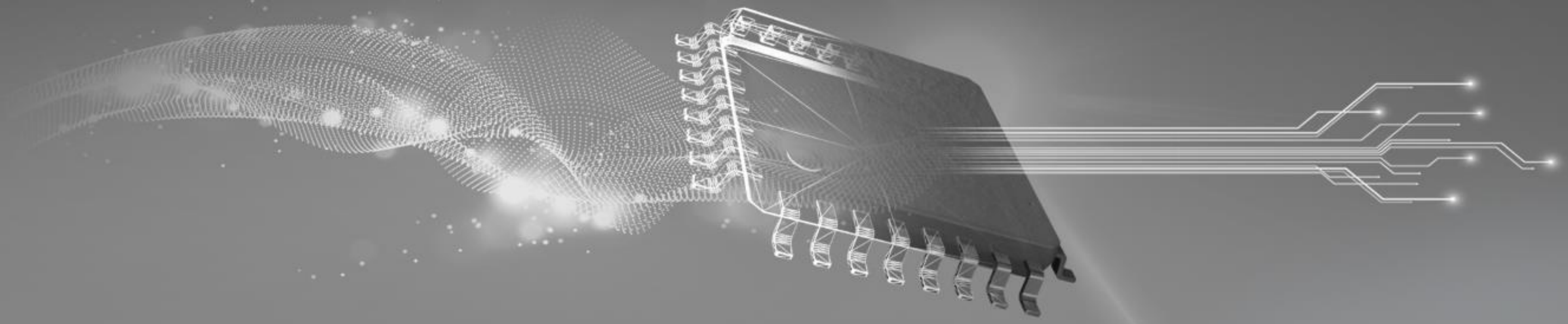
TI TECH DAYS



Increasing system robustness with integrated protection and diagnostics by using TI high-side switches

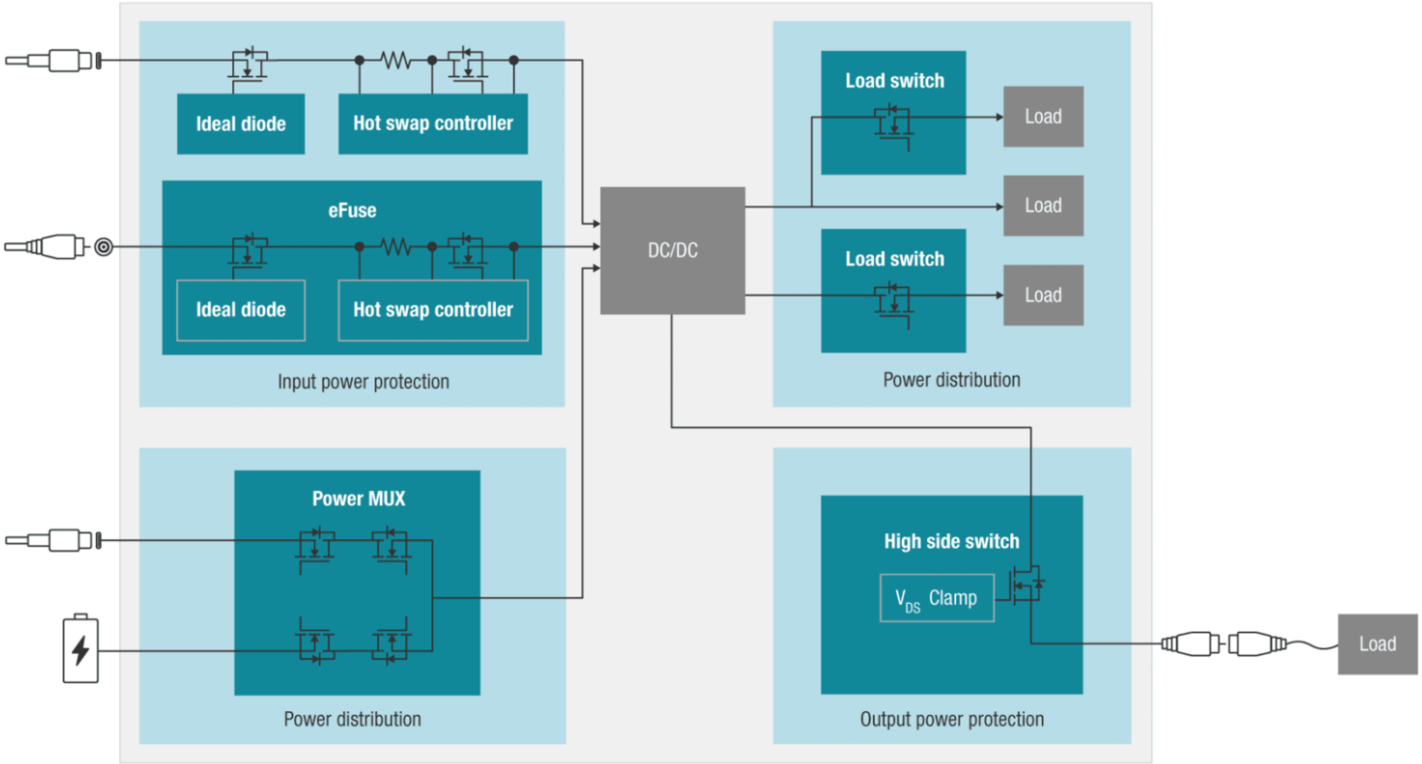
Shreyas Dmello

APP-PSIL-PS

Agenda

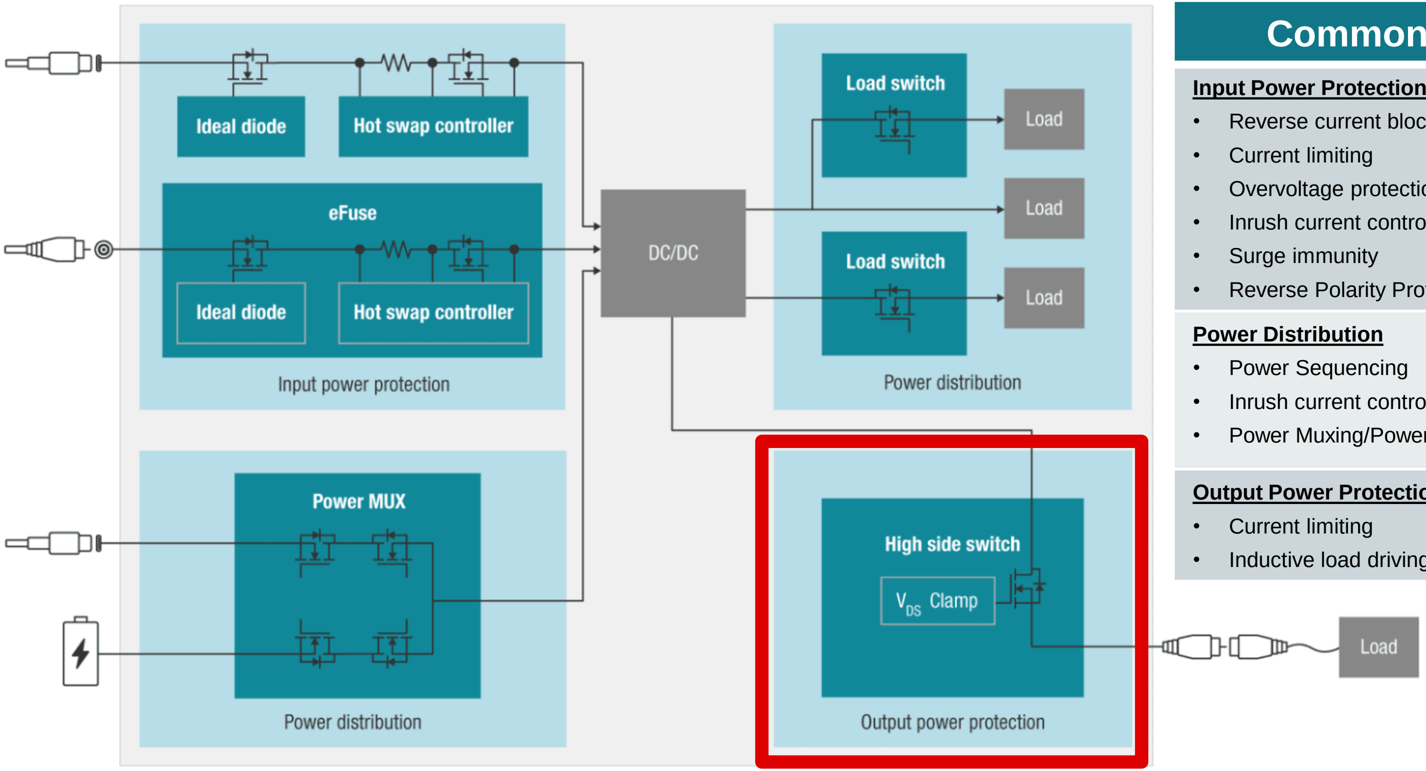
- What is a High-side switch?
- Where do I use a smart High-side switch?
- Applications of a smart High-side switch
  - Capacitive/Inductive load driving
  - Short circuit/Overload protection
  - Diagnostics/Current sensing

