Input protection introduction: Hot-swap/eFuse/Power switch/Oring

Analog FAE : Redick Lee

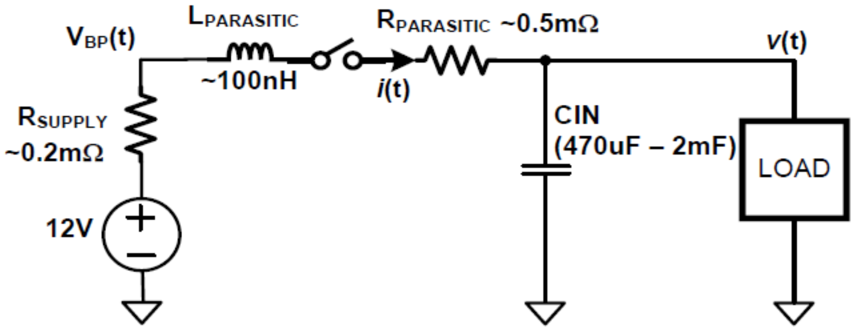
Agenda

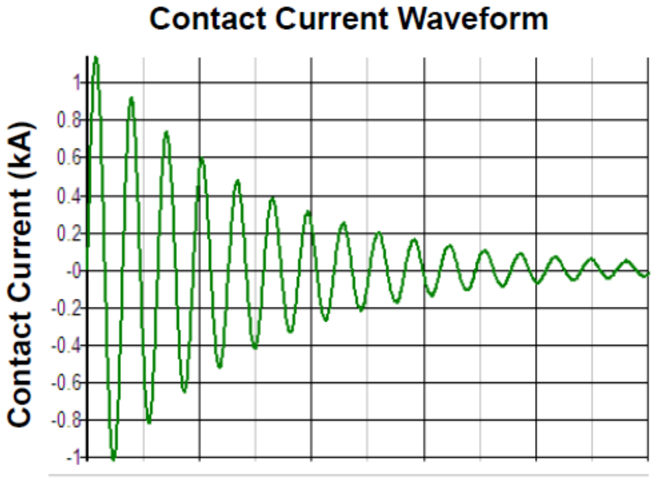
- *Hot-swap*
- *Power switch*
- *eFuse*
- *Oring*

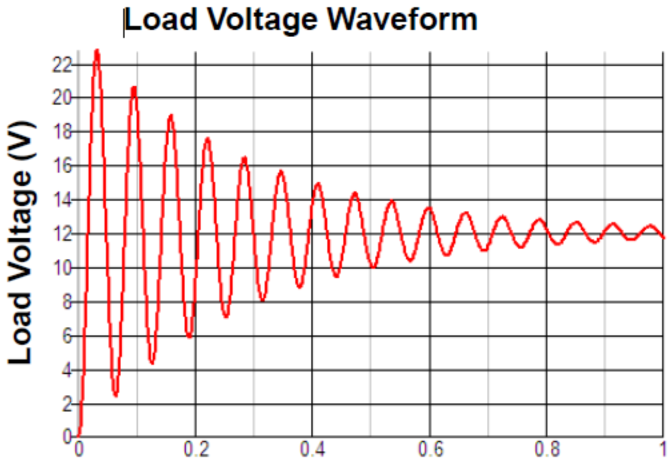
Why Protection Devices?

- High Availability Systems
  - Cannot be shutdown
  - Redundancy, No single point of failure
  - Live maintenance
- Who uses High Availability Machines
  - Follow the money
    - Stock markets, Amazon
  - Mission Critical
    - Air traffic control, Google
- User Expectation

Hot Insertion without a Hot-Swap







What Problems are Addressed by Protection Circuits?

- Inrush Currents
- Damage
  - Connector Pins
  - Board Etch
  - Components
- Disrupt The Backplane Voltage
  - Backplane voltage droop can shutdown the system

