Protect your high-side switch with a controller that leaves nothing to chance

*Here, **Michael Jackson, Principal Technical Writer and Sean Long, Executive Director, Applications for the Industrial & Healthcare Business Unit at designer & manufacturer of analogue & mixed-signal integrated circuits (ICs), Maxim Integrated** review some of the challenging operating conditions and common failure mechanisms for high-side switch circuits used in actuators operating in industrial factory environments. They present a controller IC that integrates a diverse range of safety features to monitor circuit operation and take appropriate action to prevent damage should these conditions occur, increasing reliability and robustness.*

"By failing to prepare, you are preparing to fail" is an adage well worth bearing in mind when designing equipment for the modern automated factory, where failure is not an option. With dozens of actuators simultaneously opening and closing relays and solenoid valves (Figure 1), these harsh, noisy and demanding environments can stretch the performance of even the most robust components to their limit – and even then, carefully designed protection circuitry is required to ensure that they are not pushed beyond safe operating boundaries. Nonetheless, even the best laid plans can go awry, and an unanticipated overload or undetected short circuit can quickly destroy a switching component, leading to costly production downtime.

Figure 1. Actuated control valve

In this article, we review the operation of the high-side switch circuit and consider some common operating and fault conditions, which if not detected and responded to in a timely manner, have the potential to permanently damage, or even destroy, a switch and/or its controller. We then present a new controller IC that integrates a myriad of safety and protection features, making it ideally placed to provide the highest levels of protection to high-side switch circuits, if these (or other) fault conditions were to occur.

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What is a high-side switch?

A transistor that switches on/off a ground-connected load is commonly referred to as a "high-side switch", since it is used to

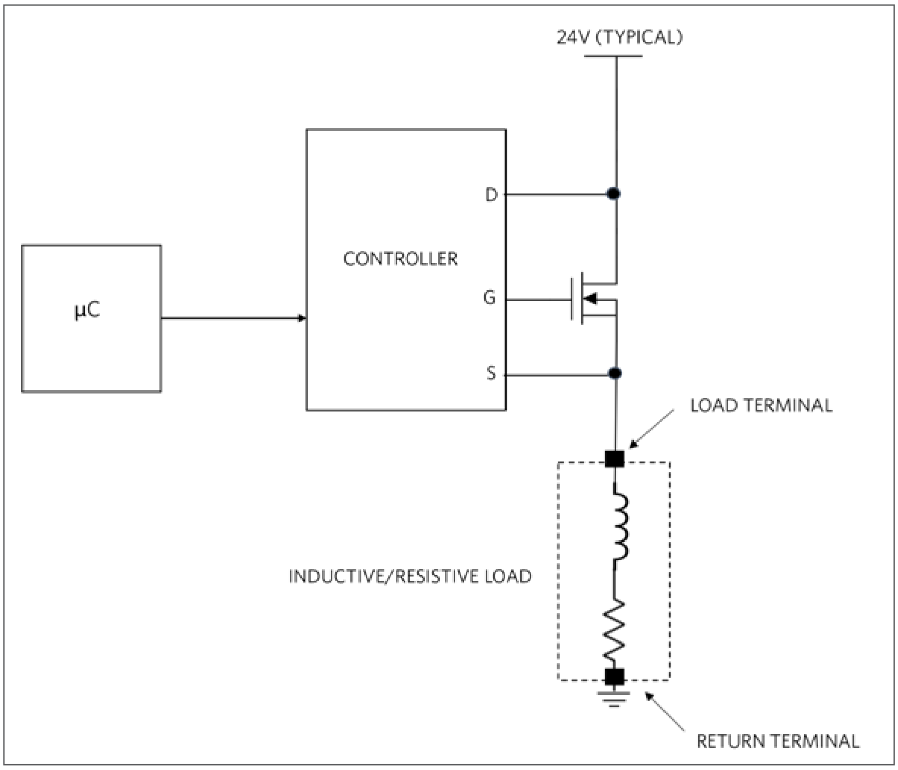

Figure 2. Simplified high-side switch arrangement

conduct current from a 'high' voltage rail (typically 24V in an industrial application) to the load, which is connected to a lower voltage (typically 0V). An n-channel FET operating in the saturation region is required for this type of arrangement (see Figure 2). A low voltage on/off signal is sent from a microcontroller to the switch controller IC, which then provides the higher gate voltage required to turn on and off the switch as required. These simple circuits, sometimes also referred to as "digital outputs", are often used in industrial actuators to open/close valves, energize solenoids and for motor braking.

