Designing Smart High Side Switch Solutions

Driving, Protecting, and Diagnosing Loads

Systems Training

Alec Forbes

Detailed Agenda

- Introduction to Smart High Side Switches
  - Functional Block Diagram
  - Applications
  - Features and Diagnostics

- Challenges for different load profiles
  - Resistive loads
  - Bulb Loads
  - Capacitive loads
  - Inductive Loads
- TI Resources
- Summary

Power Switches Overview

Load Switches
Power Distribution & Savings

Benefits
- Extends battery life
- Simplifies power sequencing
- Mitigates inrush current damage
- Saves space & reduces solution size
- Inrush current control

Product Families
- Non-current / Current Limited
- Power Mux
- Solid State Relays

Sectors/EE’s
- Industrial PC cards
- Industrial PCs
- PLC, power sequencing

www.ti.com/LoadSwitch

eFuse
Input Power Protection

Benefits
- Protects against under/over-voltage, over-current, and inrush events
- Maximizes equipment uptime & reduces maintenance costs
- Prevents failure during hot-plugging, hot-swapping & transient events
- Faster time to market – UL recognized

Product Families
- > 40V eFuse
- < 30V eFuse
- Hot Swap Controllers
- Ideal Diode Controllers

Sectors/EE’s
- PLC
- Factory Automation
- Motor Drives

www.ti.com/eFuse

Smart High Side Switches
Output Power Protection

Benefits
- Increased reliability against short-circuit
- Accurate, real-time load diagnostics
- Drive inductive loads like solenoids, relays

Product Families
- Smart High Side (HS) Switch

Sectors/EE’s
- Remote I/Os
- Digital I/Os
- CNC controllers
- Motor Drives

www.ti.com/HighSideSwitch

ESD & Surge
Port Protection

Benefits
- Meets or exceeds the maximum specified level in the IEC 61000-4-x standard
- Packages are 80-90% smaller than that of the competition
- Low leakage provides better fidelity

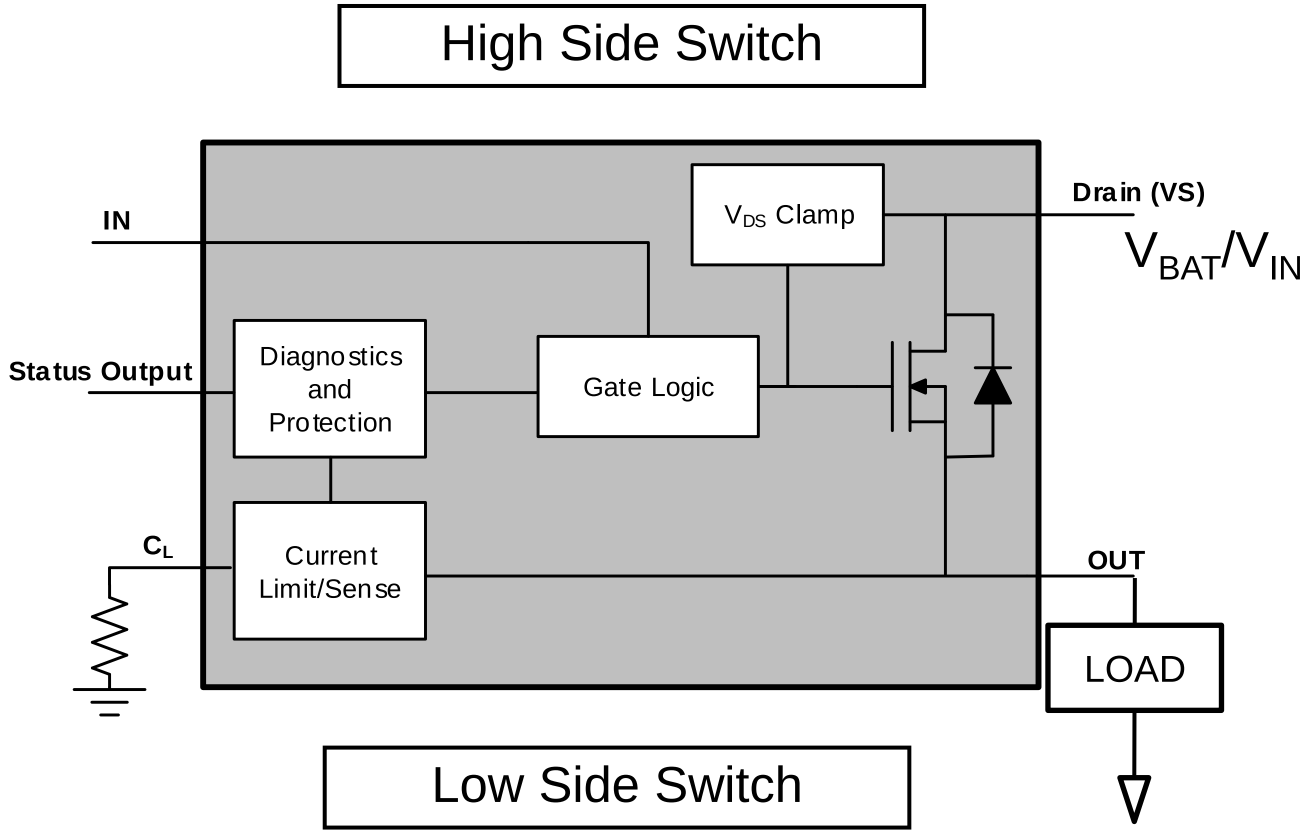
Product Families
- Flat-clamp TVS
- ESD port protection

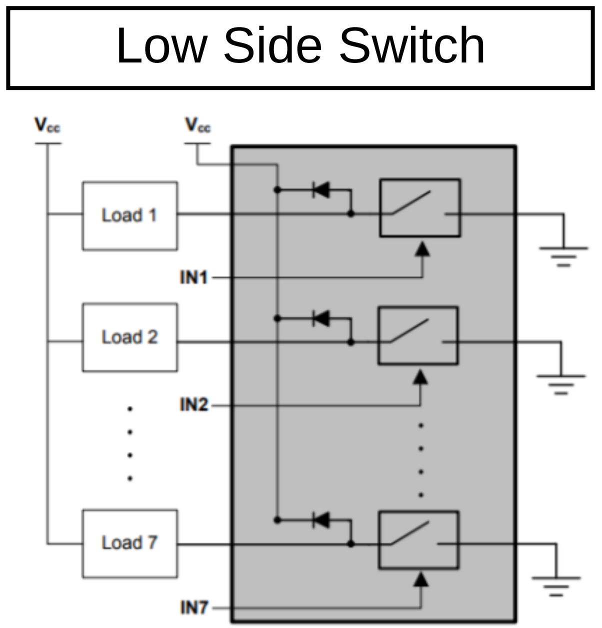
Sectors/EE’s
- Appliances
- Building Automation
- Grid Infrastructure
- Body Electronics & Lighting

http://www.ti.com/esd

Smart High Side Switch

- A **high-side switch** is a power management device that connects to a battery input and switches on/off downstream loads and protects against short circuit and other faults
- A **low-side switch** is a power management device that connects from the load and switches on/off to ground
- High-side switch is preferred due to improved protection, as constant load current can be avoided when a short to ground at the load occurs

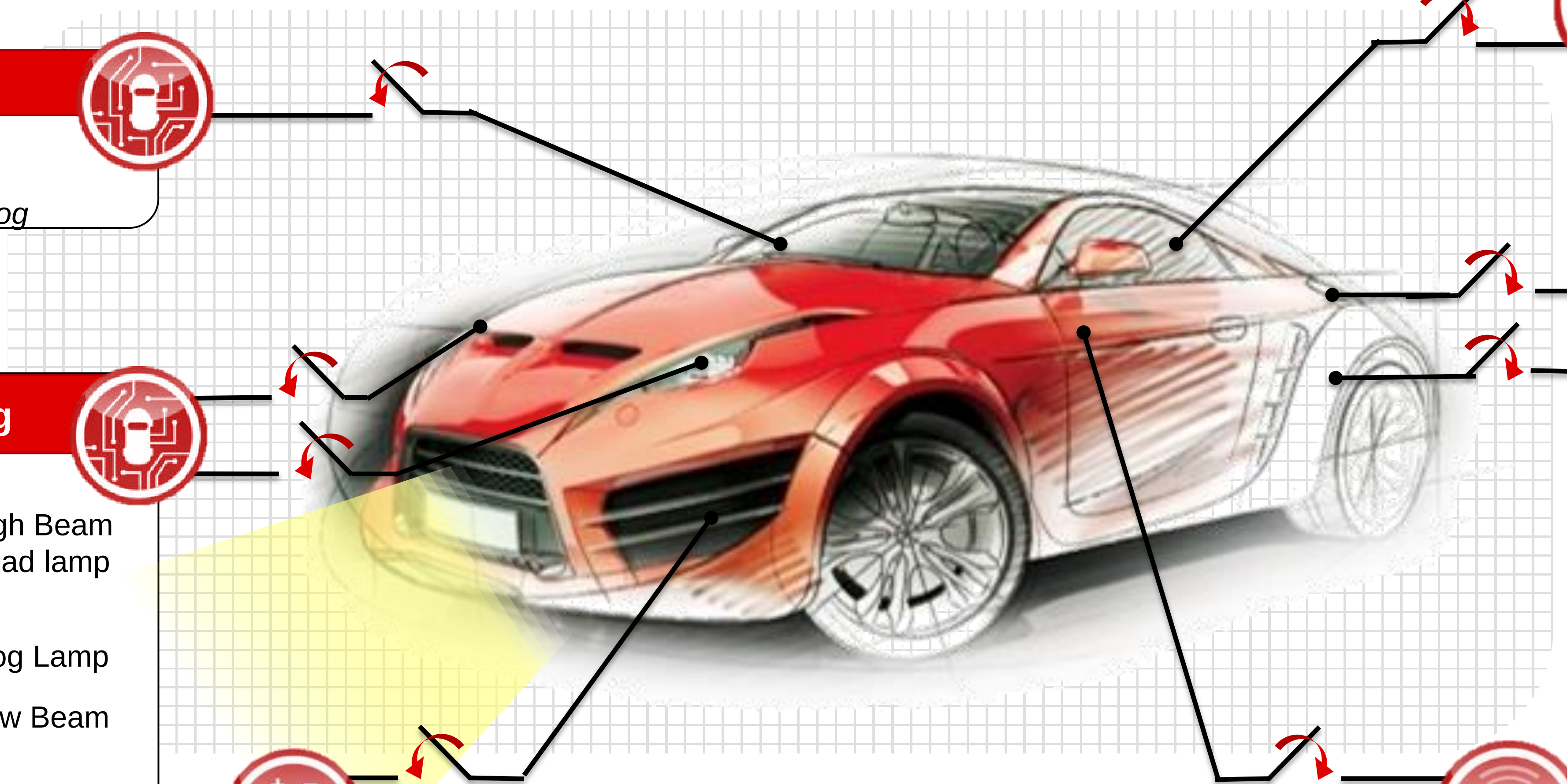




Learn More: Basics of Power Switch App Note

Smart High Side Switch Solutions

Power ON from headlights to taillights and everything in between



Seat Heating

TPS1HA08-Q1
40V, 8 mΩ, 1-ch
Integrated Watchdog

Front Lighting

65W Loads
TPS1HA08-Q1
TPS1/2HB08-Q1
High Beam Head lamp

55W Loads
TPS1/2HB08-Q1
Fog Lamp
Low Beam

27W Loads
TPS1/2HB16-Q1
TPS1/2HB35-Q1
Parking Light
Signal Turn Indicators

Powertrain Transmission

TPS1HA08-Q1
40V, 8mΩ, 1-ch
High accuracy current sense

ADAS

TPS4H000/TPS4H160-Q1
40V, 1Ω/160mΩ, 4-ch
Adjustable Current Limit

Infotainment/Cluster

TPS1H100-Q1
40V, 100mΩ, 1-ch
Adjustable current limit

Rear Lighting

Third Stop Lamp
Stop Lamp
Reverse Lamp
Fog Lamp
Signal Turn Indicators

27W Loads
TPS1/2HB16-Q1
TPS1/2HB35-Q1

21W Loads
TPS1/2HB35-Q1
TPS1/2HB50-Q1

Tail Light
License Plate Light

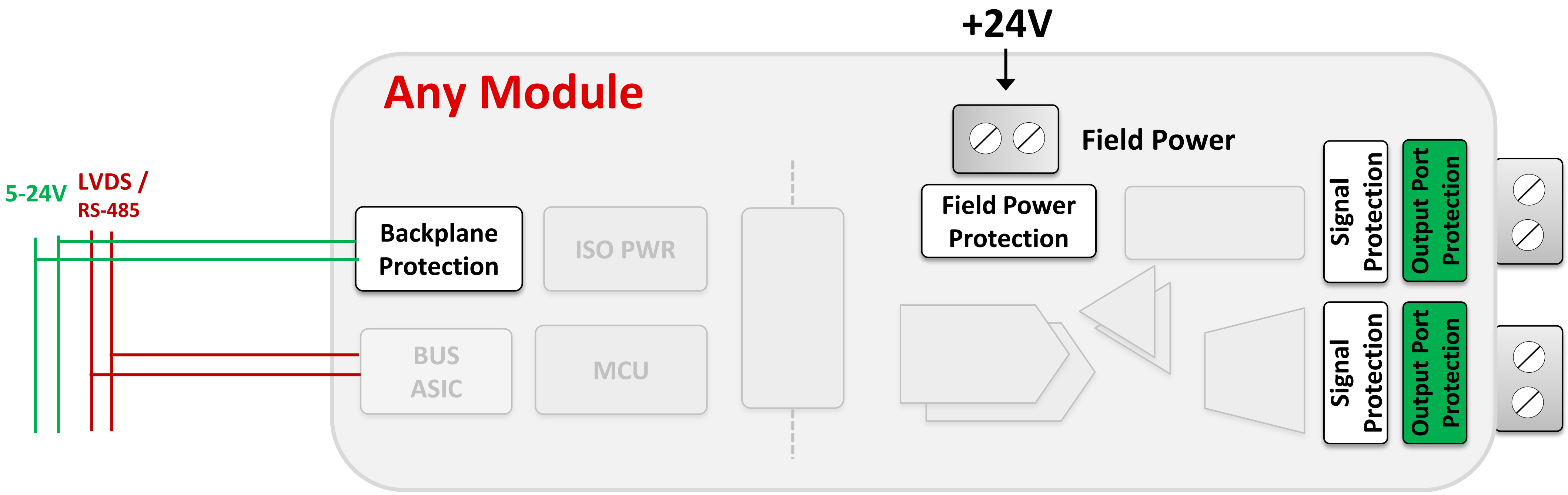
10W/5W Loads
TPS1H100B-Q1
TPS2/4H160B-Q1

Int. Lighting LEDs

LEDs and Relays
TPS1/2/4H000-Q1

Smart High Side Switches in Industrial Applications

- Smart High Side Switches provide protection for outputs in **any given factory automation module (PLC, DCS, CNC, etc…)**
  - 24V Digital Output
  - 24V Analog Output
  - Sensor Supply for Analog/Digital Input



Module Type	Device	Description
≤ 100mA	TPS4H000	**4-CH, 40V, 1Ω**, TSSOP
≤ 500mA	TPS4H160	**4-CH, 40V, 160mΩ,** TSSOP
	TPS27S100	**1-CH, 40V, 100mΩ,** TSSOP, *UL cert pend.*
≤ 1A	TPS27S100	**1-CH, 40V, 100mΩ,** TSSOP, *UL cert pend.*

*** = Sampling Now*

Smart High Side Switch Features

TI Smart High Side Switch Features

– Smart High-Side Switches | Overview | TI.com

High accuracy current sensing

Integrated current sense accuracy enables real-time monitoring for open-load and short-to-battery detection without any calibration needed, ultimately reducing production cost and test time.

Select your device

Adjustable current limit for targeted protection

Smart High-Side Switches from TI protect against Short-to-GND and short-circuit events through the flexibility to select current limit values for targeted thresholds. This also allows you to reduce PCB traces and connector sizes to lower system cost.

Select your device

Robust automotive solutions

TI's experts have designed solutions to meet the rigorous requirements of the automotive standards: AEC-Q100 ISO7637 ISO16750

Select your device

Current Sense Accuracy

Highest Accuracy Current Sense

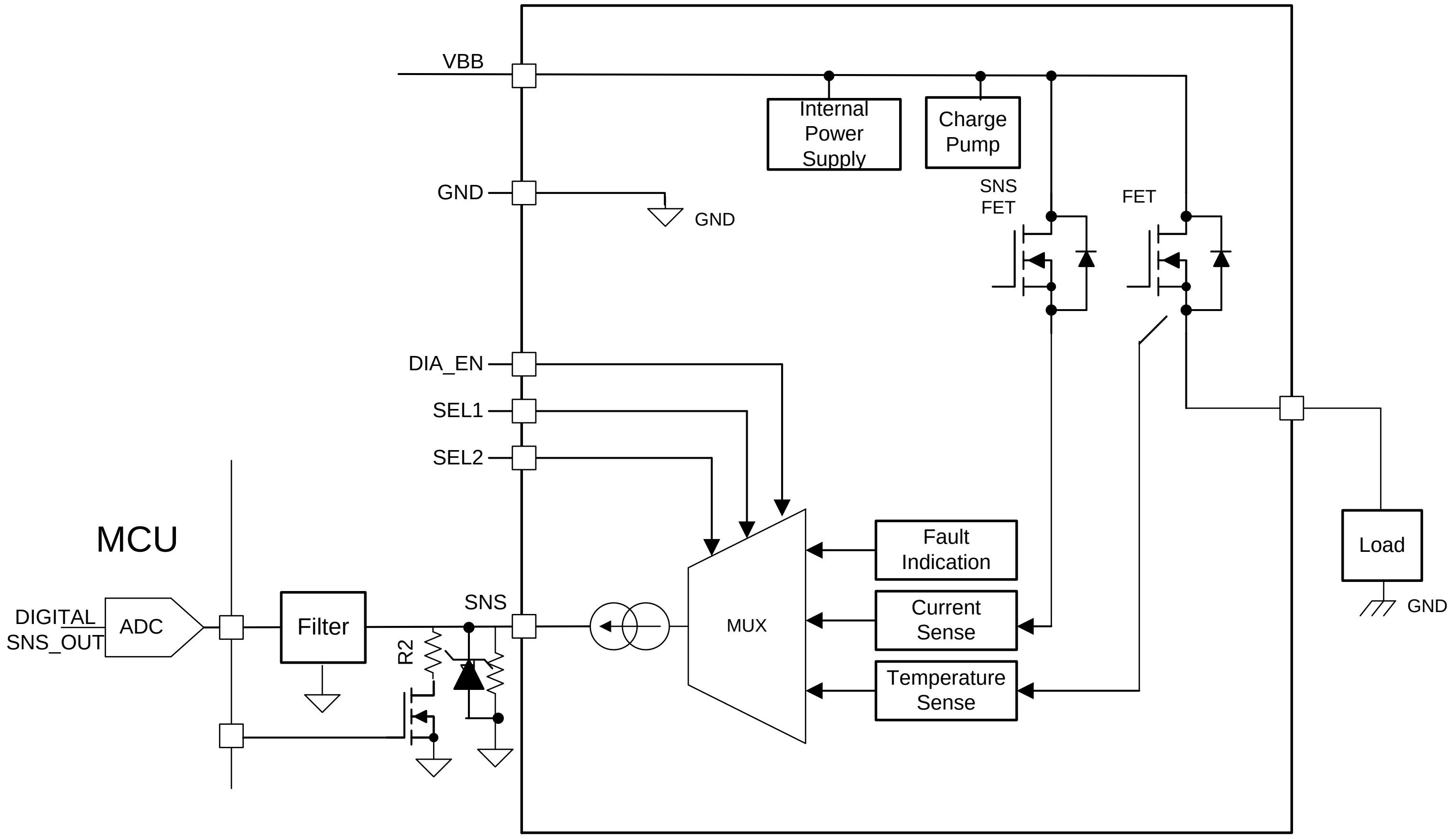
- ✓ Accurate, real-time load diagnostics even in light loads (such as LEDs)
- ✓ Reduce system cost - eliminates the need for current sense calibration
- ✓ Enables predictive maintenance by looking for slow current creeps

- Sensed load current is calculated by

$$I_{OUT} = \frac{V_{SNS}}{R_{SNS}} I_{SNSR}(1 + \varepsilon(T, IOUT))$$

Where $\varepsilon(T, IOUT)$ is residual error

- In addition to load current, FET Temperature can also be sensed by configuring SELx pin.
- High accuracy current sense at allows open load detection by measuring change in current flow.
- I_{SNSR} is calibrated in device production test at 25°C and offset correct to improve low current accuracy
- Accuracy specified in datasheet is+/-4% for I_{OUT} >1A and +/-10% for I_{OUT} = 300mA, over temperature and process.

