safety and reliability. They have replaced and supplemented fuses (which are for one use only and need to be replaced after a failure) in almost all use cases. Fuses are still being used in industrial grade systems as additional protection to increase redundancy and for protection of specific components or circuits.

In the residential sector, the most commonly used type of circuit breaker is the thermal-magnetic circuit breaker. These breakers combine thermal and magnetic mechanisms to protect against both overloads and short circuits, making them highly effective for home electrical systems. Circuit breaker can detect both overload and short-circuits in the connected electrical circuit. Unlike fuses, they can be reset and manually disconnected using a lever, which vastly improves their usefulness.

During overloads, the temperature of the wire can rise above critical value and may cause a fire. To protect against this, the low voltage circuit breaker is equipped with a bimetallic strip. This strip is made of two different conductors with different thermal expanse coefficients. This separates contact at smaller, longer-term overcurrent.

During short-circuits when the current rises quickly, a solenoid is engaged for protection. As the high current spikes, the magnetic field of the solenoid pulls down a level to rapidly separate the contact.

Arcing

When electrical contacts open, to interrupt a large current, an arc between the opened contacts tends to form, which allows the current to continue flowing. The energy of the arc can cause significant damage to the insides of the circuit breaker or even to the case. Therefore, various features are implemented to extinguish the arc and dissipate its energy safely.

The thermal portion of the circuit breaker provides a time-response feature that trips the circuit breaker sooner for larger over-currents but allows smaller overloads to persist for a longer time. This allows short current spikes, like those are produced when a motor or other non-resistive load is switched on. With a very large over-current, such as those caused by a short circuit, the magnetic element trips the circuit breaker with no intentional additional delay.

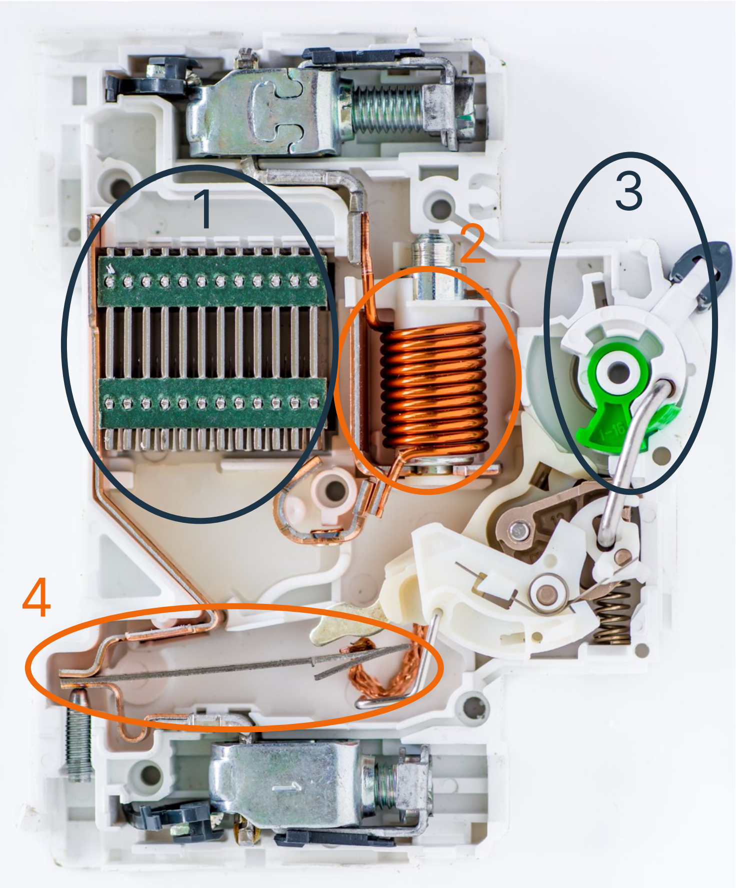

Figure 1: Miniature circuit breaker. 1: Arc extinguisher, 2: Solenoid with metal lever, 3: Actuator lever, 4:Bimetallic strip

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Advancements in Circuit Breaker Technology

Innovative circuit breakers, like ground fault circuit interrupters (GFCI) and arc fault circuit interrupters (AFCI), have significantly advanced circuit breaker technology. However, traditional circuit breakers with mechanical relays still face limitations. Mechanical relay contacts can produce arcs when opening or closing, especially during high-current faults. The disconnection speed of electromechanical circuit breakers is constrained by the physical properties of their coils and relay mass. Additionally, mechanical relay contacts degrade over time, limiting the number of interruption cycles.

The latest trend in circuit protection replaces electromechanical relays with semiconductor power devices, known as solid-state circuit breakers (SSCB). These SSCBs offer numerous advantages. Semiconductor switches connect and disconnect without producing arcs, eliminating the need for arc-suppression features.

Free from the limitations of magnetic coils, semiconductor switches operate hundreds of times faster than electromechanical relays, interrupting current before it becomes hazardous. Without mechanical parts, semiconductor switches can perform unlimited connect/disconnect cycles without degradation. This innovative approach replaces traditional moving parts with semiconductors and advanced software algorithms, enabling faster interruption of extreme currents. Solid-state technology ensures extremely fast fault interruption, clearing faults in microseconds compared to milliseconds for mechanical circuit breakers of the same size. Wide bandgap (WBG) semiconductors offer superior material properties, allowing power devices to operate at higher voltages, temperatures, and switching rates.

Table 1: Comparison between electro-mechanical and solid-state circuit breakers

	Electro-Mechanical	Solid-State
Design	Contains moving parts and contacts	**Uses semiconductor as a switch**
Speed	Milliseconds	**Microseconds**
Durability	Mechanical wear and tear	**Durable**
Precision	Limits are set by manufacturer	**Offer precise control**
Arcing	Yes	No
Power Dissipation	Lower efficiency	**Higher efficiency**
Isolation	Yes	**No**

Market Information

Solid-state circuit breakers market is on the upward trajectory with expected steady increase of at least 8% CAGR during 2025 to 2030.

Over the long term, the growing penetration of renewable sources in the energy mix is expected to drive the market during the forecast period.

On the other hand, technical limitations of solid-state circuit breakers are likely to limit their uses, thus hindering market growth in the forecast period.

Nevertheless, the demand for robust electric vehicle (EV) charging infrastructure is expected to create an opportunity for the market to expand in the upcoming years.

Market is separated into direct (DC) and alternating current (AC). DC market is expected to rise more due to SSCB being more suitable for applications in ships, urban subways and trams, battery systems (data centers) and more.

For AC systems, capability of SSCBs to withstand high voltage fluctuations from the grid makes them essential for traditional power systems and they are on track to replace traditional circuit breakers.

Sources: Mordor Intelligence, Market Research Future

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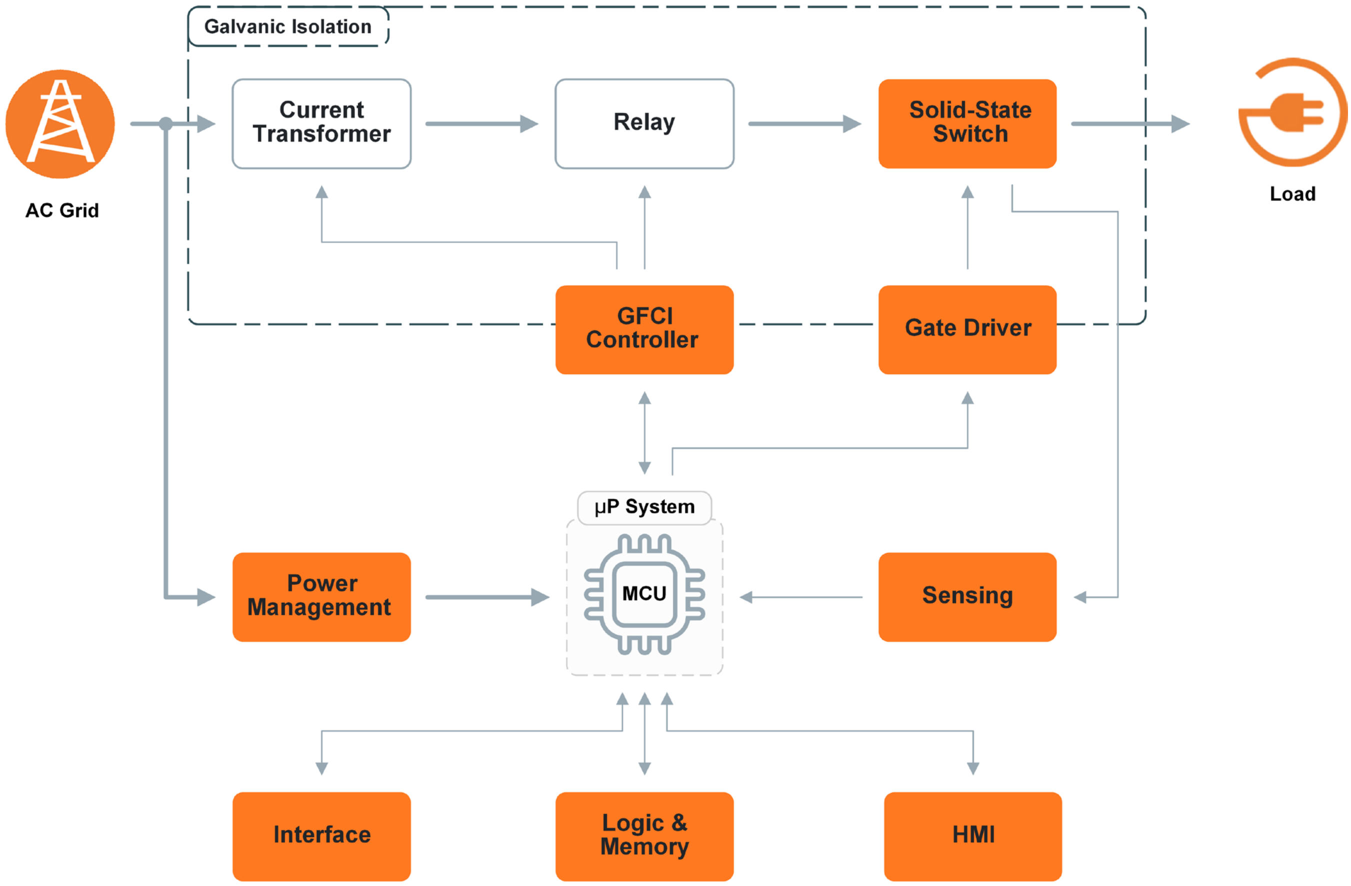
Solid-State Circuit Breaker Block Diagram