Power switches | Use cases



Learn more at: Products → Power Management → Power Switches → Power Switches portal Page

Power switches | High-side switches



Common Design Challenges

Input Power Protection

- Reverse current blocking
- Current limiting
- Overvoltage protection
- Inrush current control
- Surge immunity
- Reverse Polarity Protection

Power Distribution

- Power Sequencing
- Inrush current control
- Power Muxing/Power Oring

Output Power Protection

- Current limiting
- Inductive load driving

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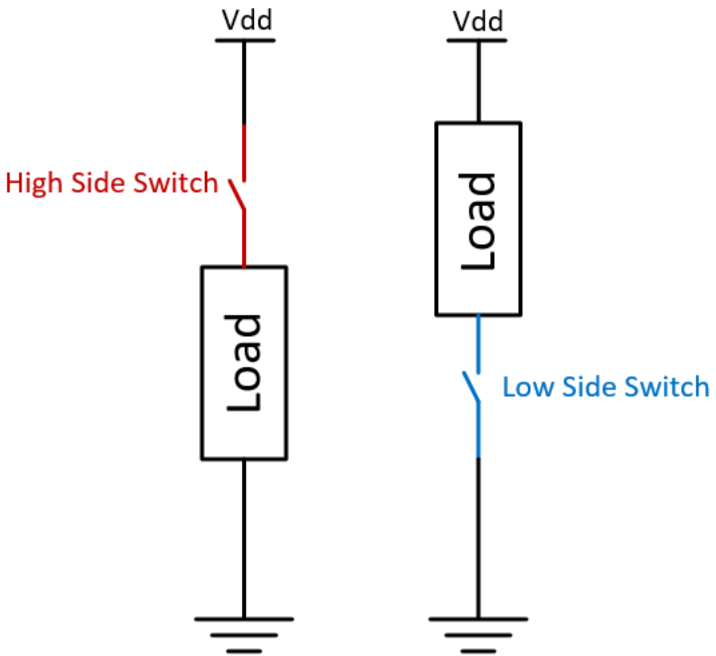
What is a High-side switch?

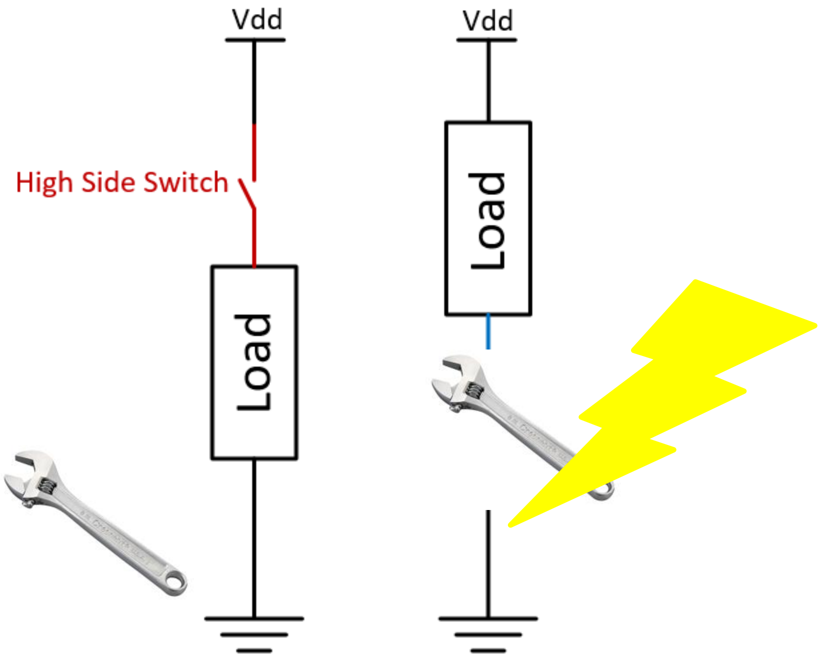
High-side switches placed between source and load. Using these devices allow for no floating nodes when the system is off. The load is safely pulled to GND.



What is a High-side switch?

High-side switches placed between source and load. Using these devices allow for no floating nodes when the system is off. The load is safely pulled to GND.

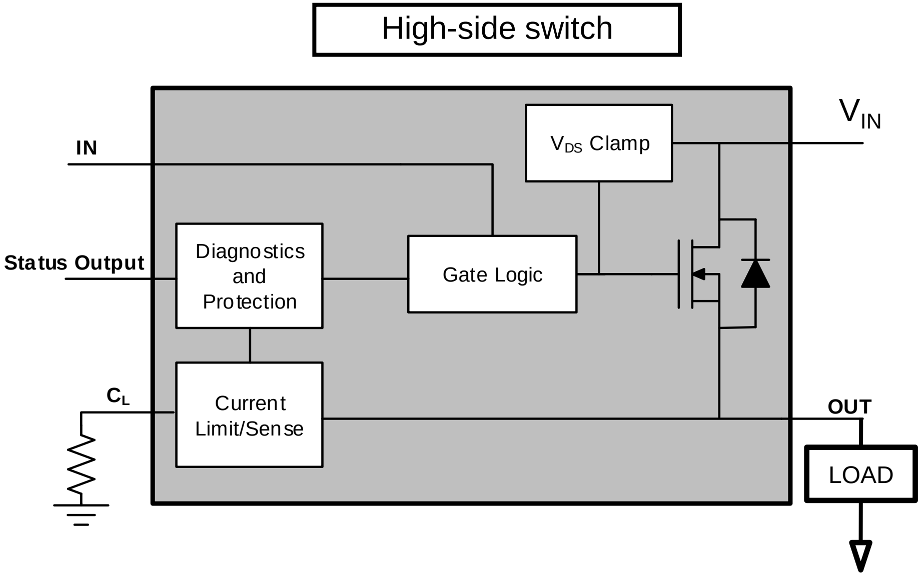
In the event of a failure, High-side switches are preferred as they disconnect the power source from the system rather than the system GND.



What is a smart High-side switch?