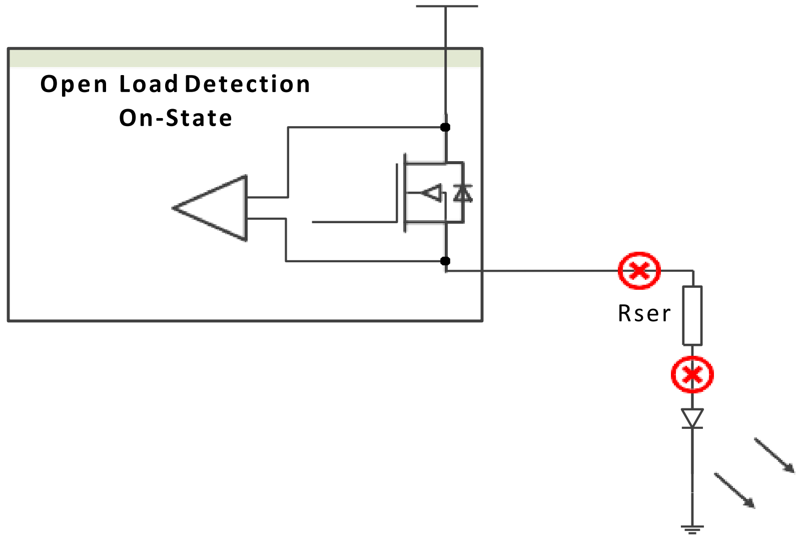


Load Diagnostics – Open Load Diagnostics

Open Load detection enables detection of broken cables or miswiring conditions. TI Smart High Side Switches provide both off state and off state open load detection

On State Detection

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

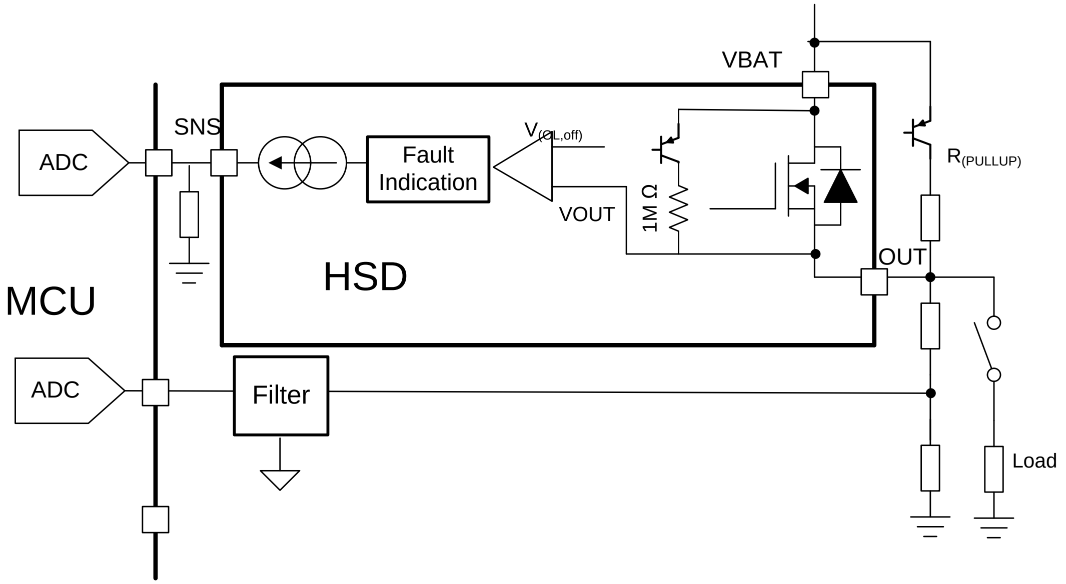


Iol,on Open load detection threashold in ON-state		2	5	8	mA
Tol,on Open load detection threshold deglitch time in on state		200	250	300	us

Off State Detection

Open Load Detection requires DIA_EN pin high and 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)

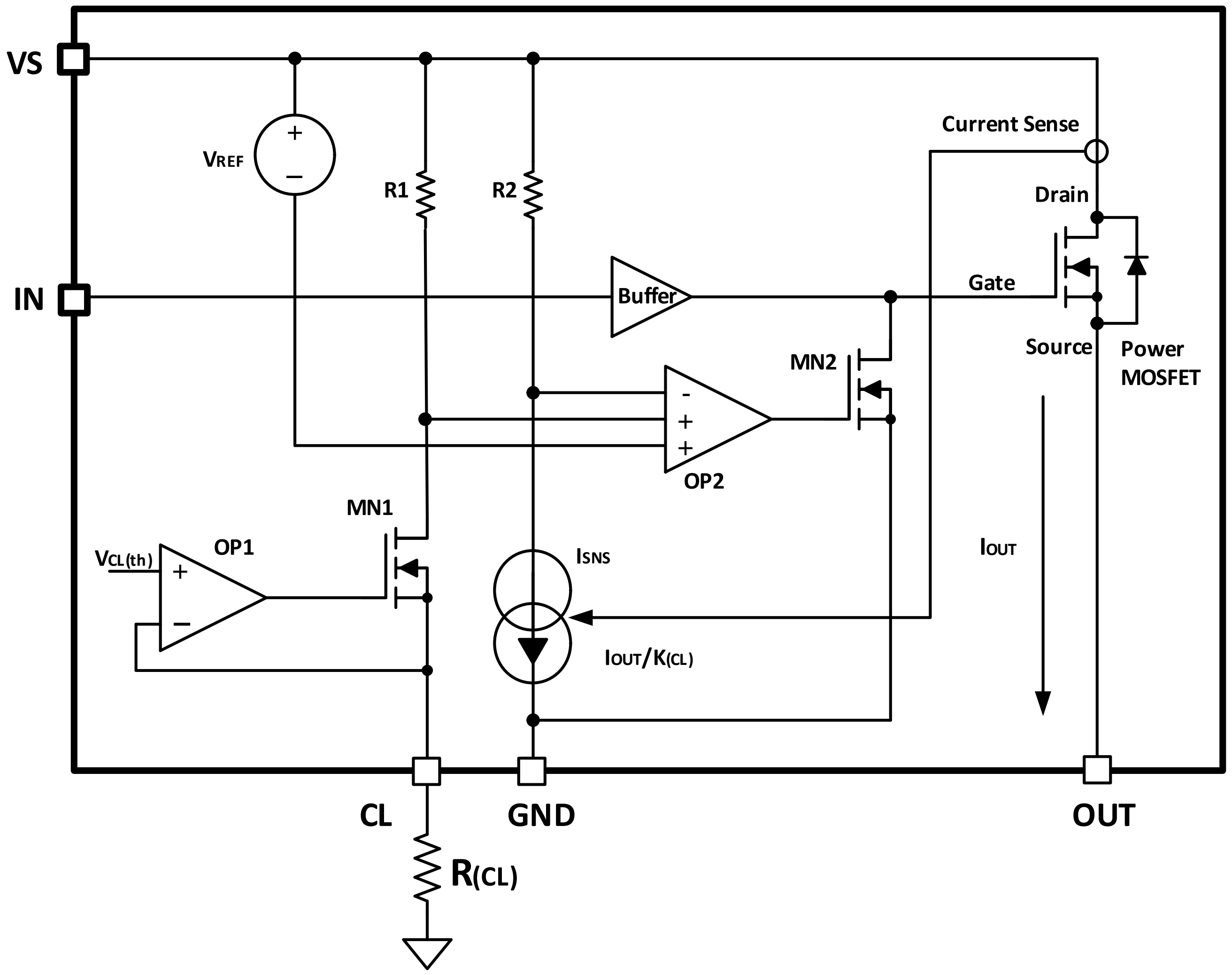


Adjustable Current Limit

1. An external resistor is used to generate a threshold reference current based on a reference voltage.
2. A current proportional to the load current is created and compared against the threshold reference.
3. When the proportional current exceeds the threshold, the current is clamped at the current limit threshold.

The current limit is implemented by the FET regulating the RDSON to increase the VDS and create a constant current source

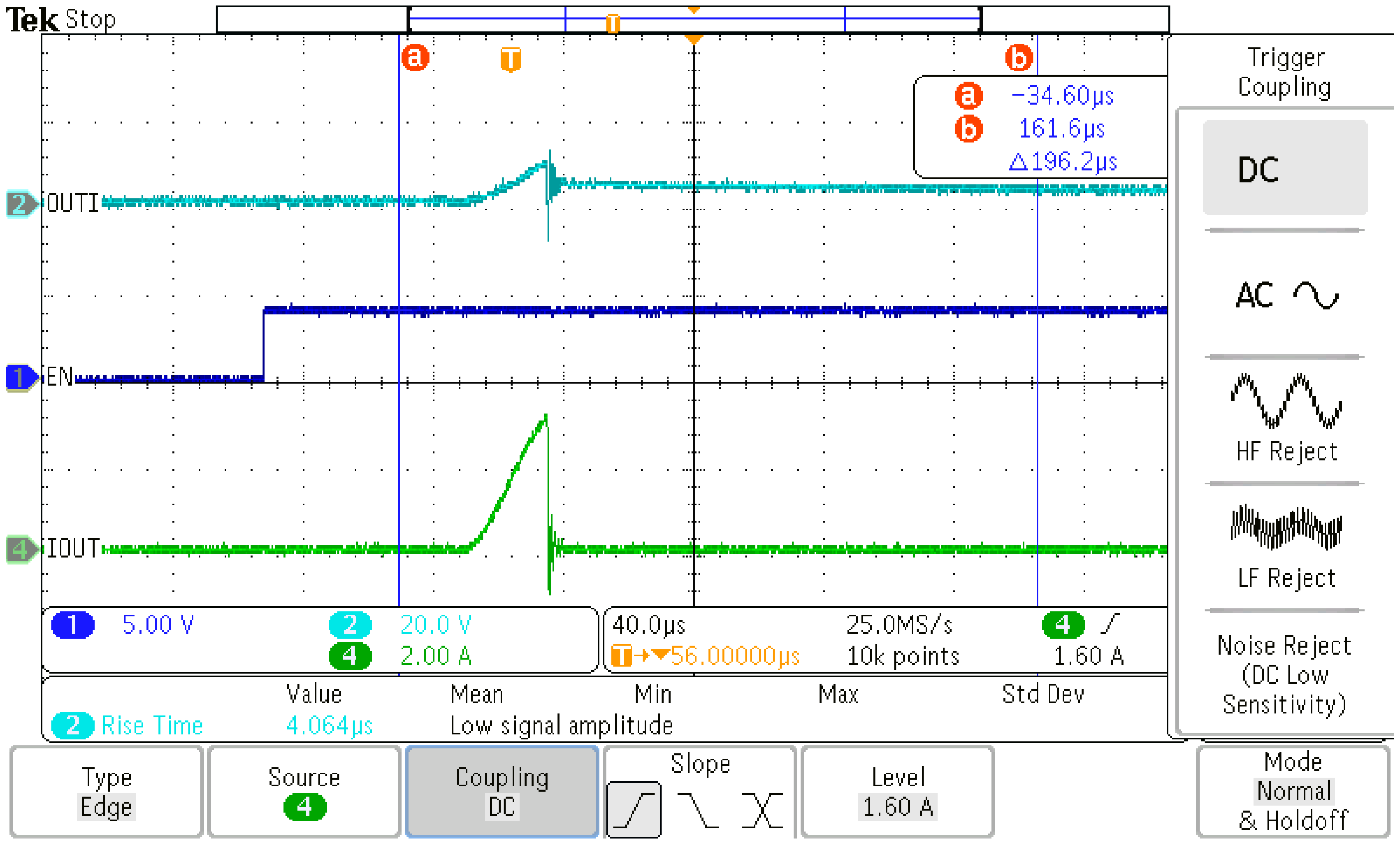
$$I_{CL} = \frac{V_{CL,th}}{R_{CL}} = \frac{I_{out,\lim}}{K}$$



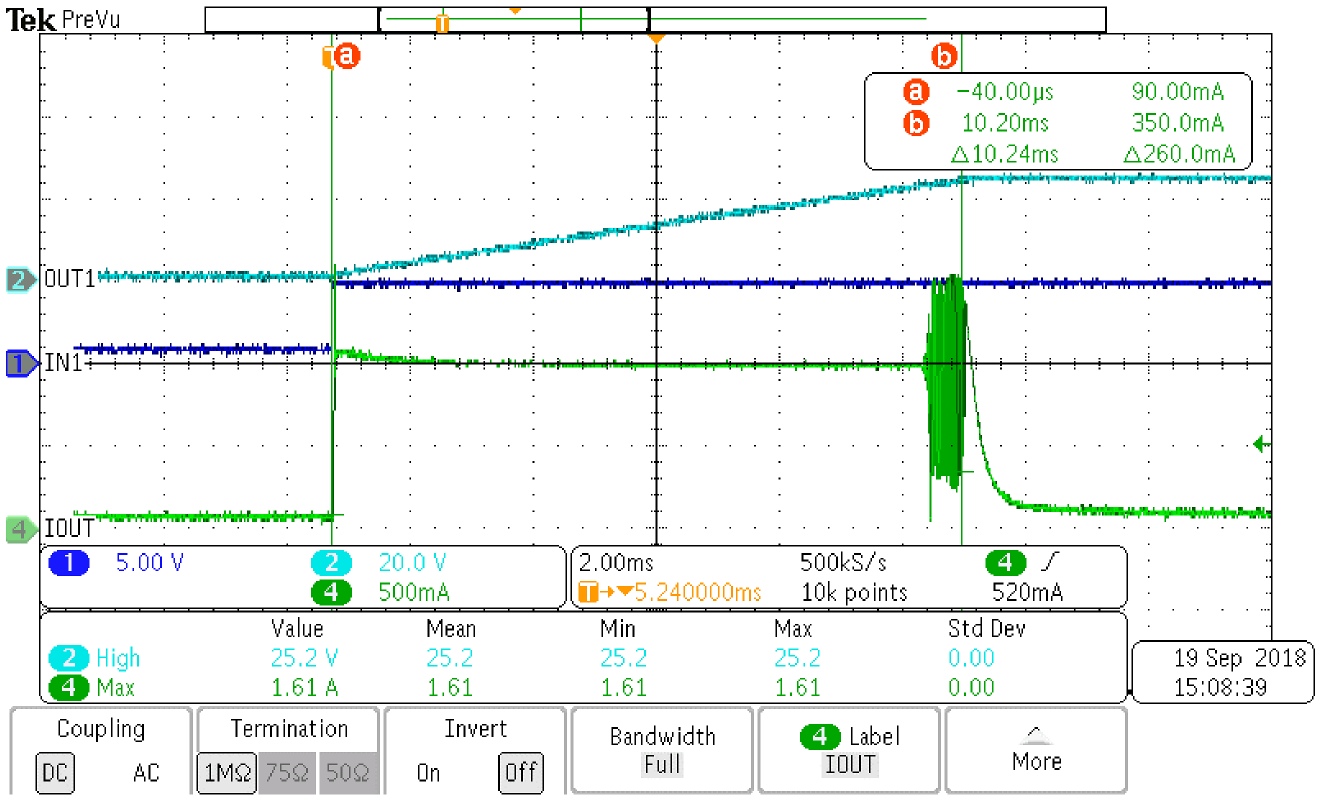
Adjustable Current Limit

TI devices all include an adjustable low current limit so that the device can better meet system requirements
Advantages:

- High Reliability – protects power supply during short circuit or inrush current
- Predictive Maintenance – Protects against slow current creep failures
- Lower System Costs – Reduce PCB trace and connector size as well as input power stage robustness



Circuit Breaker Mode

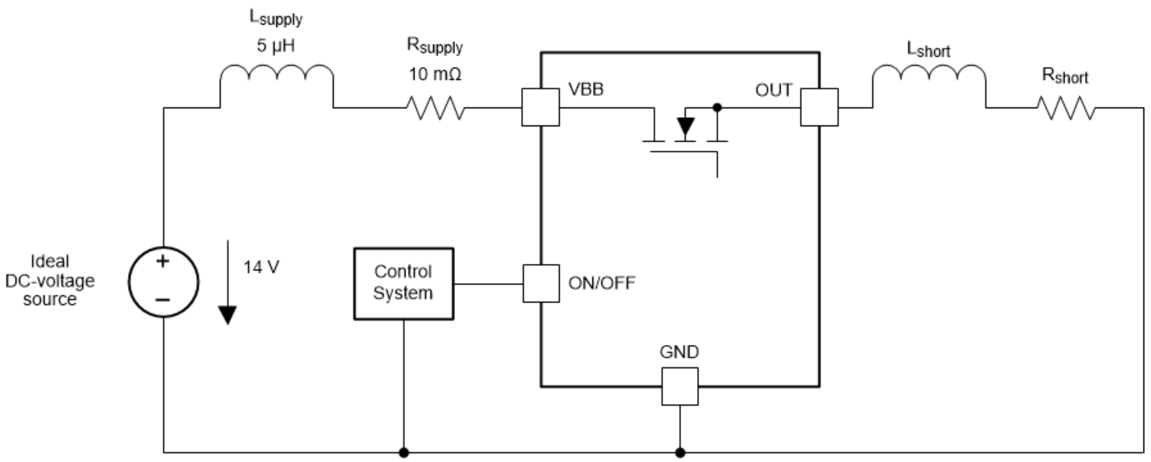


Current Clamping Mode

AEC Q100-012 Short Circuit Testing

AEC Q100 mandates protection against output short circuits, including input and output parasitic elements modeling a cable. All TI Smart Power Switches are tested according to these standards

Test Item	Sample Size	Test Cycles
Cold Repetitive Short Circuit Test - Short Pulse	-40C, 10ms EN pulse, cool down.	1 Million
Cold Repetitive Short Circuit Test - Long Pulse	-40C, 300ms EN pulse, cool down	1 Million
Hot Repetitive Short Circuit Test	25C, keeping short	1 Million



