POWER-GATE Relay (Generation 4.0) Application Sheet

CONDUCTOR SIZING IMPORTANCE

The MOSFET array used in the generation 4.0 POWER-GATE relays has been designed to provide industry-leading, ultra-low on-state resistance. This results in extremely low voltage drops at continuous currents up to 600 A and surge currents up to 3000 A, even at an ambient temperature of over 100 °C (212 °F). In order to maintain a low-voltage drop (and, consequently, low internal power dissipation), it is essential that the cables or bus bars connected to the device are properly sized for the currents expected in the application. Undersized conductors can cause heat to be transferred into the relay, which will cause the MOSFET array resistance to increase, negating the low resistance the relay was designed to provide. Additionally, when operating at high continuous currents and ambient temperatures, the extra heat from the undersized conductors can raise the internal junction temperatures of the MOSFETs beyond their safe operating area, generating the potential for failure.

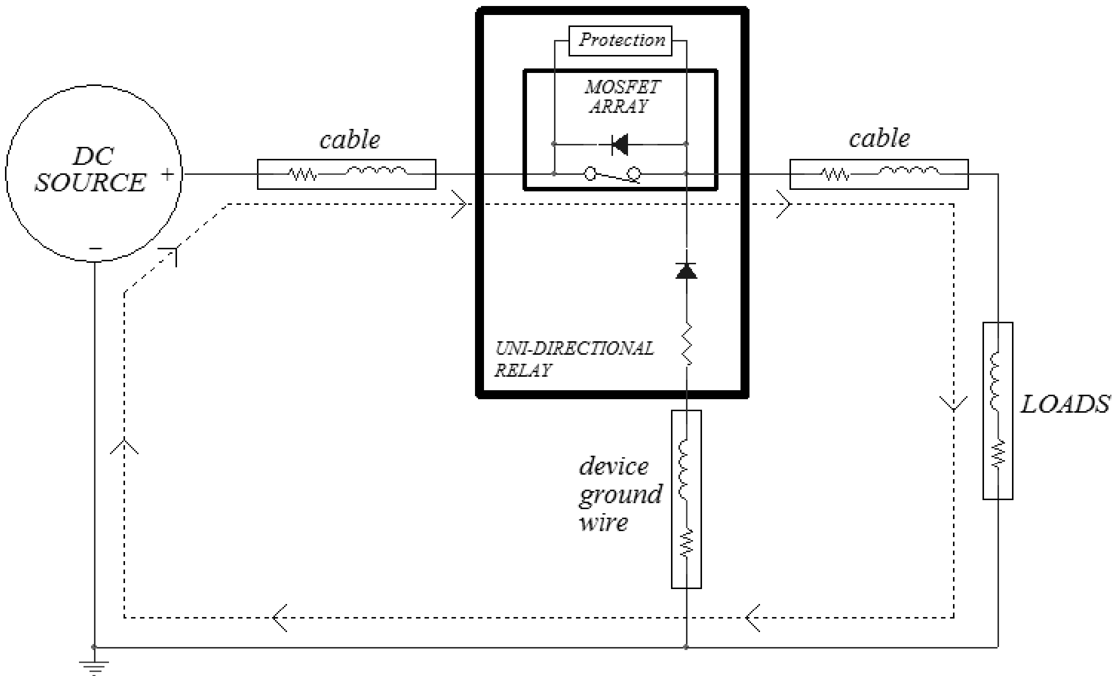
Typical applications use cable gauges anywhere from 4 to 4/0 AWG (with insulation ratings of at least +105 °C) depending on the continuous current rating, but other system parameters such as increased cable thermal resistance due to bundling and very high duty cycles at high currents may dictate the use of paralleled cables or large bus bars coupled with forced airflow. Ultimately, it is up to the user to determine the appropriate external conductor to be used in any particular application.

If the device flashes an over-temperature warning (which occurs when the internal device temperature exceeds +135 °C), then, assuming the device is operating within its current limitations outlined in the specification sheet, either the external conductors are undersized for the current flowing through the device, the ambient temperature surrounding the device is in excess of the maximum rating, or a combination of both. The system should then be shut down and the thermal conditions reevaluated so as to ensure the device's continued reliability.

