AN1163
Introduction to Load Switches

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Integrated load switches are electronic switches used in systems to turn power rails on and off, similar to a relay or a MOSFET. Integrated load switches provide many benefits, including protection features that are too difficult or complex to implement with discrete components. Diodes Incorporated’s DML series is one such example of integrated load switches. The DMLxx series load switches can be used in numerous applications, and their features include:

- Inrush current control
- Quick (output capacitor) discharge
- Short-circuit protection
- Undervoltage lockout protection
- Thermal shutdown protection
- Power good

What is a load switch?

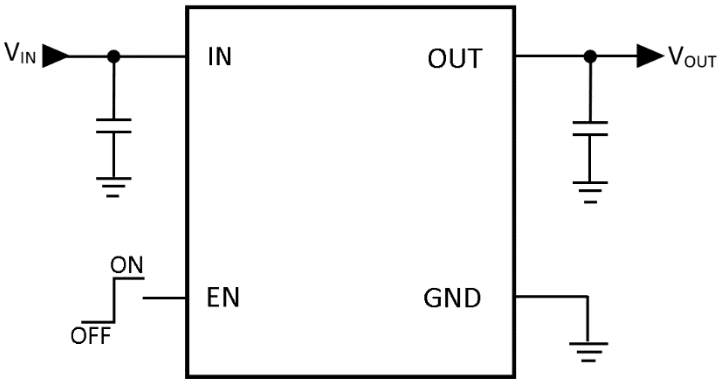

Figure 1: Basic load switch circuit diagram

Figure 1 shows a basic load switch arrangement. The switch shown has four pins: IN and OUT (for the input and output respectively), GND (ground), and EN (enable). The EN pin allows the input to propagate to the output when the switch is active. The input and output capacitances are external to the switch, but are highly recommended to include as they stabilise the voltages and make transients smoother. More complex load switches have more pins, which in turn provide additional functionality, such as Diodes’ DML3006LFDS and DML3009LDC.

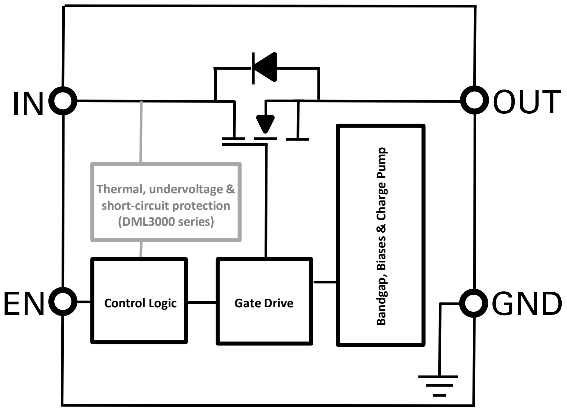

Figure 2: Functional block diagram

Figure 2 shows the functional block diagram of a basic load switch. The main component of the switch is the N-channel MOSFET, which allows the input signal to propagate to the output when turned on. The gate drive charges and discharges the gate of the MOSFET and is controlled by the control logic, which takes the enable signal as an input and switches on the FET when the enable is high. The charge pump circuit (connected to the gate drive) is required as the gate voltage must be above the source voltage for the FET to be active. Thermal shutdown, undervoltage, and short-circuit protection (grey block) are additional features not included in all load switches. Diodes' DML3006LFDS and DML3009LDC include all of the features shown above.

Why are load switches required?

Although discrete components can be used to achieve part of the functionality of a load switch, there are several reasons why implementing the load switch is a better choice for your design.

Note: All measurements and results below were obtained under these test conditions: V_{CC} = 5 V, V_{IN} = 10 V, Load = 10 Ω, 10 µF.

Solution Size and Simplicity

An appealing characteristic of the load switch is its significant reduction in size compared to a discrete solution. Several discrete components are necessary to provide the same functionality as a load switch, which increases the size and complexity of the circuit. This can be a problem, especially when the design space is limited. However, an integrated load switch can easily be accommodated in that limited space. Moreover, no additional time needs to be spent designing a discrete solution as the integrated chip can be implemented into your design straight away