SUPPLY

CONNECTORS

POWER FET

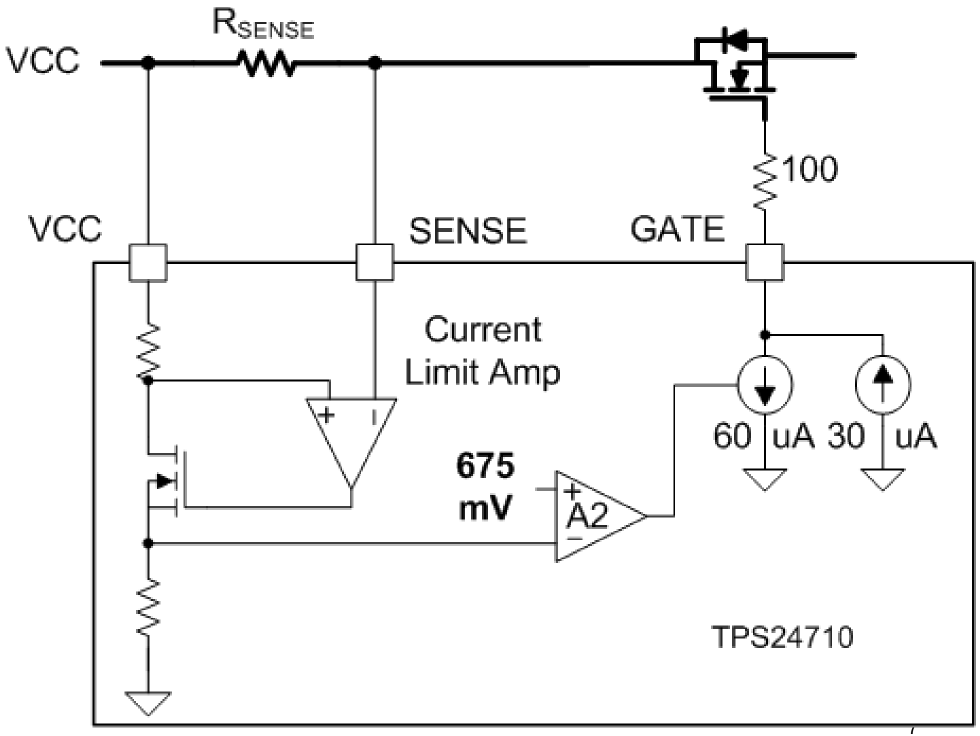
LOAD

What Problems are Addressed by Protection Circuits?

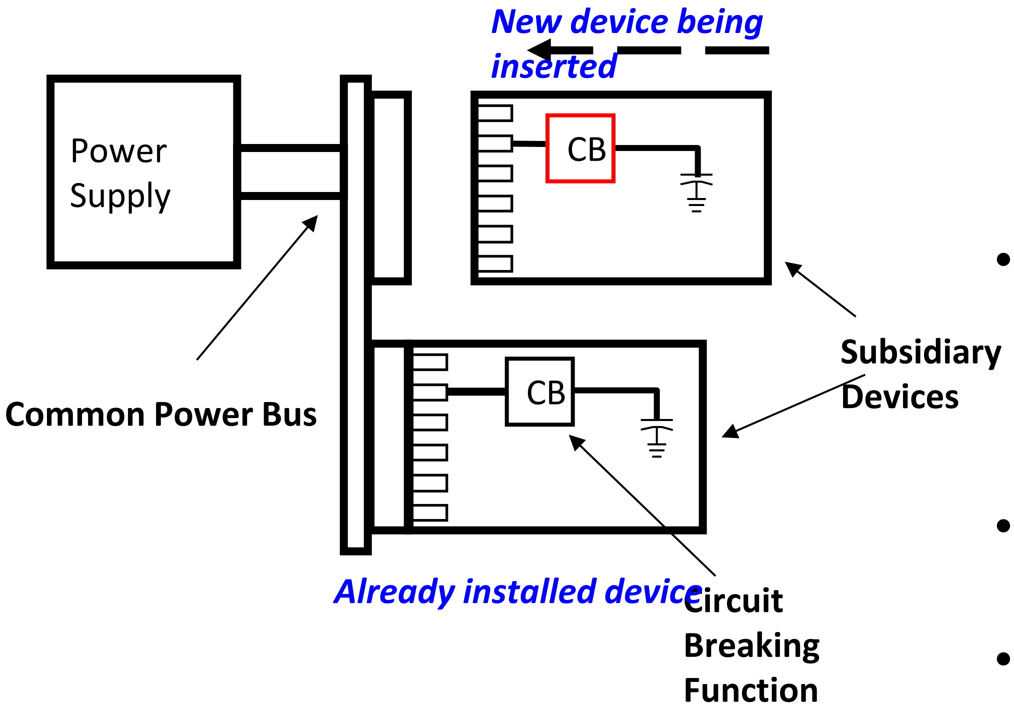
- Manage Power-on
  - Power Limit
  - dv/dt
  - di/dt
- Shutdown
  - Over Voltage
  - Under Voltage
  - Current Overload
  - Load Shorted
  - Latchoff
  - Re-try

Components of a Protection Circuit

- MOSFET
  - Pass element controls flow of current to the output
- Sense Resistor
  - A few milliohm resistor senses current
- Controller
  - Reads the current sense
  - Operates the MOSFET
- Over-load
- Fast Turn Off



What is circuit protection?