- A **smart High-side switch** is a power management device that connects to a power supply input and **switches** on/off downstream loads, **protects** against faults, and provides output **diagnostics**

Module Type	Device	Description
≤ 100mA	TPS4H000	**4-CH, 40V, 1Ω**, TSSOP
≤ 500mA	TPS1H200	**1-CH, 40V, 200mΩ**, TSSOP
≤ 750mA	TPS4H160	**4-CH, 40V, 160mΩ,** TSSOP
	TPS27S100	**1-CH, 40V, 100mΩ,** TSSOP
≤ 2A	TPS27S100	**1-CH, 40V, 100mΩ,** TSSOP



Learn More: 11 Ways to Protect Your Power Path

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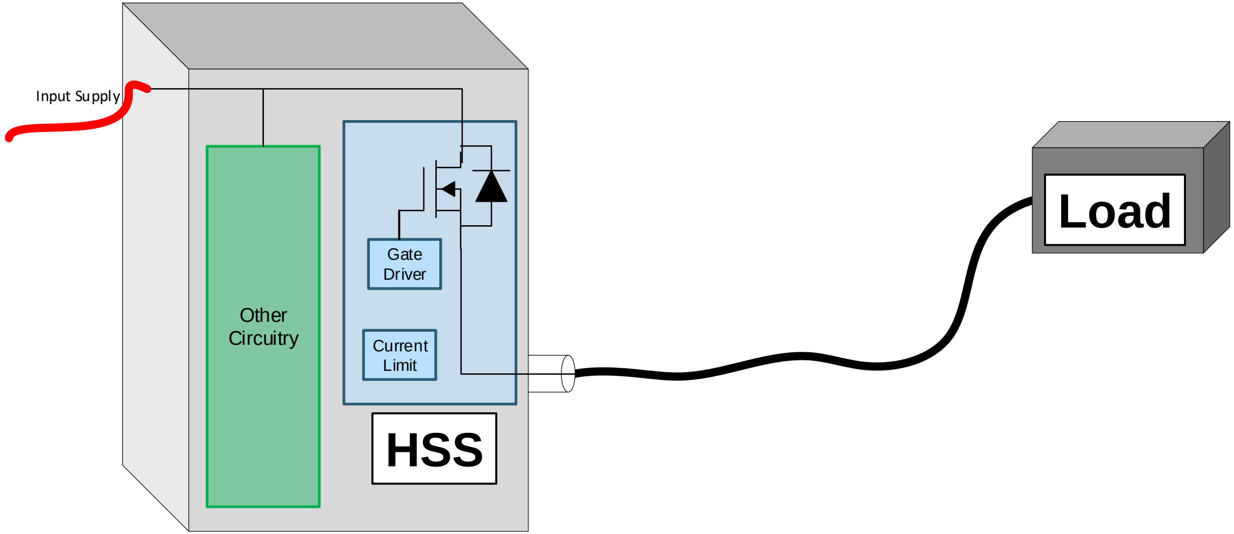
Where do we use a smart High-side switch?

- Smart High-side switches are ON/OFF switches that sit on the high-side of the load



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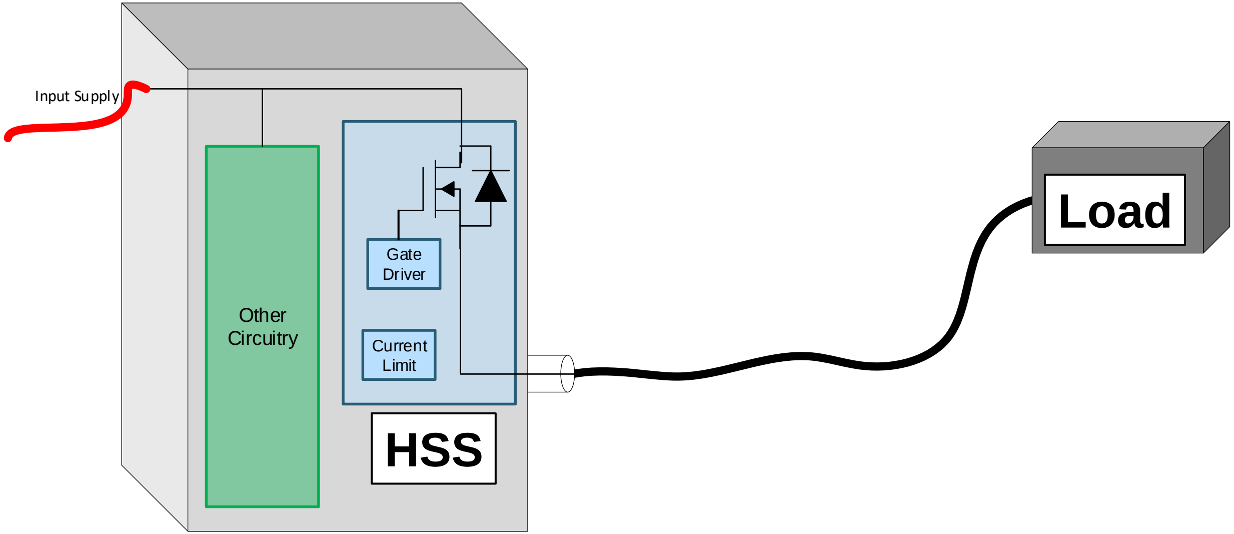
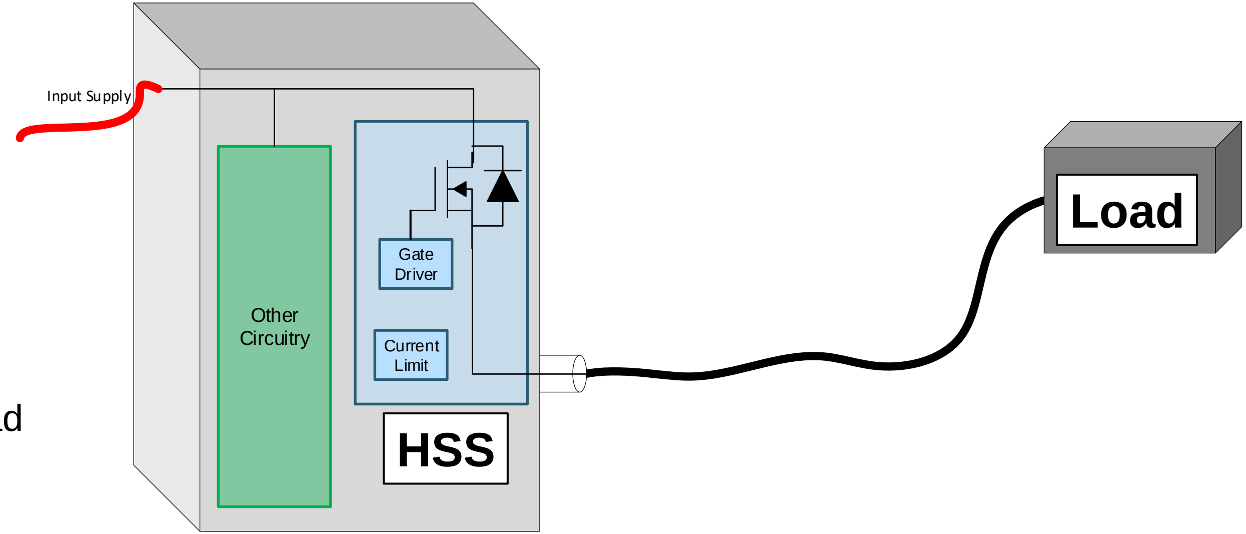
- Smart High-side switches are used anywhere where **output** power protection is required



Where do we use a smart High-side switch?

- Smart High-side switches are ON/OFF switches that sit on the high-side of the load
- Smart High-side switches are used anywhere where **output** power protection is required
- Any system powering an off-board load runs the risk of a load failure that the primary board cannot control
  - Short-Circuit
  - Load Current Overload
  - Inductive Kickback



High-side switches: Inside a wide range of industrial systems

Factory Automation and Control

Digital outputs provide power to sensors, motors, and valves throughout the factory floor

Motor Drives

Brakes, sensors, and general purpose I/O's communicate between the motor drive and the motor

Building Automation

Centralized building control systems distribute power to subsystems like fire, alarm, and HVAC systems.