The block diagram below illustrates a solid-state circuit breaker solution featuring recommended products from **onsemi**. The most important building block is the switch which replaces traditional electro-mechanical relays. The Gate Driver controls the switch, and the Interface allows it to communicate with the device. Another important part is Sensing which includes both current and temperature sensing. For additional functionality, GFCI can be incorporated. Other components, including power management, logic, memory and many more, can be sourced from **onsemi's** comprehensive range of solutions.



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Solid-State Switches

Semiconductor switches bring many advantages compared to mechanical switches. They have high switching speed, turning on and off almost instantly. They are much more durable as they have no moving parts and thus are less prone to wear and tear. They eliminate arcing, when huge currents are being disconnected, which may damage the system. Last but not least, they are smaller and can be integrated into compact designs. Their major drawbacks include heat generation, which needs to be dissipated to ensure operation. They are sensitive to temperature variations and are susceptible to electromagnetic interference (EMI).

Figure 2 illustrates typical AC solid-state breaker power channel diagram. It includes bidirectional blocking using back-to-back (common-source) Combo JFETs. Common-source connection allows using common gate driver. It also shows shunt resistors, which are inserted into common source and are used for current sense. Other commonly used parts are RC snubber, transient voltage suppressor (TVS) and metal-oxide varistor (MOV); which are used to damp the ringing, which occurs when switching. Note that the diagram uses two sets of parallel switches. Paralleling is used to reduce the overall channel resistance, since in bi-directional application the resistance is increased by having two devices in the current path.

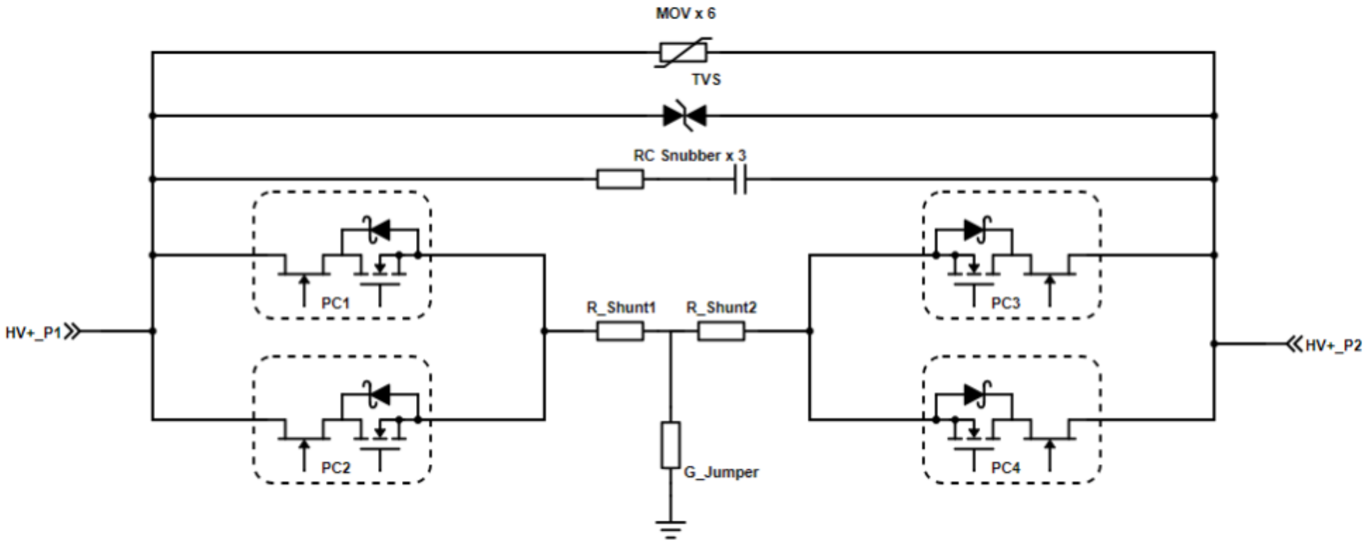

Figure 2: Power channel diagram of SSCB

There are more possible semiconductor switches available on the market.

Table 2: Comparison of semiconductor switches

Technology	On-resistance x Area	Switching Speed	Die-size (20mΩ)	Typical $R_{DS(on)}$
SiC JFET	0.7 Ω.cm²	500 kHz	4.0 mm²	> 4 mΩ
SiC MOSFET	1.4 Ω.cm²	200 kHz	7.2 mm²	> 12 mΩ
GaN	2.1 Ω.cm²	1 MHz	8.8 mm²	> 50 mΩ

Silicon Carbide JFETs

Junction field effect transistor (JFET) is a type of unipolar transistor, so it only uses majority carrier type. It is similar to MOSFET as it is operated on the electric field principle, it is voltage controlled and does not require biasing current. The main difference between the two of them is that JFET is a depletion-mode device (normally on) and requires reverse bias to switch and remain off. While some semiconductor-relay applications benefit from this normally-on state, most require a default normally-off state. Addition of a few components can create a normally-off switch even without applied power.

Figure 3 shows a cross-section of SiC JFET with V_{GS} = 0 and drain-source voltage VDS nearly zero. This represents one of the thousands of parallel cells in a JFET chip. The **onsemi** SiC JFET has two PN junctions (diodes): drain-to-gate and gate-to-source. In this unbiased state, a highly conductive channel exists between the Drain and Source, allowing electrons to freely flow in either direction, yielding the distinctive low on-resistance of the **onsemi** SiC JFET.

onsemi offers SiC JFETs, SiC Cascode JFETs and SiC Combo JFETs, each type has its unique characteristics and is suitable to different application. SiC JFET allows the SSCB to operate at up to 175 °C, which is material limit for enclosure; SiC is able to withstand even higher temperatures.

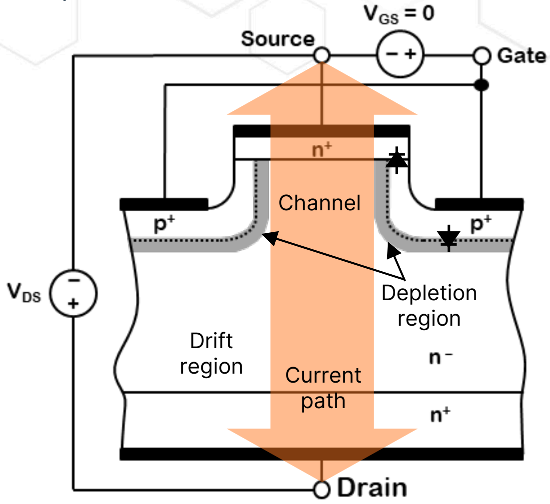

Figure 3: Vertical JFET structure with shown direct current path

SiC JFET

- Normally-on SiC JFET
- Lowest available Rds
- $R_{DS}(V_{GS}$ 2V) = 7 mΩ, $R_{DS}(V_{GS}$ 0V) = 8 mΩ
- Useful for circuit breaker and current limiting applications
- JFET V_{GS} in the on-state is a direct measure of device T_J, ideal for self-monitoring power devices

SiC Cascode JFET

- Co-packaged Si MOSFET
- Normally-off
- Standard gate drive
- Built-in JFET gate resistor
- Suitable for fast switching applications

SiC Combo JFET

- Separate access to MOS and JFET gates enables more control of switching dV/dt
- Enables direct drive of JFET gate for 10-15% lower $R_{DS(ON)}$ at @ V_{GS} =+2 V
- Simplifies paralleling of multiple JFETs
- Same gate drive as separate JFET + MOSFET
- Significant space savings