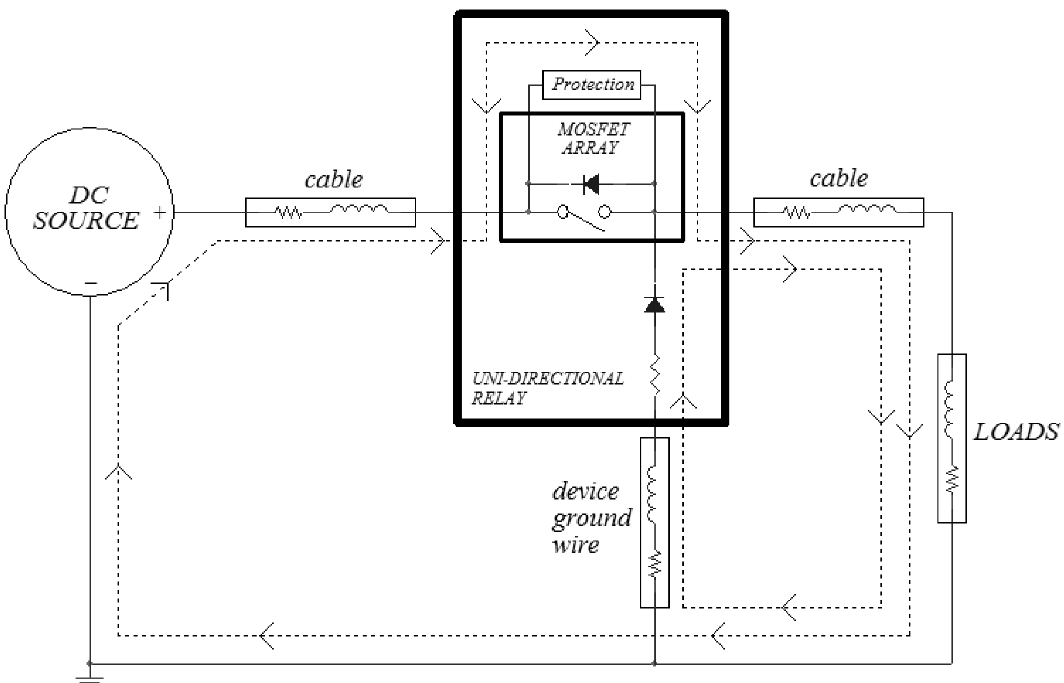
HIGH CURRENT TURN-OFF AND SYSTEM LOOP INDUCTANCES

Device reliability is also greatly affected by the system loop inductances during turn-off conditions. When operating at the high currents the MOSFET array was designed for, the total inductance of the external world it is connected to must be carefully evaluated to ensure that under worst-case conditions, the device will be able to safely dissipate the large amount of energy stored in the inductance's magnetic field.

Figures 1 and 2 show a common use of the relay, which is to connect/disconnect a DC source to/from any number of arbitrary loads (including ones with high inductance, such as a winch motor, for example), essentially as a replacement for a traditional solenoid. Figures 1a and 2a depict the current flow (as indicated by the dotted line) originating from the source, passing through the MOSFET array (represented as a simple switch in parallel with a body diode) to the loads (which are assumed to have significant inductance), and finally returning to the source. The inductance of the interconnecting cables is shown, but that of the common ground node has been omitted for simplicity (although they must be considered as well when calculating the