Distributed Power Outputs

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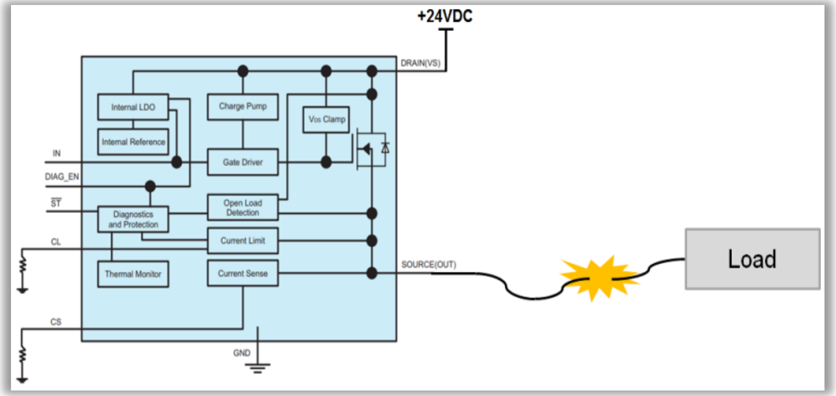
Smart High-side switch | Applications



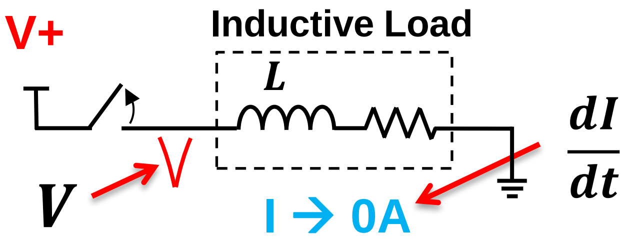
Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting

Short Circuit and **current limiting protection** improves system reliability and reduces system costs

Integrated **current sense** and **open-load detection** enables the detection and diagnosis of faults

High-side switch | Inductive load

Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting



- *As the current flows through the inductor, energy is stored in it according to $E=1/2LI^2$*
- *When the High-side switch opens, the current through the inductive load jumps from I to 0A*
- *An inductor wants to resist the change in current so a large negative voltage transient appears at the output of the switch according to the below equation*

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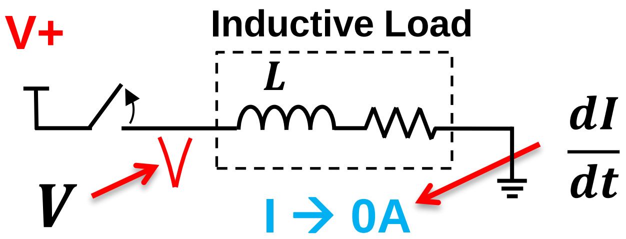

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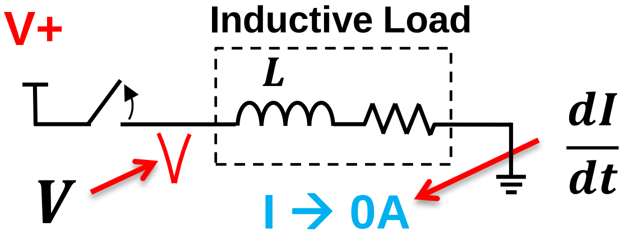

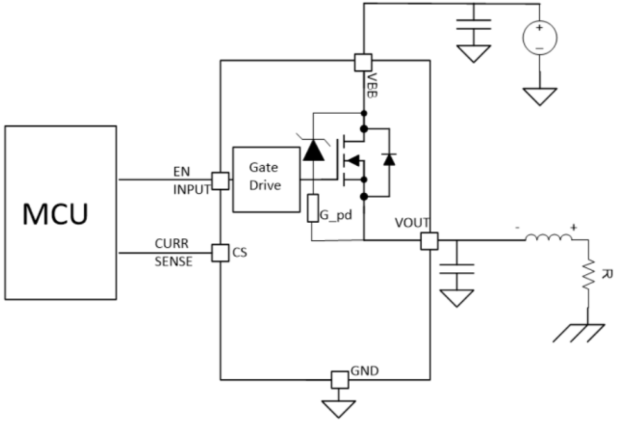

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What is the High-side switch's role in driving inductive loads?

- TI's smart High-side switches have an integrated VDS clamp which clamps the negative voltage swing to a safe level to prevent damage to its output.
- Depending on the load, it also helps to dissipate the energy stored in the inductive element by turning on its MOSFET and dissipating the energy through it.

High-side switch | Inductive load

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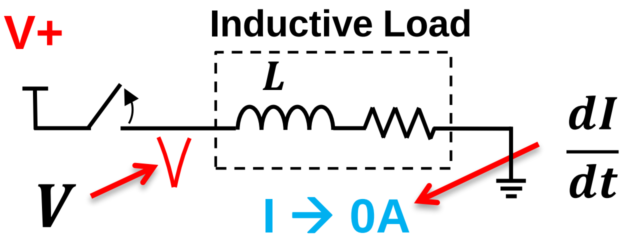

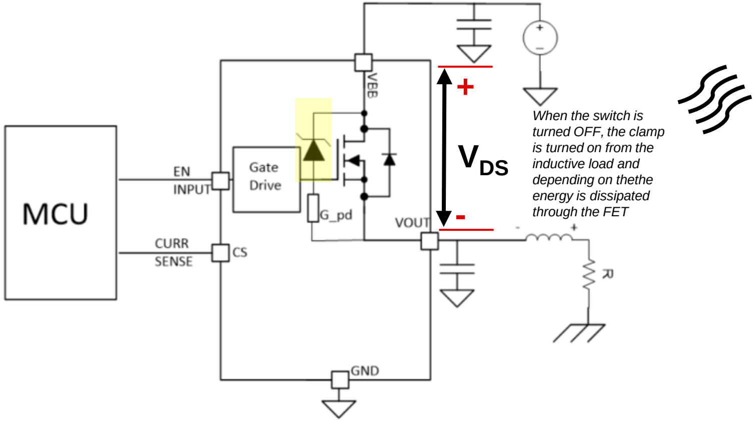

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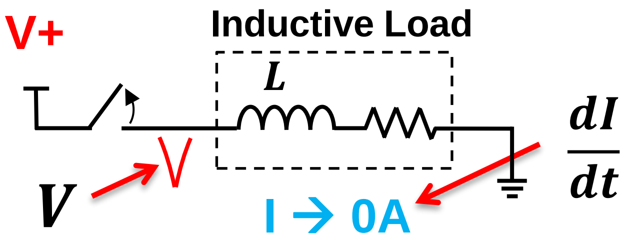

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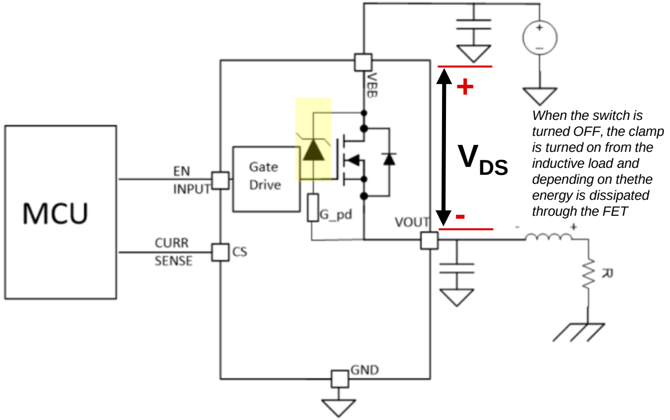

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High-side switch | Capacitive load

Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting

TI Smart High-side switches enable systems to limit the inrush current through the adjustable current limit I_{LIM}

Advantages:

- **High Reliability** – protects power supply during short circuit or inrush current, prevents upstream supply collapse
- **Lower System Costs** – Reduces the PCB trace and connector size as well as reduces the input power supply

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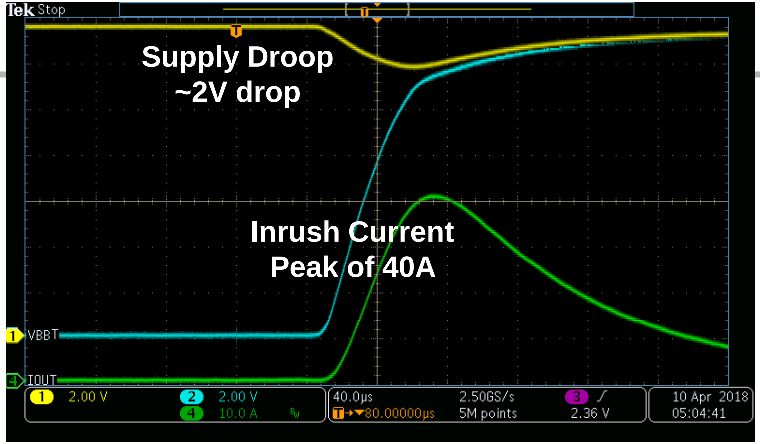
With no current limit, 330 µF charged to 13.5V creates significant supply droop.