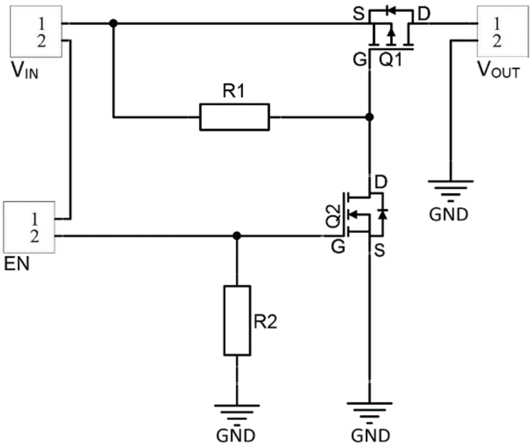

Figure 3: Discrete solution implementation

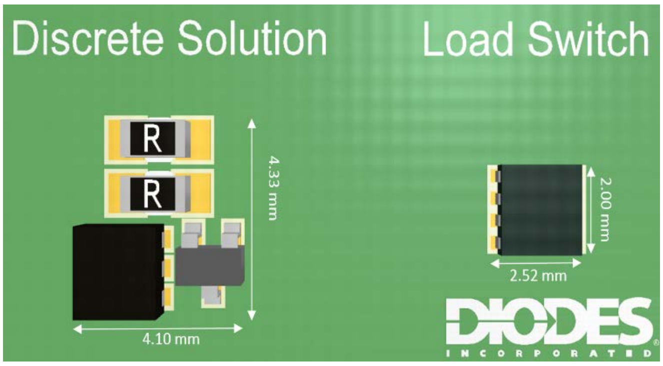

Figure 4: Discrete vs. integrated solution

Figure 3 shows the implementation of a load switch using discrete components. It consists of two resistors, an n-FET (Q2) and a p-FET (Q1). The on-resistance, $R_{DS(ON)}$, of the p-FET used (DMP2008UFG) matches the on-resistance of the load switch used (DML3006LFDS). It can clearly be seen that any discrete solution using the DMP2008UFG FET will result in a bigger overall solution than the load switch. This is because the DMP2008UFG comes in the same package as the load switch (DFN2020).

As shown in Figure 4, there is a significant difference in size between the discrete solution and the load switch. Moreover, as less components and connections are required, the complexity of the circuit is reduced when implementing the load switch. Note that the discrete solution shown above does not include any additional features. Implementing these onto the discrete solution would require even more components and further increase the complexity of the design.

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Power Sequencing

It is often necessary, or essential, to sequence the distribution of power within a system. Load switches can be used to achieve this, as shown below:

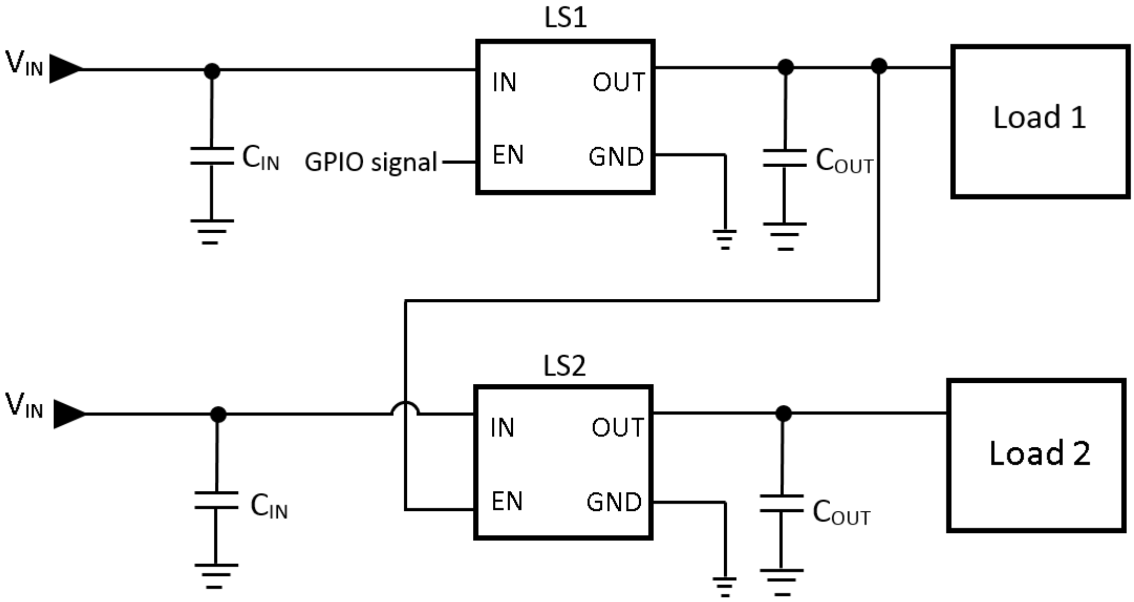

Figure 5: Power sequencing using load switches

As shown in Figure 5, the output of the first load switch can be fed as an input to the enable pin of the second load switch, provided that the input signal is within the range the enable pin is rated for (-0.3V – 6V). There will be a certain propagation delay before the second load is powered, hence the sequential power distribution. Note that this could be replicated with multiple loads. For instance, the output of load switch 2 above could be fed as an input to a third load switch, and so on. If this is not desired, different GPIO signals can be used through a microcontroller to drive the enable pins of the switches as required. The Power Good signal can also be used for power sequencing (see "Power Good" section for details).

Inrush Current Control

When the FET first becomes active, a large current known as inrush current, flows into the uncharged output capacitors and into any capacitive load. This can cause a few problems within the system. Firstly, due to the large rise, the current can exceed the absolute maximum current ratings of components in the system, which can damage these components and possibly lead to system failure. Secondly, the power supply voltage may not remain stable when supplying the required current, which can lead to a drop in voltage. If the voltage drops below a certain level, it may reset parts of the system or even lead to system failure.

The inrush current in a system following turn-on is given by:

$$I = C \cdot \frac{dV}{dt}$$

Where I = inrush current due to the total capacitance,
C = total capacitance
dV = change in voltage
dt = change in time

Note that the inrush current is directly proportional to the total capacitance and inversely proportional to *dt*, the rise time. Therefore, if the inrush current is to be reduced for a fixed load, the rise time must be increased. However, this also means the time taken to power up (rise time) and power down (fall time) increases, which may be undesirable.

Although a discrete solution can be implemented to deal with inrush current and reduce the rise time, a large solution size with several discrete components of values within a specific range are required. This limits the flexibility to trade-off the magnitude of the inrush current and the power up timings.

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Integrated load switches, such as Diodes' DML3006LFDS and DML3009LDC, use a soft-start mechanism. They have controlled rise time and adjustable slew rate capabilities, providing the design flexibility to trade-off inrush current and power timing requirements. Although this requires the addition of a capacitor to the load switch arrangement, the overall size and complexity are greatly reduced in comparison to the discrete solution.