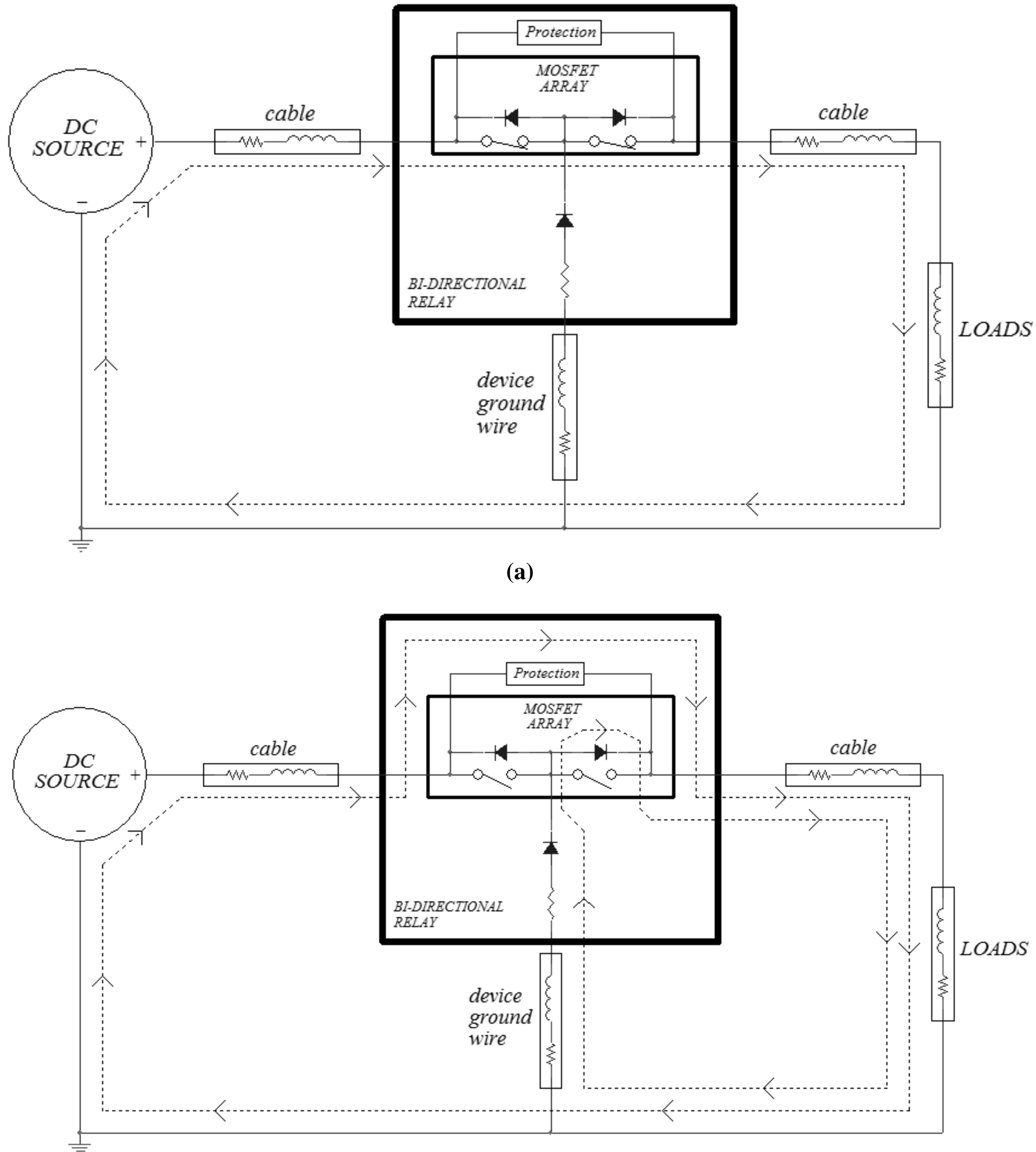


(a)



(b)

Figure 1: High current turn-off transient behavior with system loop inductances (uni-directional relay). (a) Relay shown in closed state (MOSFET array represented by simple switch in parallel with body diode) powering a highly inductive load. (b) Current paths during magnetic field decay, after MOSFET array has completely opened.



(a)

(b)

Figure 2: High current turn-off transient behavior with system loop inductances (bi-directional relay). (a) Relay shown in closed state (MOSFET array represented by two simple switches in series, with each switch having a parallel body diode) powering a highly inductive load. (b) Current paths during magnetic field decay, after MOSFET array has completely opened.

system loop inductance).

In Figures 1b and 2b, the MOSFET array has completely turned off in response to either a user request from one of the triggers, or from an internal detection of a current, voltage, or temperature-related fault. In many cases, the magnetic field energy in the system inductance (usually dominated by the load, but also including interconnect contributions), will not be able to decay within the MOSFET array's short turn-off time. Consequently, current is forced through the MOSFET protection circuitry, flyback diode, or both, until the field energy has completely dissipated. The length of time this process takes is dependent upon the magnitude of the current when the MOSFET array completes turn-off, and the total inductance through which it is flowing.

The specification sheet details the maximum allowable current upon turn-off (i.e. interrupting current) at various system loop inductances and temperatures, conditions which should always be adhered to in order to ensure maximum device reliability. If an application has system loop inductances that exceed those detailed in the specification sheet, additional external protection may be required.