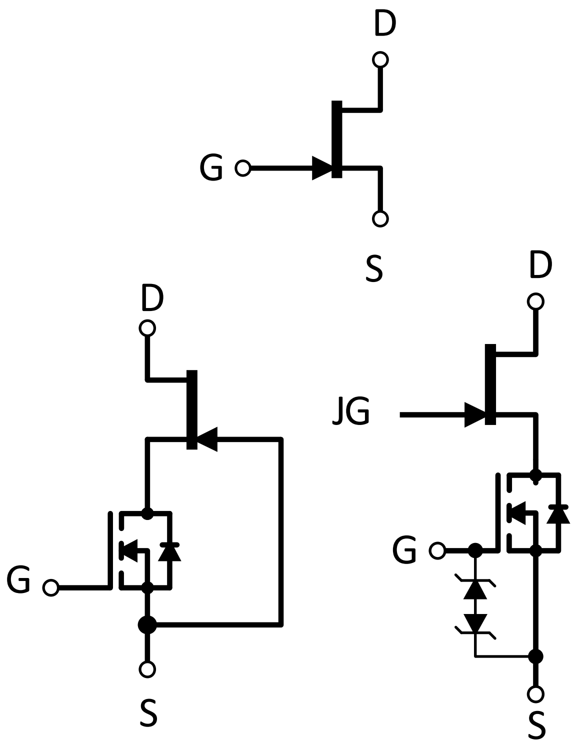

Figure 4: JFET (top), Cascode JFET (bottom left) and Combo-JFET (bottom right) schematic symbols

SiC JFETs Characteristics and Advantages

SiC JFET offers advantages over competing technologies. It has particularly low on-resistance for a given chip area, known as R_{DS}*A due to direct current path from source to drain. The losses can additionally be improved by gate overdriving. This is done by using positive gate-source voltage to further widen the channel and reduce the $R_{DS(ON)}$ by ~15 %. The forward biasing of JFET is illustrated in figure 5.

JFETs are reliable and easy to control. They contain no charge traps and exhibit no parameter drift or hysteresis. Furthermore, they are tolerant to gate under and overvoltage and can withstand high current spikes.

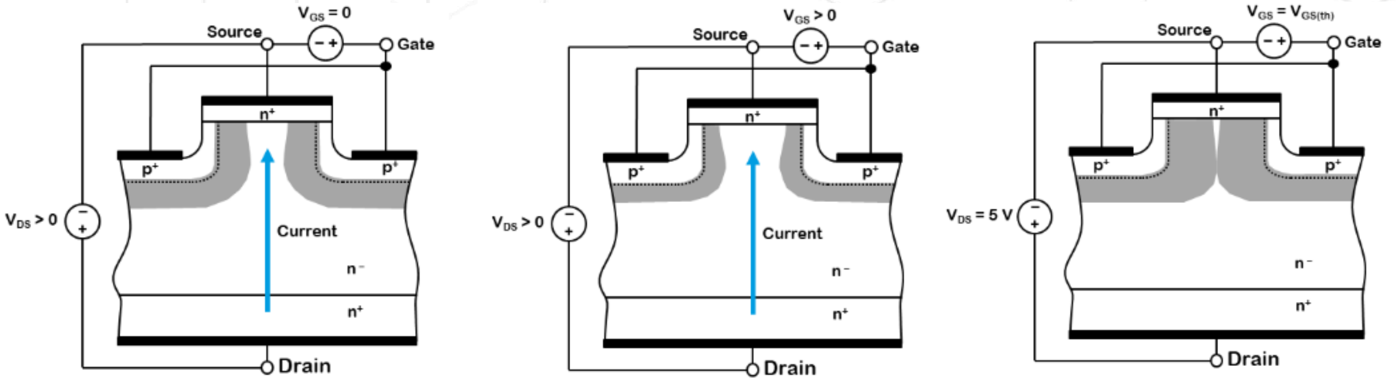

*Figure 5: Forward bias of **onsemi** SiC JFET: left - V_{GS} = 0; middle V_{GS} > 0; right – depletion region expansion caused by negative gate-source voltage – channel is "pinched off"*

SiC JFET Reverse Conduction

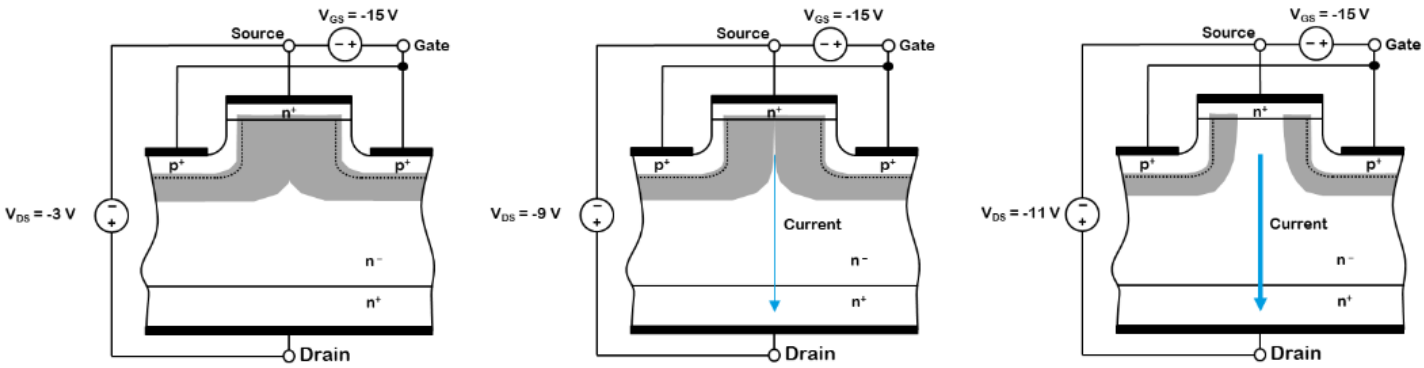

*Figure 6: Reverse bias of **onsemi** SiC JFET: left - turned off; middle - small current flows; right – V_{DS} is above threshold voltage, depletion region is reduced, and channel is opened*

Since **onsemi** Gen3 and Gen4 SiC JFETs do not have body diode, they exhibit unique reverse conduction characteristics. Figure 6 shows a reverse biased SiC JFET cell with V_{GS} = −15 V and various drain-source biases. Negative V_{GS} expands the depletion regions, whereas negative V_{DS} contracts the depletion region. When the V_{DS} is above threshold voltage, current can flow much more freely.

SiC JFET Parallelling

In solid-state circuit breaker application, the overall footprint of the device is given by needing to conform to the size of the traditional electro-mechanical circuit breakers. Therefore, huge importance if given to heat dissipation. What is more, to block AC voltage, two back-to-back switches are needed, which effectively doubles conduction loss. Solution to this is paralleling, which reduces total on resistance and thermal losses using two or more sets of back-to-back SiC JFETs.

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onsemi EliteSiC JFETs

*Table 2: **onsemi** SiC JFET portfolio*

650V	750V		1200V		1700V
TO-247 (3L)	TO-247 (4L)	TOLL	TO-247 (3L)	TO-247 (4L)	D2PAK (7L)
UJ3N065025K3S 25mΩ UJ3N065080K3S 80mΩ	UJ4N075005K4S 4mΩ	UJ4N075004L8S 4mΩ	UJ3N120035K3S 35mΩ UJ3N120065K3S 65mΩ UJ3N120070K3S 70mΩ	UF3N120007K4S 7mΩ	UF3N170400B7S 400mΩ

SiC JFETs UJ4N075004L8S

- 750 V, 120 A
- Ultra-low $R_{DS(on)}$: 4.3 mΩ @25 °C, 11.5 mΩ @175 °C
- Normally-on JFET
- Improved parallel device operation
- Operating temperature: 175 °C (max)
- High pulse current capability
- Excellent device robustness
- Leadless TOLL package

SiC JFETs UF3N120007K4S

- 1200 V, 120 A
- Ultra-low $R_{DS(on)}$: 7.1 mΩ @25 °C, 17.8 mΩ @175 °C
- Normally-on JFET
- Operating temperature: 175 °C (max)
- High pulse current capability
- Excellent device robustness
- Short circuit rated
- TO-247-4L package