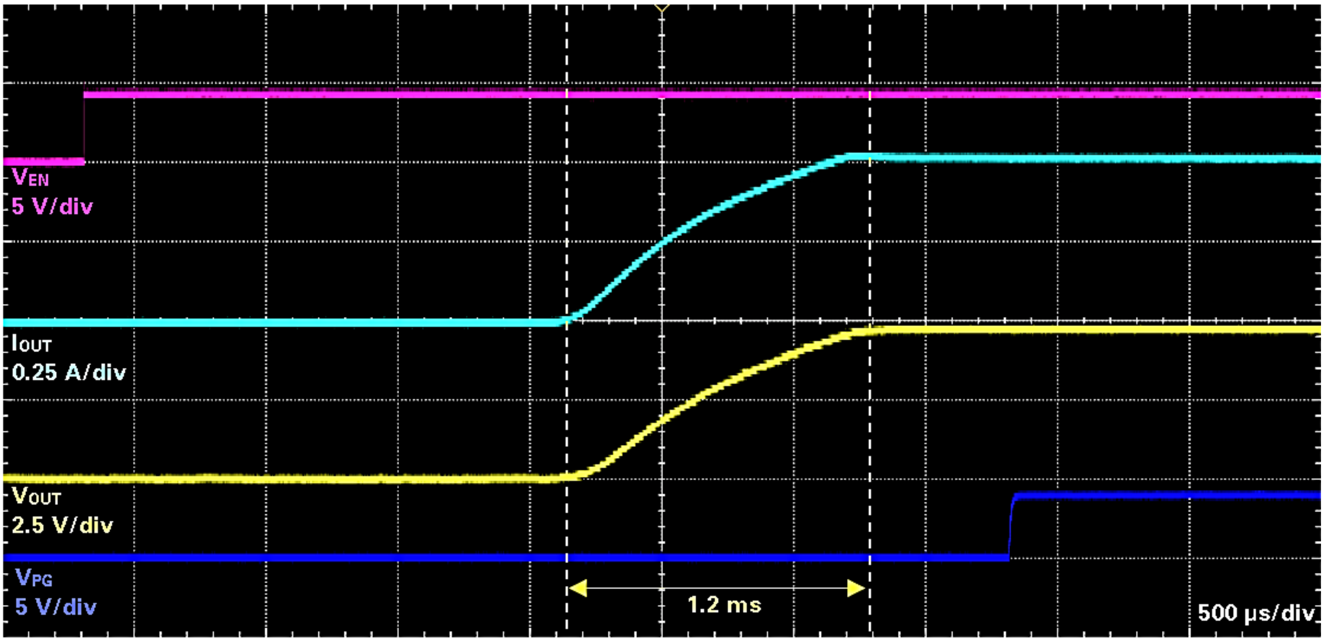

Figure 6: Inrush current at V_{IN} = 5V

Figure 6 shows the response of the DML3009LDC device to an inrush current due to a capacitive load of 10µF. The controlled rise time prevents damage to the component and the rest of the circuitry, as well as keeping a stable supply voltage. A rise time of 1.2ms can be seen for V_{IN} = 5V. With increasing V_{IN}, we would expect a larger inrush current and hence a larger rise time to control the current. This can be seen in Figure 7 below:

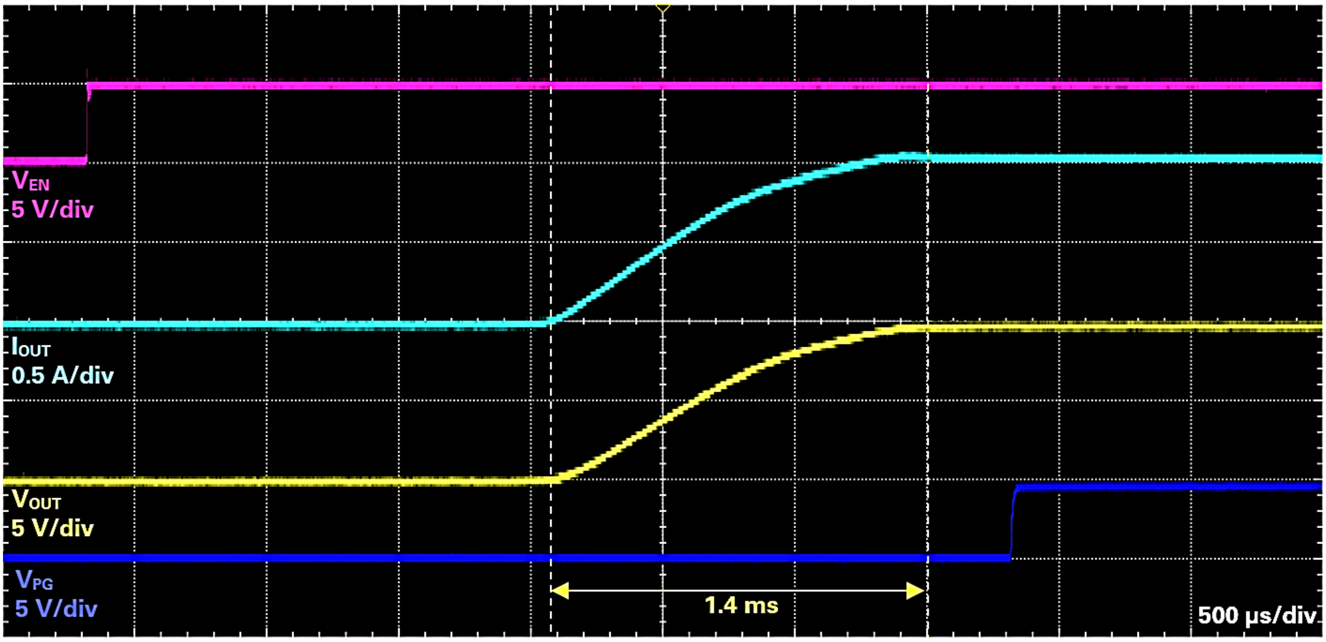

Figure 7: Inrush current at V_{IN} = 10V

The rise time has increased to 1.4ms to control the larger inrush current at V_{IN} = 10V.

Power Good

Having a power good (PG) signal can be very useful, especially when it comes to power sequencing. As shown in Figure 5, an output signal from one load switch can act as the input to another to achieve sequentially distributed power. Diodes' DML3006LFDS and DML3009LDC devices include a power good output that can be used to indicate when the gate of the MOSFET is driven high and the switch is on, with the on-resistance close to its final value (at the full load condition).