During current limiting, the FET regulates the R_{DSON} to increase the V_{DS} and create a constant current source



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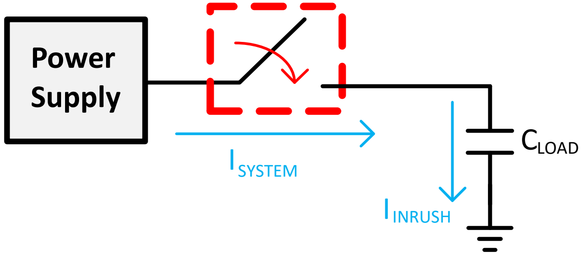

$$I_{SYSTEM} = I_{INRUSH} + I_{LOAD}$$

$$I_{INRUSH} \approx C_{LOAD} \times \frac{dV_{OUT}}{dt}$$

$I_{CL} = I_{INRUSH}$, *where* I_{CL} equals the current of the High-side switch

$$dt \approx C_{LOAD} \times \frac{V_{OUT}}{I_{CL}} \approx 2\,ms$$

The max charging current is set by the current limit (I_{INRUSH}=I_{CL}) , linearly charging the capacitor.

- Peak current from transient overshoot is limited to <4A due to the Smart High-side switch
- Lower charging current results in lower peak currents during inrush which minimizes supply droop and reduces component current handling requirements.
- Charging time is increased as a function of the lower current limit

High-side switch | Capacitive load

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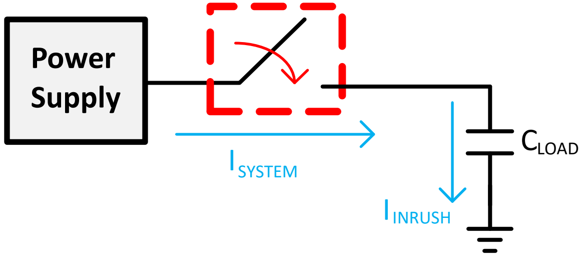

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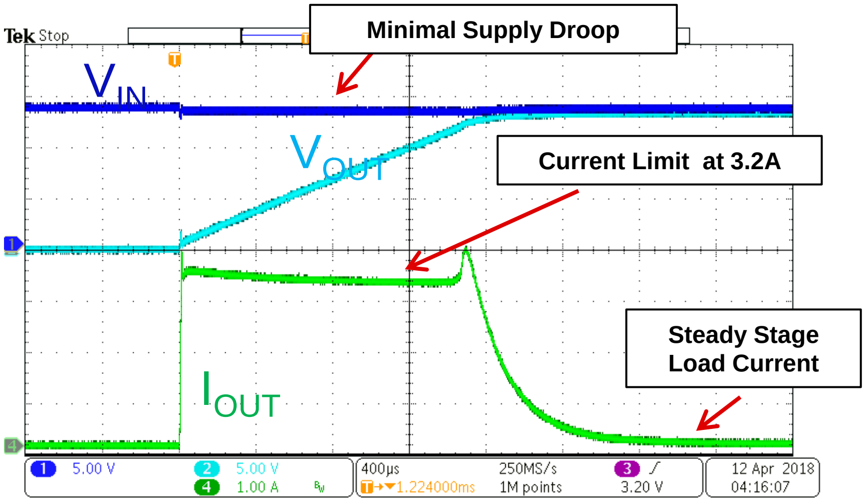
330 µF charged to 13.5V with 3.5A current limit



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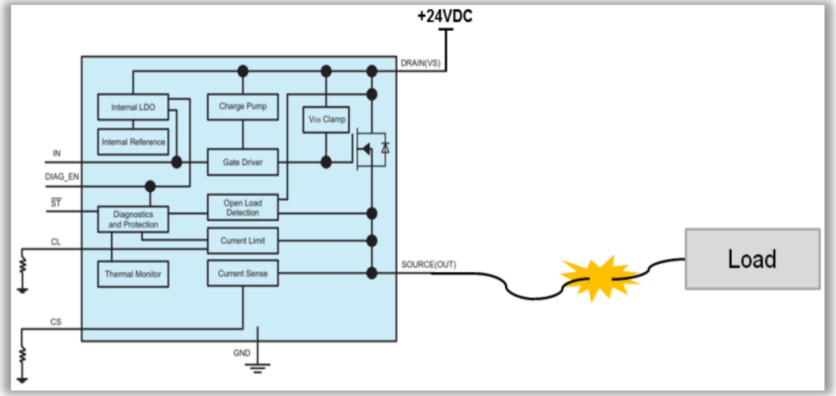
Smart High-side switch | Applications



Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting

Short Circuit and **current limiting protection** improves system reliability and reduces system costs

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High-side switch | Short circuit

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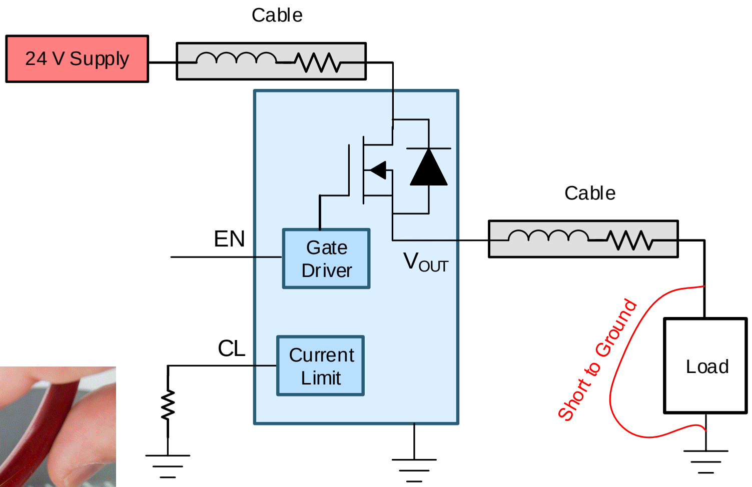

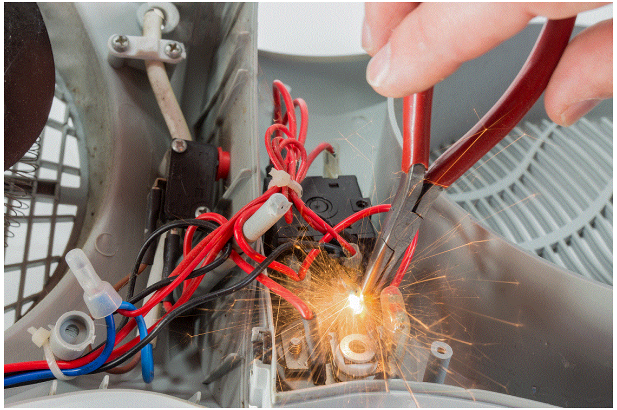

High-side switch | Current limit

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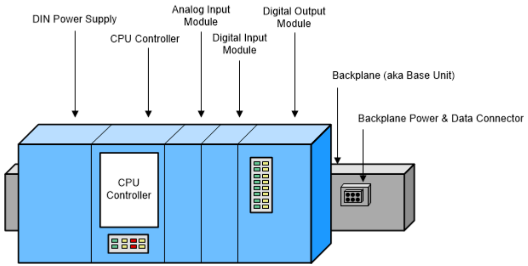