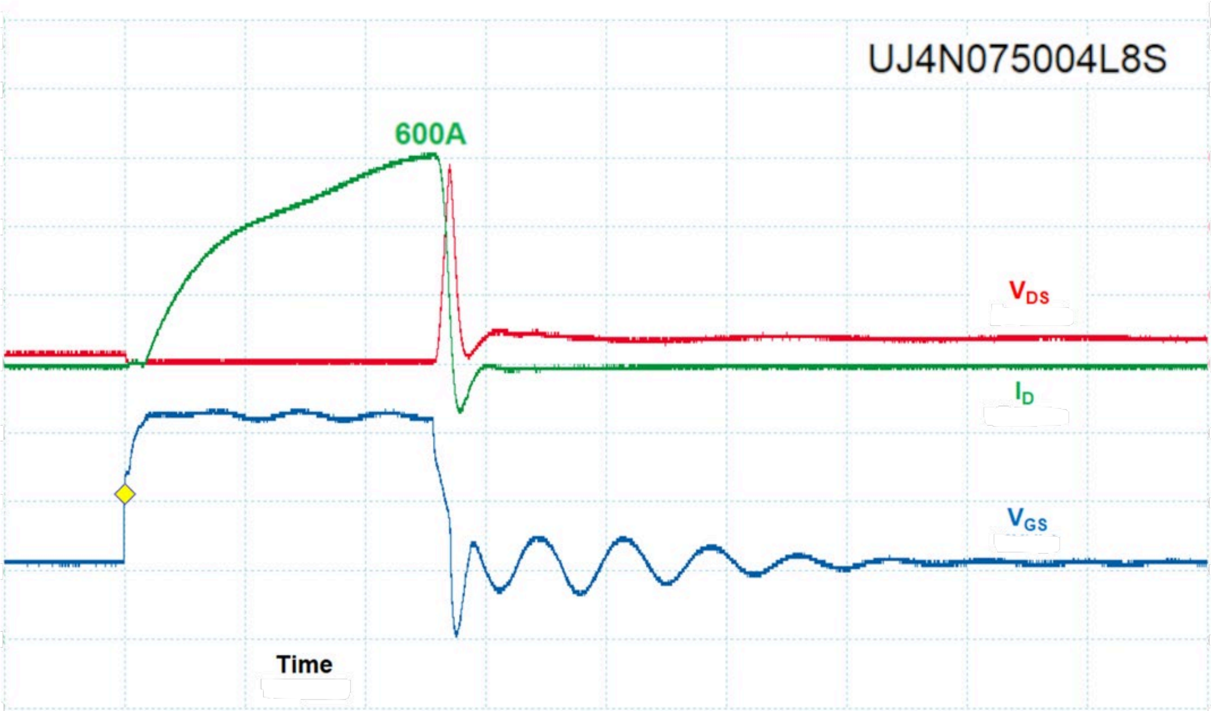

*Figure 7: Ruggedness of the **onsemi** SiC JFET switch – withstands huge current spikes*

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onsemi EliteSiC Combo JFETs

onsemi silicon carbide combo JFETs consists of both normally-on SiC JFET and LV Si MOSFET. The source of SiC JFET is connected to drain of Si MOSFET. This configuration makes the device normally-off, which is helpful for some applications.

Main Features:

- Access to both gates separately
- Enables fully independent turn-on & turn-off control of switching speed
- Simplifies paralleling
- Enables slow-switching speeds in ultra-high current applications (>200 A)

*Table 3: **onsemi** Combo SiC JFET portfolio*

750V		1200V
TO-247 (4L)	TOLL	TO-247 (4L)
UG4SC075006K4S 5mΩ UG4SC075009K4S 9mΩ UG4SC075011K4S 11mΩ	UG4SC075005L8S 5mΩ	UG3SC120009K4S 9mΩ

*Figure 8: **onsemi** EliteSiC JFET and Combo EliteSiC JFET packages*

SiC Combo JFETs UG4SC075005L8S

Integrates both a 750V SiC JFET and a low voltage Si MOSFET into a single TOLL package

- 750 V, 120 A
- Ultra-low $R_{DS(on)}$: 5 mΩ @25 °C, 12.2 mΩ @175 °C
- Normally-off capability
- Improved parallel device operation
- Operating temperature: 175 °C (max)
- High pulse current capability
- Excellent device robustness
- Short circuit rated
- Leadless TOLL (MO-229) package

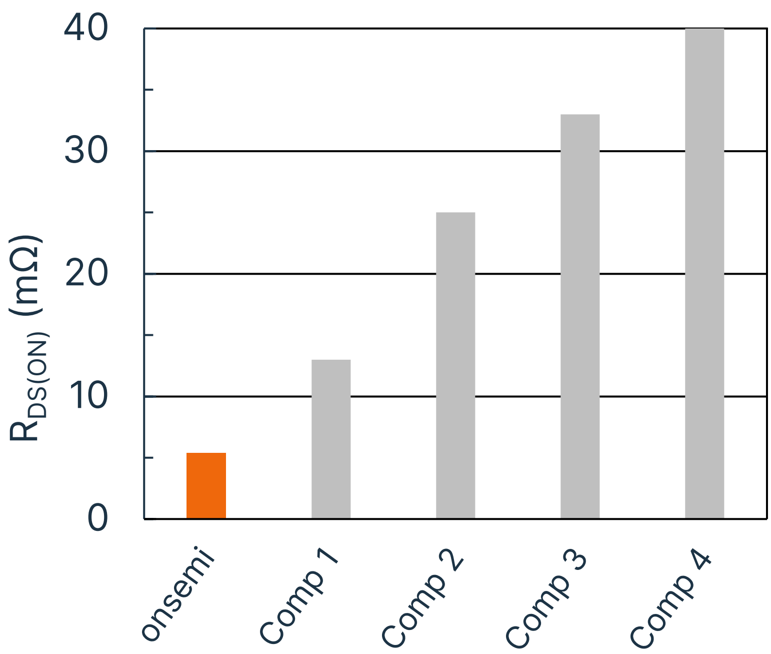

Figure 9: Comparison of $R_{DS(on)}$ (mΩ) of UG4SC075005L8S and its competition

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Combo JFET Evaluation Board

The evaluation board demonstrates the design of solid-state circuit breaker with onsemi Combo JFET device UG4SC075005L8S. SiC Combo JFETs are composite devices consisting of a low-voltage Si MOSFET and a high-voltage SiC normally on JFET. Both gates of SiC JFET and silicon MOSFET are accessible. Compared with standard cascode structure, the SiC Combo JFET has advantages of lower $R_{DS(ON)}$ by over-drive, full switching speed control and junction temperature sensing. At the same time, with simple external configuration, the Combo JFET has normally off feature same as the standard cascode.

The evaluation board contains seven functional blocks:

- Power channel: includes power cells, snubbers and gate drivers
- Current sensing: current sensing conditioning and over current protection
- JFET junction temperature sensing: measure the JFET gate to source voltage drop
- V_{DS} sensing: measure the drain to source voltage drop of power FET
- ADC: analog to digital conversion
- MCU: micro-computer unit and interfaces
- Auxiliary power supply: auxiliary power input and control power converter

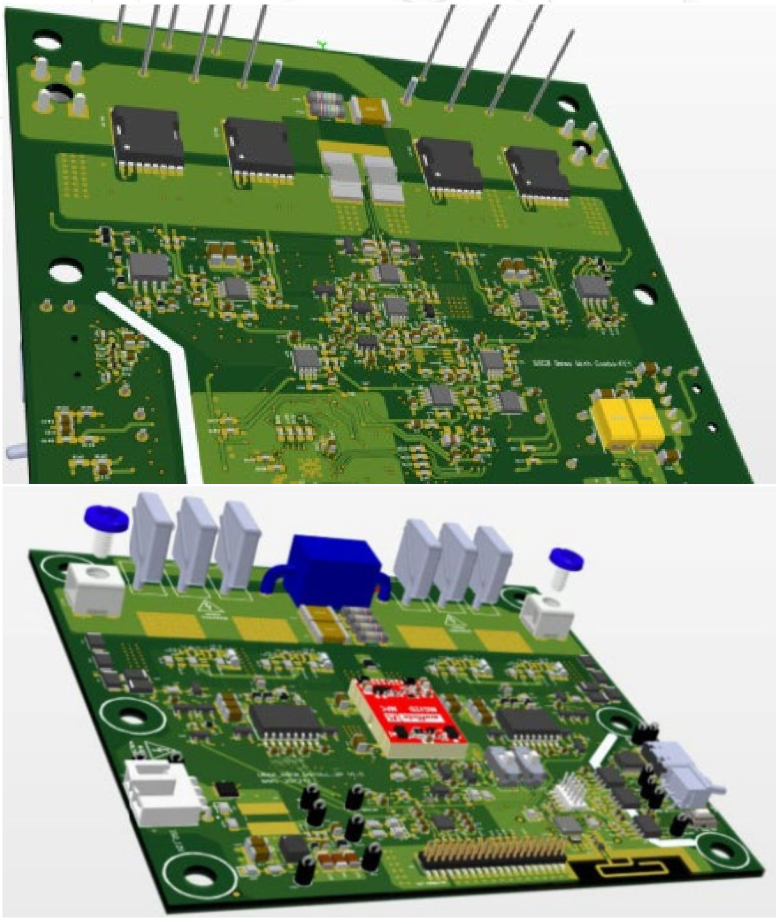

Figure 10: Combo JFET Evaluation Board top and bottom sides

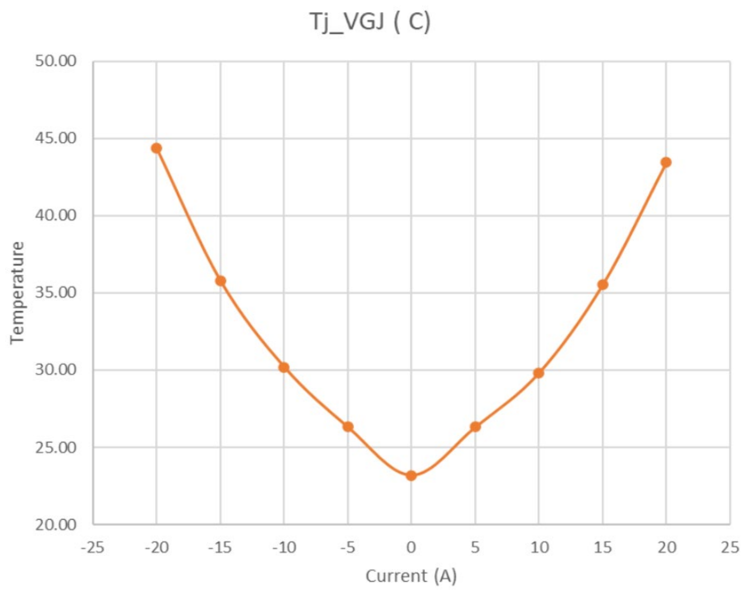

Figure 11: Junction temperature sensing test results under different DC current

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onsemi SiC JFET Calculator and Simulator

onsemi offers online tools that helps with choice of SiC JFET components and facilitate the design of semiconductor circuit breakers, relays and battery disconnects. This tool works with all released SiC JFETs and Combo JFETs from **onsemi** and can be found directly in the product page of the SiC JFETs and Combo JFETs. Input and output of the simulation can be downloaded for further analysis.