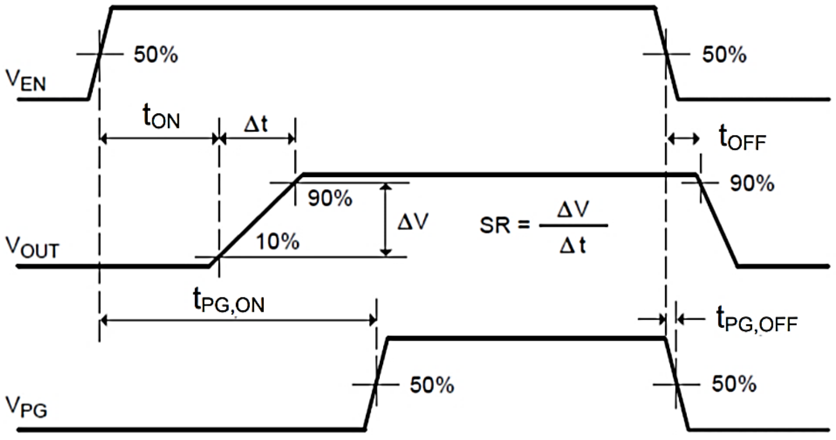

Figure 8: PG timing diagram

Figure 8 above shows the PG output response. As the enable signal goes high and reaches 50% of its final value, the output voltage begins to rise following a delay, t_{ON}. V_{OUT} then rises and stabilises following a delay of Δt. The slew rate is given by the following equation:

$$SR = \Delta V/\Delta t$$

Where SR = output slew rate
Δt = change in time
ΔV = change in voltage

When V_{OUT} stabilises, PG goes high following a delay. The delay between the enable and PG going high is labelled above as $t_{PG,ON}$. When the enable signal goes low and reaches 50% of its final value, PG begins to fall and will reach 50% of its final value after a delay of $t_{PG,OFF}$. The output also begins to fall following a delay of t_{OFF} as the enable goes low. Typical values of these parameters for Diodes' DML3009LDC and DML3006LFDS load switches are shown below:

Note: The parameter values below were measured at the following conditions: V_{IN} = 1.8V, V_{CC} = 5V.

Table 1: Typical values of switching parameters for DML3009LDC and DML3006LFDS

Parameter	DML3009LDC	DML3006LFDS	Unit
t_{ON}	370	190	µs
t_{OFF}	0.5	0.4	µs
$t_{PG,ON}$	1.3	1.05	ms
$t_{PG,OFF}$	6	8	Ns
SR	9	24	kV/s

Figures 6 and 7 also show the measured response of the PG output on the DML3009LDC device when the enable signal changes. When enable is driven high, the output rises. Once stable, PG will output a high. The delay between EN going high and PG outputting high corresponds to the time taken for the switch to turn on and the on-resistance to approach its final value. When enable is driven low, PG outputs a low and the gate switches off following a delay (see Table 1 above).

The PG output can be used as the enable signal for other active-high devices in the system. This allows for a guaranteed-by-design power sequencing and reduces the number of enable signals needed from the system controller. If the PG feature is not used, the pin can be tied to GND.

Quick Discharge

It is useful (and often essential for reverse flow protection) to discharge the load to ground, ensuring it is in a known state and not floating. Diodes' DML3006LFDS and DML3009LDC devices include a "BLEED" connection to the output, capable of discharging the output load when the MOSFET is disabled. Again, to implement the same functionality in a discrete solution requires additional components and design time.

Thermal Shutdown Protection

It is important to protect the circuit from damage at high temperatures. In a discrete solution, the FET is unable to protect itself against excessive temperatures and can break, potentially causing damage to other components.

Diodes' load switches are equipped with thermal shutdown protection for excessive temperatures, internally or externally generated. When the temperature exceeds a certain limit, the MOSFET is immediately switched off and the output is discharged. This protects the MOSFET and the upstream/downstream circuitry as it ensures that the MOSFET does not pass through any current. When the temperature falls back to a safe operating temperature, the switch exits the thermal shutdown state. If the enable pin is still active, the MOSFET is switched on in a controlled fashion and will continue to operate as normal. For instance, the DML3009LDC trips when it exceeds a temperature of typically 145 ˚C. It has a thermal shutdown hysteresis of 20 ˚C, and will exit the shutdown at approximately 125 ˚C.