- Without circuit protection, current inrush to a subsidiary device during live insertion is limited by the ESR of the capacitor's DC contact resistance.
  - Typically over 80 Amps for a 3A board or device!
- Without a Circuit Breaker / inrush-limiter there will be a logic glitch or an over designed power supply
- Circuit Breaker Limits Current Inrush and load to less than 4A (or some preset level)

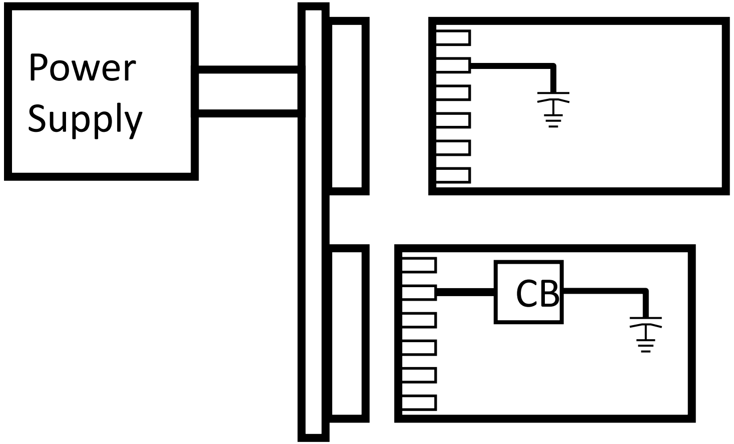
Hot Swap: Power Glitch Issues

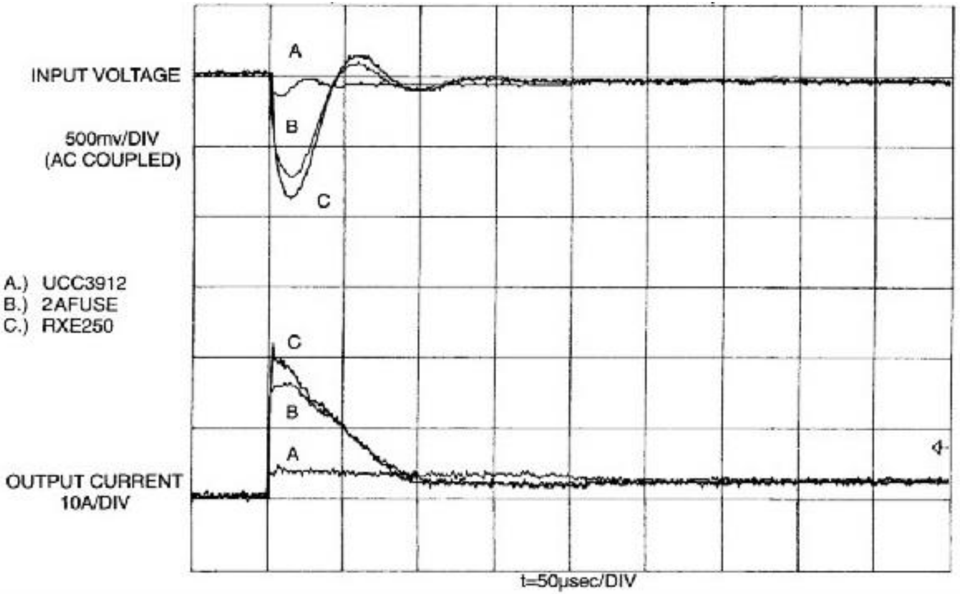
Without a Circuit Breaker, current is limited by the ESR of the capacitor's DC contact resistance.

– Typically over 80 Amps for a 3A board!