AC Leakage Calculator

Simulate Now

- Used for calculation of AC breakers and relays
- Simulates common source design with two devices
- Can specify input RMS voltage and order and voltage of up to three harmonics
- Can state snubber capacitance and resistance
- Graph shows AC Voltage and Total RMS Leakage Current
- Simulator estimates chip and case temperatures and power loss

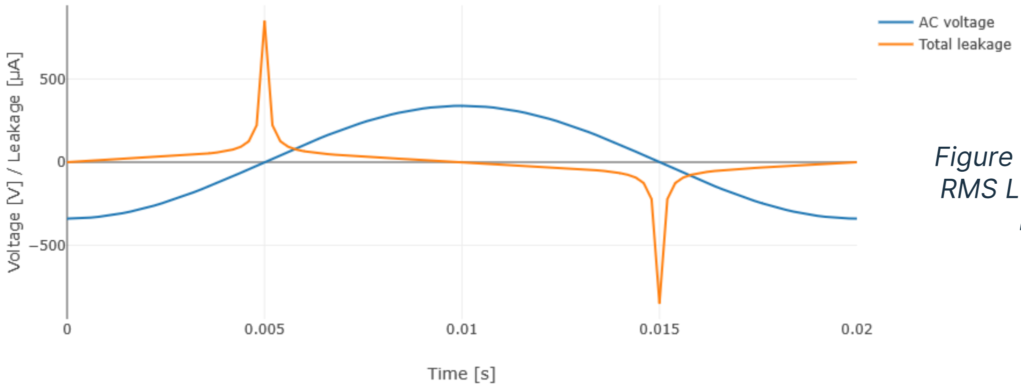
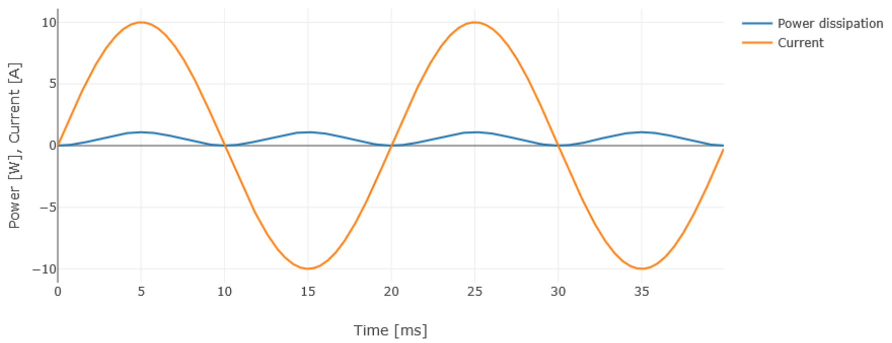


Figure 12: AC Voltage and Total RMS Leakage Current from AC leakage calculator

CB-JET Simulator

Simulate Now

- Used for estimation of temperatures and power loss of single device
- Can specify operating parameters and input current waveform
- Shows graphs with: Junction and Case Temperature, Current and Power Dissipation per Device and Total Output Current



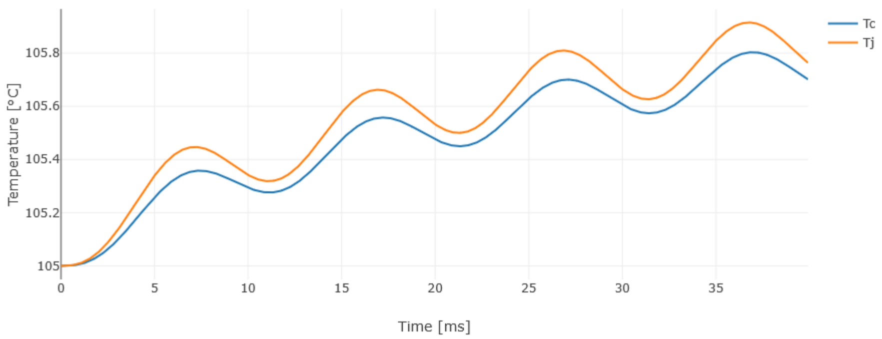


Figure 13: Current and Power Dissipation (top), Junction and Case Temperature (bottom) estimation

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onsemi EliteSiC MOSFETs

The EliteSiC MOSFETs have minimal switching and conduction losses, high efficiency operation and reduced EMI. The EliteSiC MOSFETs are available with a breakdown voltage ranging from 650 V to 1700 V. For single phase 650 V or 750 V provide sufficient headroom. All families of EliteSiC SiC MOSFETs exhibit no drift in $R_{DS(ON)}$, V_{TH}, or diode-forward voltage over a lifetime due to a special planar design. Silicon Carbide MOSFETs may be used as an alternative to Silicon Carbide JFET in solid-state breaker applications.

SiC MOSFETs NTH4L023N065M3S

650V EliteSiC M3S SiC MOSFET optimized for fast switching applications. Planar technology works reliably with negative gate voltage drive and turn off spikes on the gate.

Key features:

- 650 V, 67 A
- Ultra low gate charge ($Q_{G(tot)}$ = 69 nC)
- High-speed switching with low capacitance (C_{oss} = 153 pF)
- 15V to 18V gate drive
- Typ. $R_{DS(on)}$ = 23 mΩ at V_{GS} = 18 V
- 100% Avalanche tested
- TO-247-4L package with Kelvin source configuration

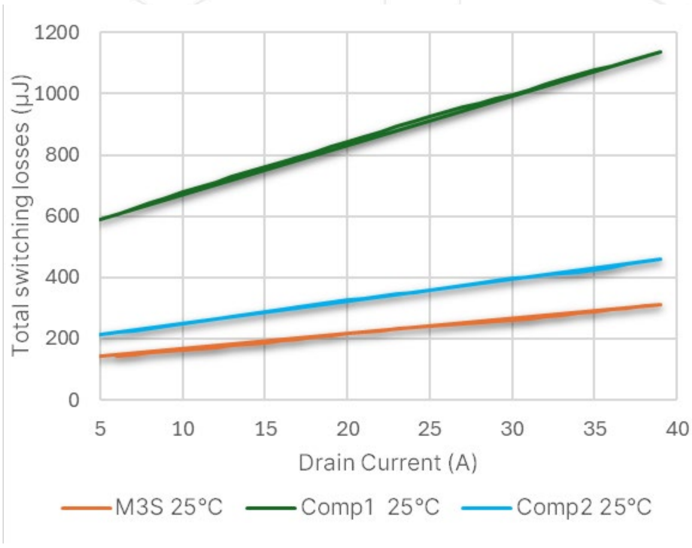
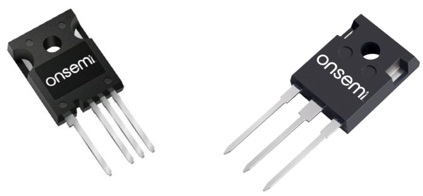


Figure 14: Switching performance of NTH4L023N065M3S at 25°C compared to competition

*Table 4: **onsemi** Elite SiC MOSFET portfolio depending on the mounting technology*

Voltage Rating	Through-Hole	Surface Mount
650-750 V	M2 Family M3S Family	M2 Family M3S Family
900 V	M2 Family	M2 Family
1200 V	M1 Family M3S Family	M1 Family M3S Family



TO-247-4 TO-247-3

D2PAK-7 H-PSOF8L

*Figure 15: **onsemi** EliteSiC MOSFET packages*

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Gate Driver

Control of silicon MOSFETs is simple. To turn them on them gate-source voltage needs to be sufficiently positive in order for the channel be fully open. This voltage typically needs to be around 10 V depending on the voltage rating. To turn off, the voltage has to be zero. The operation of silicon carbide MOSFETs is different. The switching profile is very similar to Si MOSFET, except to turn on the gate-source voltage needs to be higher, around 15-20 V. While negative bias is not required to correctly control silicon carbide MOSFETs, it is recommended as it reduces switching losses and chance for spontaneous turn on which could lead to damage.

