Technical Article

Silicon Carbide-Based Circuit Breakers for High-Power DC Systems

from Microchip

Circuit breakers are one of the most common components used in a short-circuit and overcurrent protection circuit, especially for higher-power systems. Microchip's E-Fuse technology demonstrator using mSiC™ products provides a faster and more reliable high-voltage circuit protection solution over conventional solutions.

There are many considerations for implementing an E-Fuse solution and this article will show:

- Why it's important to build in the protection
- Advantages of silicon carbide (SiC)-based solid-state circuit breakers
- Explanations of how SiC provides an edge over traditional silicon (Si) devices and other circuit-breaker technologies
- Reference designs/circuits
- Tips on designing for transient or surge immunity

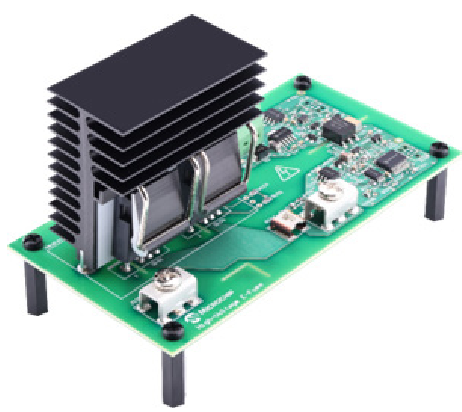

Figure 1: Microchip's silicon carbide E-Fuse demonstrator

High-power DC distribution system

Figure 2 shows a generalized DC distribution system with the energy sources shown on the left and the various loads shown on the right. This type of DC distribution system can be used for fault protection such as over-current, short-circuit and transients in electrification applications like EVs, trains, aviation, data centers, industrial equipment and energy grid and storage.

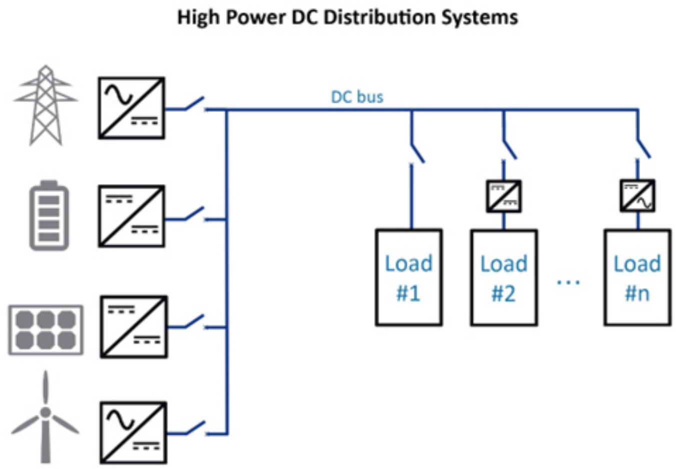

Figure 2: Generalized high-power DC distribution system

The energy source could consist of power coming from a grid such as utility power, battery packs, and solar or wind or hydro-generated power, while the loads themselves can vary with DC bus, power electronics or AC drives. In these power distribution networks, protection is typically required for the wiring and the load (fuses, circuit breakers, etc.) across a range of high-voltage applications. For electric-vehicle applications, a battery pack that powers the DC link/bus can have a high-voltage contactor as well as a manual service disconnect or fuse to protect the downstream loads. This can be represented as Load #1 in the figure above. Load #2 might consist of a DC/DC converter that regulates down to something like 12V. The last load might appear as an inverter or traction drive. In all conditions, it's critical to protect these loads.

Let's visit a protection device that is commonly used today: the circuit breaker. There are several kinds of technologies that help break a circuit during unsafe conditions, such as a thermal breaker/fuse that contains a heating element that indicates overcurrent, which radiates heat to a bi-metal strip that bends to open a connection between contacts and interrupts the current. The time for this interrupt isn't instantaneous; however, with higher currents comes faster heat and thus a faster trip response. The trip response time can be very non-ideal for some applications and can end up tripping after damage is already done to the load or distribution system.