Short Circuit at the load

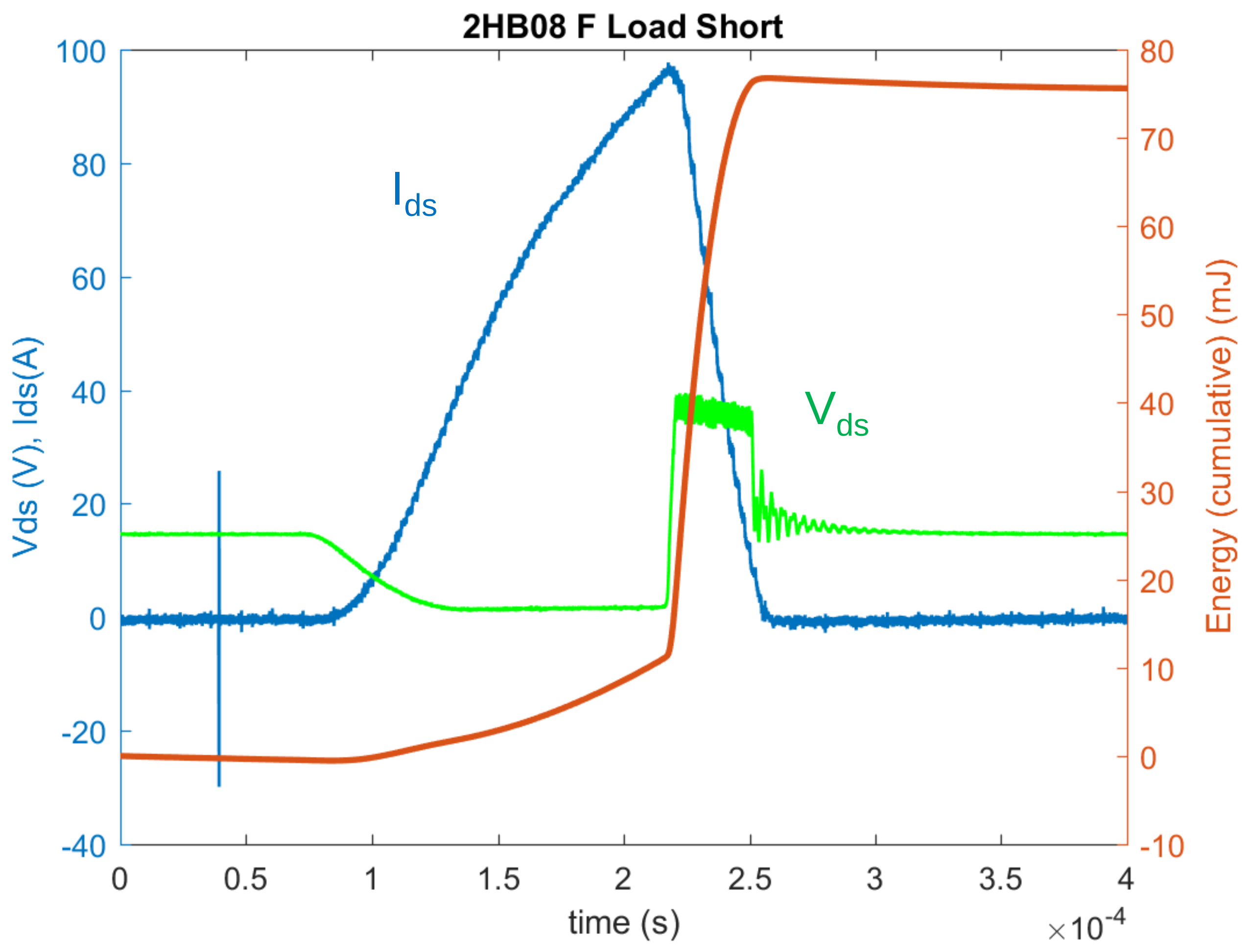
- R_{SHORT} = 50 mΩ
- L_{SHORT} = 5 uH

Cable inductance stores energy which makes the short more challenging to survive

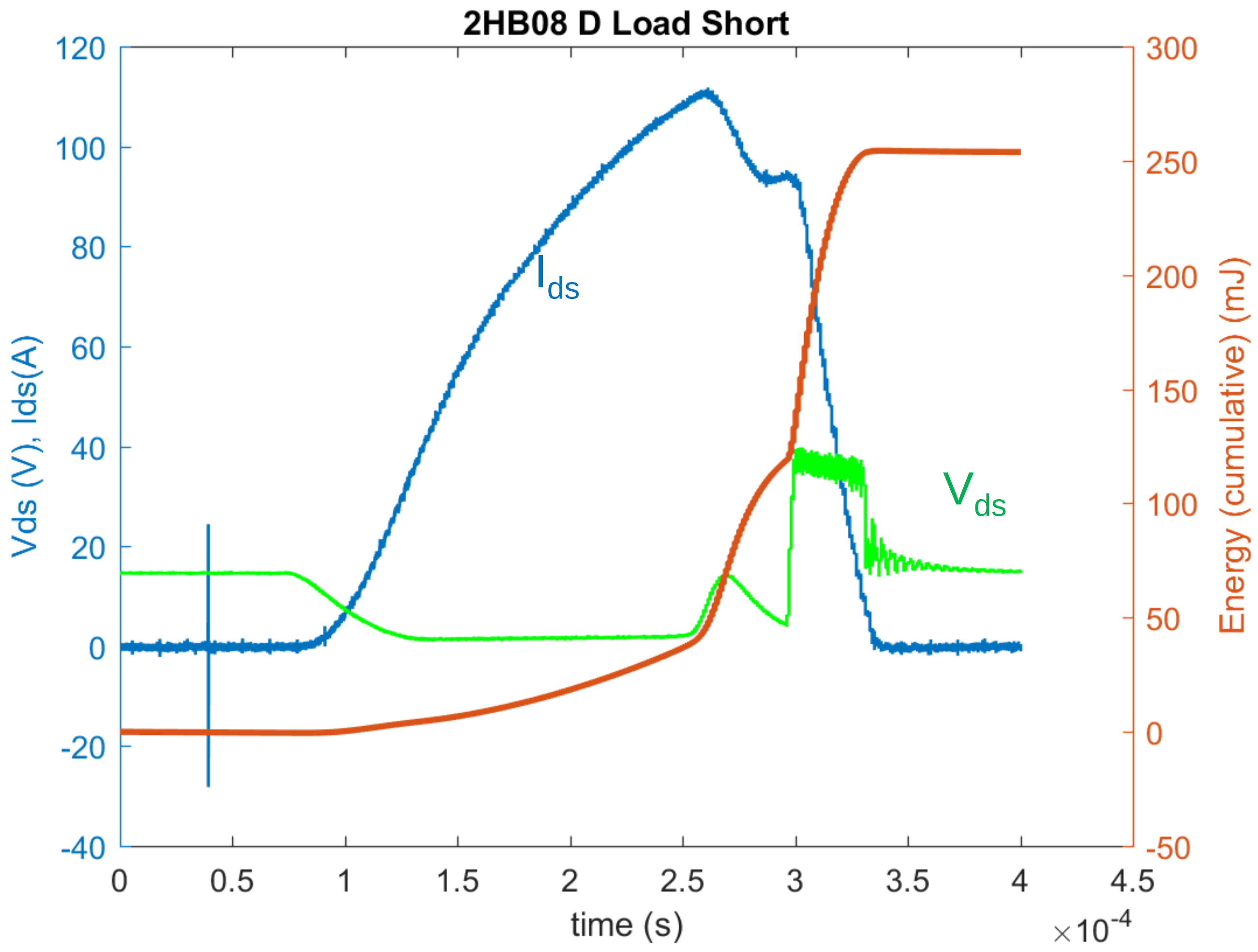
Learn More: Short-Circuit Reliability Test App Note

Smart High Side Switch behavior during Short Circuit

Circuit Breaker



Current Limiting Regulation



Lower energy on 5 µH inductive short with circuit breaker mode than regulation mode.

AEC Q100-012 Grade A

Table 2: Cycle Capability Grades

Grade	# Cycles	Lots/Samples per lot	# Fails
A	>1,000,000	3/10	0
B	>300,000 – 1,000,000	3/10	0
C	>100,000 – 300,000	3/10	0
D	>30,000 – 100,000	3/10	0
E	>10,000 – 30,000	3/10	0
F	>3,000 – 10,000	3/10	0
G	>1,000 – 3,000	3/10	0
H	300 – 1,000	3/10	0
O	< 300	3/10	0

TI Smart Power Switch

Test Procedure	Lots/Samples per lot	Temp	Cycles	Failure	ATE Test
Cold Repetitive Short Pulse	3/10	-40℃	1,000,000	0	PASS
Cold Repetitive Long Pulse	3/10	-40℃	1,000,000	0	PASS
Hot Repetitive Pulse	3/10	25℃	1,000,000	0	PASS

Load Profiles

Resistive

Bulb

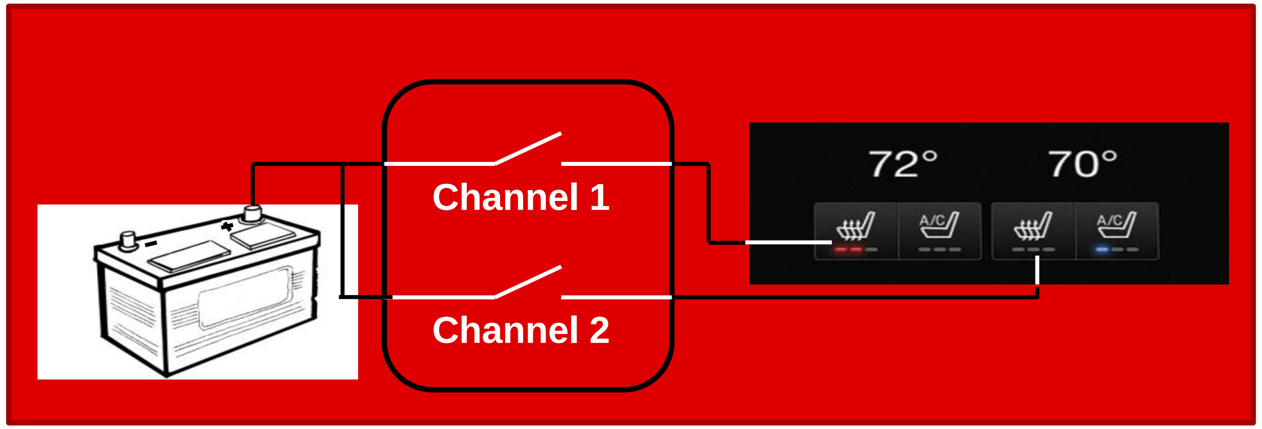
Capacitive

Inductive

Resistive Loads

Almost all loads include a resistive component, however some loads are purely resistive.

Application Example: Seat Heating



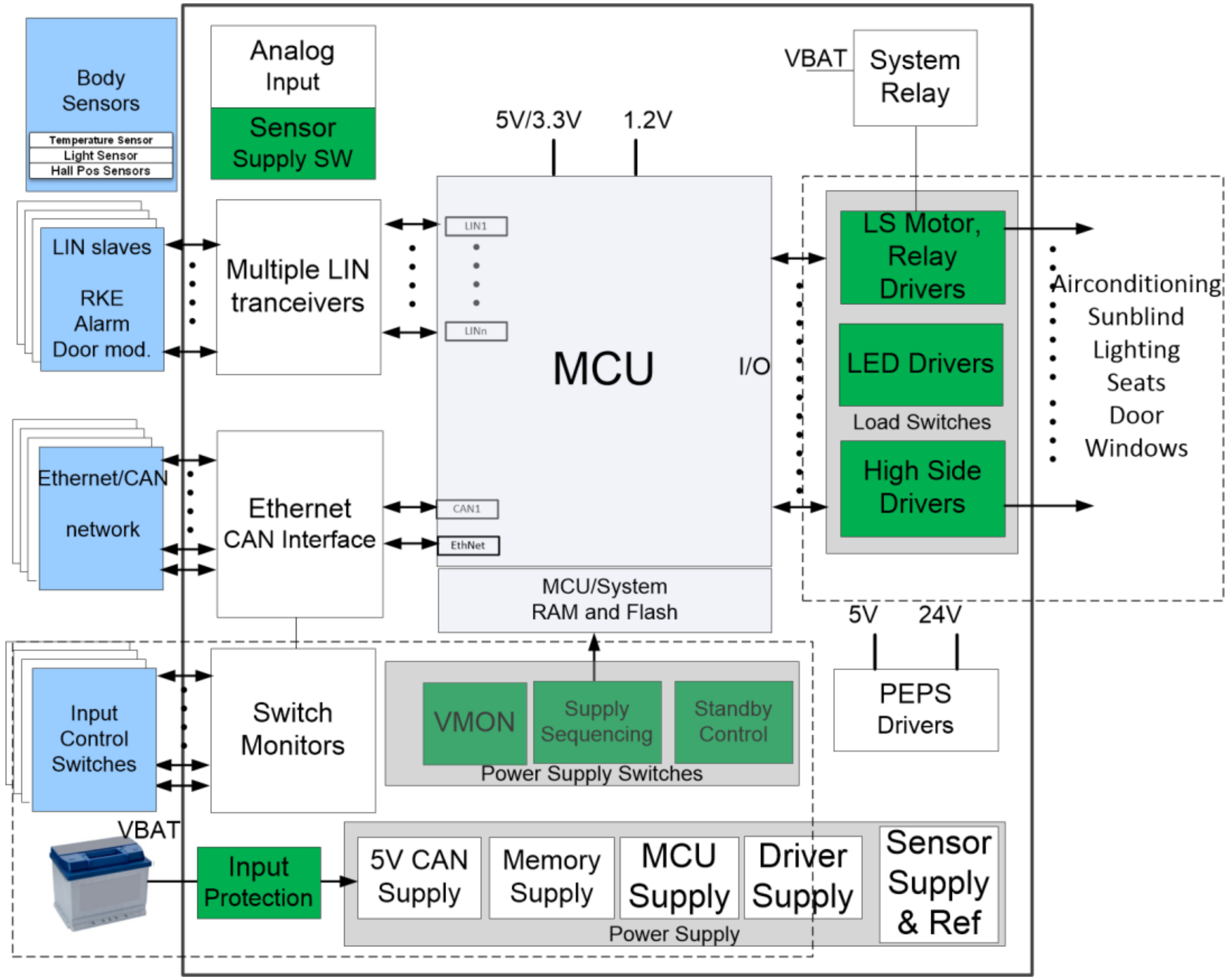
- For driving resistive loads, the primary concern is heating caused by DC current flow
- Thermal issues are caused primarily by the on-resistance of the switch, though are affected by ambient temperature and heat dissipation as well
- **Regardless of load, all load profiles must consider the heating caused by DC current flow**

Device	On Resistance	Max DC Current
TPS1H000-Q1	1 Ω	0.75 A
TPS2H000-Q1		
TPS4H000-Q1		
TPS1H200-Q1	200 mΩ	2.5 A
TPS2H160-Q1	160 mΩ	2.5 A
TPS4H160-Q1		
TPS1H100-Q1	100 mΩ	4 A
TPS27S100		
TPS2HB50-Q1	50 mΩ	4 A
TPS2HB35-Q1	35 mΩ	5 A
TPS2HB16-Q1	16 mΩ	7 A
TPS2HB08-Q1	8 mΩ	8 A
TPS1HA08-Q1		11 A

Bulb Loads – Application Example

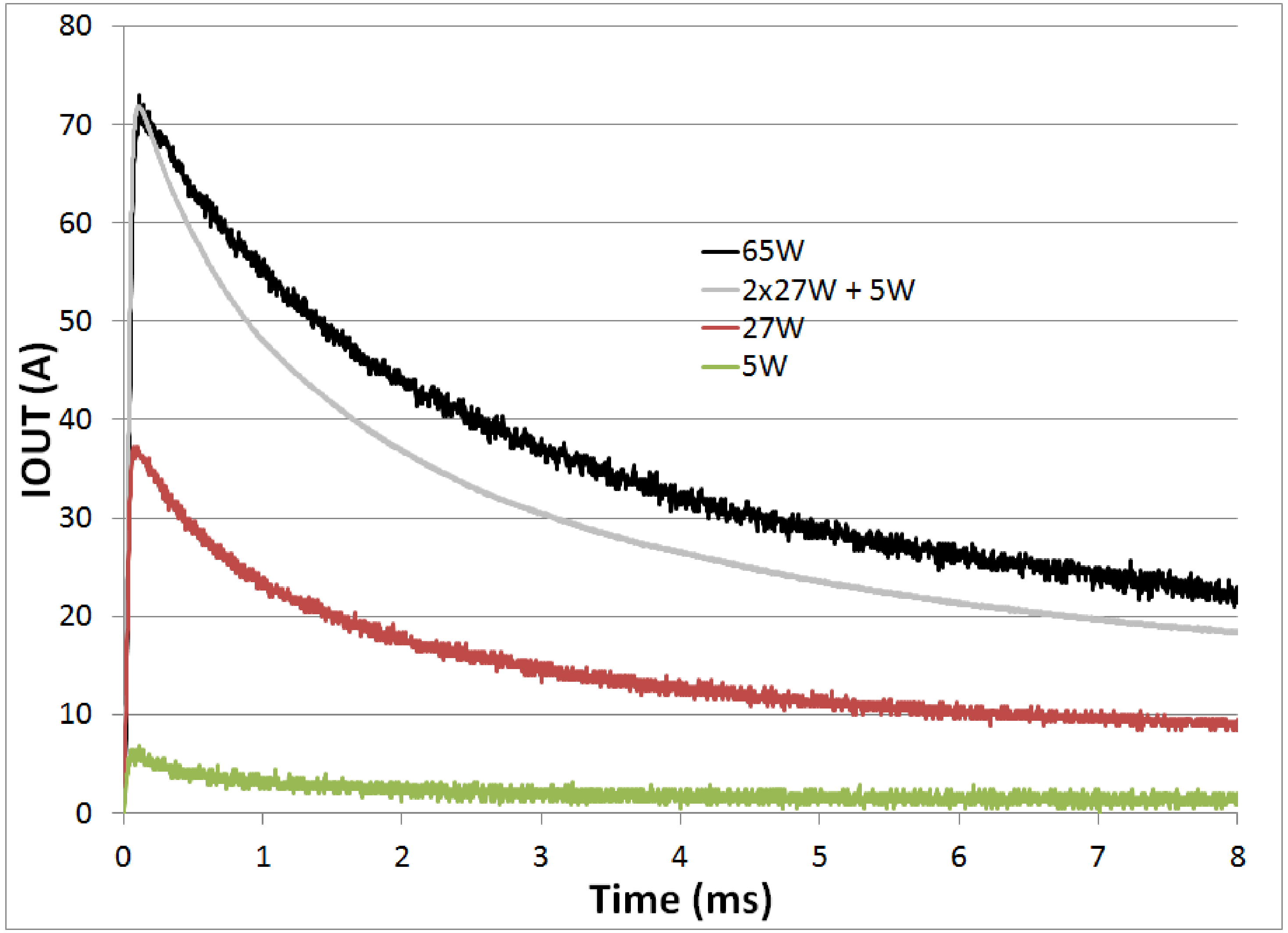
Incandescent Bulb Loads

High Side switches turn on incandescent bulb loads which must have **very high inrush currents (>10x nominal load)** while the bulb warms up to incandescent temperature levels.