OVER-CURRENT AND SHORT-CIRCUIT PROTECTION

The POWER-GATE generation 4.0 relays are equipped with five levels of over-current protection, and a single short-circuit level. In a uni-directional relay, these features operate on current flowing from source-to-load only, while in a bi-directional relay the features operate on currents flowing in either direction. It achieves this functionality by constantly monitoring the current flowing through the MOSFET array and comparing it to the settings loaded in the device firmware. The lowest level has a typical threshold of 2 times the maximum rated continuous current ($I_{L,CONT(MAX)}$) and a delay time of one minute (see specification sheet for threshold and delay tolerances); i.e. if the current flowing through the MOSFET array exceeds and stays above the threshold for one minute (while simultaneously not exceeding any of the other over-current or short-circuit thresholds for their respective delay periods), the microcontroller will determine that a level one over-current event has occurred and will command the MOSFET array to turn off to protect from over-heating. It will also flash the red fault LED with the blink pattern assigned to the level (see section "FAULT LED DIAGNOSTICS"). Table 1 summarizes all the over-current and short circuit thresholds and delay times; it is important to note that these settings are specifically designed to protect the MOSFET array under worst-case conditions, while also allowing the passage of large surge currents, and, therefore, cannot be modified by end-user request.

If at any time the relay opens due to either an over-current or short-circuit condition, it can be reset by a toggle of the main trigger (be it remote or on-board) after a 10 second lockout period. It is up to the user to determine if the cause of the shutdown is simply due to a request by the loads for too much current, or if there exists a true fault (e.g. a short-circuit) in the system.

OVER-TEMPERATURE PROTECTION

The POWER-GATE generation 4.0 relays come equipped with over-temperature shutdown to protect both the MOSFET array and circuitry from overheating. Should the internal temperature ever reach ~ +135 °C, the MOSFET array will be opened and the red fault LED will flash the blink pattern

Fault Mode	Threshold	Delay
Over-Current Level 1	2 x $I_{L,CONT(MAX)}$	60 s
Over-Current Level 2	3 x $I_{L,CONT(MAX)}$	1 s
Over-Current Level 3	3.25 x $I_{L,CONT(MAX)}$	500 ms
Over-Current Level 4	3.5 x $I_{L,CONT(MAX)}$	200 ms
Over-Current Level 5	3.75 x $I_{L,CONT(MAX)}$	20 ms
Short-Circuit	4 x $I_{L,CONT(MAX)}$	4 ms max

Table 1: Summary of over-current and short-circuit thresholds and delays (over-current levels have a maximum detection time of 15 ms that should be added to delay time for overall response; short-circuit delay time noted includes detection time)

associated with that feature (see section "FAULT LED DIAGNOSTICS"). When the internal temperature falls below ~ +130 °C, the relay will resume normal operation. [NOTE: While the relay is in its over-temperature mode, it will continue to monitor the source voltage, along with the main and override trigger states. For example, if the main trigger state changes while an over-temperature condition is present, then upon disappearance of that condition, the MOSFET array will revert to the position commanded by the current state of the trigger, as opposed to the one that was present when the condition first appeared. Similarly, if an enabled under-voltage condition appears while in over-temperature mode, then upon exiting that mode, the MOSFET array will remain open even if the main trigger is commanding it closed (unless the override trigger is active).]

CIRCUIT BREAK FEATURE

As stated earlier, the over-current and short-circuit features are used to protect the MOSFET array from damage and cannot be changed or disabled. However, applications exist where a circuit-break is required for load protection, but the standard over-current and short-circuit settings are insufficient (e.g. open the relay when the load current exceeds 1.5 x $I_{L,CONT(MAX)}$ for one second). For cases such as this, the POWER-GATE generation 4.0 relays are available with two circuit-break levels; in a uni-directional relay, these features operate on current flowing from source-to-load only, while in a bi-directional relay the features can be programmed to operate on currents flowing in either direction (e.g. one circuit-break level can be used to open the path between a source and a load during discharge, while the second level can be used to open the relay at a different value during charging of the source from a charger attached to the load side). Should the MOSFET array open due to a circuit-break condition, the red fault LED will flash the blink pattern associated with that feature (see section "FAULT LED DIAGNOSTICS").

The relay can be programmed with one of three available reset options: 1) Main trigger toggle (exactly the same method used to reset the relay after an over-current or short-circuit shutdown), 2) limited auto-retry where the relay will reset a user-defined number of times before reverting to main trigger toggle mode, and 3) unlimited auto-retry where the relay will continuously attempt to reset itself indefinitely. All three of these reset methods require a minimum reset delay of 10 seconds (i.e. the lockout period, same as that for an over-current or short-circuit shutdown).