A magnetic breaker uses an electro-magnet to generate a magnetic field with higher currents. When the magnetic field is high enough, it can pull open the contacts and interrupt the current. Though its response time is far better than the thermal breaker, it's not as sensitive and may trip at multiples of the ratings of the breaker. Additionally, it may end up "nuisance tripping" during in-rush or surge currents — when motors are turned on while the thermal breaker allows a time window for this.

A thermomagnetic breaker combines these two technologies to provide the best of both worlds. In this case, the device trips for low over-currents while also responding quickly to short-circuit currents. This device is still fairly limited in terms of response time (>1 ms).

Figure 3 compares the current versus time characteristics of these circuit-breaker technologies.

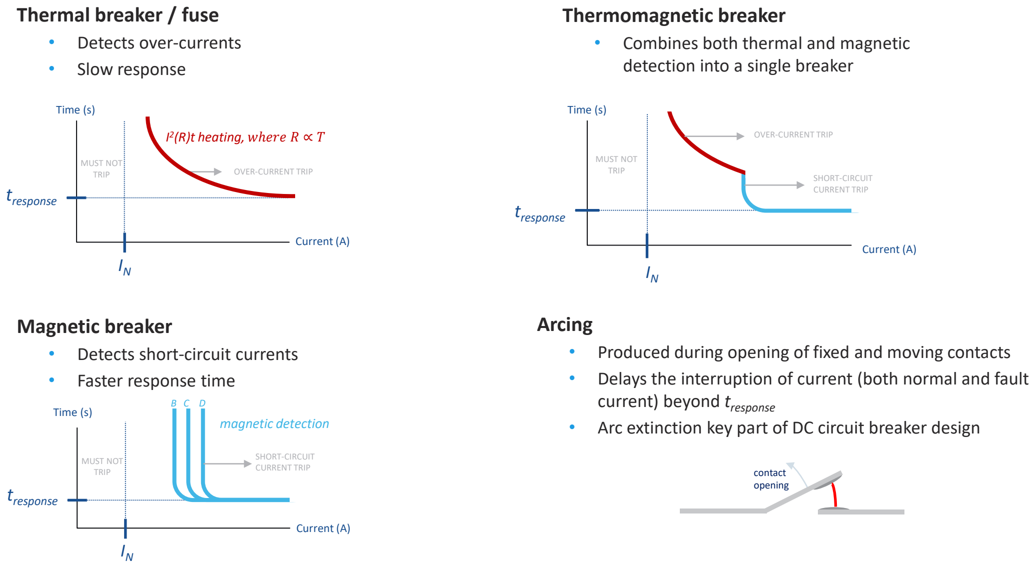

Figure 3: Circuit-breaker technologies

When opening these contacts, inductance in the system could lead to arcing. This can be present in each of the breaker technologies described above and can be a real problem for DC distribution networks as the contacts can degrade each time this happens. Special design considerations must be made for the contactors to quickly extinguish this arc and prolong the life of the device.

Characteristics of solid-state devices and benefits of SiC

If we analyze a fault condition such as a short-circuit for a thermomagnetic circuit breaker (*Figure 4*), the current rises until it hits a threshold (battery pack voltage divided by the parasitic resistance of your system), which can be as high as 30,000A. At this point, the breaker still hasn't reacted, and the current has traveled through the system wiring and into your load. The current rise profile follows a positive slope at first (defined by bus voltage divided by the system's parasitic inductance), with a time constant that is still relatively small when compared with the response time of the system. It'll reach the short-circuit current, and then when the system finally reacts, arcing will occur between the contacts — once they open — over the course of tens or even hundreds of milliseconds.