Often >20 incandescent lighting loads are driven from standard electrical control modules

Incandescent Bulb Inrush Current



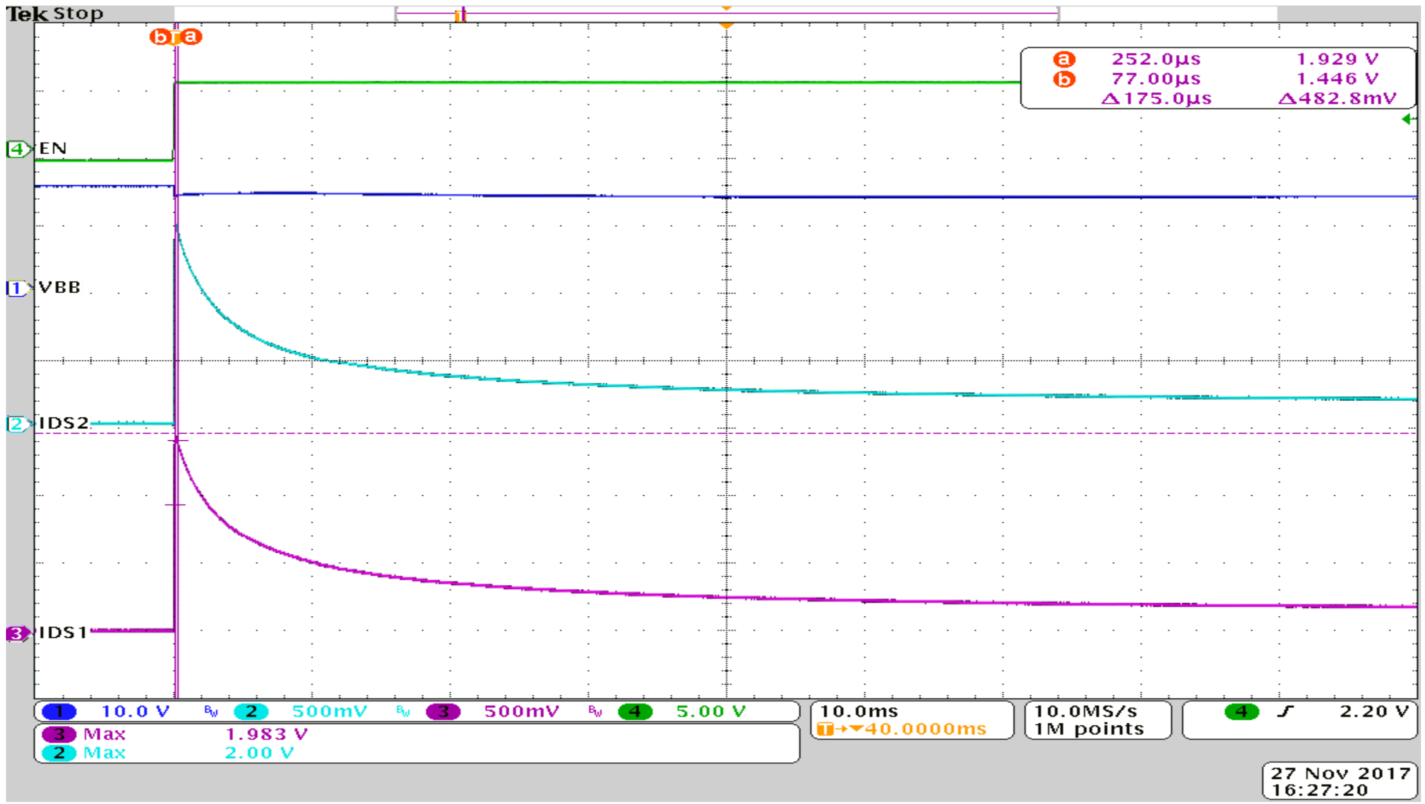
Conditions	
VBB (V)	16
Bulb Temp (°C)	-40
Device Temp (°C)	25
Wiring resistance (mΩ)	60

Power	DC Load (A)	Peak Transient (A)
65W	6.4	73
2x27W+5W	5.8	72
27W	2.6	37
5W	0.7	6.5

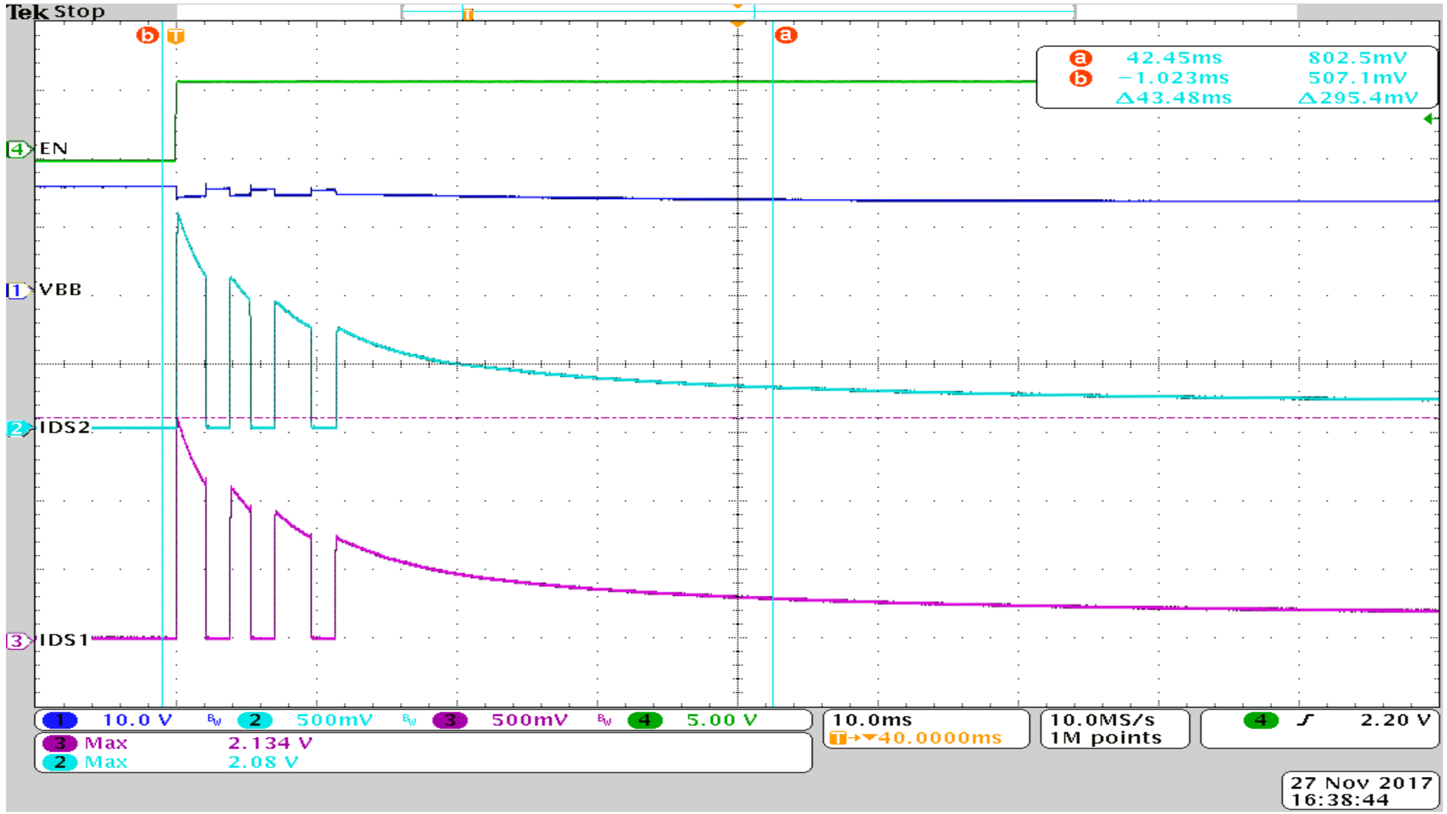
- Driving bulbs requires devices with current limits that are high enough to pass inrush current. Low R_{ON} is necessary to avoid thermal shutdowns during inrush
- After the bulb is on, steady state load current is much lower. Thermal requirements (like ambient temperature) may still require a lower R_{ON}

Bulb Turn-on Thermal Considerations

Even if current limit is high enough, the high inrush current can cause issues if the R_{ON} is too high

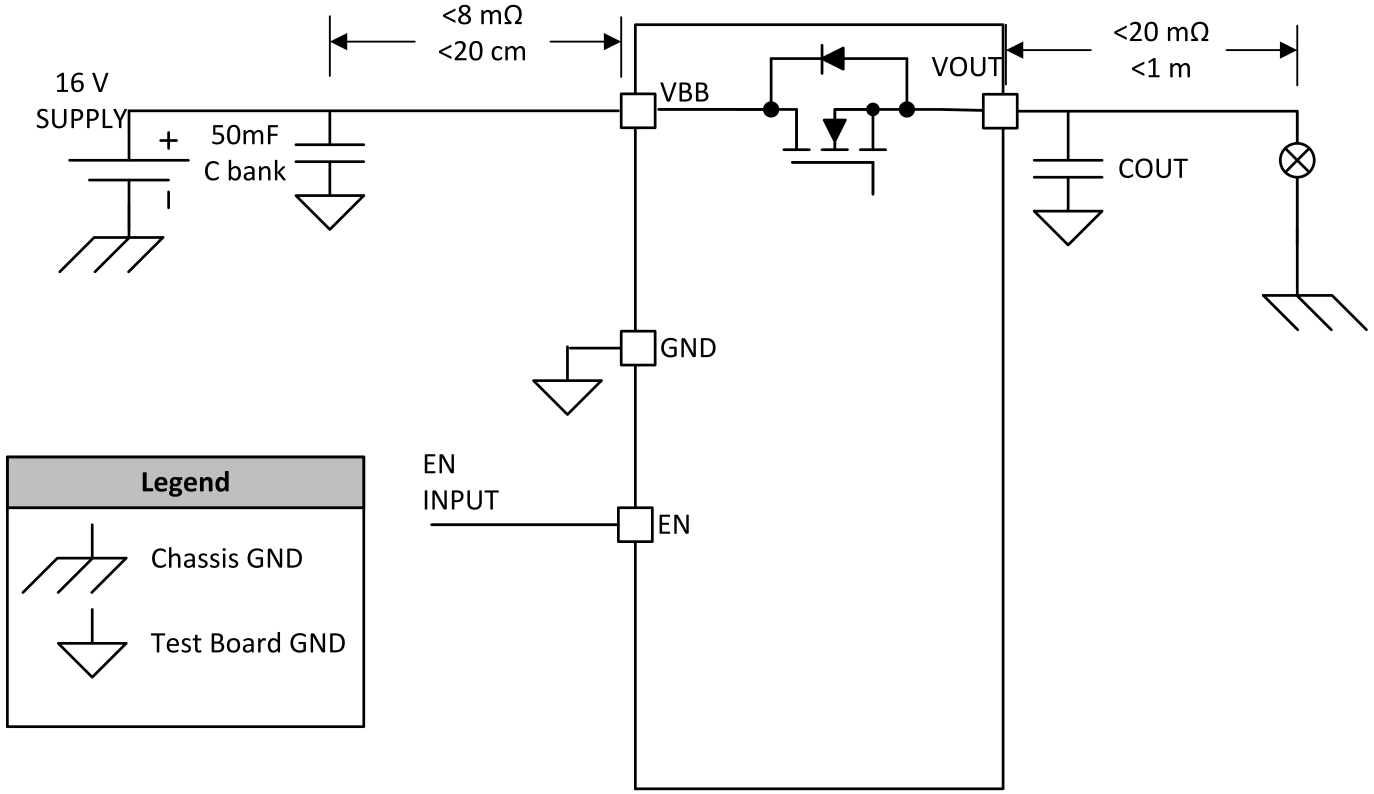


8 mΩ Smart High Side Switch can drive **65W** bulb with no thermal issues



8 mΩ Smart High Side Switch will see thermal shutdowns when driving **65W + 27W** bulbs in parallel

Bulb Inrush Current Handling Test



- To drive a bulb, it's necessary to test switching capability. There are many factors that must be matched:
  - Accurate parasitic resistance, inductance, and capacitance caused by differing cable makeup and length
  - Ambient temperature of bulb/device, as inrush will vary significantly from -40°C to 125°C
- The pass criterion will be to turn on the bulbs within timing requirements
  - Thermal protection can be engaged if on-resistance is too high
  - Turn-on delay spec is typically 10 ms, so even a couple of thermal shutdown cycles could be a problem

Bulb Load Driving Considerations

Inrush Current Limit

- Ensure the Smart High Side Switch current limit is high enough to initially power up the bulb

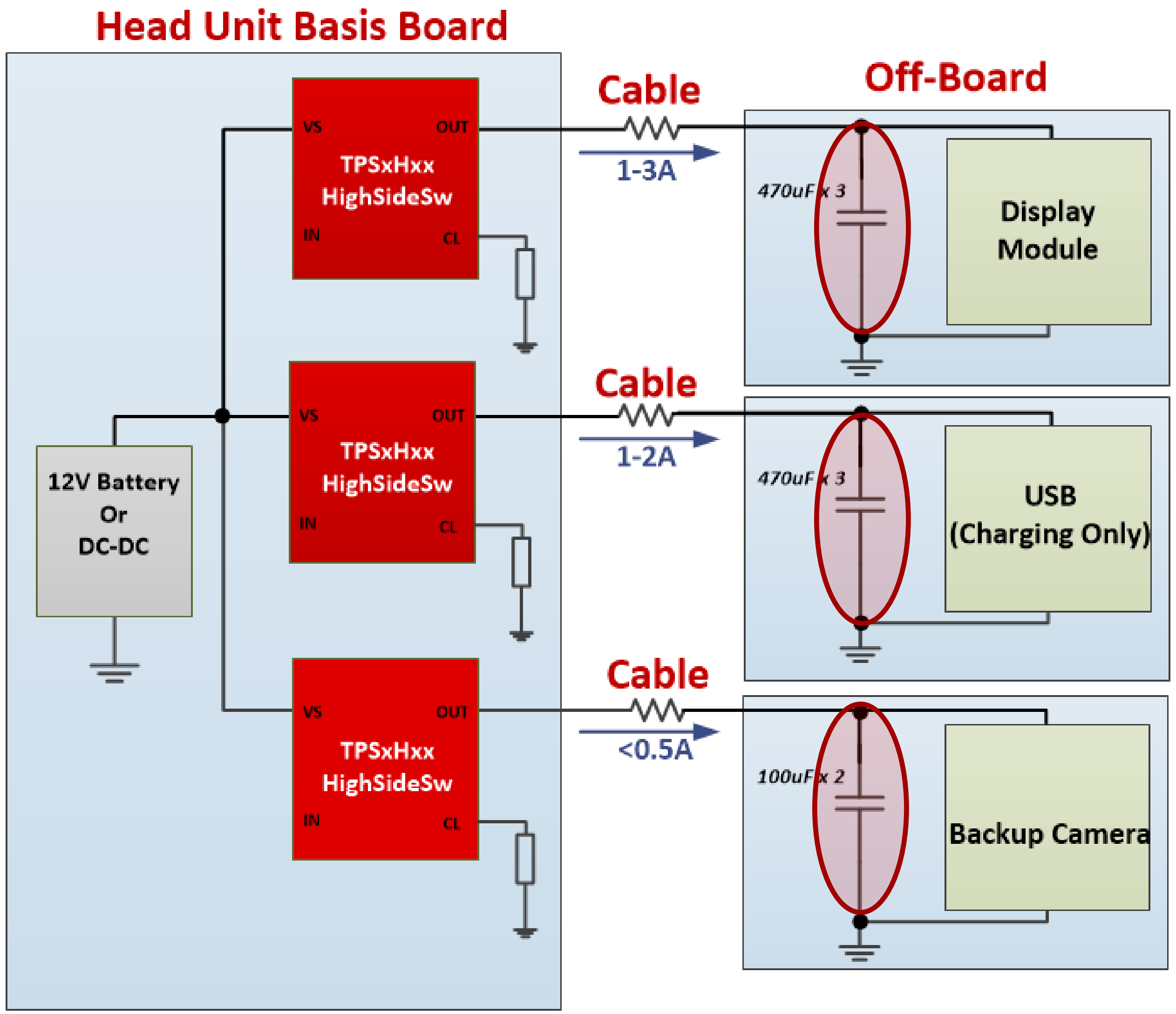
Inrush Current Thermals

- Ensure that the switch has a low enough R_{ON} that it can charge the bulb with limited thermal shutdowns

Steady State Current Thermals

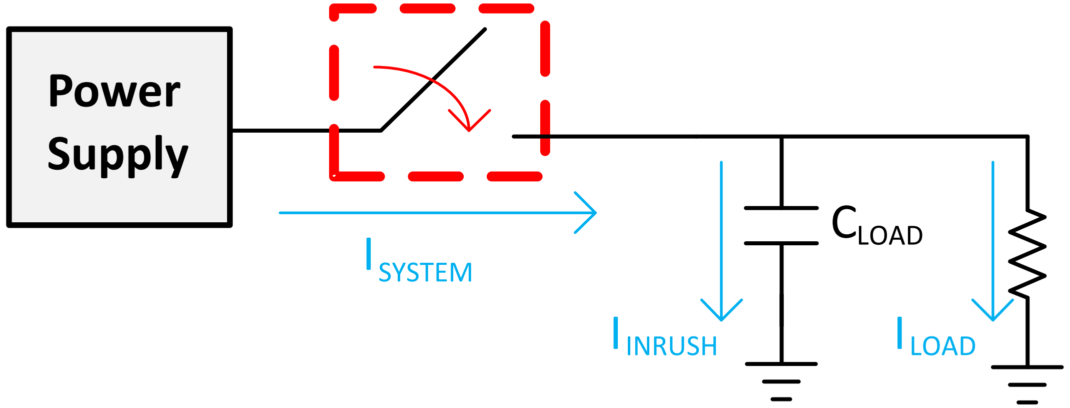
- Ensure that the switch has a low enough R_{ON} that it can provide rated DC current with no thermal issues

Capacitive Loads - Application Example



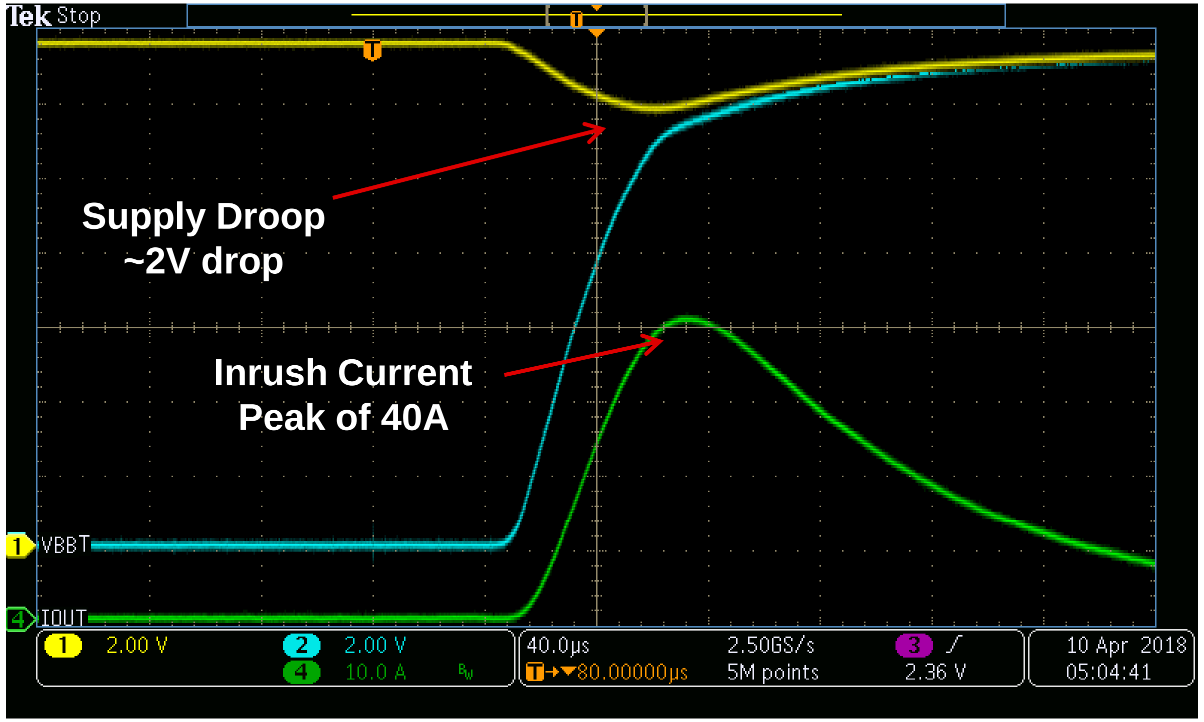
Capacitors are typically used as stabilizing capacitors at input of modules and can go up to 5mF depending on the application.

Peak (inrush) Current without Current Limiting



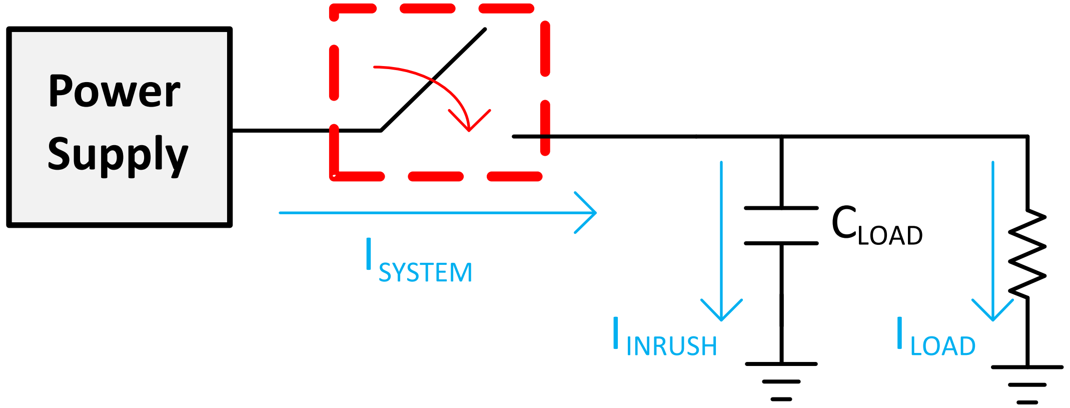
$$I_{SYSTEM} = I_{INRUSH} + I_{LOAD}$$

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



- **Inrush current** is the transient current drawn by load capacitance of a system when first turned on. If the inrush current is high, the power supply voltage may droop and components can be damaged.
- Typical high side switches set the current limit high to avoid limiting during inrush, however this does not provide protection against inrush current.