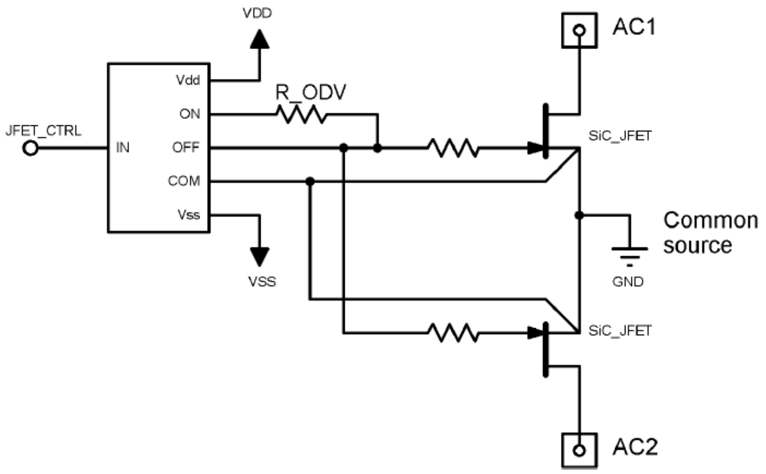

Figure 16: Direct drive circuit with bidirectional blocking and normally on state

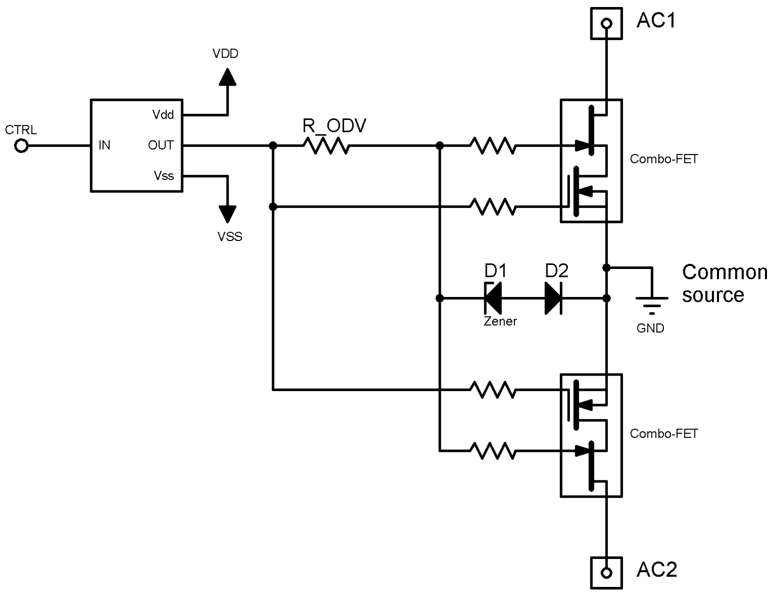

Figure 17: Quasi-cascode drive circuit with bidirectional blocking and normally off state

Table 4: Recommended gate drive voltage

	SiC MOSFET	SiC JFET
Turn-on	15 to 20 V	0 V
Turn-off	-2 to -5 V	-15 to -20 V

JFET Drive

JFET is a different from previous devices, it is normally on, so it does not require positive voltage to be turn on. On the other hand, it requires negative gate-source voltage typically in the range of -15 to -20 V to be turned off. For control of SiC JFETs a specific technique called gate “overdrive” is used. This is used to positively bias the gate, which reduces the on-resistance and therefore reduces losses.

Normally On JFET Drive Circuit

Normally on state is desirable for some semiconductor circuit protection and relay applications. Figure 14 shows normally on circuit, meaning the absence of gate drive keeps the JFETs on. A current of at least 1 mA is sufficient to forward-bias the JFET gate and reduce the RDS(on), whereas 5 to 10 mA is recommended for temperature sensing. Switch-on speed is relatively slow because of the large on-state gate resistance, but this is desirable for many SCB and relay applications.

Normally Off Combo JFET Drive Circuit

Normally off state is achieved by using combo JFETs or by using separate JFET and Si MOSFET. Figure 15 shows normally off configuration using combo JFETs.

Gate driver directly drives gate of each JFET and MOSFET. If the voltage between the JFET drain and the common source point exceeds the breakdown voltage of the MOSFET, then the MOSFET will avalanche during JFET switch-off. MOSFET must therefore be capable of high current, single pulse avalanche. Combo JFETs are 100% tested for this.

*Table 4: **onsemi** Gate Driver portfolio suitable for SSCB application*

Gate Driver Type		
Single Channel	Non-Isolated	Galvanic Isolation
Dual Channel	Non-Isolated	Galvanic Isolation

Gate Drivers NCD5703

Family of high-current gate drivers

- High current (+4/-6 A) at Miller Plateau
- Low output impedance
- DESAT protection with programmable delay
- Tight UVLO thresholds for bias flexibility
- NCD5703A – Active Miller Clamp
- NCD5703B – Negative output voltage
- NCD5703C – Separate outputs for V_{OL} and V_{OH}
- NCD5703D – Enable pin for independent driver control
- SOIC-8 package

Gate Drivers NCP51152

Isolated single-channel gate driver with 4.5-A/9-A source and sink peak current

- 3.7 kV_{RMS} input-output isolation
- Internal negative bias - saves system cost
- 3 to 20 V input supply voltage
- 200 V/ns dV/dt immunity
- Propagation delay typical 36 ns
- SOIC-8 package

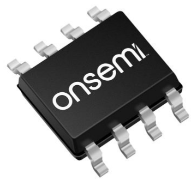

Figure 18: SOIC-8 package

Evaluation Board NCP51152GEVB

Evaluation boards for NCP51152 gate driver family

Three versions each allows for evaluation with specific MOSFET packages:

- Type–A : TO–3P, TO–247, D–PAK, and D2PAK
- Type–B : TO–247–4L
- Type–C : D2PAK–7L

Features:

- Variant A: separated outputs (OUTH, and OUTL)
- Variant B: wide bias voltage range including negative VEE and VCC UVLO referenced to GND2 for only
- 3 V to 20 V Input Supply Voltage
- Output supply voltage from 6.5 V to 30 V
- 4.5A and 9A source/sink current driving capability.

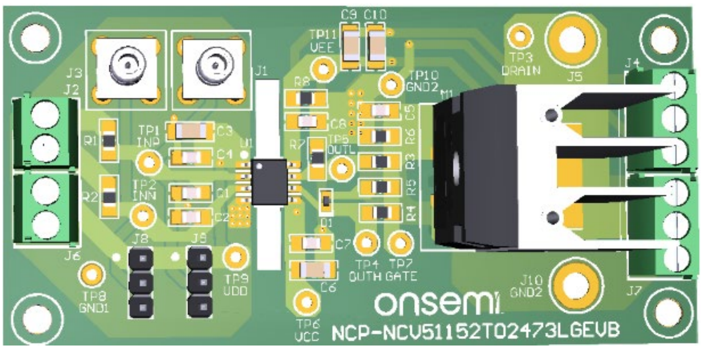

Figure 19: NCP51152 evaluation board with TO-247-3 power switch

Find Evaluation Board

Temperature Sensing

Temperature sensing is required to be able to detect overloads in the system and prevent potential fire and electrical hazards. Although it would be possible to measure the temperature using thermistor, using JFET switch simplifies the circuit, due to its inherent properties. It depends on the fact that the JFET gate-source forward voltage decreases linearly with increasing temperature. Therefore, it is possible to sense the temperature of the JFET chip by measuring VGS while overdriving the JFET gate. The advantages of this solution are as follows: high accuracy, since temperature is sensed directly across the chip itself; quick response; very little space is required and only minimum of parts is needed.

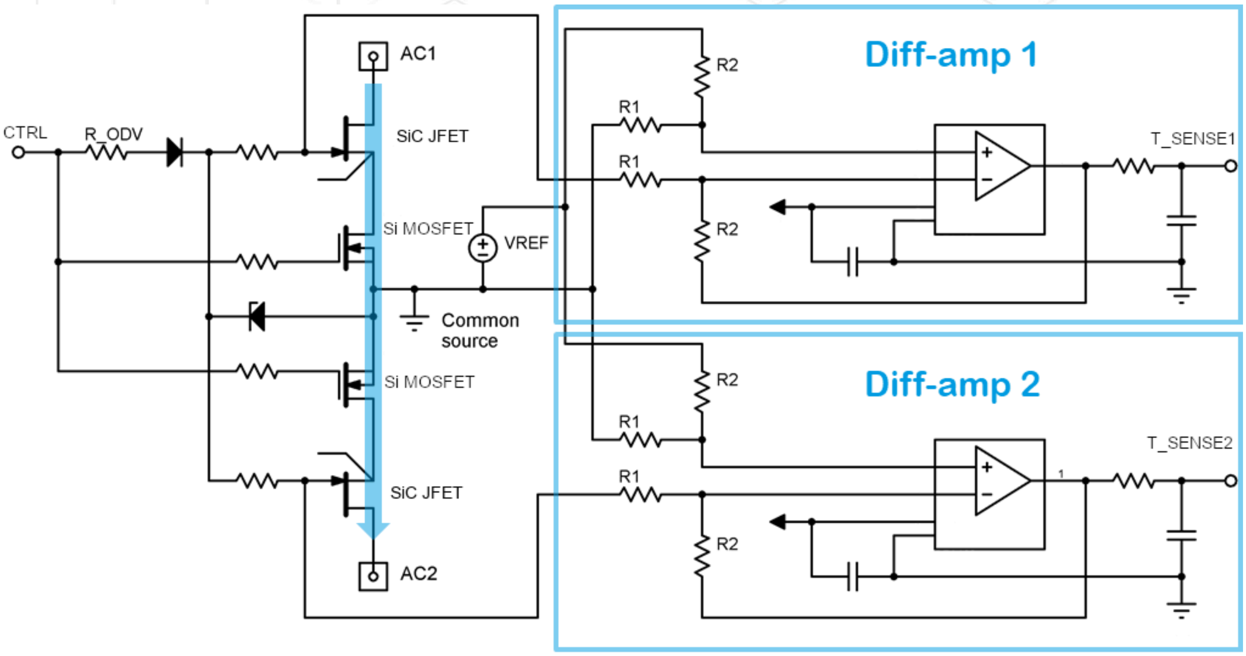

*Figure 20: Recommended two serially connected **onsemi** Combo-JFET temperature sense circuit*

On-chip JFET Temperature Sensing

It would be possible to only use single differential amplifier to sense the VGS of the JFET, but the voltage swing across the entire temperature range is too small. Figure 20 illustrates the temperature sensing circuit when using two Combo-JFETs in AC voltage application. It uses two differential amplifiers, each measuring a JFET to MOSFET source voltage. A single reference voltage attaches to the common source point, from which each VGS is subtracted by the differential amplifiers.