When you compare these same short-circuit conditions with a solid-state circuit breaker (*Figure 4*), you can see how the added inductance (which may be 5 µH or more) can really slow down the current ramping to give time to trip and protect downstream wiring and loads. This results in a few microseconds of response time during short-circuit conditions, and instead of behaving as a hard-fault or failure, it can become a recoverable fault. Though energy does get stored in the inductance (now appearing as avalanche energy), there is no arcing, which, in turn, results in safer, more reliable operation as well. Additionally, the time-current trip behavior for the solid-state circuit breaker is completely programmable. It can be optimized to match a system's thermal characteristics as well as the system's wiring and load requirements.

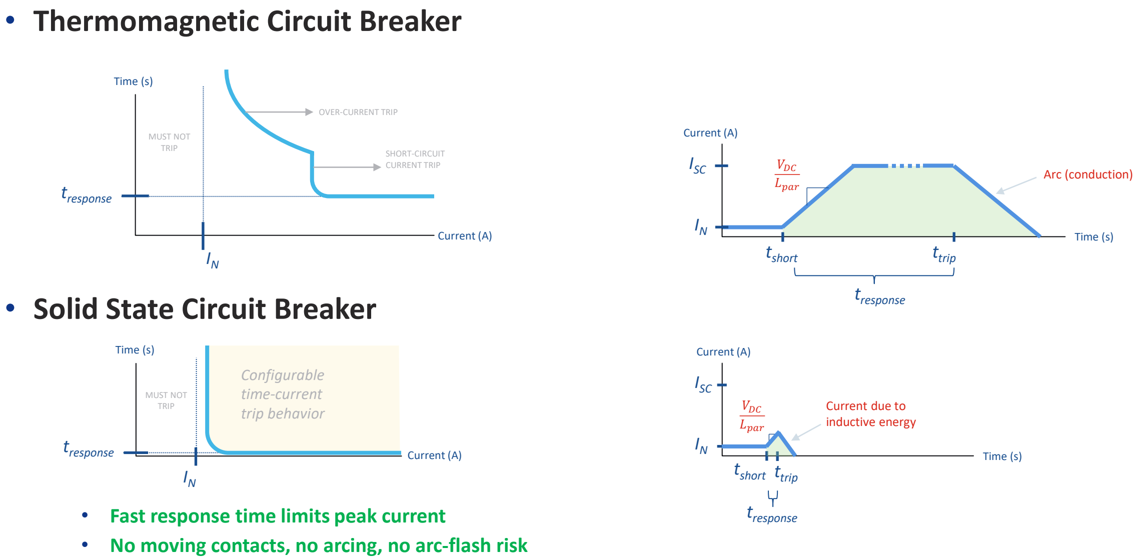

Figure 4: Thermomagnetic circuit breaker vs. solid-state circuit breaker during short-circuit conditions

To truly appreciate the difference in response time of an E-Fuse compared to a conventional automotive high-voltage fuse, each was subjected to a short-circuit under similar test conditions of 450V and approximately 3 µH of line inductance. The resulting waveforms are shown in *Figure 5*. The black waveform is of current flowing through the high-voltage fuse under test. Within 30 µs, the current reaches 3800A, which is the limit of the measurement equipment, and blows the high-voltage fuse 50 µs later. Based on the test parameters, the peak current is estimated to have exceeded 6000A. However, with an E-Fuse, as shown in the blue waveform, the current reaches only 128A before tripping. This is a significant reduction in let-through current, minimizing the stress on the wiring and downstream loads.

It gives system designers the option of optimizing the wiring for weight and cost. In some cases, the E-Fuse's low let-through current will be the difference between a tow-condition, where a fault causing a high current stress results in permanent damage to hardware, and a recoverable fault that allows the system to automatically reset and the driver to continue operating the vehicle.