Current Limiting Charging

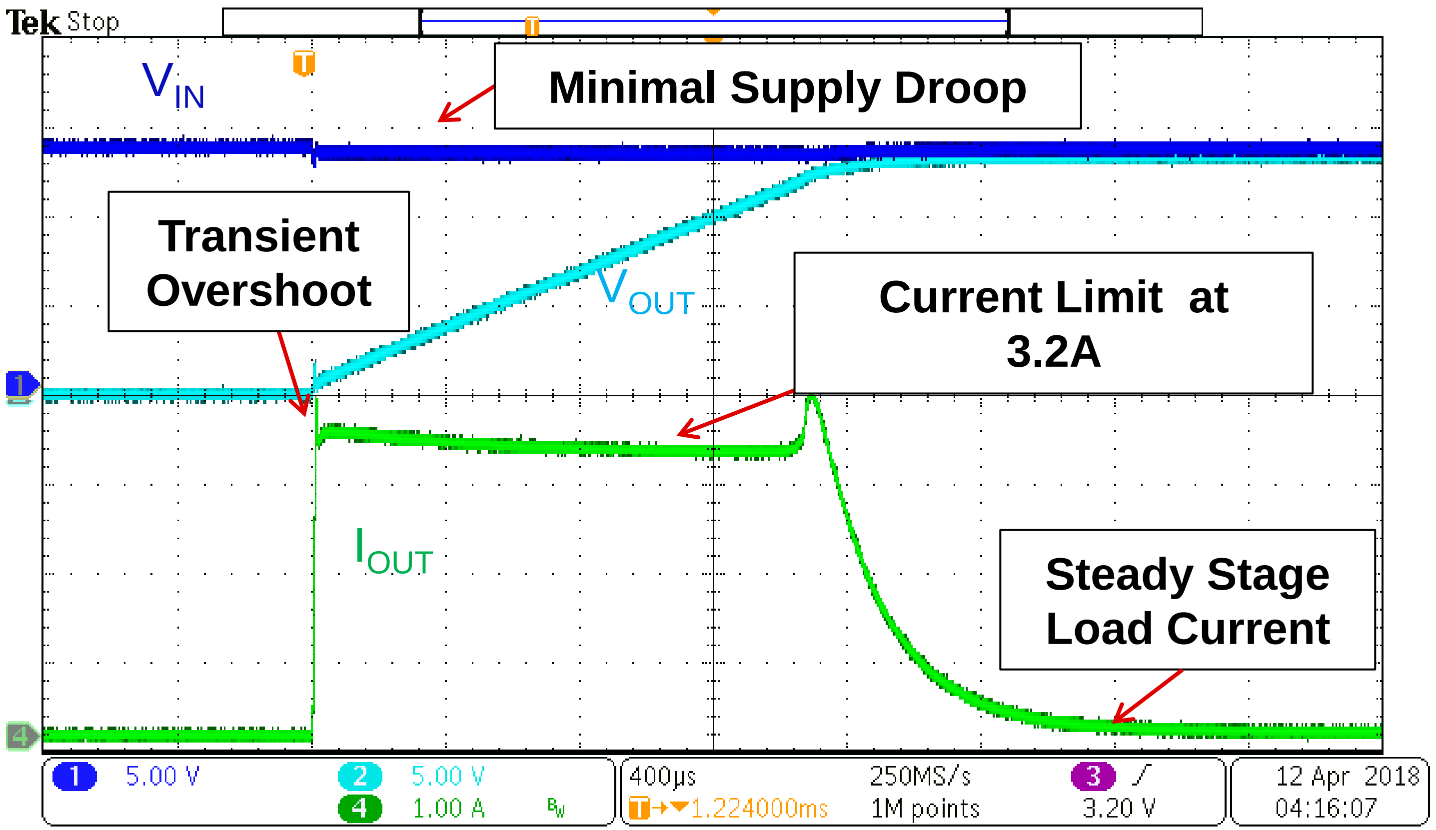


$$I_{INRUSH} = I_{CL} + I_{Overshoot}$$

$$I_{CHARGE} = I_{CL}$$

$$T_{CHARGE} \approx C_L \times \frac{V_{in}}{I_{CL}} \approx 2\ ms$$

330 µF charged to 13.5V with 3.5A current limit



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

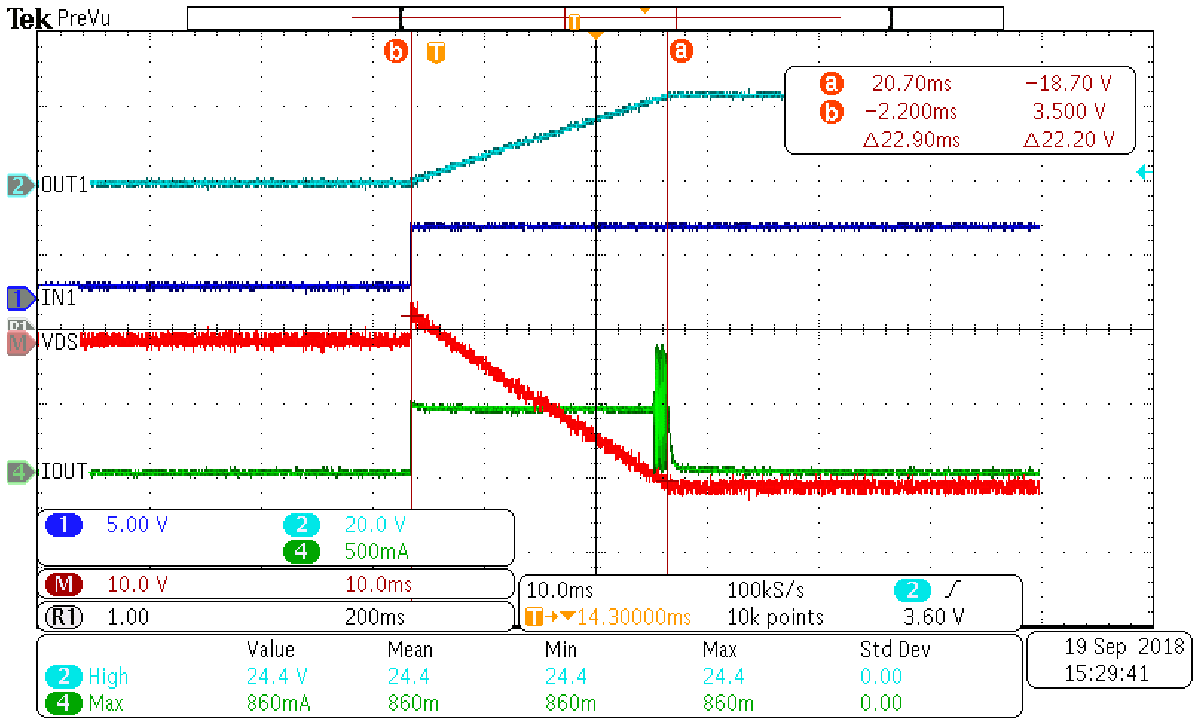
- Peak current from transient overshoot is limited to <4A due to the Smart High Side Switch
- Lower charging current results in lower peak currents during inrush which minimizes supply droop and reduces component current handling requirements.
- Charging time is increased as a function of the lower current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

Smart High Side Switch Power Dissipation

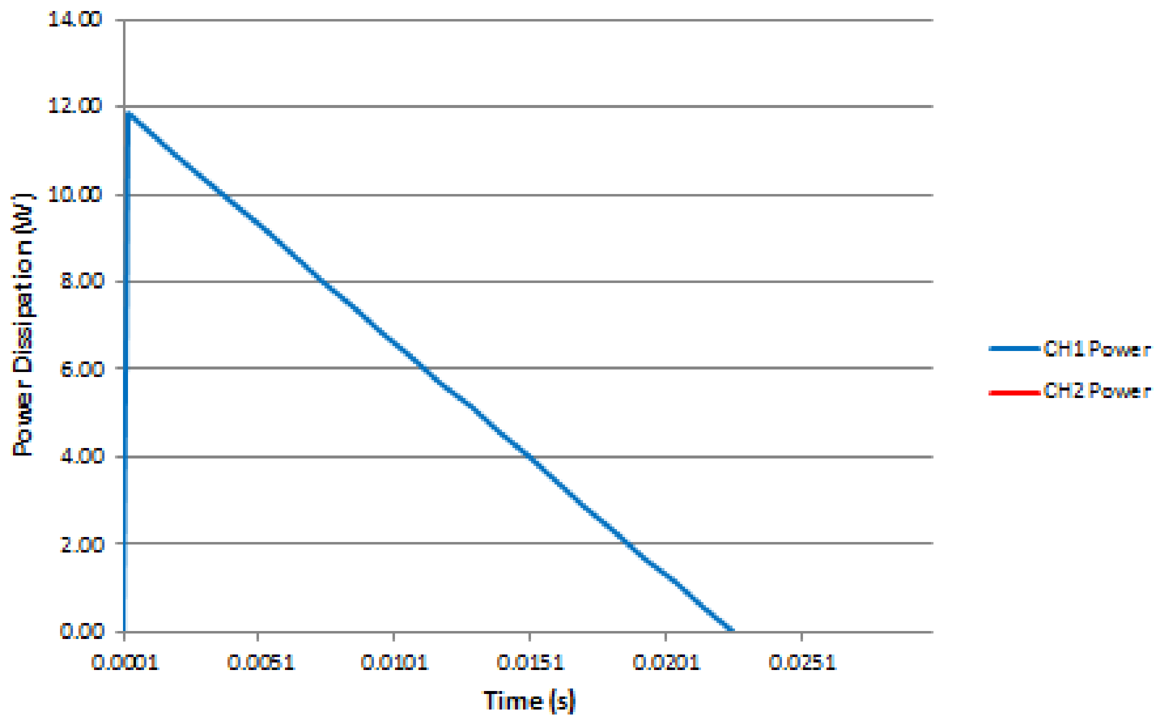
While the Smart High Side Switch is current limiting there is a large amount of power dissipation. This is because V_{DS} is large and the charging current is flowing through the switch.

- As the capacitance is charged, the voltage across the FET is reduced and the power dissipation is decreased.
- A higher charging current will reduce the total energy dissipated in the switch but the peak inrush and short circuit current will be increased.

TPS2H160 charging 470 µF to 24V, 500mA current limit



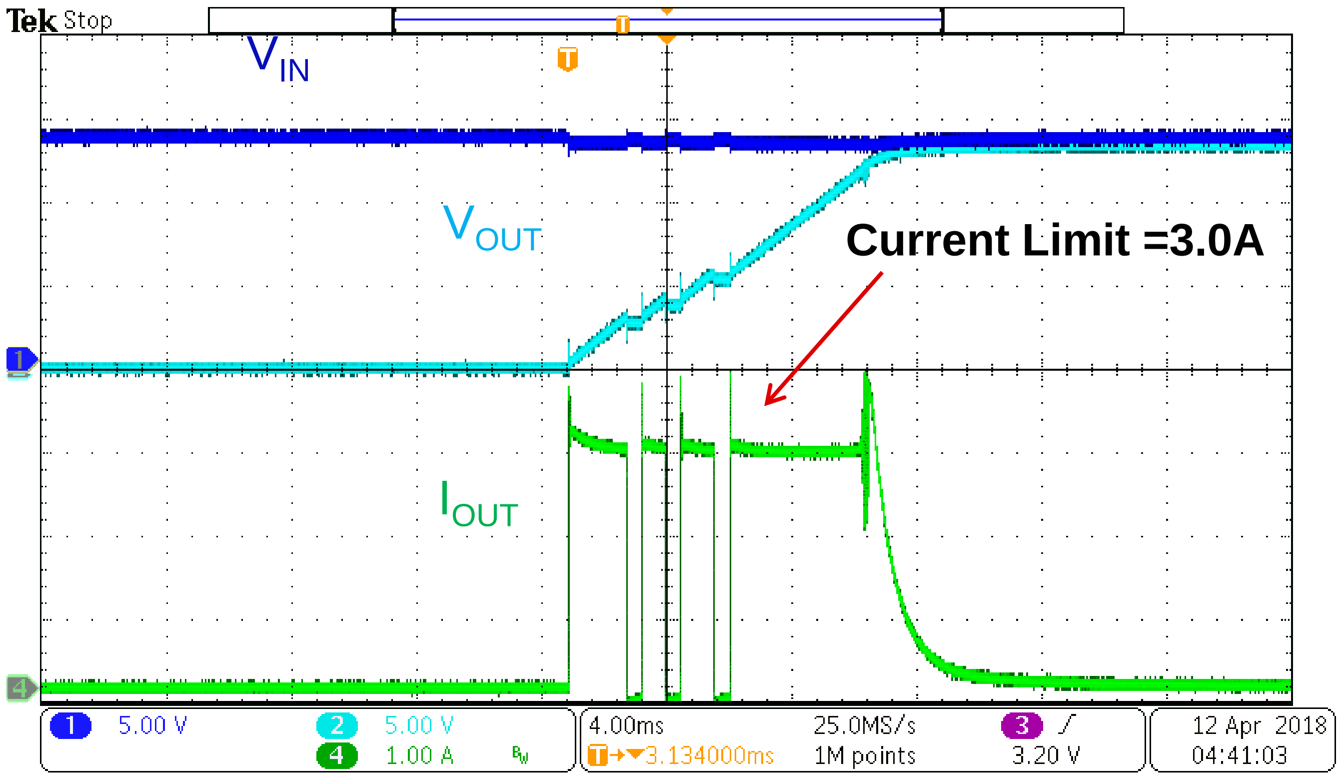
$$P_D = V_{DS} \times I_{OUT}$$

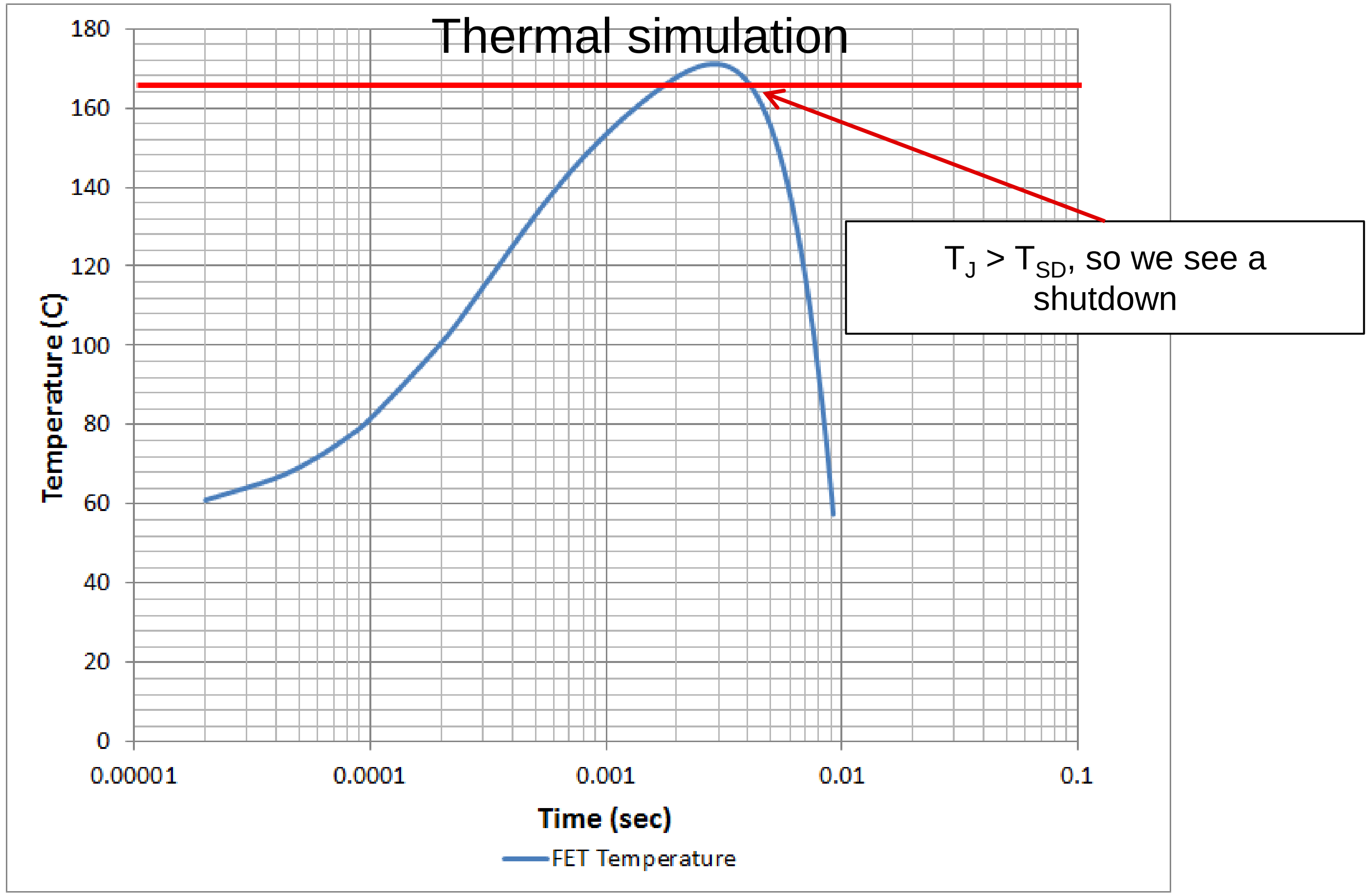


Power Dissipation

- Transient thermal impedance models can predict thermal shutdown point
- Charging large value caps at high currents can result in thermal shutdown, however auto-recovery mode permits full charging.
- Thermal model and power dissipation model will be available to use in the next few months.