- Below are some technical specifications for an example digital output module

Parameter	Value	Unit
Voltage (typ)	24	V
# of Channels	16	-
I_{OUT}, per CH	0.5	A
Short-circuit threshold (typ)	1	A

- Picking power supply based on load current is insufficient in case of faults and overcurrent events

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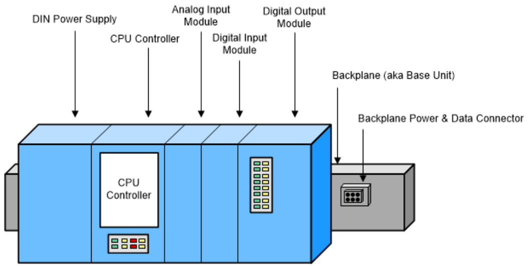

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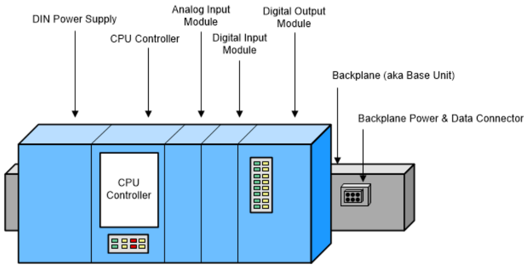

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Power Supply Output Current Requirements @ 24VDC			
Use cases	**# of channels**	**I_{OUT}, per CH (A)**	**Total I_{OUT} (A)**
Case #1 - nominal current	16	0.5	8
Case #2 - fault case	16	1	16
Case #2 - fault case **w/ TPS27S100**	16	0.75	12

High-side switch | User set CL

Short Circuit and **current limiting** improves system reliability and reduces system costs

How is I_{LIM} set?

An external resistor generates a reference current from an internal reference voltage that is compared to I_{LOAD}

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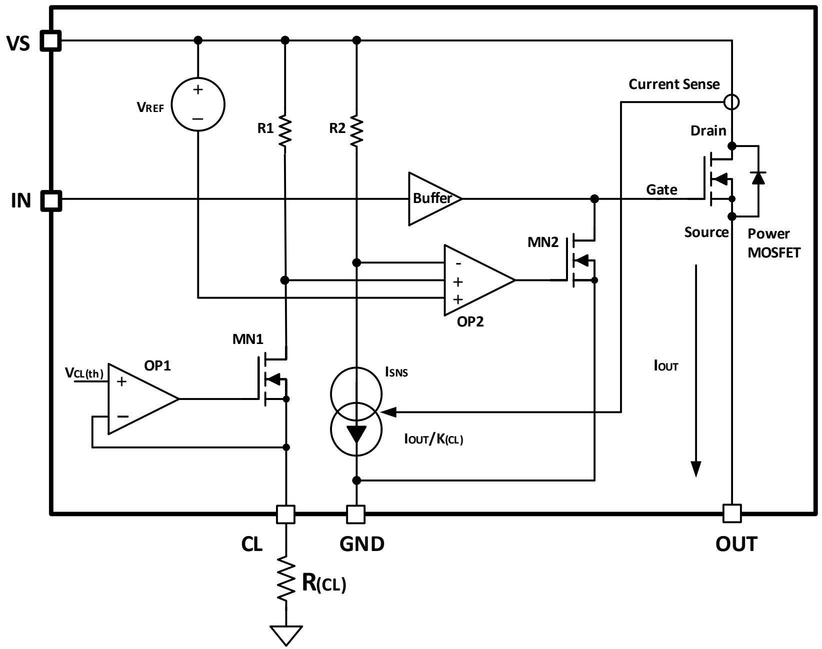

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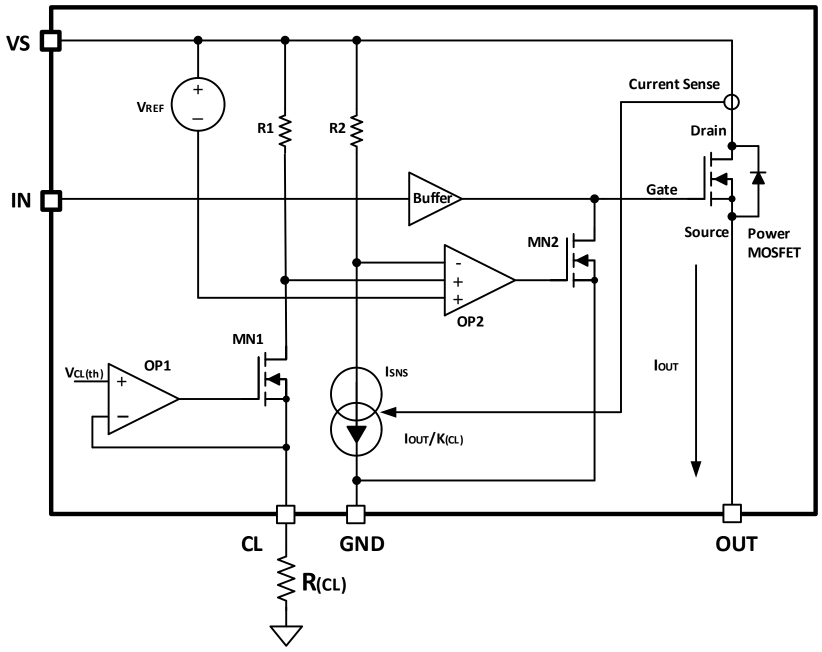
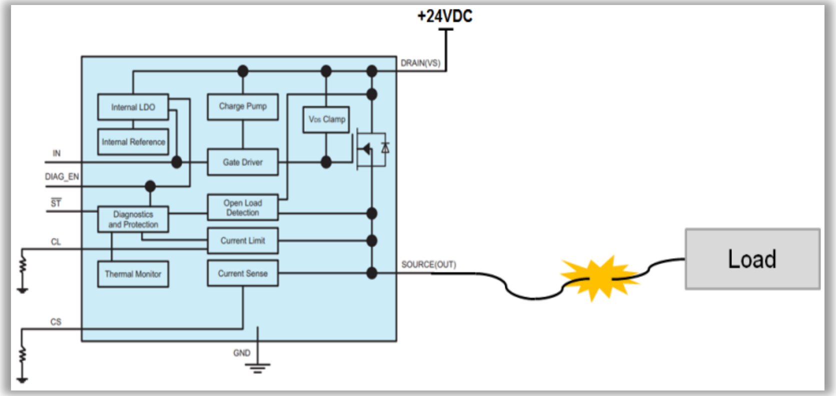
$$I_{CL} = \frac{V_{CL,th}}{R_{CL}} = \frac{I_{out,\lim}}{K}$$



High-side switch | Applications



Safe inductive and capacitive load driving through integrated clamp and adjustable current limiting

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Smart High-side switch | Diagnostics

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- Increasing safety and reliability requirements are driving the need for smarter outputs that can detect and respond to fault conditions

Smart High-side switch | Diagnostics

Integrated **current sense** and **open-load detection** enables the detection and diagnosis of faults

- Increasing safety and reliability requirements are driving the need for smarter outputs that can detect and respond to fault conditions
- Smarter outputs enable:
  - Reduce system downtime
  - Smart power management
- High-side switches integrate **load current sense and open load detection** functionality to meet requirements

Smart High-side switch | Diagnostics

Integrated **current sense** and **open-load detection** enables the detection and diagnosis of faults

– High-side switches can output multiple system variables to the system
  - Load Current
  - Temperature Sense
  - Supply Voltage Sense