UNDER- AND OVER-VOLTAGE

An additional feature of the POWER-GATE generation 4.0 relays is the ability to open the MOSFET array should the source voltage fall and stay below a user-defined threshold for a user-defined period of time (often used to protect a battery from deep discharge or loads from an over-voltage condition). The voltage threshold can be set in 0.1 V increments over the entire operating voltage range (see specification sheet); the delay time can be set in 20 ms increments (see specification sheet for the minimum available response time) up to any practical maximum length of time.

Up to four under-voltage and four over-voltage threshold/delay combinations are available to provide the user with maximum source voltage monitoring flexibility. For example, in a 12 V automotive application the user may set two under-voltage levels, one for relay opening when the battery drops and stays below 12.0 V after 1 hour [allowing for a period of time that it can power loads when the vehicle's charging system is not operating (e.g. the engine is not running) before being disconnected], and the other for immediate relay opening when the battery drops below 11.0 V (to protect the battery from yielding a vehicle no-start condition).

Once an under- or over-voltage condition is detected, the MOSFET array will open (if it is closed) and the red fault LED will turn steady on (if a circuit-break, over-current, short-circuit, or over-temperature condition is not already present; see section " FAULT LED DIAGNOSTICS" for more information). While in the under- or over-voltage mode, the override trigger can be used to force the relay closed, assuming the main trigger is also active. Word of caution: It is highly recommended that a momentary-type switch is used to activate the override trigger. This ensures that the MOSFET array will default to the open position when the relay detects an under- or over-voltage condition, unless the user purposefully actives the override trigger; use of a non-momentary switch creates the possibility that the user can accidentally leave the relay in the override state, which can drain the source even though the user is expecting the protection to be active.

SLEEP MODE

The POWER-GATE generation 4.0 relays were designed to draw very little operating current (< 20 mA open, < 23 mA closed), especially with respect to the large amounts of current the MOSFET array can pass. However, in some applications even this small amount of current can be problematic (e.g. the case where a vehicle is stored unused for days or weeks). To accommodate applications where minimal operating current is a priority, the relays can be programmed with a low-power "sleep" mode.

Whenever the relay enters an idle state [i.e. 1) no timers for voltage- or current-related features, or trigger delays, are running, 2) the relay is not in an over-temperature, over-current, short-circuit, circuit-break, or blown-fuse fault mode, and 3) if the MOSFET array is closed, the current passed is less than the sleep threshold (see specification sheet)] the MCU will begin a timer, set at a value specified by the customer (e.g. 24 hours). If at any time one or more of the conditions specified in the preceding parenthesis change (the "idle conditions"), the timer will be reset, and will not restart until the relay once again enters an idle state.

Should the relay remain in an idle state the entire duration of the sleep timer, the MOSFET array will be opened (if it is not already) all LEDs will be turned off, and the relay will go into its low-power mode where the operating current falls to < 2.5 mA under worst-case conditions. Every ~33 seconds (the watchdog period as defined in the specification sheet) the relay will be restored to the state it was in just prior to entering the sleep mode and will begin monitoring all voltages and the MOSFET array current. Should any of the idle conditions change (or, if the under-voltage feature is enabled, the source voltage is measured to be above the under-voltage reset value), the relay will permanently exit the sleep mode and normal operation will commence; if none change within approximately 66 ms, the relay will go back into its low-power mode for another 33 second window. The relay can also be woken from its sleep mode by a change-of-state of either the main or override trigger.

All three of the wake-up methods (timer, main trigger state-change, override trigger state-change) can be enabled/disabled independently, providing maximum sleep mode management flexibility.

FAULT LED DIAGNOSTICS

As the reader will have gathered by this point, the red LED is used to indicate that the MOSFET array has opened due to a fault and has various illumination patterns to identify the particular fault mode that is active. Table 2 summarizes the illumination patterns for each possible fault mode, along with their priority (higher number = higher priority; e.g. if both the over-current and the over-temperature fault modes are present, the fault LED will flash the over-current pattern; if the over-temperature fault is still present when the over-current fault is cleared, the fault LED will begin to flash the over-temperature pattern).

EXTERNAL LEDS

The POWER-GATE generation 4.0 relays also come equipped with a harness used to connect external LEDs for device status and fault monitoring. Every on-board LED is duplicated on the harness so that all functionality, operating states, and fault conditions can be monitored from a remote location, such as a vehicle's cabin. While not required for operation, the external LEDs are highly recommended so that fault conditions such as over-current, over-temperature, or a blown fuse can be immediately detected and resolved before device health is put at risk.