TPS2H160 2ch charging 2200 µF

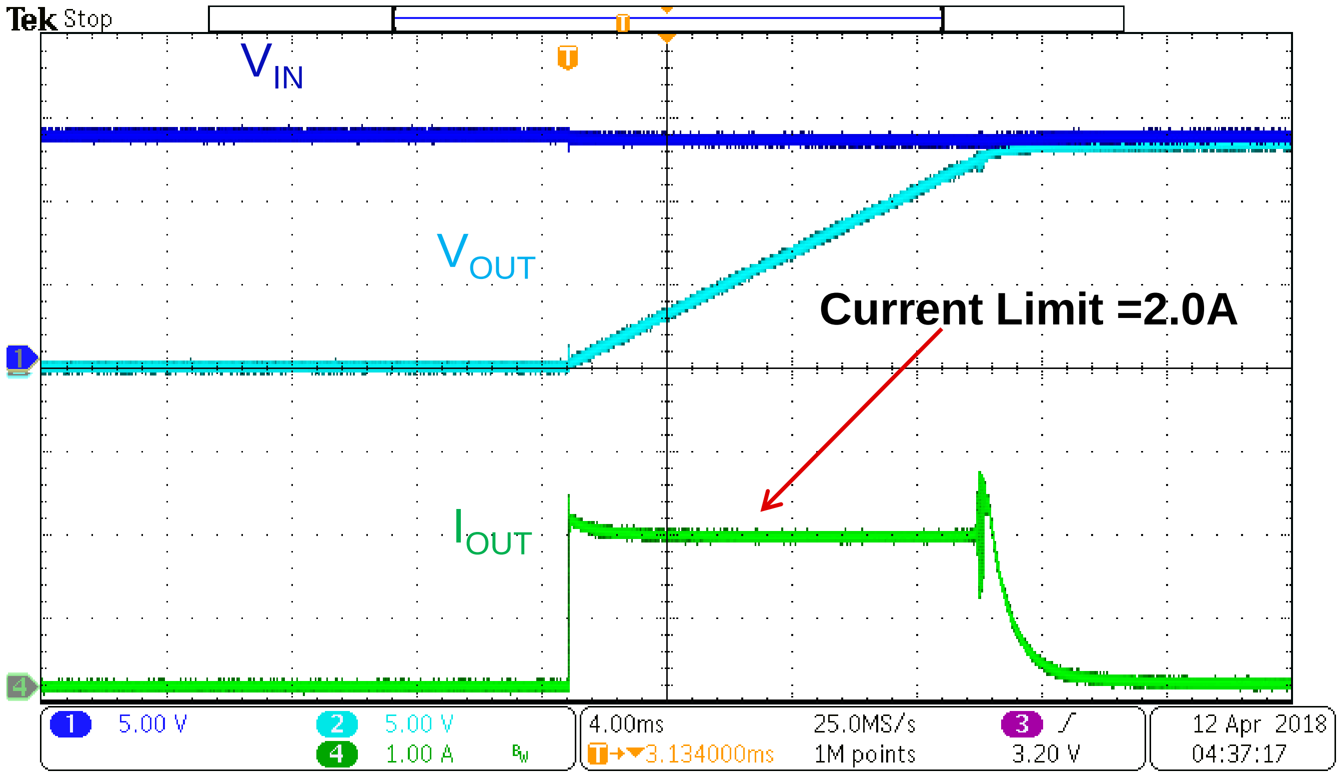


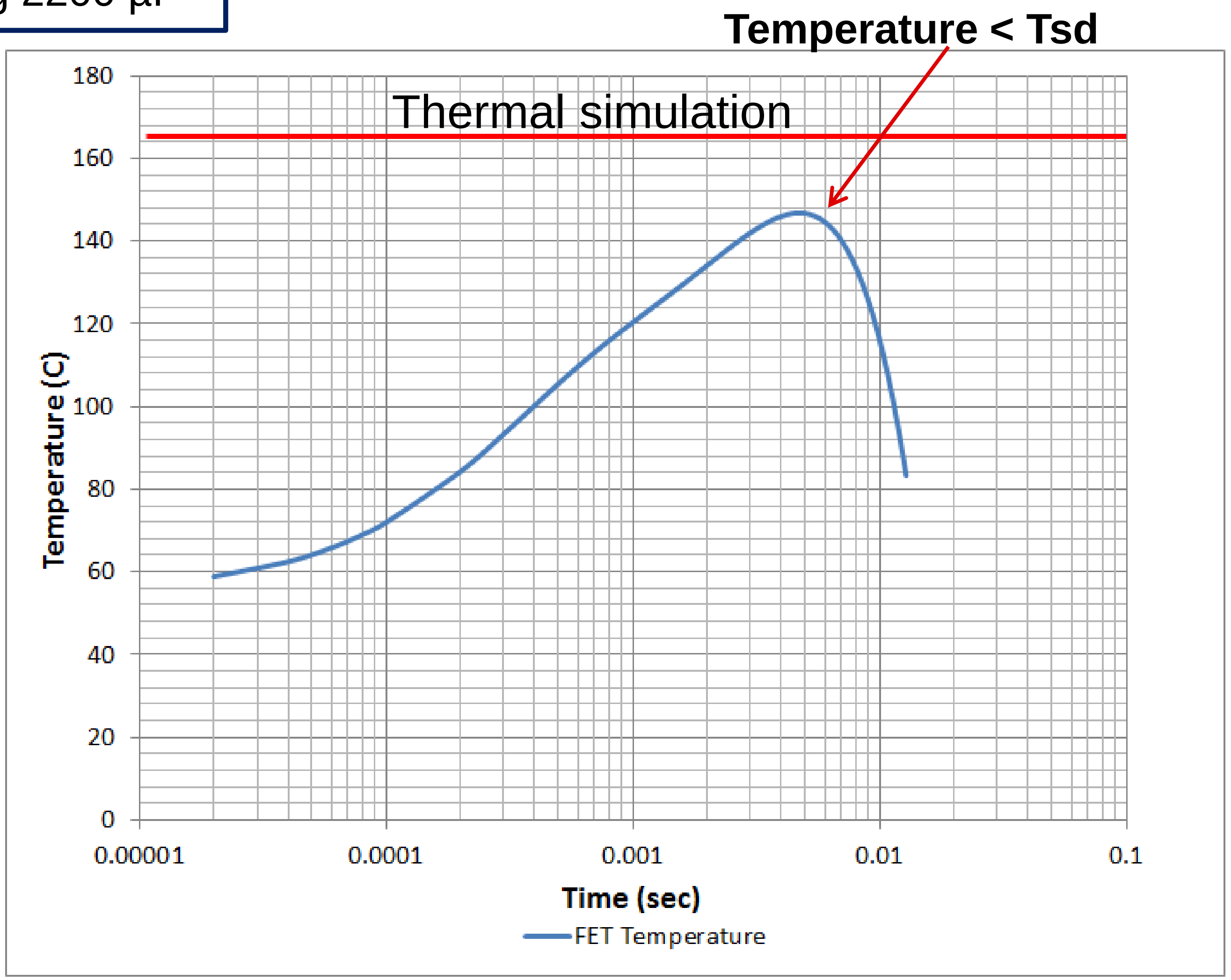


Power Dissipation

- Thermal shutdown can be averted by changing the charging current.
- The same scenario sees no thermal shutdown even when charging at a lower 2A current limit

TPS2H160 - 2ch charging 2200 µF

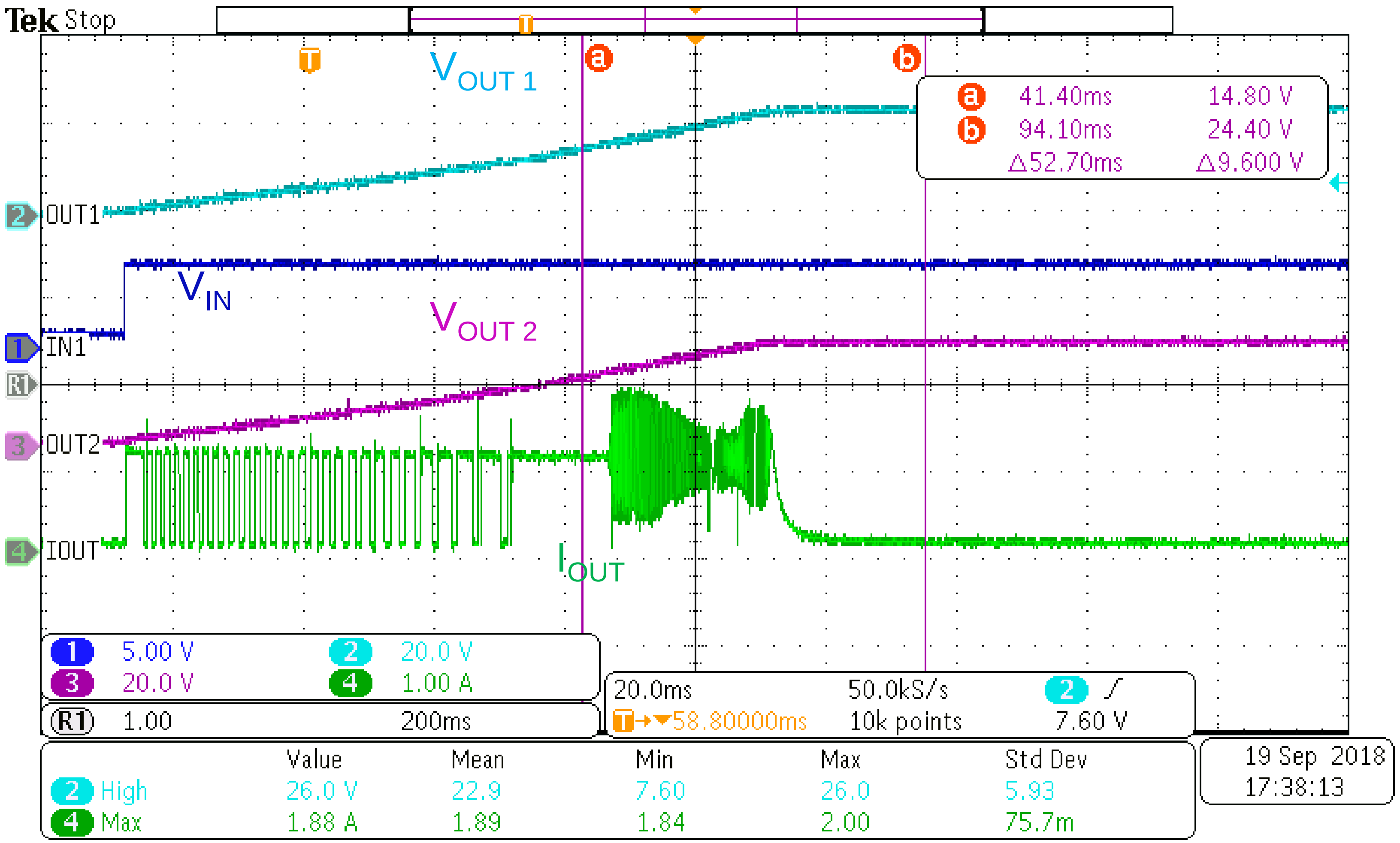




Power Dissipation

- Even very large capacitive loads can be charged in this method, though it can take longer

TPS2H160 - 2ch charging 3300 µF at 1A



Capacitive Load Driving Considerations

Charging time

- Determined by current limit, capacitive load, and supply voltage
- Lower charging time makes it faster to charge up off board loads

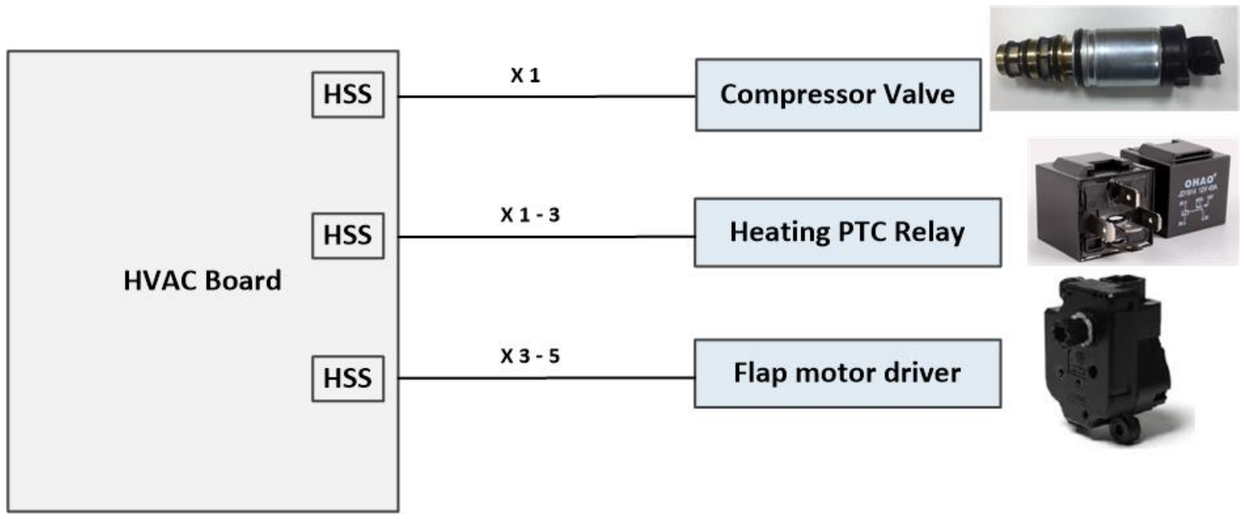
Maximum Inrush Current

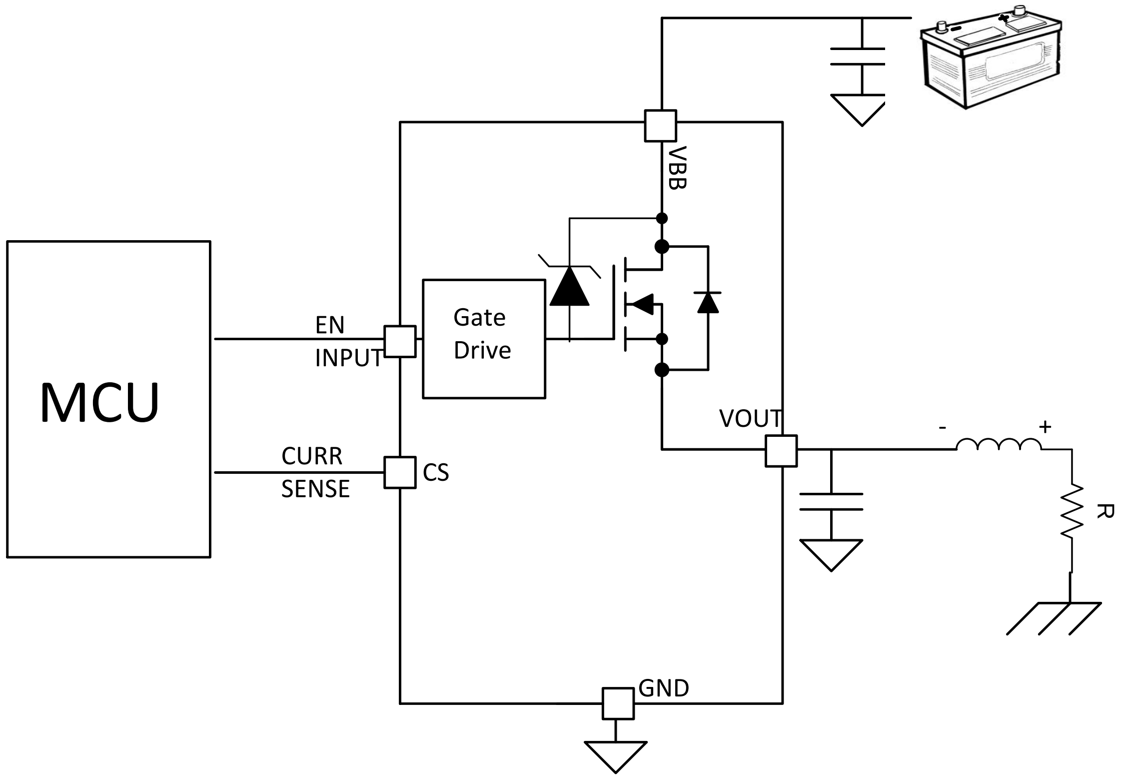
- Determined by current limit
- Lower current limit saves system costs and enhance reliability during short circuit events

Switch Power Dissipation

- Determined by current limit, capacitive load, and supply voltage
- Lower power dissipation avoids switch shut downs that slow down charging and well as lower charging efficiency

Inductive Loads



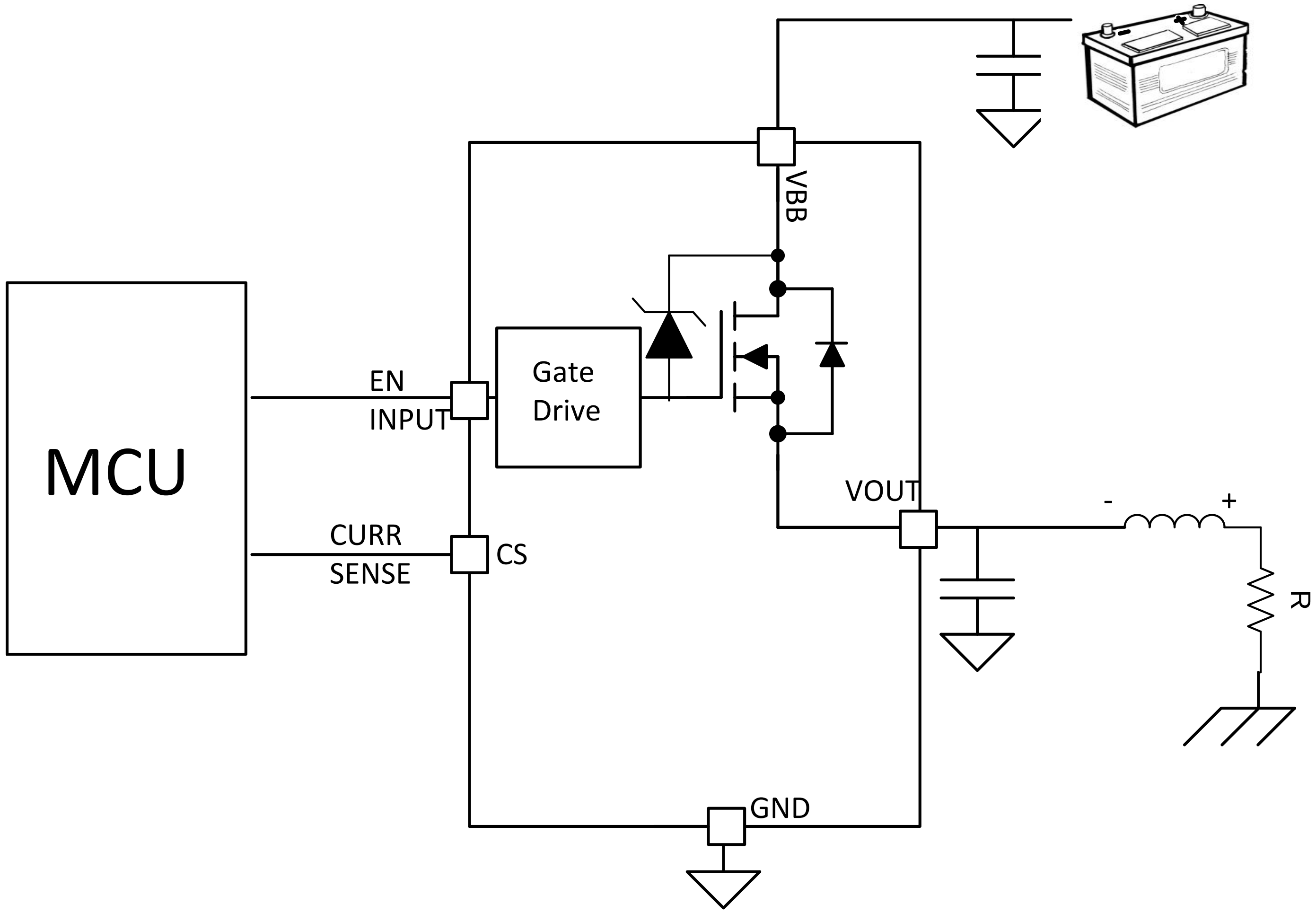


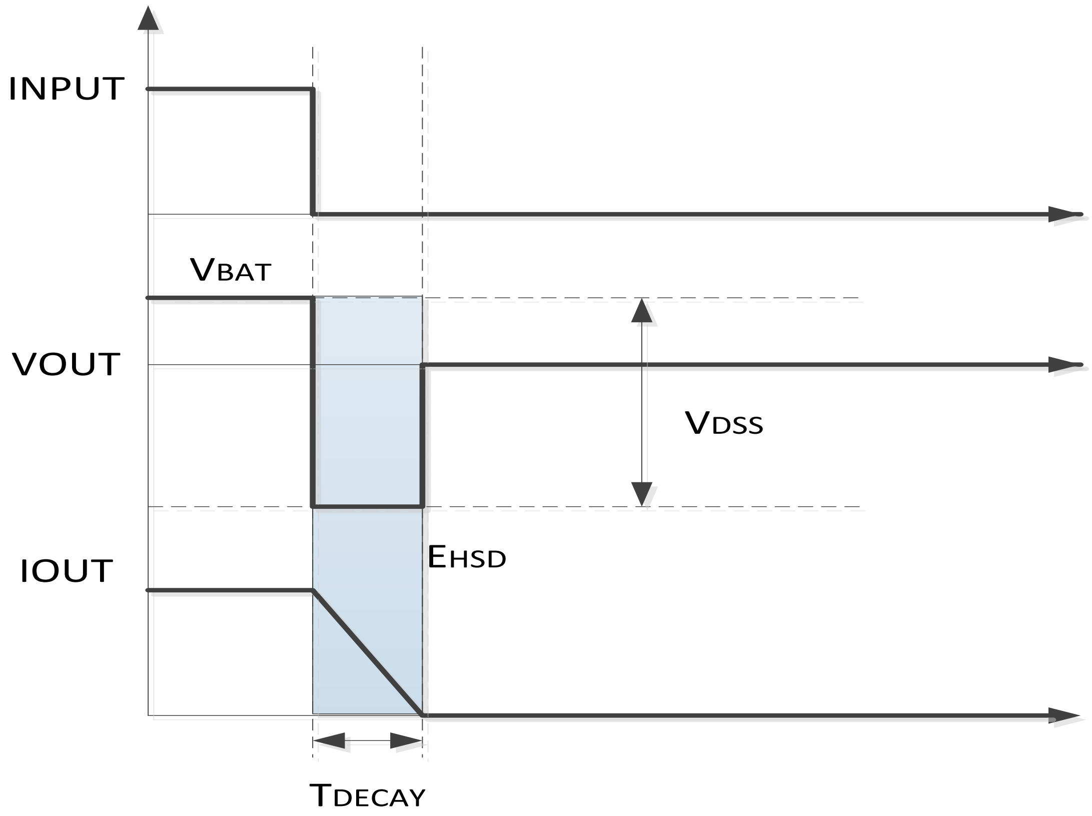
Inductive loads are typically found as solenoids, relays, valves, etc in systems and are commonly seen in both automotive and industrial applications. Inductances can be seen as high as 1-2H