In some versions of this circuit, for example, the MAX14915, the switch is integrated into the controller IC, while in other implementations, it is an external discrete component. While integration is the obvious appeal of the former, the advantage of the latter approach is that it provides the freedom to choose a switch with a drive current appropriate to a specific load.

We next consider some common operating and fault conditions that can occur in the factory environment, their potential implications for a high-side switch circuit and some approaches to protecting the circuit from lasting damage should these conditions occur.

Inductive voltage surge

When a valve is closed (or opened, depending on the polarity of the system), the switch is turned off and current flowing into the inductive load (such as a solenoid) is abruptly stopped, starting the process of demagnetization. The nature of an inductor is to oppose this effect, and in so doing creates a large kickback voltage, in an attempt to keep current flowing. This kickback voltage, which appears at the S terminal of the controller, must be limited/clamped at a voltage in the middle of the range of the "Absolute Maximum Ratings" of the controller IC. This prevents damage from being caused by the large negative voltage that develops between the S and G terminals of the device. A common way to do this is to use a transient voltage suppression (TVS) diode that clamps the voltage level on the source terminal at a predetermined safe voltage level. When choosing a TVS diode, its rated peak current should be greater than the peak current flowing through it during normal application. During voltage clamping, the peak power dissipated in the TVS should be within its rated specification (for the highest operating temperature). To prevent damage, it is also critical that the source terminal of the driver IC can withstand the maximum clamping voltage of the TVS.

Stuck valve

Sometimes in an industrial process, a valve may become temporarily stuck in a position that prevents it from opening or closing fully. This can cause an 'overcurrent' condition to occur, where the switch driver IC gradually increases current to the load to try and free up the valve. If the valve is suddenly freed, the problem is resolved and the current flowing in the switch will quickly return to normal. However, if the valve remains stuck in one position, then current may continue to increase beyond the rated value for the switch. If this condition persists for more than a short period of time, excess heat can permanently damage or even destroy the switch. Therefore, it is important to limit the size and duration of overcurrent that can occur.

Short-circuit

A short circuit of the LOAD and RETURN terminals is the most extreme type of overcurrent condition. In this case, the current is limited only by the on-resistance $R_{DS(ON)}$ of the switch, and, if not quickly detected and/or guarded against, will cause the switch to burnout, resulting in irreparable damage. Protecting against a short circuit is done in the same way as for an overcurrent condition.

Overheating

In the event of an unexpected rise in temperature (for instance, a cooling fan failure), the ambient operating conditions of industrial equipment can exceed maximum ratings. In an actuator, this can push the transistor switch outside of its rated operating temperature range. At best, this may cause degraded performance; at worst, it can cause total burnout. It is important to continuously monitor equipment ambient operating temperature, so that it can be shut down quickly if necessary.

Incorrect wiring

Humans are not infallible, and even the best-trained technicians can make mistakes, especially when under pressure to commission a new production line and quickly get it up and running. When