The outputs are of the open-drain type, with an in-line Schottky diode incorporated to protect the MOSFETs from an accidental reverse voltage condition (see functional block diagram on the specification sheet). Consequently, they can be used not only with external LEDs, but with any other monitoring system that has its own pull-up scheme (e.g. an external computer), as long as the maximum current and voltage as detailed in the specification sheet are adhered to.

FUSE

Like all POWER-GATE devices, the generation 4.0 relays uses a fuse in order to protect the flyback diode from a reverse battery condition. If this fuse should blow, the “FUSE OPEN” LED will illuminate. Do not replace the fuse with any other than that specified by the manufacturer.

FAULT LED DIAGNOSTIC TABLE						
Fault Mode	**Illumination Pattern Type**	**Number of Blinks**	**Blink On-Time**	**Blink Off-Time**	**Dark Time Between Blink Sets**	**Priority**
Short-Circuit	Blinking	6	¼ second	¼ second	2 seconds	3
Over-Current Level 5	Blinking	5	¼ second	¼ second	2 seconds	3
Over-Current Level 4	Blinking	4	¼ second	¼ second	2 seconds	3
Over-Current Level 3	Blinking	3	¼ second	¼ second	2 seconds	3
Over-Current Level 2	Blinking	2	¼ second	¼ second	2 seconds	3
Over-Current Level 1	Blinking	1	¼ second	¼ second	2 seconds	3
Circuit-Break Level 2	Blinking	1	½ second	½ second	-	3
Circuit-Break Level 1	Blinking	1	1 second	1 second	-	3
Over-Temperature	Blinking	1	⅛ second	⅛ second	-	2
Under-/Over-Voltage	Steady	-	-	-	-	1

Table 2: Summary of red fault LED illumination patterns (1 is lowest priority, 3 is highest priority)

LOSS OF GROUND

In order to operate properly, the relay requires a good ground connection. If ground is lost, the internal circuit board will not receive power, and thus, will not be able to properly operate the MOSFET array. This is another reason why use of the external LEDs is highly recommended, as loss of ground will also cause all LEDs to go dark, immediately indicating to the user that the POWER-GATE requires attention.

NOTE: If any of the on-board LEDs are disabled, the corresponding external connections will be as well. It is possible to enable only the external LEDs, but this requires the on-board LEDs to be physically removed and is not recommended.

TRIGGERS

MAIN TRIGGER: The MOSFET array is controlled through the main trigger line, which can be configured in five different ways: 1) Active-high, non-isolated, remote only, 2) active-low, non-isolated, remote only, 3) on-board only, 4) on-board AND active-high, non-isolated, remote, and 5) on-board AND active-low, non-isolated, remote.

Active-high and Active-low Non-isolated Remote Only Types: The most common main trigger option used is the active-high, non-isolated, remote type as it requires only one wire for control, interfaces with a wide variety of control signals, and has low current draw (< 0.8 mA). The active-low, non-isolated, remote option may not be as easily integrated into a system that generally uses high-side switched signals (e.g. a 12 V automotive application), but has the lowest available trigger current draw (< 40 μA) and, thus, may be preferable in some applications.

On-board Only Types: Some applications only require that the relay respond to voltage conditions, as opposed to state changes on the main trigger; in those cases, the main trigger can be configured in the on-board only type by moving the remote main trigger to an on-board switch, simplifying the wiring of the POWER-GATE into the larger system. Although the user will rarely interact with the relay through the on-board main trigger, it is required for two reasons: 1) To allow for device reset after the MOSFET array has opened due to a circuit-break (if enabled), over-current, or short-circuit condition (all requiring a toggle of the switch to achieve reset), and 2) to allow the relay to be forced into the open state for safe installation/removal purposes. A remote override trigger can still be with an autonomous master trigger to force the relay closed when required.

On-board AND Non-isolated, Remote Types: Some applications require relay triggering through automated means, such as battery management systems (BMS) commonly used with lithium-ion batteries. While this is a perfectly acceptable triggering source, using it as the lone method of turning on and off the relay leaves open the possibility of a latch-up condition should that source fail. For example, imagine that the relay is connected between a lithium-ion battery and various loads, while its trigger line is connected to the under-voltage warning output of a BMS; the intention being that this will trigger the relay open (disconnecting the loads from the battery) when the BMS detects the batteries have been discharged too much and need to be charged. Should the relay automatically open due to an over-current or short-circuit event, while the battery is fully charged (and thus the main trigger line tied to the under-voltage remains in its “ok” state), the on-board switch is required in order to reset the relay, since a master trigger toggle is the method in which this is accomplished. NOTE: You could also reset the relay by unplugging and then plugging in the control harness, although this is not generally recommended as it yields undue harness strain and fatigue.