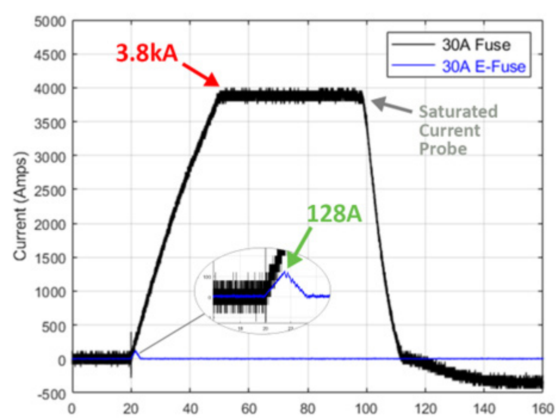

Figure 5: Current waveforms for E-Fuse vs high-voltage fuse

Below is a summarized list of reliability, performance, and safety benefits seen with solid-state breakers:

- No degradation from vibration, mechanical shock and drop
- Minimized voltage overshoot and ringing
- Low operating current and elimination for economizer
- Fast response time

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- Capable of pulse-width–modulation operation
- No issues with DC systems
- Diagnostics, programmability, current and voltage measurements
- Contactor and circuit breaker in one device
- No exposed arc
- Safe for hazardous environments
- Resettable E-Fuse without need to for system downtime

Figure 6 demonstrates the various configurations that utilize solid-state breakers.

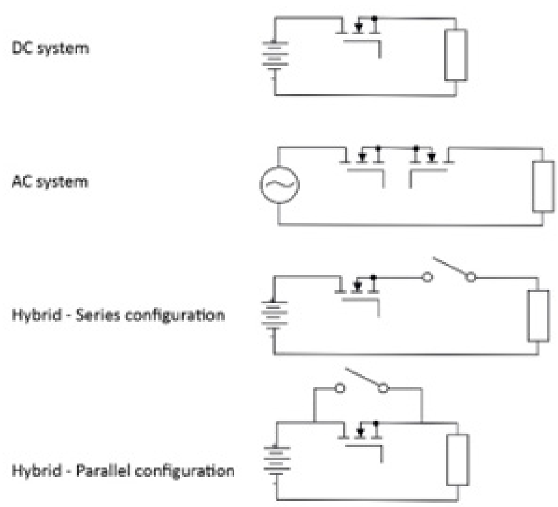

Figure 6: Various configurations of a solid-state breaker

The designer can benefit greatly by incorporating SiC technology into their solid-state breaker designs due to their superior performance over traditional Si devices. Many companies utilize SiC components for high-power electronics applications such as EVs, data centers, grid management, industrial equipment and power supply applications due to their many advantages, including lower conduction and switching losses, tolerance for higher operating temperature, faster switching and overall higher reliability and efficiency. When compared with Si components, the designer can benefit from 10× higher breakdown field (MV/cm), which results in lower on-resistance and lower conduction loss; twice as much electron saturation velocity (cm/s), translating to faster switching with no tail currents; a bandgap energy (eV) that's typically 3× as much as Si, giving a higher junction temperature (175˚C versus 150˚C); lower off-state leakage current; and 3× higher thermal conductivity (W/m·K), thereby providing higher power density and quicker release of heat during conduction.

Given these benefits, SiC has proven to be a great solution for solid-state circuit breakers.

Solid-state circuit-breaker design considerations

With SiC solid-state circuit breakers, Microchip offers greater ruggedness and reliability when compared with other competitors. This includes high single-event and repetitive avalanche capabilities (upon tripping) and no need for a snubber circuit (depending on the system's characteristics). Datasheets typically publish the single-shot avalanche capabilities and can be compared with other similar devices. When the MOSFET is in avalanche mode, the device has the highest electric field across the gate oxide, which is the weakest point of operation. Microchip has measured the device's life after subjecting it to a repetitive avalanche test, which hits the MOSFET with 100,000 cycles, and then compared it with similar devices. *Figure 7* shows a time-dependent dielectric breakdown test for "pristine devices" shown in gray and then for tests subjected to this repetitive avalanche test shown on the right side of it for direct comparison of the device's impact on life. Competitor A has seen a negative impact to the device's life expectancy (likely due to its trench-field construction), while Competitors B and C have little or no impact, though all three competitors have a lower gate oxide life expectancy when compared with Microchip's SiC MOSFETs.