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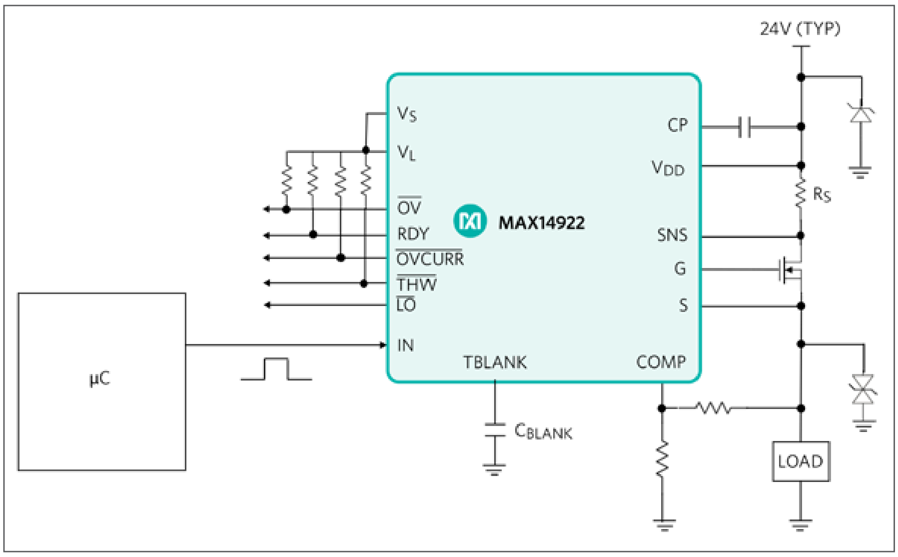

Figure 3. A high-side switch controller with current limiting

confronted with a 'rat's nest' of wires, one of the easiest and therefore most common mistakes a technician can make is to connect a positive terminal to negative or vice-versa. High-side driver circuits must be robust enough to safely handle this condition.

Power supply overvoltage

While 24V DC is the nominal voltage level used by most industrial equipment, it is not uncommon for this voltage to vary considerably (due to cross-contamination from surges in adjacent high-current switching equipment). While a degree of variation in supply voltage is to be expected, and is usually planned for, a fault in the power supply used to generate the 24V rail could cause it to rise substantially beyond the safe operating threshold of the switch and/or controller. Guarding against this event requires having some means to detect that the supply voltage has risen beyond a pre-set threshold, beyond which the switching circuit can be shut down if this occurs.

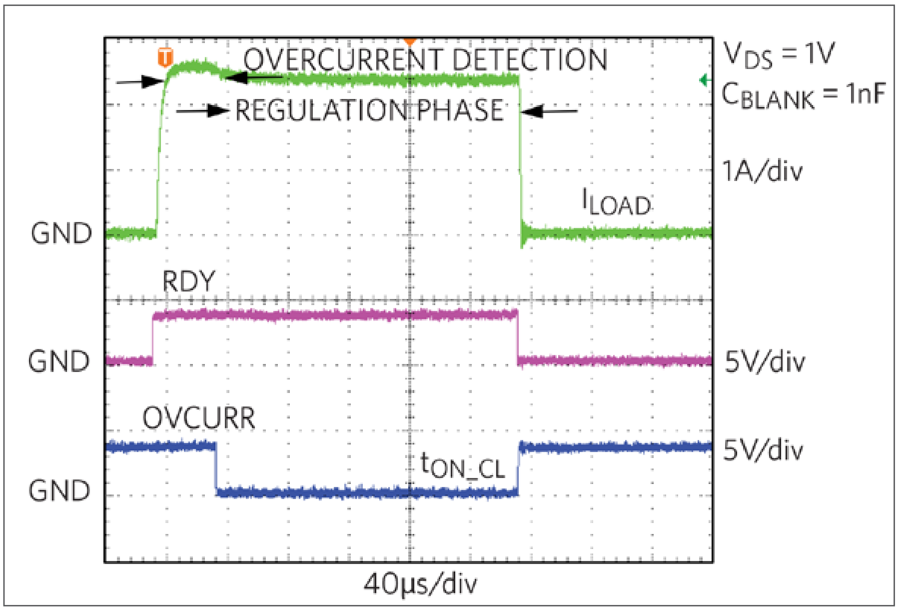

Figure 4. Regulation takes place during the "blanking time" interval

High-side switch controller ICs provide an array of safety features to protect the complete circuit, making it reliable and robust, even when confronted with the most challenging operating and fault conditions.