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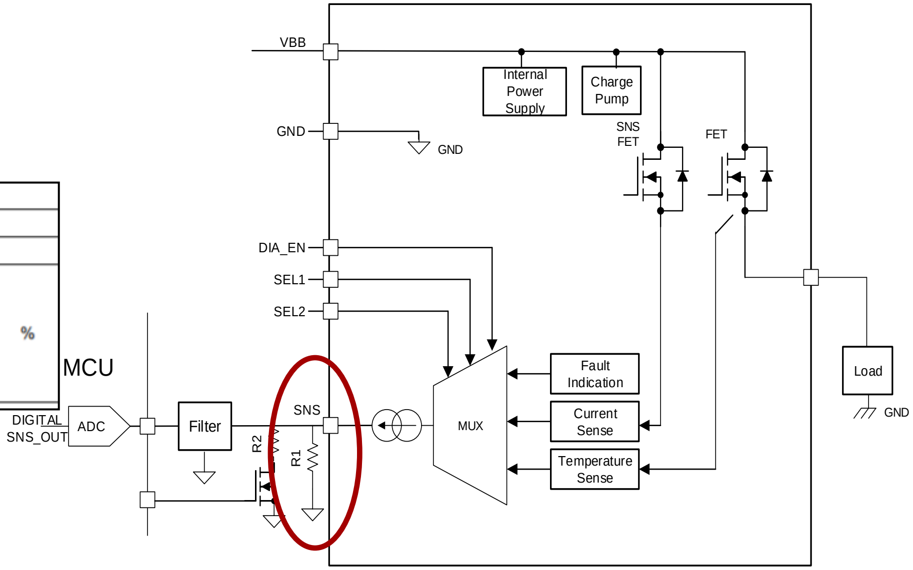
CURRENT MONITOR AND CURRENT LIMIT						
$K_{(IMON)}$	Current sense current ratio			500		
$K_{(ILIM)}$	Current limit current ratio			2000		
$dK_{(IMON)}/K_{(IMON)}$	Current-monitor accuracy	$I_{load} \geq 5$ mA	–80		80	%
		$I_{load} \geq 25$ mA	–12		12	%
		$I_{load} \geq 50$ mA	–8		8	%
		$I_{load} \geq 0.1$ A	–5		5	%
		$I_{load} \geq 1$ A	–3		3	%



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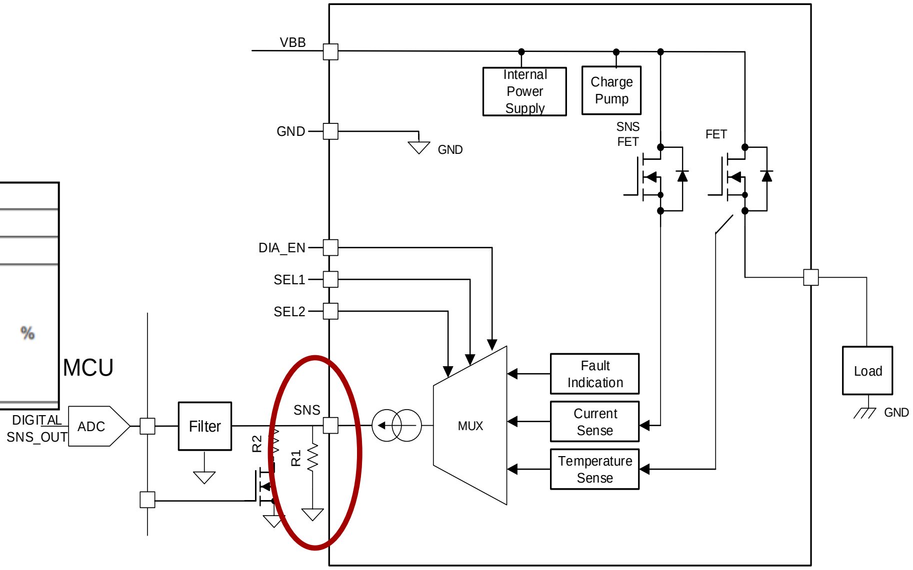
		$I_{load} \geq 25$ mA	–12		12	
		$I_{load} \geq 50$ mA	–8		8	
		$I_{load} \geq 0.1$ A	–5		5	
		$I_{load} \geq 1$ A	–3		3	



– Values are output as an analog current on the SNS pin

Smart High-side switch | Diagnostics

Integrated **current sense** and **open-load detection** enables the detection and diagnosis of faults

Open load detection enables detection of broken cables or mis-wiring conditions.

Smart High-side switch | Diagnostics

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Open load detection enables detection of broken cables or mis-wiring conditions.

On State Detection

If load current drops below the threshold in datasheet, the device will register a fault.

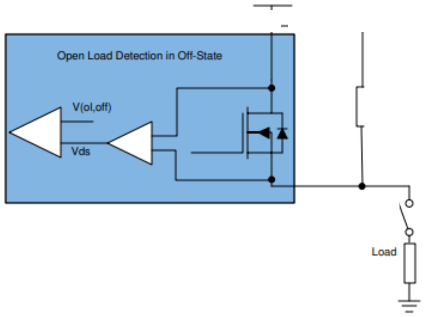


Figure 29. Open-Load Detection Circuit in Off-State

Iol,on Open load detection threashold in ON-state		2	5	8	mA
Tol,on Open load detection threshold deglitch time in on state		200	250	300	us

Smart High-side switch | Diagnostics

Integrated **current sense** and **open-load detection** enables the detection and diagnosis of faults

Open load detection enables detection of broken cables or mis-wiring conditions.

On State Detection

If load current drops below the threshold in datasheet, the device will register a fault.

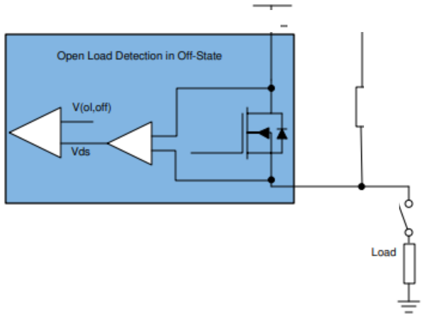


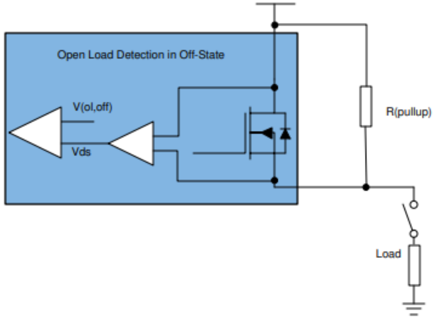
Figure 29. Open-Load Detection Circuit in Off-State

Iol,on Open load detection threashold in ON-state		2	5	8	mA
Tol,on Open load detection threshold deglitch time in on state		200	250	300	us

Off State Detection

Open Load Detection requires a pull up resistor on the output. If V_{OUT} > threshold the device recognizes that there is no load attached.

Choose pull-up resistor to overcome any pulldown including leakage other than the load. (A resistor divider for VOUT monitoring is shown)



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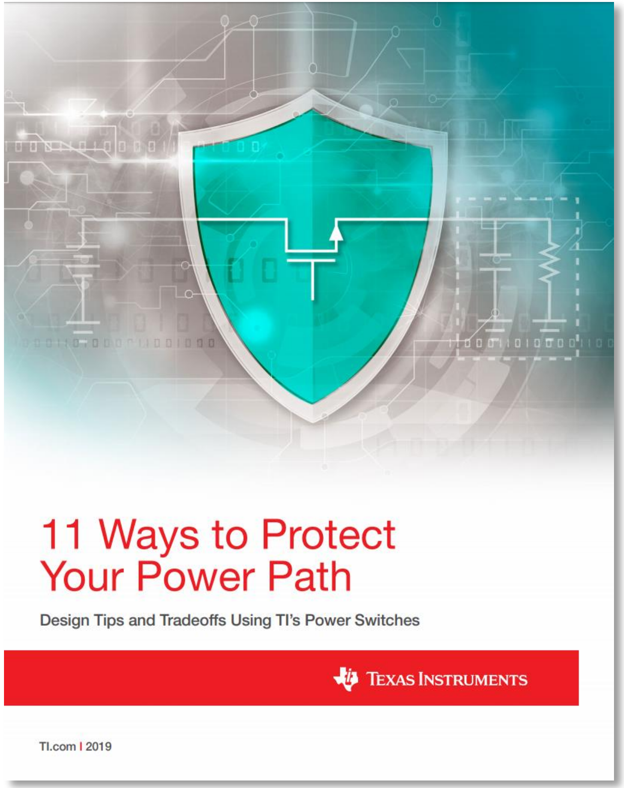