Assuming equal voltage drop across the MOSFETs, when we add Tsense1 and Tsense2, the MOSFET voltage drops cancel out. Then dividing by 2 results in the amplified average JFET V_{GS}. From VGS the temperature can be extracted since it directly depends on it (see figure 21). To further reduce the noise, it is a good practice to overdrive the gate, since higher gate current corresponds to a higher IG versus VGS slope. Therefore, V_{GS} varies less with any change (noise) in IG.

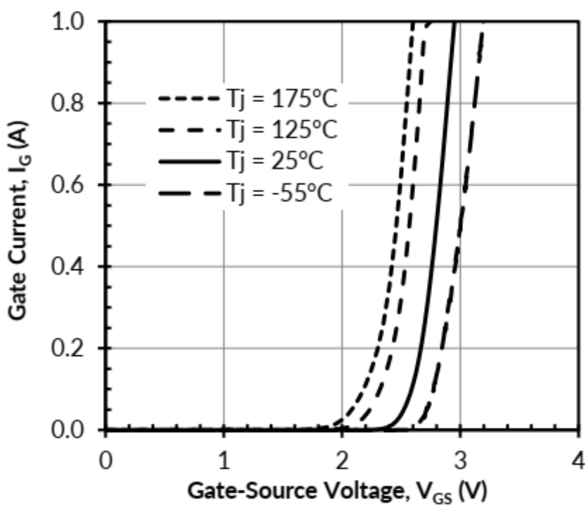

Figure 21: Example of gate current versus Gate-source voltage of JFET

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Current sensing

Main purpose of any circuit breaker is to sense overcurrent and to turn-off when it is detected. When using fully solid-state architecture, current can be easily sensed, and threshold can be set up precisely. Furthermore, it would make it possible for limits to be changed on the go on the complete product, so end customer can themselves change the current limit if needed.

JFET or Combo-JFET can be used as a current sensor if used in conjunction with a gate driver with DESAT function. Drain-source current can be sensed by measuring drain-source voltage of the JFET.

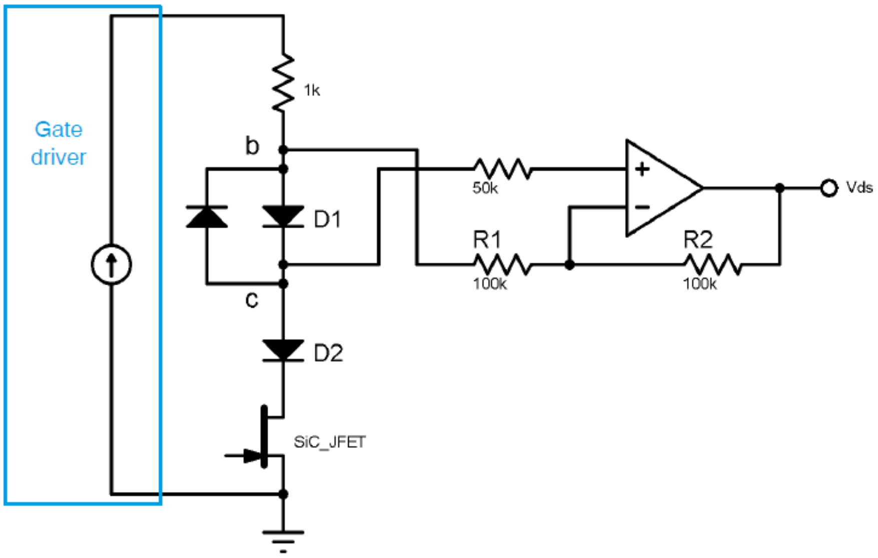

Figure 22: Recommended VDS sense circuit using gate driver with DESAT function

Figure 22 shows a constant current source that is inside a DESAT sensing gate driver, SiC JFET and all remaining components that are used for sensing. Diode D2 blocks high voltage when the JFET is off. D1 is used as part of the VDS measurement. It has an anti-parallel diode to prevent high voltage from developing across it.

To measure current any gate driver with DESAT function can be used. Gate driver provides small bias current via DESAT pin. V_{DS} is measured by non-inverting op-amp circuit. D1 enables simple measurement, since it compensates for the temperature effects of D2 because it is the same type of diode mounted thermally close to D2. Then from known chip temperature, $R_{DS(ON)}$ is estimated. Drain current can subsequently be calculated as a ratio of V_{DS} and $R_{DS(ON)}$.

Read More

Op Amps NCS20166

- Precision operational amplifier
- Rail−to−rail input and output
- Supply range: 3 to 5.5 V
- Low quiescent current: 1.55 mA max
- Voltage noise density: 10 nV/√Hz
- Temperature range: -40 to 125°C
- Gain bandwidth: 10 MHz typical
- SOT23-5 package

Current Sense Amplifiers NCS21671

- Voltage output current sense amplifier
- Wide common mode input range: −0.1 V to 40 V
- Supply range: 1.8 to 5.5 V
- Low Offset Voltage: ±25 µV max
- Rail−to−rail output
- Low current: 80 µA max
- Gain: 25, 50, 100, and 200 V/V
- Temperature range: -40 to 125°C
- SOT363 and Micro10 packages

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Ground Fault Circuit Interrupter

Solid-state circuit breakers can incorporate other protections, including ground fault circuit interrupter (GFCI) or residual current device (RCD). They both serve same function, and it is to protect people from electric shocks and to reduce the risk of electrical fires. This device interrupts the electric circuit when the current passing through line and neutral conductors in not equal, indicating current leaking to ground or unintended bypass of the protection. The device need to adhere to strict regulations - UL 943 or IEC 60479-1 standards. Figure 23 shows impact of passing current from hand to feet: AC-1: imperceptible, AC-2: perceptible but no muscle reaction, AC-3: muscle contraction with reversible effects, AC-4: possible irreversible effects

GFCI Controllers NCS37021

- Self-test ground fault circuit interrupter
- Meets UL943 self-test GFCI requirements
- 4.0 – 12 V Operation - 120–480 V AC mains with the appropriate series impedance
- Fault response time: max 20 ms at current difference higher than 30 mA
- Wide temperature range from 40°C to 95°C
- Low quiescent current
- QFN16 package

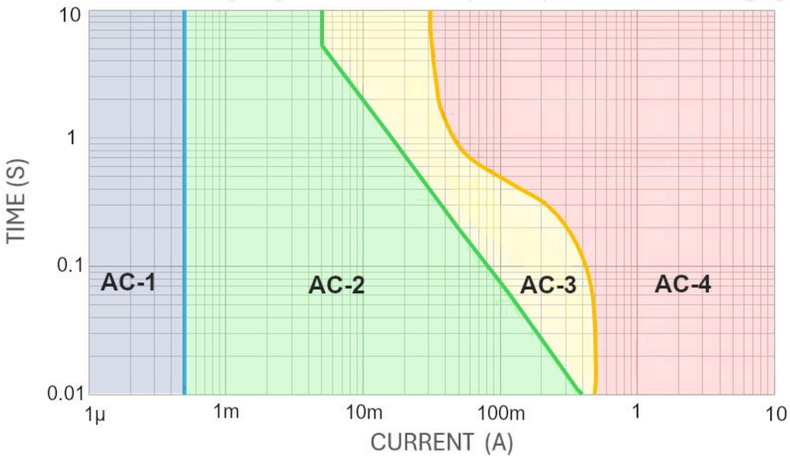

Figure 23: Log-log graph of the effect of alternating current on duration as defined in IEC 60479-1.

Wireless Communication

Solid-state circuit breaker can be accessed remotely either via wired or wireless protocols. It is possible to monitor its parameters, states and change the limits. This makes them much more versatile than electro-mechanical variants

Bluetooth(R) Low Energy RSL15

Wireless microcontroller unit (MCU) that employs Bluetooth® Low Energy 5.2 technology and a secure Arm® Cortex®-M33 processor.