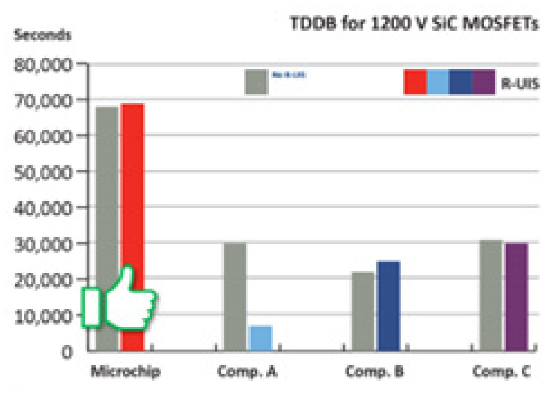

Figure 7: Repetitive avalanche test results comparison with Microchip and competitors

In addition to avalanche performance, Microchip offers devices with a very low $R_{DS(on)}$ temperature coefficient. *Figure 8* shows a plot where the blue trendline (Microchip) demonstrates a lower $R_{DS(on)}$ temperature coefficient when compared with other competitors. It still rises with temperature but not as much, providing lower conduction losses over similar devices. Silicon devices will rise 2× or 3× as much with increased temperature, while Microchip's 1200V SiC MOSFET rises to only 40% to 45%.

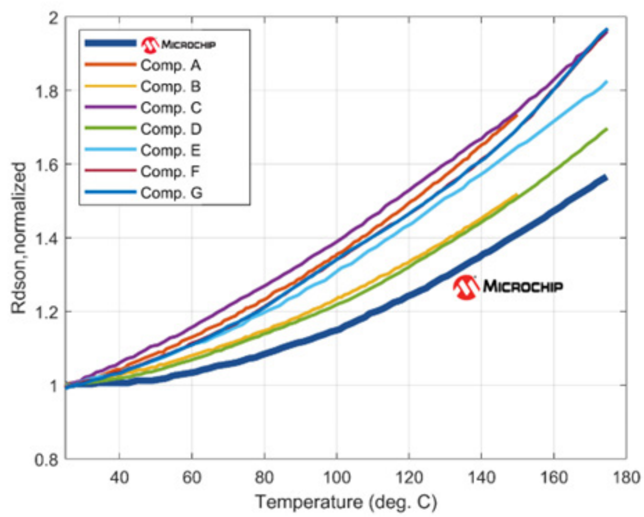

Figure 8: $R_{DS(on)}$ comparison between Microchip (blue) and other similar devices

As discussed, short-circuit withstanding time can be critical to a system's safety and protection. *Figure 9* shows a comparison between Microchip's gate voltage versus withstand time (in microseconds) and other similar devices. The blue datapoint (Microchip) at 20V and 10 μs is comparable to insulated-gate bipolar transistor devices. If you lower the gate voltage, you can extend the withstand time accordingly. This is something to consider when designing a solid-state circuit breaker and will be discussed further in the following sections.

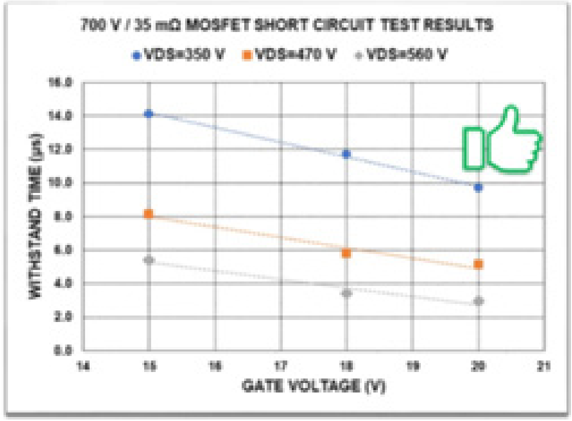

Figure 9: Microchip's SiC MOSFET gate voltage vs. withstand-time characteristics

Many designers are concerned with the ruggedness of SiC, mostly regarding the body diode. Third-party testing shows that for Microchip's SiC MOSFET there is no degradation on the body diode after 20 hours of stress testing. This supports Microchip's value proposition to 'Adopt SiC with Speed, Ease and Confidence.' Microchip prioritizes quality in terms of ruggedness to provide a reliable, trustworthy product. Multiple sources and dual fabrication solutions help the designer with a solution that is easily sourced. Additionally, Microchip follows a "no end of life" practice. Die, discrete and modules are all offered to meet a variety of needs, along with gate drivers for both large and small customers.