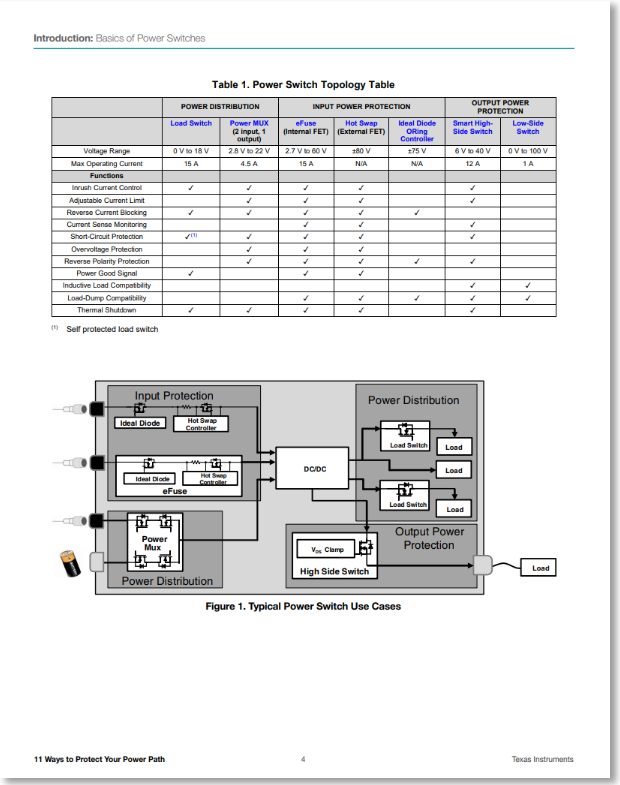

Introduction: Basics of Power Switches

Table 1. Power Switch Topology Table

	POWER DISTRIBUTION		INPUT POWER PROTECTION			OUTPUT POWER PROTECTION	
	Load Switch	Power MUX (2 input, 1 output)	eFuse (Internal FET)	Hot Swap (External FET)	Ideal Diode ORing Controller	Smart High-Side Switch	Low-Side Switch
Voltage Range	0 V to 18 V	2.8 V to 22 V	2.7 V to 60 V	±80 V	±75 V	6 V to 40 V	0 V to 100 V
Max Operating Current	15 A	4.5 A	15 A	N/A	N/A	12 A	1 A
Functions							
Inrush Current Control	✓	✓	✓	✓		✓	
Adjustable Current Limit		✓	✓	✓		✓	
Reverse Current Blocking	✓	✓	✓	✓	✓		
Current Sense Monitoring			✓	✓		✓	
Short-Circuit Protection	✓(1)	✓	✓	✓		✓	
Overvoltage Protection		✓	✓	✓			
Reverse Polarity Protection		✓	✓	✓	✓	✓	
Power Good Signal	✓		✓	✓			
Inductive Load Compatibility						✓	✓
Load-Dump Compatibility			✓	✓	✓	✓	✓
Thermal Shutdown	✓	✓	✓	✓		✓	

(1) Self protected load switch

Figure 1. Typical Power Switch Use Cases

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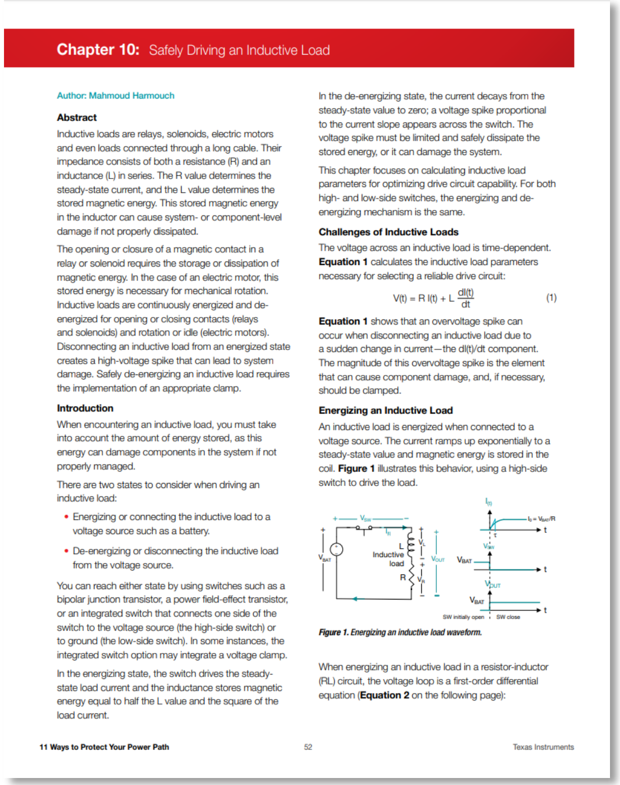

Chapter 10: Safely Driving an Inductive Load

Author: Mahmoud Harmouch

Abstract

Inductive loads are relays, solenoids, electric motors and even loads connected through a long cable. Their impedance consists of both a resistance (R) and an inductance (L) in series. The R value determines the steady-state current, and the L value determines the stored magnetic energy. This stored magnetic energy in the inductor can cause system- or component-level damage if not properly dissipated.

The opening or closure of a magnetic contact in a relay or solenoid requires the storage or dissipation of magnetic energy. In the case of an electric motor, this stored energy is necessary for mechanical rotation. Inductive loads are continuously energized and de-energized for opening or closing contacts (relays and solenoids) and rotation or idle (electric motors). Disconnecting an inductive load from an energized state creates a high-voltage spike that can lead to system damage. Safely de-energizing an inductive load requires the implementation of an appropriate clamp.

Introduction

When encountering an inductive load, you must take into account the amount of energy stored, as this energy can damage components in the system if not properly managed.

There are two states to consider when driving an inductive load:

- Energizing or connecting the inductive load to a voltage source such as a battery.
- De-energizing or disconnecting the inductive load from the voltage source.

You can reach either state by using switches such as a bipolar junction transistor, a power field-effect transistor, or an integrated switch that connects one side of the switch to the voltage source (the high-side switch) or to ground (the low-side switch). In some instances, the integrated switch option may integrate a voltage clamp.

In the energizing state, the switch drives the steady-state load current and the inductance stores magnetic energy equal to half the L value and the square of the load current.

In the de-energizing state, the current decays from the steady-state value to zero; a voltage spike proportional to the current slope appears across the switch. The voltage spike must be limited and safely dissipate the stored energy, or it can damage the system.

This chapter focuses on calculating inductive load parameters for optimizing drive circuit capability. For both high- and low-side switches, the energizing and de-energizing mechanism is the same.

Challenges of Inductive Loads

The voltage across an inductive load is time-dependent. **Equation 1** calculates the inductive load parameters necessary for selecting a reliable drive circuit:

$$V(t) = R\,I(t) + L\,\frac{dI(t)}{dt} \qquad (1)$$

Equation 1 shows that an overvoltage spike can occur when disconnecting an inductive load due to a sudden change in current—the dI(t)/dt component. The magnitude of this overvoltage spike is the element that can cause component damage, and, if necessary, should be clamped.

Energizing an Inductive Load

An inductive load is energized when connected to a voltage source. The current ramps up exponentially to a steady-state value and magnetic energy is stored in the coil. **Figure 1** illustrates this behavior, using a high-side switch to drive the load.

Figure 1. Energizing an inductive load waveform.

When energizing an inductive load in a resistor-inductor (RL) circuit, the voltage loop is a first-order differential equation (**Equation 2** on the following page):

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