Taking control

The high-side switch circuit shown in Figure 3 features a high-side switch controller IC (MAX14922) that provides an array of safety features to protect the complete circuit, making it reliable and robust, even when confronted with the most challenging operating and fault conditions, such as those considered previously.

This controller provides fast inductive load turn-off at the S (source) input, which can be achieved by using a ground-connected high-voltage TVS diode to provide voltage clamping against voltage (and ESD) surges from -70V (max) up to V_{DD} + 6V.

It also enables current limiting, when a sense resistor (R_S) is connected between the V_{DD} and the SNS input terminals. The maximum overcurrent is then $I_{OC} = V_{OC}/R_S$. If an overcurrent condition occurs, the controller takes a number of precautionary actions. Firstly, an open-drain diagnostic output (OVCURR), which is high during normal circuit operation, transitions low. This can be used as a flag to the microcontroller to take appropriate action, if desired. The switching controller then begins to adjust V_{GS} of the switch to actively regulate the current for a fixed "blanking time" (set by the capacitor value on the t_{BLANK} input). If the overcurrent condition persists for a period longer than the "blanking time", the controller then turns the switch off for protection purposes. After an off-delay equal to about 50 "blanking time" intervals, the switch is automatically turned on again. Auto-retry on/off-cycling continues until the cause for overcurrent is removed by a technician. The OVCURR output remains low until the overcurrent condition is removed.

For example, in Figure 4, a 1nF capacitor has set the "blanking time" interval to 200µs.

After an off-delay equal to about 50 "blanking time" intervals (or 10ms), the switch is automatically turned on again (Figure 5), and this "auto-retry" cycle repeats indefinitely until the fault has been resolved.

In the event of a short circuit, the controller turns the switch off for approximately 5µs, and then turns it back on at a controlled rate, so that the short-circuit load current is then determined by the sense resistor value (Figure 6). Similarly, to the overcurrent condition, the regulation phase and auto-retry intervals are determined the by the value of the C_{BLANK} capacitor.

Another benefit of this IC is that it includes integrated temperature monitoring and a protective shutdown feature. An integrated temperature sensor signals a thermal warning at 110ºC (typical). When this occurs, the THW logic output goes low, indicating an overtemperature event, although the device continues to function normally. If the temperature cools down by 10ºC, the THW logic output returns high. However, if the temperature continues to rise above 150ºC, the controller enters shutdown mode, regardless of the state of the IN input (from the microcontroller). In shutdown mode, the G output is turned off, forcing the switch to turn off completely. When the temperature reduces by 10ºC, the device returns to normal operation, with the THW output going low once the temperature has fallen below 110ºC.

Supply overvoltage detection is another useful safety feature of this controller. If the V_{DD} rises beyond the overvoltage threshold (approximately +39V), the OV output goes active-low. This does not affect the switch controller, which continues to operate normally (and will continue to do for V_{DD} up to 70V). But the OV output acts as a flag to the microcontroller to indicate that the supply voltage is higher than the system is designed for. For some applications, this signal could be used to gate the signal from the system microcontroller, to prevent IN going high if an overvoltage condition occurs. For even further robustness, the IC provides integrated protection against supply voltage miswiring.

Apart from the safety features of this IC, it also includes an internal charge pump to provide higher drive current to the gate of the switch. This ensures that it is fully saturated with minimum on-resistance $R_{DS(on)}$. This reduces I^2R power dissipation (and associated heating), which is undesirable if the circuit is housed in a small enclosure, and allows switching rates up to 50kHz. Conveniently, this switching controller IC also includes an on-board 5V LDO regulator, capable of delivering up to 50mA of current to external circuitry, where required.