Isolated Type: An isolated type of main trigger is currently in the design phase and will be released shortly as an accessory. It will be useful when the relay and trigger source have different ground references (e.g. relay on a vehicle, trigger originating from a mobile device such as a laptop) or when the trigger wire is routed through a high noise environment (i.e. the isolated trigger can be used to ignore common-mode noise between the positive and negative trigger wires). The trade-off for choosing to use the isolated over the non-isolated trigger, however, is the need for two, instead of only one, control wires, and a higher current draw (anywhere from 2 to 5 mA, depending on the voltage difference between the trigger wires).

Whenever the main trigger is active the MOSFET array will be closed as long as there is not a circuit-break, under-voltage, or over-voltage condition (if any of those features are enabled), or an over-current, short-circuit, or over-temperature fault. Should a current-related fault cause the MOSFET array to open, the main trigger can reset the relay through a simple toggle (refer to specification sheet for minimum trigger hold time to ensure proper reset).

OVERRIDE TRIGGER: If a voltage-related fault is the cause of the MOSFET array opening, the override trigger can be used to force the relay closed (assuming the main trigger is active), which may be required, for example, when powering a load becomes more important than preserving battery life. Just like the main trigger, the override trigger can be configured as active-high or active-low in the non-isolated remote form, both with identical electrical specifications as those of the main trigger (isolated override trigger will be added to the same future accessory for the isolated main trigger type). The standard configuration is the active-low type, which allows the connection of a small switch between the override trigger wires (OVERRIDETRIG+ and OVERRIDETRIG-) that can be routed to a vehicle cabin, for example. NOTE: It is recommended that a momentary switch type be used for override functionality. This ensures that if the relay has detected an under-voltage condition, the MOSFET array is not accidentally left in the closed state due to an override switch being unintentionally left in the active position.

TRIGGER DEBOUNCE AND DELAYS: Both the main and override triggers have a minimum hold time on the order of 40 ms, which is used both for mechanical switch debouncing and noise filtering. Should additional delays be required between a trigger state change and relay response, the POWER-GATE can be programmed with trigger delays in 20 ms increments to any practical value.

Trigger debouncing delays can be removed for customers that require faster relay response, but a request for such must first be analyzed by Perfect Switch engineering for approval.

LOAD-DUMP TOLERANCE

The POWER-GATE generation 4.0 relays have been designed to withstand a load dump pulse rated up to the ISO7637-2:2004[1] pulse 5 specification, as long as that pulse is externally clamped to a maximum of 60 V for both the 12 and 24 V versions. This feature allows the relay to survive a variety of extreme voltage spikes that occur when a load drawing large amounts of current is suddenly (and, usually, unintentionally) disconnected.

REVERSE POLARITY PROTECTION

Many applications (in particular, those in the automotive industry) are subject to possible reverse polarity source conditions; e.g. a replacement battery being installed backwards. While the on-board fuse will likely blow to protect the flyback diode (see section “FUSE”), no further damage to the relay will occur as long as the reverse voltage conditions stated in the specification sheets are adhered to. In general, a uni-directional relay will only be used between one source and one or more loads, so as long as the loads are protected against reverse polarity (the load(s) will actually see the negative source voltage minus the body diode forward voltage drop), then there will be no reverse current flow through body diodes and the relay will survive an indefinite reverse polarity condition. On the other hand, if the application requires the relay to be connected between two sources, or, if between one source and one or more loads, the load(s) is(aren't) reverse polarity protected, then a bi-directional type must be used; the fuse will still likely blow, but no current will flow through the MOSFET array body diodes and the relay will survive an indefinite reverse polarity condition (the load(s) will also be protected).

COLD-CRANK TOLERANCE

The internal resistance of most batteries increases as temperature decreases, which can result in a very low terminal voltage under high current load conditions. Of particular concern is the case of a 12 V automotive cold-crank condition, where the battery terminal voltage can fall to as low as 3 V for 15 ms. While much equipment can be allowed to reset during this low-voltage condition, other electronics such as safety equipment must continue to operate throughout the entire cranking process (this situation has become more prevalent with the popularity of hybrid vehicles that stop and start an internal combustion engine while the vehicle is in motion in order to maximize fuel efficiency).