E-Fuse Technology Demonstrator (Reference Design)

Microchip has released an E-Fuse technology demonstrator (see *Figure 10*) rated for both 400V and 800V automotive systems at up to 30A. The design is configured for 10 µs short-circuit withstand time with a programmable current-limit profile curve set up over a Local Interconnect Network (LIN) communication bus. This helps with configuring system parameters and diagnosing issues during development and test. Also, the design is meant to be snubber-less, depending on system characteristics, demonstrating the strong avalanche capabilities of their SiC MOSFET.

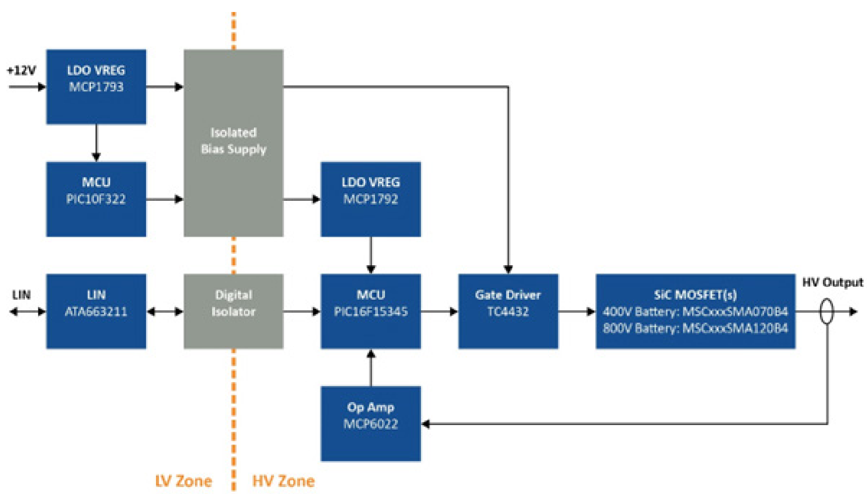

Figure 10: Microchip E-Fuse reference design with SiC MOSFET short-circuit protection

Circuit design: overcurrent protection and the TCC curve

Here are a few considerations regarding the Time-Current Characteristic (TCC) curve of a solid-state circuit breaker when configuring the time-current trip behavior. *Figure 11* shows a horizontal blue line that represents the short-circuit current time. This time must be carefully designed and is dependent on the system's response requirements and gate drive voltage. The blue vertical line near the top is the design margin that should be built into the system to account for different tolerances and thermal management. The blue dashed lines in between them indicate the requirements of the wiring, loads and even the thermal design of the breaker itself. It's all very flexible and can be controlled via software/firmware.