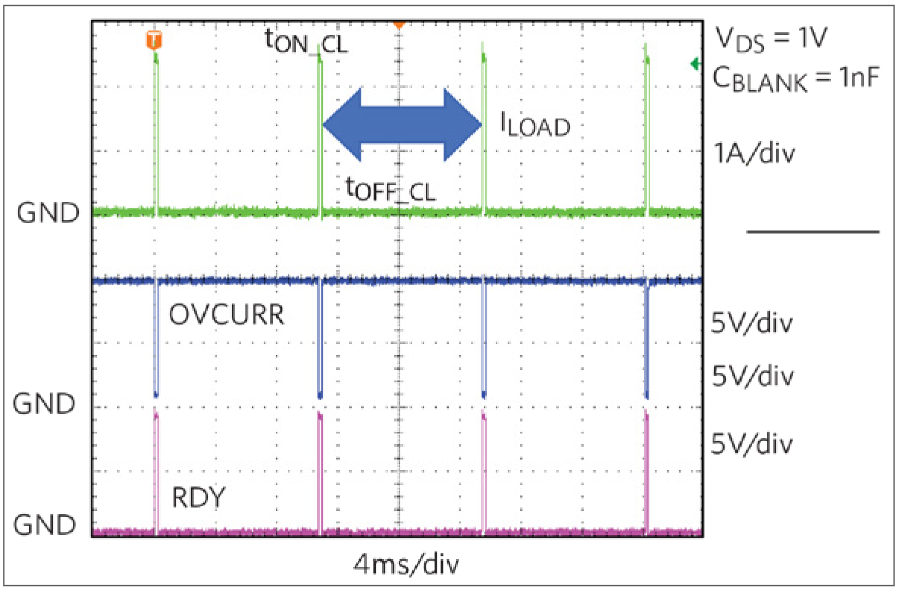

Figure 5. Blanking time and auto-retry during overcurrent condition

Summary

At first glance, the industrial high-side switch appears to be a relatively trivial circuit. However, when confronted with the task of operating in a harsh factory environment, there are many ways in which it can fail, with the potential to cause costly production downtime. In this article, we have considered some of the challenging operating and failure conditions that a high-side switch can encounter. We then presented a new high-side switch controller IC that includes a multitude of diagnostic and safety features to confer these circuits with an unsurpassed degree of robustness while in operation on the factory floor. Available in a 3mm x 3mm 16-TQFN package, it is ideal for use with a wide selection of n-channel FET devices, in relay/solenoid valves and motor braking applications that require between 1A and 10A of current.

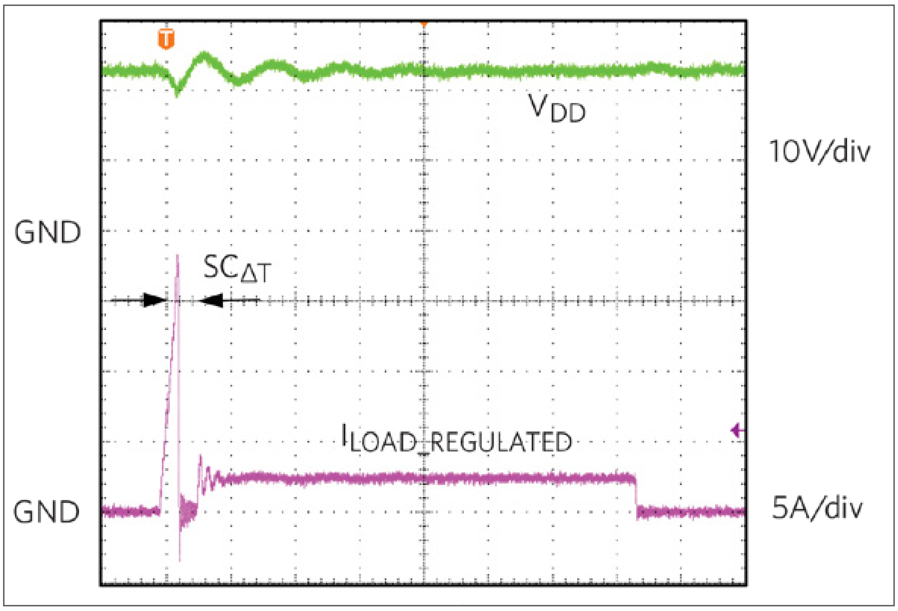

Figure 6. Short-circuit detection and intervention

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