Inductive Load Turn-Off

Due to the nature of inductors, when inductive loads switch off the inductance causes a large negative voltage on the output pin that can destroy equipment. Smart High Side Switches integrate a V_{DS} clamp to protect the device and demagnetize the inductance.

$$V_L = L * \frac{dI(t)}{dt}$$



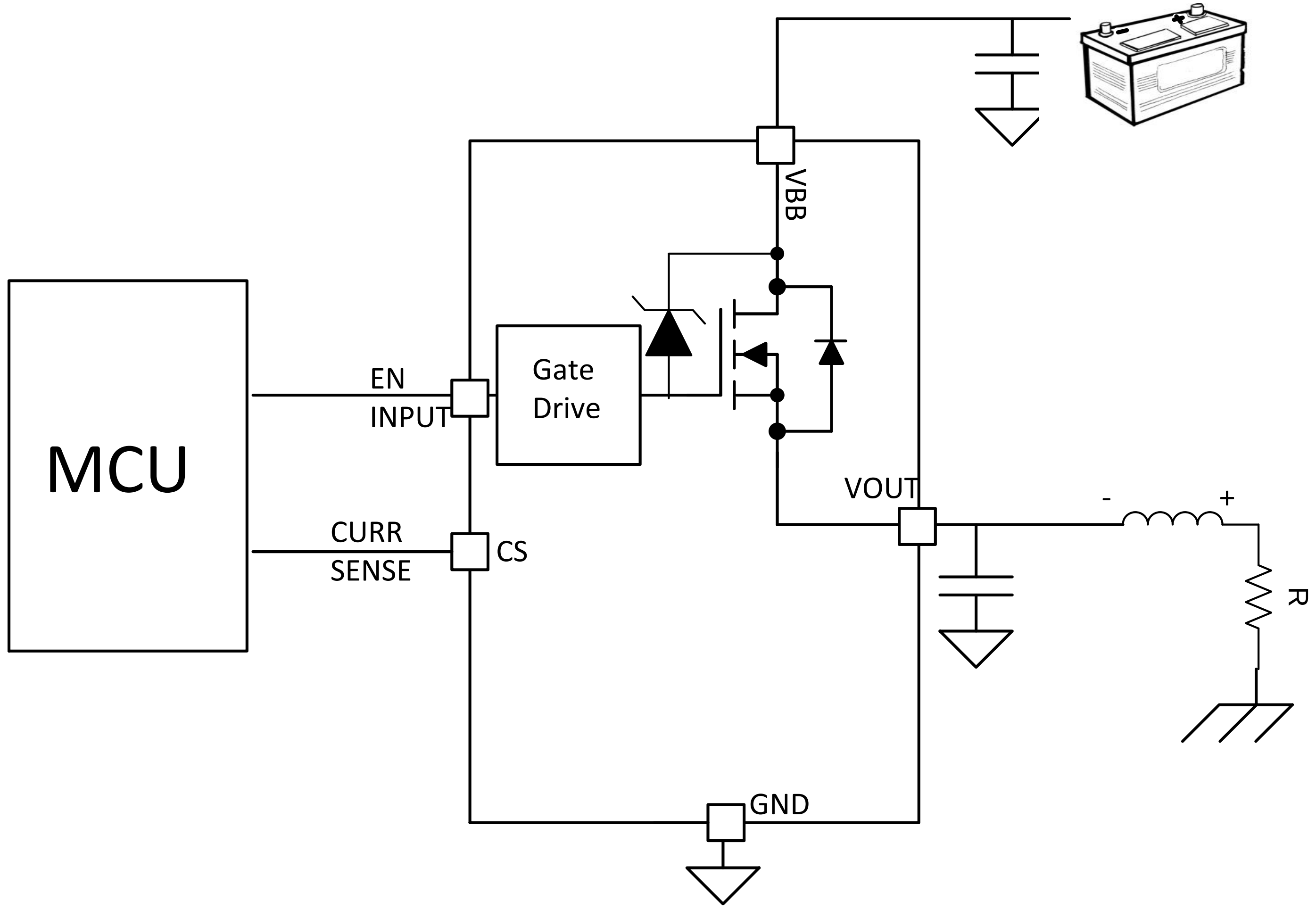


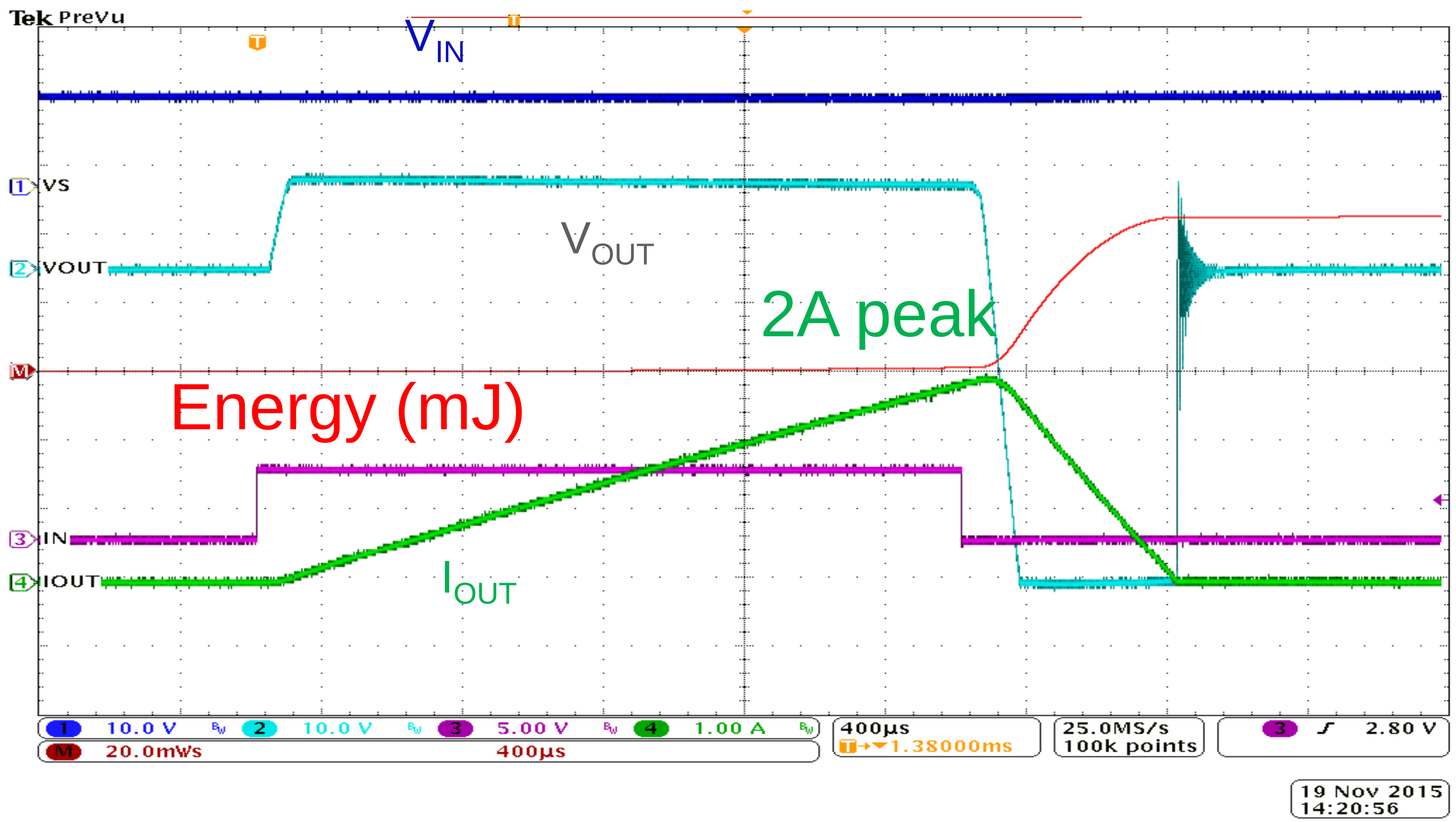
Inductive Load Turn-Off

During turnoff, the Smart High Side Switch is dissipating a very high energy due to the large V_{DS} and I_{OUT}. This energy is determined by the inductance value and the load current.

$$V_{DSS} = V_{BAT} - V_{OUT}$$

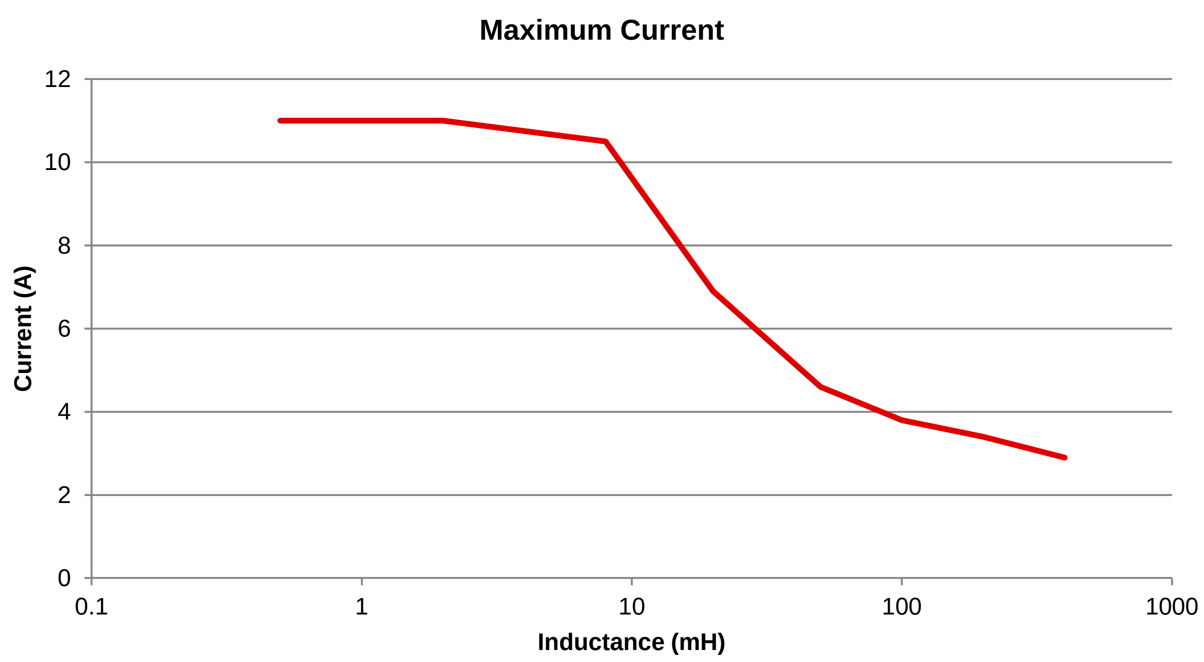
$$E_{HSD} = \int_0^{T_{DECAY}} V_{DSS} \cdot I_{OUT}(t)\, dt$$

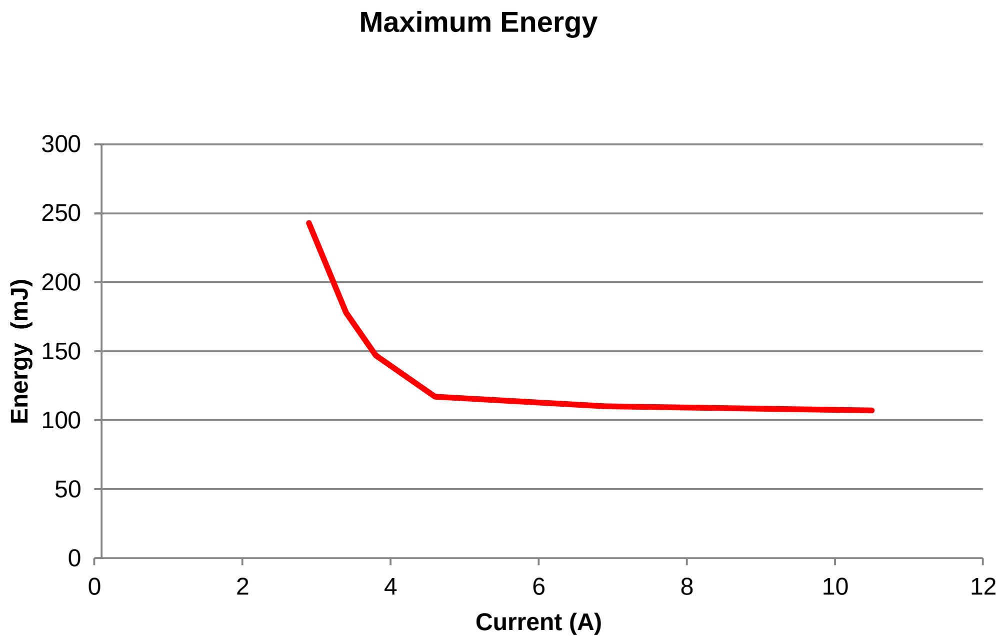




Maximum Energy Dissipation

If inductive energy is too high, the Smart High Side Switch can break. Reference the datasheet curves to ensure that the required load profile is within range of the switch. If the inductive load energy is beyond the maximum specified in the datasheet, an external TVS diode is required.



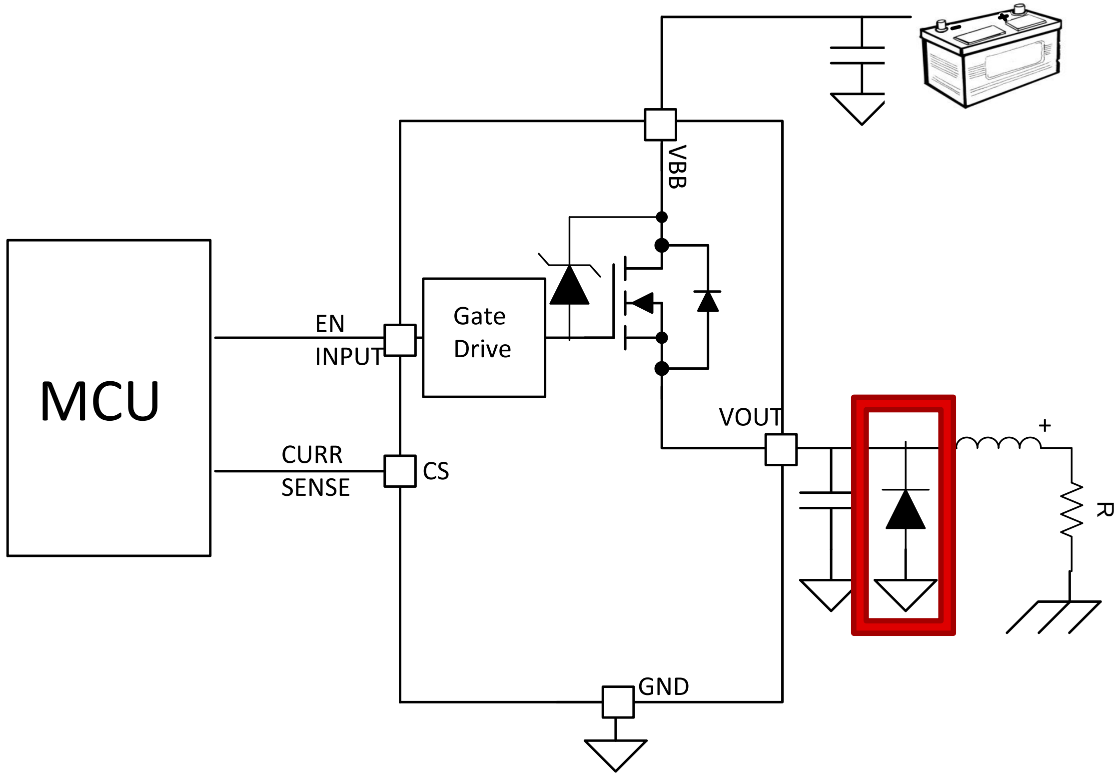


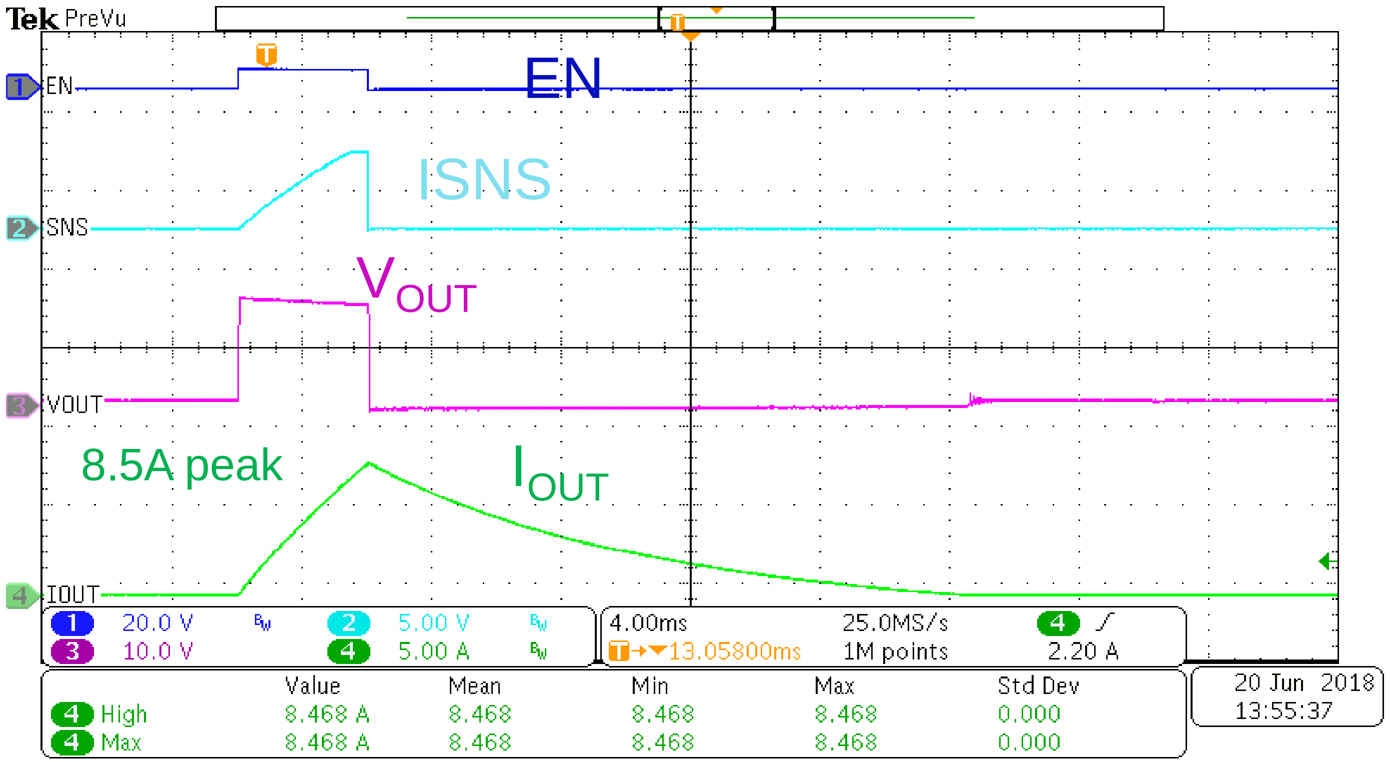
TPS1H100–Q1 maximum inductive dissipation at T_A = 150°C

Turn off with External Diode

When using an external diode, the load demagnetization time will depend on the V_{CLAMP}. TI Smart High Side Switches integrate a clamp with V_{CLAMP} approximately = 50V. External diode V_{CLAMP} of 0.7V means even small 1mH load takes ~10ms to dissipate, compared to internal clamp which would take <1ms.

$$T_{DEMAG} = \frac{L}{R} * \ln\left(1 + \frac{R * I_0}{V_{CLAMP} - V_{BAT}}\right)$$





V_{CLAMP} of 0.7V means even small 1mH load takes ~20ms to dissipate

Inductive Load Driving Considerations

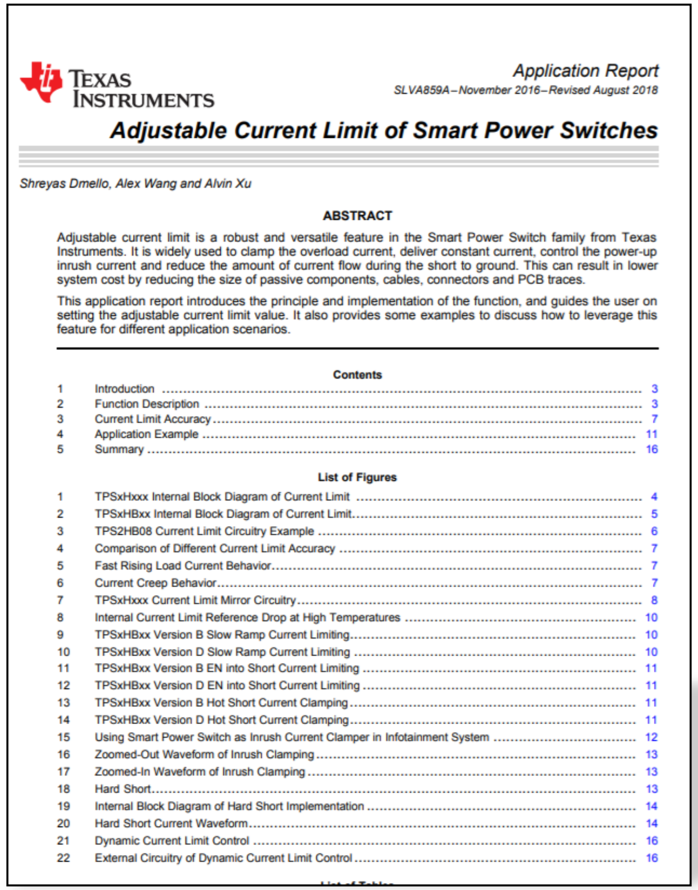
Maximum Energy Dissipation

- Ensure the Smart High Side Switch can dissipate the required inductive load energy.