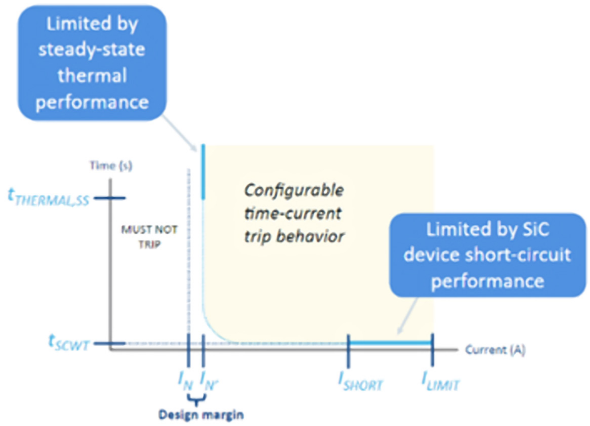

Figure 11: TCC curve of solid-state circuit breaker and parameters to consider

As previously mentioned, for short-circuit conditions, the designer can configure for a higher gate drive voltage (for example, 20V) for lower $R_{DS(on)}$ and low conduction losses. Then when a short-circuit is present, the system can lower its gate drive voltage (to something like 18 V or 15 V), thereby increasing short-circuit withstand time. And if the condition is transient, with only 10 or 14 µs, the need to shut things off can be avoided and the design can simply "ride through" the event. This allows time to service fault conditions without damage to the system while also building immunity to system transients and surges.

Figure 12 shows an example of short-circuit and overcurrent detection circuitry that can be handled almost entirely within an MCU. Microchip's 8-bit, 16-bit and 32-bit MCU devices have core independent peripherals (CIPs) that offer features that can be leveraged for these circuits, such as digital-to-analog converters (DACs), op-amps, comparators, fixed-voltage references, configurable logic cells and latches, to provide a highly integrated design.

For current detection, a shunt is shown on the left and is monitored via two paths. The top path is meant for fast response and uses a differential amplifier, comparator with a DAC, and latch. This allows the system to quickly (within a few hundred nanoseconds) reduce gate voltage when overcurrent occurs. If the condition persists, the time will expire and the MOSFET is shut off. If the problem goes away, the latch can be reset, and the system can continue to drive at full gate voltage. The bottom path handles lower over-currents and is processed via an analog-to-digital converter (ADC) and then configures the TCC curve accordingly. In the figure, blue denotes functions that can be utilized internally to the MCU.

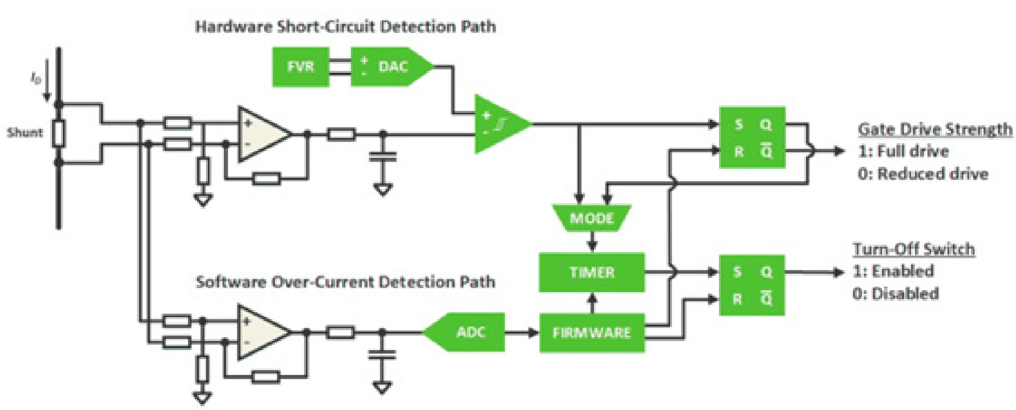

Figure 12: Short-circuit and overcurrent detection handled with MCU

As depicted above, the gate drive circuit can be designed for variable drive strength and controlled via the MCU, along with a separate turn-off signal to the MOSFET. Again, this allows the system to extend the short-circuit withstand time and ride through an event such as a transient.

Microchip's 8-bit, mid-range PIC® MCUs provide good short-circuit protection using CIPs and low-resolution ADCs, while the 16-bit high-performance dsPIC DSCs can provide higher-resolution ADCs with faster sampling that allow for a higher order and more sophisticated TCC curve.

To conclude, Microchip's SiC devices enable DC circuit protection with highly flexible fast overcurrent and short-circuit detection and protection. Microchip offers a broad portfolio of rugged and reliable SiC components in the form of die, discretes and power modules, as well as gate driver solutions, which allow the designer to adopt SiC with ease, speed, and confidence to produce a more reliable product.

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