Short-Circuit Protection

Diodes' DML300x series load switches, such as the DML3006LFDS and DML3009LDC, are equipped with short-circuit protection. This is to help protect the part and the system from a sudden high-current event, such as the output, V_{OUT}, being shorted to ground. This circuitry is only active when the gate of the MOSFET is fully charged.

Once the device is active, the voltage difference between the input and output is monitored. If the voltage drop across the MOSFET equals or exceeds the short-circuit protection threshold voltage, the MOSFET is immediately switched off and Load Bleed (Quick Discharge) is activated. The part remains latched in this off state until the enable pin (EN) is toggled or V_{CC} supply voltage is cycled, at which point the MOSFET switches on following the usual turn-on delay. The current through the MOSFET that will cause a short-circuit event can be calculated using the following equation:

$$I_{SC} = \frac{V_{SCP}}{R_{DS(on)}}$$

Where I_{SC} = current through MOSFET that will cause a short-circuit event
V_{SCP} = short-circuit protection threshold voltage
$R_{DS(on)}$ = on-state resistance of the MOSFET

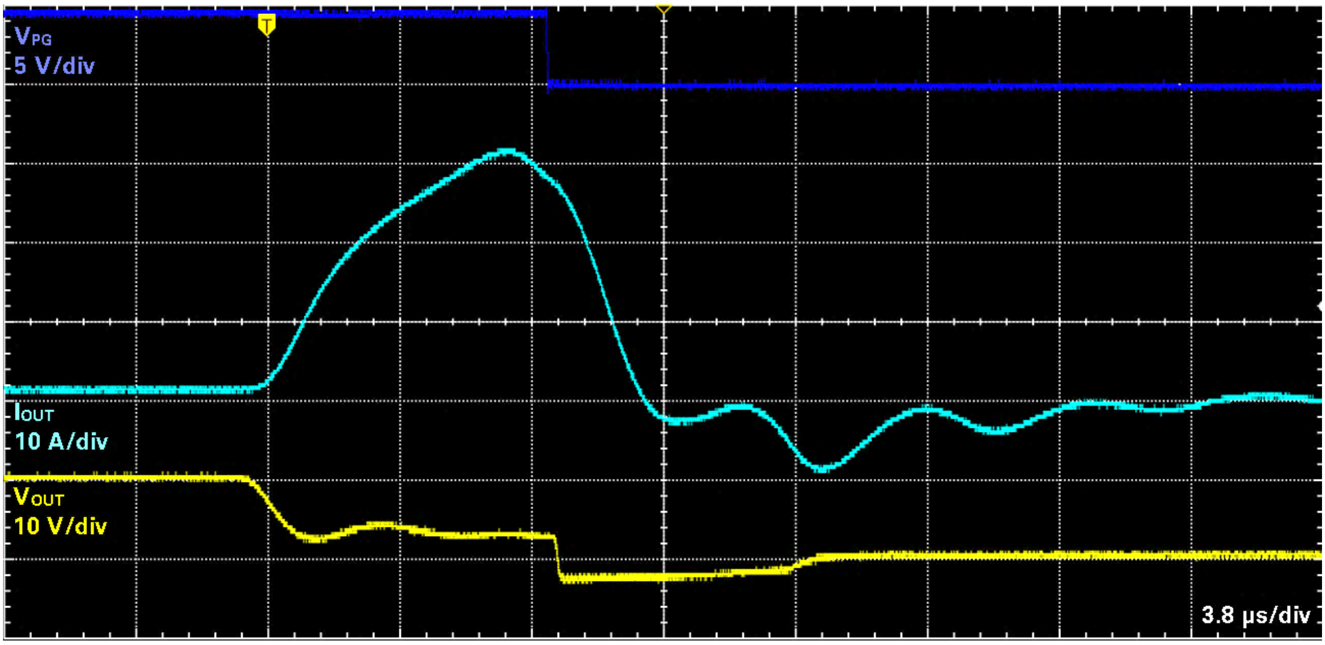

Figure 9 : DML3009LDC's short-circuit protection

Figure 9 above shows the response of the DML3009LDC load switch to a short-circuit event. For this test, V_{OUT} was shorted to ground. A large increase in current can be seen, peaking at 31.8A. As soon as this is detected, the MOSFET is switched off, as shown by the drop in the PG, and V_{OUT} outputs within µs of the short-circuit. This protects the device and the rest of the circuitry from damage due to the high current.