- Provides maximum design flexibility for high performance and ultra-low-power applications with its built-in power management, flexible GPIO and clocking scheme, and wide supply voltage range.
- Optimizes energy efficiency with minimal battery drain allowing for smaller batteries and extended life of battery-powered sensors
- Industry leading ultra-low power microcontroller with easy-to-use SDK

Key Features:

- Higher temperature range (-40 to + 85°C)
- Ultra–low power operation: sleep mode wakeup 3 V Vbat: 36 nA
- Sleep mode deep sleep, IO Wake–up: 25-57 nA
- Rx sensitivity (Bluetooth® Low Energy Mode, 1 Mbps): –96 dBm
- Data rate: 62.5 to 2000 kbps, transmitting power: –17 to +6 dBm

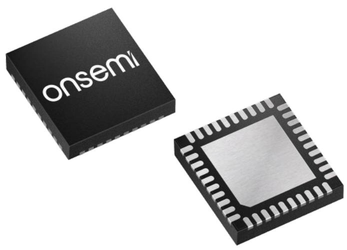

Figure 24: QFN-40 package

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Suggested Block	Part Number	Description
Solid-State Switch		
SiC JFET	UJ4N075004L8S	SiC JFET - EliteSiC, 4.3 mΩ, 750V, TOLL
	UJ4N075005K4S	SiC JFET - EliteSiC, 4.8 mΩ, 750V, TO-247-4L
	UF3N120007K4S	SiC JFET - EliteSiC, 7.1 mΩ, 1200V, TO-247-4L
SiC Combo JFET	UG4SC075005L8S	SiC Combo JFET - EliteSiC, 5.0 mΩ, 750V, TOLL
	UG4SC075006K4S	SiC Combo JFET - EliteSiC, 5.3 mΩ, 750V, TO-247-4L
	UG3SC120009K4S	SiC Combo JFET - EliteSiC, 8.8 mΩ, 1200V, TO-247-4L
	UG4SC075009K4S	SiC Combo JFET - EliteSiC, 8.4 mΩ, 750V, TO-247-4L
Si MOSFET	NTMFS0D55N03CG	MOSFET, Power, 30V N-Channel, SO8-FL, 435A
	NTMJS0D7N03CG	MOSFET 30V N Channel LFPAK, 410A
	NVMFWS0D9N04XM	Single N-Channel Power MOSFET 40 V, 273 A, 0.90 mΩ
	Recommended T10 and T6 Si MOSFET used complementarily with SiC JFET	
SiC MOSFET	NTHL015N065SC1	SiC MOSFET - EliteSiC, 12 mΩ, 650 V, M2, TO-247-3L
	NTH4L018N075SC1	SiC MOSFET, N-Channel - EliteSiC, 13.5mΩ, 750V, M2, TO247−4L
	NTH4L013N120M3S	SiC MOSFET – EliteSiC, 13 mΩ, 1200 V, M3S, TO-247-4L
	NTBG014N120M3P	SiC MOSFET – EliteSiC, 14 mohm, 1200 V, M3P, D2PAK-7L
	Recommended M3S Silicon Carbide MOSFETs	
Gate Driver		
Isolated Single Channel	NCP51152	3.75 kVRMS, 4.5-A/9-A Isolated Single Channel Gate Driver
	NCD57080	Isolated High Current Gate Driver
	NCD57100	Isolated Single-Channel High Current Gate Driver
	Recommended Isolated Single Channel Gate Driver	
Non-Isolated Single Channel	NCV5703	IGBT Gate Drivers, High-Current, Stand-Alone
	NCD5701	IGBT Gate Drivers, High-Current, Stand-Alone
	Recommended Non-Isolated Single Channel Gate Driver	
Isolated Dual Channel	NCP51561	5 kVrms Isolated Dual Channel 4.5/9 A Gate Driver
	NCD57200	Half Bridge Gate Driver (Isolated High Side & Non-Isolated Low Side)
	Recommended Isolated Dual Channel Gate Driver	
GFCI Controller		
GFCI Controllers	NCS37010	Ground Fault Circuit Interrupter (GFCI) with Self Test and Lockout
	NCS37020	Self-Test Appliance Leakage Circuit Interrupter (ALCI)
	NCS37014	Self Test GFCI controller compliant with UL943

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Sensing		
Temperature Sensors	NCT375	Digital Temperature Sensor with 2-wire Interface and SMBus Time-Out
	NCT72	±1°C Temperature Monitor with Series Resistance Cancellation
	N34TS108	Low-Voltage Digital Temperature Sensor
Comparators	FAN156	Comparator, Low Voltage
	LM211	Comparator, Single
	LMV331	Comparator, Single, Low Voltage
	Recommended Comparators	
Current Sense Amplifiers	NCS210R	Current Sense Amplifier, 26V, Low-/High-Side Voltage Out, Bidirectional Current Shunt Monitor
	NCS211R	
	NCS213R	
Op Amps	NCS20166	Precision Operational Amplifier, Low Offset, 10 MHz, Rail-to-Rail I/O
	NCS20282	7 MHz, Dual Operational Amplifier with Enable in CSP, Low Power
	NCS20164	8 MHz, Rail-to-Rail CMOS Operational Amplifier.
	Recommended Operational Amplifiers	
Interface		
Ethernet Controllers	NCN26000	10BASE-T1S Ethernet PHY with MII interface
	NCN26010	Ethernet Controller, 10 Mb/s, Single-Pair, MAC + PHY, 802.3cg, 10BASE−T1S Compliant
	T30HM1TS2500	10BASE-T1S Ethernet Controller, Treo Platform, MAC-PHY with SPI Interface
Wired Transceivers	NCV7390	CAN Transceiver, ISO 11992
	NCV7357	CAN FD Transceiver, High Speed
	NCV7344	CAN FD Transceiver, High Speed, Low Power
BLE	RSL15	Bluetooth® 5.2 Secure Wireless MCU
	RSL10	Radio SoC, Bluetooth® 5.2 Certified

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Power Management		
Offline Regulators	NCP11184	Enhanced standby mode 2.25Ω, 800 V Switcher
	NCP11185	Enhanced standby mode 1.3 Ω, 800 V Switcher
	NCP11187	Enhanced standby mode 0.87 Ω, 800 V Switcher
	Recommended Offline Regulators	
Offline Controllers	NCV1362	Automotive Primary Side PWM Controller for Low Power Offline SMPS
	NCP1239	Fixed Frequency Current Mode Controller for Flyback Converter with HV startup
	NCP12400	Fixed Frequency Current Mode Controller for Flyback Converters (Integrated HV Startup and X2 Discharge Circuit)
	Recommended Offline Controllers	
LDO	NCP151	LDO Regulator, 300 mA/300 mA, Dual Output, High PSRR
	LM317M	Linear Voltage Regulator, 500 mA, High PSRR, Adjustable, Positive
	LM2931	LDO Regulator, 100 mA, Ultra-High PSRR
	Recommended LDOs	
Logic & Memory		
EEPROM	CAT24C02	EEPROM Serial 2-Kb I^2C
	CAT24C64B	EEPROM Serial 64-Kb I2C
	CAT24C08	EEPROM Serial 8-Kb I^2C
Logic Gates	MC100EL01	ECL 4-Input OR / NOR Gate
	MC10EP05	3.3 V / 5.0 V 2-Input Differential AND/NAND Gate
	NB7L86A	SiGe Differential Smart Gate, 2.5 V / 3.3 V, with Output Level Select
HMI		
LED Driver	NCV7685	12 Channels 60 mA LED Linear Current Driver I2C Controllable
	CAT4004A	LED Driver, 4-Channel, with 32 Dimming Levels and Reset
	CAT4016	LED Driver, 16-Channel, Constant Current
Protection		
ESD Protection Diodes	ESDONCAN1LT	CAN / CAN-FD Bus Protector
	NUP2105	27 V ESD Protection Diode - Dual Line CAN Bus Protector
	NUP3105L	32V Dual Line CAN Bus Protector in SOT-23
Digital Isolators	NCID9200	High Speed Dual-Channel, Ceramic Digital Isolator
	NCID9301	High Speed 3-Channel Digital Isolator
	NCID9411	High Speed Quad-Channel Digital Isolator

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Application Note	ESD Ratings of SiC FETs and Cascode JFETs
Application Note	JFET Primer
Application Note	Cascode Primer
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Application Note	Switching Characteristics of onsemi Gen3 SiC Cascode JFETs at Elevated Temperatures
Application Note	Switching Fast SiC Cascode JFETs with a Snubber
Application Note	Paralleling SiC Cascode JFETs
User's Manual	JFET and Combo JFET User Guide
User's Manual	SiC Cascode JFET & Module User Guide
White Paper	Silicon Carbide (SiC) – From Challenging Material to Robust Reliability
Application Note	A Guideline on the Usage of an Isolated Gate Driver to Efficiently Drive SiC MOSFETs
White Paper	Paralleling SiC MOSFETs Process Impacts and Gate Resistors Setup
White Paper	SiC MOSFETs: Gate Drive Optimization
Application Note	onsemi EliteSiC Gen 2 1200 V SiC MOSFET M3S Series
White Paper	onsemi EliteSiC 650 V SiC MOSFET M3S Series with Superior Switching Performance
White Paper	When Planar is Superior to Trench: An In–Depth Look at the Continued Evolution of Silicon Carbide MOSFETs
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