If a POWER-GATE generation 4.0 relay is placed between a starting battery and critical loads, it must remain closed during a cold-crank condition. With that goal in mind, the relays have been designed to operate indefinitely at source voltages as low as 4.8 V, and can remain closed during voltage dips to 3 V for up to 7 ms.

UNI-DIRECTIONAL VS. BI-DIRECTIONAL

As has been pointed out many times, the POWER-GATE generation 4.0 relays come in two varieties, uni-directional and bi-directional; understanding the differences between the two is critical when choosing the proper device for any given application.

The terms "uni-directional" and "bi-directional" do not actually refer to the ability of the MOSFET array to pass current when on, but rather its ability to block current when off. The necessity for the two different types originates from a side effect of the MOSFET manufacturing process, namely, the existence of the integral body diode and can be understood by examining Figures 1 (uni-directional relay) and 2 (bi-directional relay).

In Figure 1, we can see that the MOSFET array body diodes can be represented as a single one with its anode at the load(s) and the cathode at the source. As long as 1) the source is not connected backwards, 2) the load terminal is guaranteed never to go 0.3 V higher (referenced to the relay's ground terminal) than the source terminal, and 3) the relay is not installed improperly (i.e. the source to the load and vice-a-versa), then no current will flow through the body diodes. If the source is connected reverse polarity, then the situation arises described in the "REVERSE POLARITY PROTECTION" section; if a voltage appears at the load terminal higher than that on the source terminal (plus 0.3 V) while the relay is "open", then current will flow from the load to the source through the now forward-biased body diodes causing them to heat up and, therefore, increasing the risk of MOSFET failure; if the relay is installed backwards, current will immediately begin to flow from the source to the load through the MOSFET body diodes with no way to stop the flow. Consequently, the uni-directional relay can only be truly opened in one direction (from the source to the load terminal).

In Figure 2 we can see that the MOSFET array body diodes can be represented as two single ones in a back-to-back, common anode configuration, with the cathodes connected to the two power terminals. Due to this arrangement, a reverse polarity condition on one or both terminals will not cause current to flow through the body diodes since one is always reverse-biased (although the fuse will likely blow). Additionally, this arrangement is truly open in both directions when the MOSFET array is open, since, again, one body diode will always be reverse-biased regardless of the voltage polarity between the two power terminals.

DECISION TREE: The following decision tree will assist in deciding whether any particular application requires a uni- or bi-directional relay.

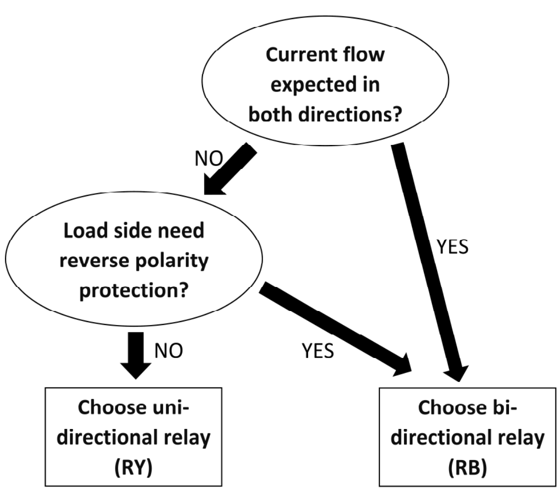


Figure 3: Uni- or Bi-directional Decision Tree

MOSFET FAILURE

Although great care has been taken during the design and testing phases of the POWER-GATE generation 4.0 relays to maximize performance, while also documenting the relay's limitations and bounds, we are also aware that an end-user may, intentionally or unintentionally, exceed the ratings of MOSFET array. If this excess leads to failure of one or more of the MOSFETs in the array, it is important to be aware of the fact that the general failure mode of MOSFETs is the shorted state. It is possible for MOSFETs to fail open, but this will usually only occur under extremely high currents where the internal wire bonds from the MOSFET substrate to the package's lead frame actually blow open. Under most practical conditions outside the allowable operating parameters outlined in the uni- and bi-directional specification sheets, the user should assume that if one or more MOSFETs were to fail, they will fail shorted.

REVISION HISTORY

Rev 1: Original release (2/20/18)