The device remains in this state unless the enable is toggled or V_{CC} supply voltage is cycled. As enable goes high, the gate of the MOSFET charges. The output voltage V_{OUT} rises following the usual delay and slew rate. Once stable, the PG output will go high.

Undervoltage Lockout

Diodes' DML300x series load switches, such as the DML3006LFDS and DML3009LDC, are also equipped with undervoltage lockout protection. The MOSFET is turned off and Load Bleed (Quick Discharge) is activated when the input voltage, V_{IN}, is less than or equal to the undervoltage lockout threshold. This circuitry is disabled when EN is not active to reduce standby current. If the input voltage rises above the undervoltage lockout threshold and EN remains active, the MOSFET will be turned on in a controlled fashion with the normal output turn-on delay and slew rate.

Design Considerations

There are some important factors which need to be taken into consideration when implementing a load switch into your design:

$R_{DS(ON)}$

$R_{DS(ON)}$ is the resistance between the IN and OUT pins, mainly the resistance of the MOSFET when it is switched on. The higher the $R_{DS(ON)}$, the higher the voltage drop across the switch and the power dissipation. Therefore, it is critical to select a load switch with an $R_{DS(ON)}$ value which will not adversely affect the normal operation of your system. The voltage drop across the load switch can be calculated as follows:

$$V_{Drop} = R_{DS(ON)} \cdot I_{Load}$$

Where V_{Drop} = voltage drop across the load switch
$R_{DS(ON)}$ = total resistance between IN and OUT pins
I_{Load} = load current

V/I Ratings

The voltage and current ratings of the load switch must match the conditions expected during the normal operation of the circuit. The load switch must be able to withstand the range of voltages expected on the input (V_{IN}) as well as the expected maximum load current ($I_{L(MAX)}$). This must account for all peak currents and transient voltages to prevent damage to the circuitry. Diodes' DML300x series load switches, such as the DML3006LFDS and DML3009LDC, are equipped with short-circuit protection to protect against high-current events and undervoltage lockout to protect the system when the input voltage V_{IN} exceeds a certain threshold.

Rise Time

As discussed, inrush currents can cause damage to the circuitry. The rise time of the device must be large enough to limit the inrush current to an acceptable value. Diodes' DML3006LFDS and DML3009LDC have controlled rise time and adjustable slew rate capabilities, providing the design flexibility to trade-off inrush current and power timing requirements. For details, refer to the "Inrush Current Control" section.

Standby and Leakage currents

Both leakage and standby currents can contribute to additional power dissipation. These values are in the order of µA for Diodes' load switches, hence reducing the total power dissipation of the load switch and ensuring the system is not adversely affected.

Thermal Considerations

To ensure proper operation, the maximum junction temperature of the load switch should not exceed a certain value. Several factors attribute to the junction temperate rise: power dissipation, junction-to-ambient thermal resistance, and ambient temperature. For a given load switch, it is important to ensure that the expected load current does not cause the maximum junction temperature to be exceeded. The maximum load current can be determined by:

$$I_{L(MAX)} = \sqrt{\frac{T_{J(MAX)} - T_C}{\theta_{JC} \times R_{DS(ON)}}}$$

Where $I_{L(MAX)}$ = maximum allowable current on load (A)
$T_{J(MAX)}$ = maximum allowable junction temperature
T_C = case temperature of the device
θ_{JC} = junction to case thermal impedance (highly dependent upon PCB layout)

Conclusion

Although discrete components can be used to achieve some of the functionality offered by a load switch, the implementation of a load switch in a system simplifies the design and offers many additional benefits, including reduced solution size, circuit protection, and low power consumption. With Diodes' DML3009LDC for instance, the solution size is significantly reduced compared with a simple discrete solution with no additional circuit protection features. The discrete solution area will significantly increase if additional features are implemented. The circuit protection features offered by Diodes' DML3006LFDS and DML3009LDC include inrush current control, short-circuit protection, undervoltage lockout, and thermal shutdown protection. To implement these using discrete components involves increased circuit complexity and design time**.**

When selecting the right load switch, there are some important design considerations (absolute maximum ratings, thermal considerations, etc.). These involve matching the requirements of the normal operating conditions of your application with the parameters of the device being implemented to ensure compatibility and optimal performance.

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