Demagnetization Time

- Ensure that the V_{CLAMP} is high enough to limit the demagnetization time

Smart Power Switch Collateral



Texas Instruments

Application Report

SLVA859A–November 2016–Revised August 2018

Adjustable Current Limit of Smart Power Switches

Shreyas Dmello, Alex Wang and Alvin Xu

ABSTRACT

Adjustable current limit is a robust and versatile feature in the Smart Power Switch family from Texas Instruments. It is widely used to clamp the overload current, deliver constant current, control the power-up inrush current and reduce the amount of current flow during the short to ground. This can result in lower system cost by reducing the size of passive components, cables, connectors and PCB traces.

This application report introduces the principle and implementation of the function, and guides the user on setting the adjustable current limit value. It also provides some examples to discuss how to leverage this feature for different application scenarios.

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4 Application Example 11
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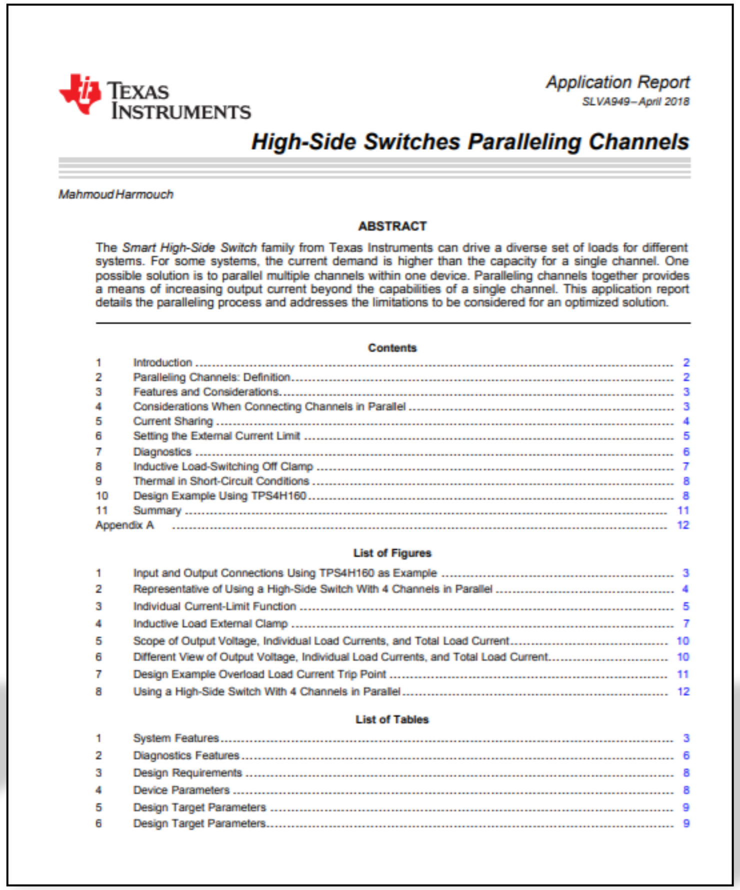
Discusses system advantages of adjustable current limiting in TI Smart Power Switches



Texas Instruments

Application Report

SLVA949–April 2018

High-Side Switches Paralleling Channels

Mahmoud Harmouch

ABSTRACT

The *Smart High-Side Switch* family from Texas Instruments can drive a diverse set of loads for different systems. For some systems, the current demand is higher than the capacity for a single channel. One possible solution is to parallel multiple channels within one device. Paralleling channels together provides a means of increasing output current beyond the capabilities of a single channel. This application report details the paralleling process and addresses the limitations to be considered for an optimized solution.

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1 Introduction 2
2 Paralleling Channels: Definition 2
3 Features and Considerations 3
4 Considerations When Connecting Channels in Parallel 3
5 Current Sharing 4
6 Setting the External Current Limit 5
7 Diagnostics 6
8 Inductive Load-Switching Off Clamp 7
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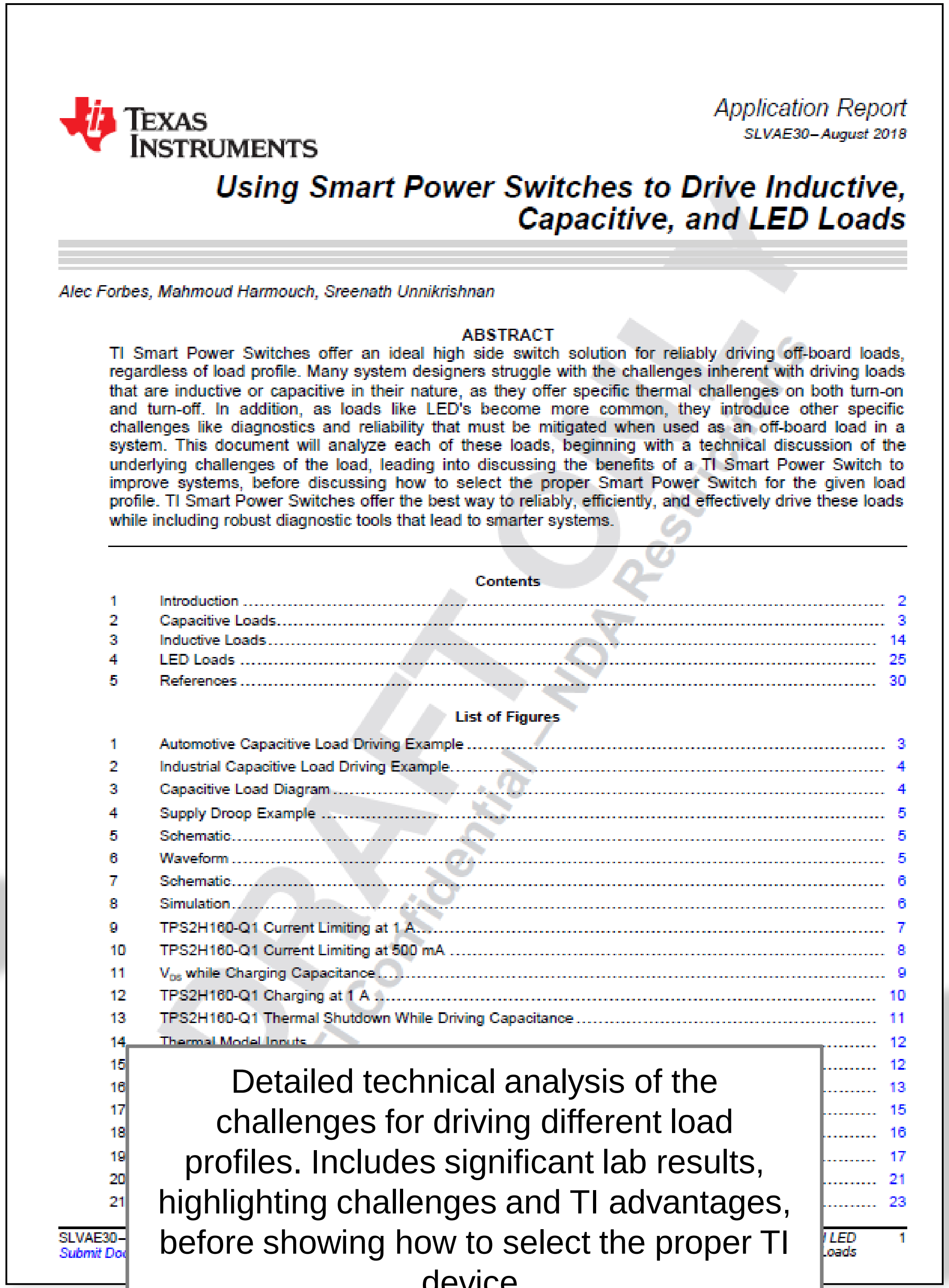
6 Design Target Parameters 9

Discusses how to increase Smart Power Switch flexibility by paralleling channels to decrease R_{DSON}



Texas Instruments

Application Report

SLVAE30–August 2018

Using Smart Power Switches to Drive Inductive, Capacitive, and LED Loads

Alec Forbes, Mahmoud Harmouch, Sreenath Unnikrishnan

ABSTRACT

TI Smart Power Switches offer an ideal high side switch solution for reliably driving off-board loads, regardless of load profile. Many system designers struggle with the challenges inherent with driving loads that are inductive or capacitive in their nature, as they offer specific thermal challenges on both turn-on and turn-off. In addition, as loads like LED's become more common, they introduce other specific challenges like diagnostics and reliability that must be mitigated when used as an off-board load in a system. This document will analyze each of these loads, beginning with a technical discussion of the underlying challenges of the load, leading into discussing the benefits of a TI Smart Power Switch to improve systems, before discussing how to select the proper Smart Power Switch for the given load profile. TI Smart Power Switches offer the best way to reliably, efficiently, and effectively drive these loads while including robust diagnostic tools that lead to smarter systems.

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SLVAE30– ... LED Loads 1

Submit Do...

Detailed technical analysis of the challenges for driving different load profiles. Includes significant lab results, highlighting challenges and TI advantages, before showing how to select the proper TI device.

Coming Soon: November 2018

Texas Instruments

TIDA-01184

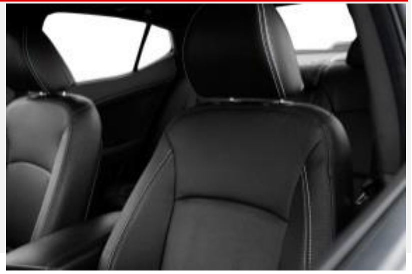
Advanced Protection and Diagnostics for Seat Heaters

Features

- Control seat heater temperature, display output resistance, and auto-disable in case of uC fault
- **Smart high side switch:** TPS1HA08-Q1
  - Operating voltage range: 3V to 28V
  - Max load dump voltage: 43V
  - Low ON-Resistance: 8 mΩ (typ)
- **Sense output:** input voltage, current sense, and device temperature
  - High accuracy current sense (+/-5% at 3A)
  - Fast current sense settling time: 165us
- **Selectable current limit:** low current and high current limit
- Interfaces with MSP430G2553-Q1, ultra-low power MCU

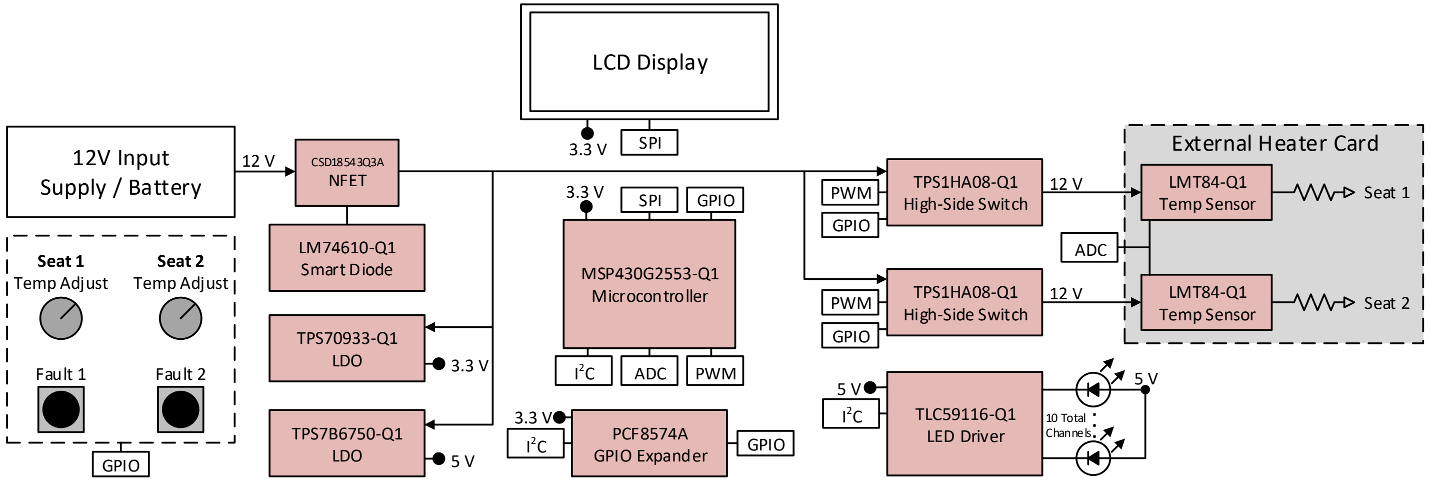
Applications

- Seat Heating
- Defrosters
- Climate Control
- Steering Wheel Heating



Benefits

- **Adjust** temperature of seat heater with high accuracy current sense (+/-5%)
- **Monitor** input voltage, current, device temperature, and resistance (via V/I=R)
- **Protect** passengers from seat overheating



TIDA-01552 – 8 Channel 1A/Ch High Side Driver for PLC Reference Design

Features

- High-density 8-channel, 24V high-side output
- 1 A/channel unregulated (+20%), 3-A peak
- 4-wire SPI MCU interface
- Fast switching of inductive loads
- LEDs to indicate output state
- BeagleBone-Black cape form factor for easy evaluation (four boards stackable)

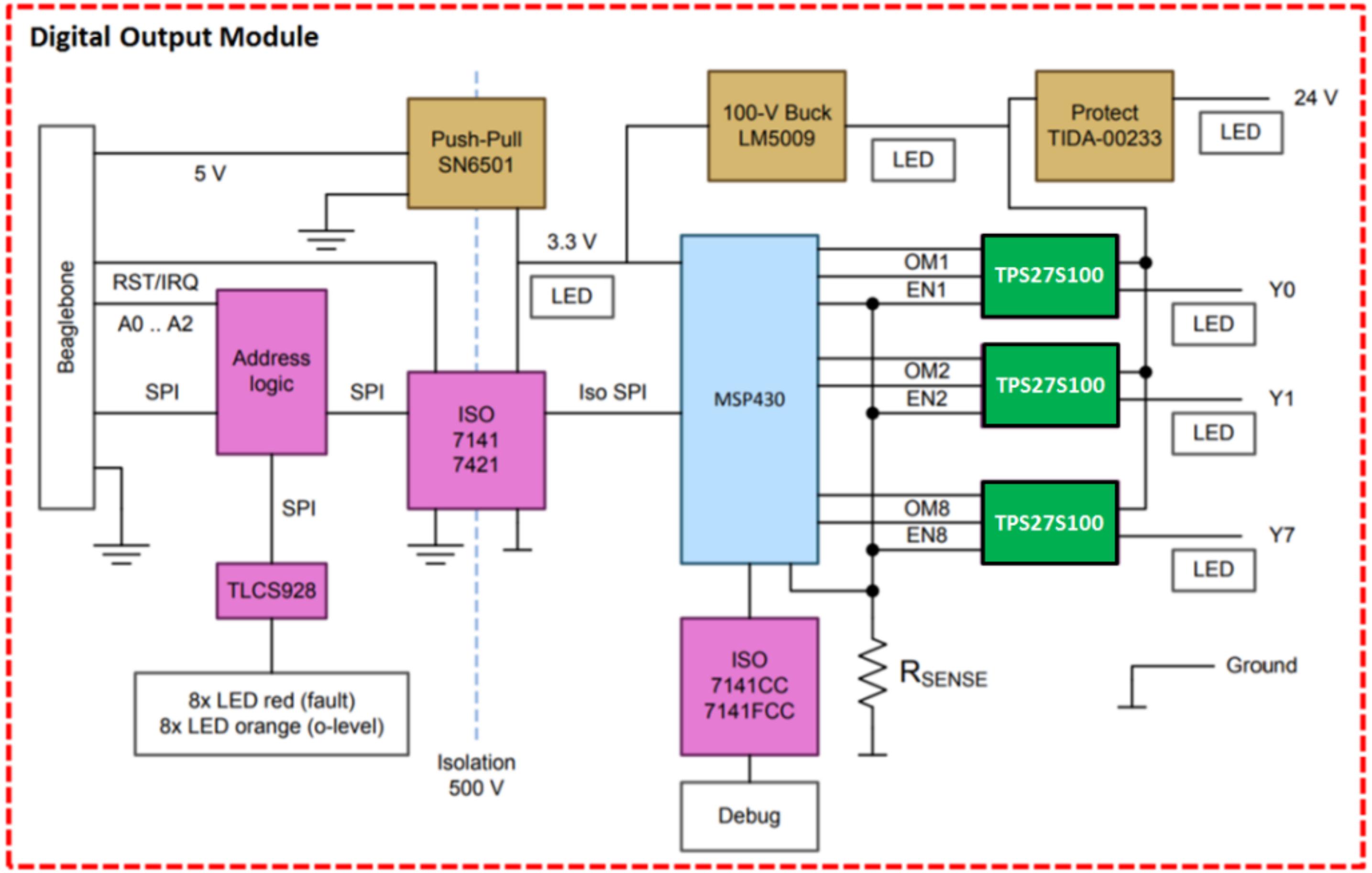
Benefits

- Fully functional 8-CH Digital Output Module
- The high-side configuration allows for the load to have zero energy in case of a wire short
- A high-side configuration is less sensitive to corrosion as the load is permanently connected to GND when the load is off

Target Applications

Target End Equipment's:

- Digital Outputs for
  - Programmable Logic Controller (PLC)
  - Distributed Control Systems (DCS)
  - Process Automation Controller (PAC)
  - Motor Control I/O Modules
  - Sensor Concentrators



Tools & Resources

- **TIDA-01552 Tools Folder**
  - User Guide
  - Relevant Design Files
- **Device Datasheets:**
  - TPS27S100
  - MSP430F2132

Summary

- TI Smart Power Switches offer significant advantages for load driving regardless of load profile.

High accuracy current sensing

Integrated current sense accuracy enables real-time monitoring for open-load and short-to-battery detection without any calibration needed, ultimately reducing production cost and test time.

Select your device

Adjustable current limit for targeted protection

Smart High-Side Switches from TI protect against Short-to-GND and short-circuit events through the flexibility to select current limit values for targeted thresholds. This also allows you to reduce PCB traces and connector sizes to lower system cost.

Select your device

Robust automotive solutions

TI's experts have designed solutions to meet the rigorous requirements of the automotive standards: AEC-Q100 ISO7637 ISO16750

Select your device