Without a Circuit Breaker there will be a logic glitch or an over designed power supply

Circuit Breaker Limits Current Inrush and load to less than 4A





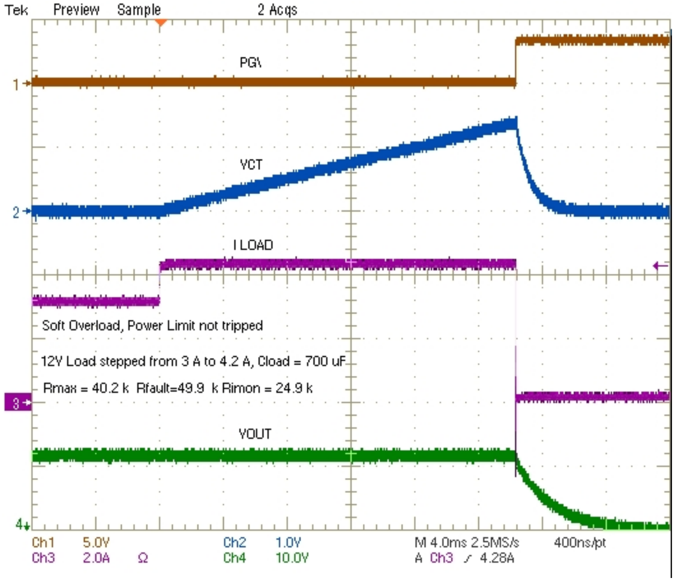
Circuit-breaking vs. Current-limiting

Circuit-breaking

- Time limit above fault current threshold exceeded
- Short-circuit event (instant)

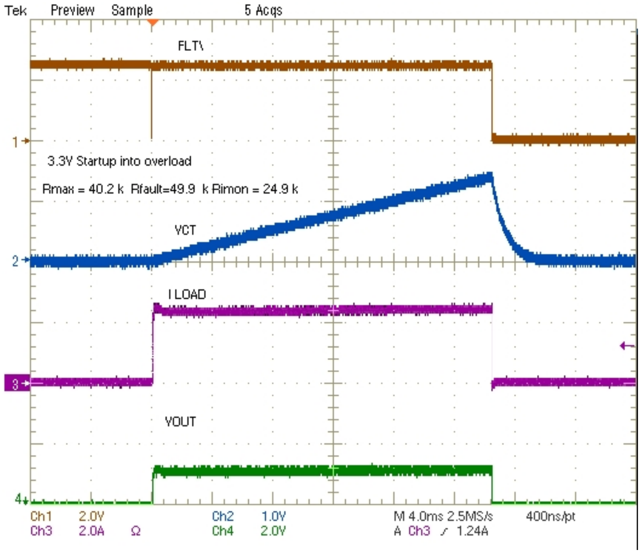
FET gate driven OFF

- No Conduction



TPS2420 going from 3A to 4.2A, Fault timer limit reached

- Current-limiting
  - Current-limit threshold exceed
  - Gate drive ramps down
    - Current-limited to desired level
    - Output voltage may droop



TPS2420 3V startup into overload – current-limited.
(Circuit not disconnected until Ct limit reached.)

Fault Timers

Hot swap managers must allow enough time for the fault condition on startup to charge bypass capacitors.

Retry Duty cycles are typically 2 - 3 % on fault conditions for auto reset parts.

External FET versions may have an additional Power Limit adjustment to reduce the duty cycle.

Latch off parts are used on systems where faults should not occur

Fault times are adjusted by the Ct capacitor

Ct calculation requires knowledge of the load

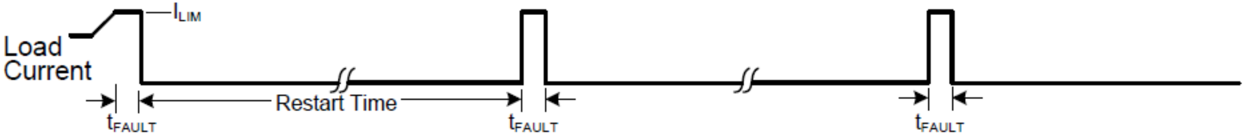
- Bypass capacitance
- Load Current

$$\text{Fault time} = 27.8 * 10^3 * Ct$$

$$\text{Cout (max)} = (\text{Imax} - \text{Iload}) * \left(\frac{28*10^3 * Ct}{\text{Vout}} \right)$$

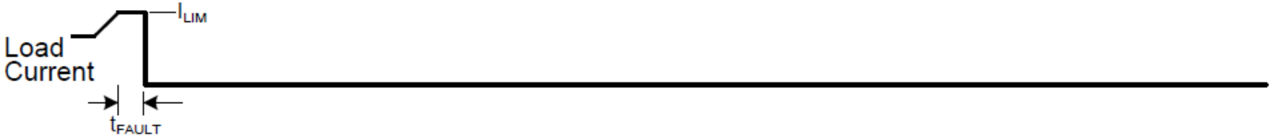
After Fault Timeout

1. RETRY OPTION



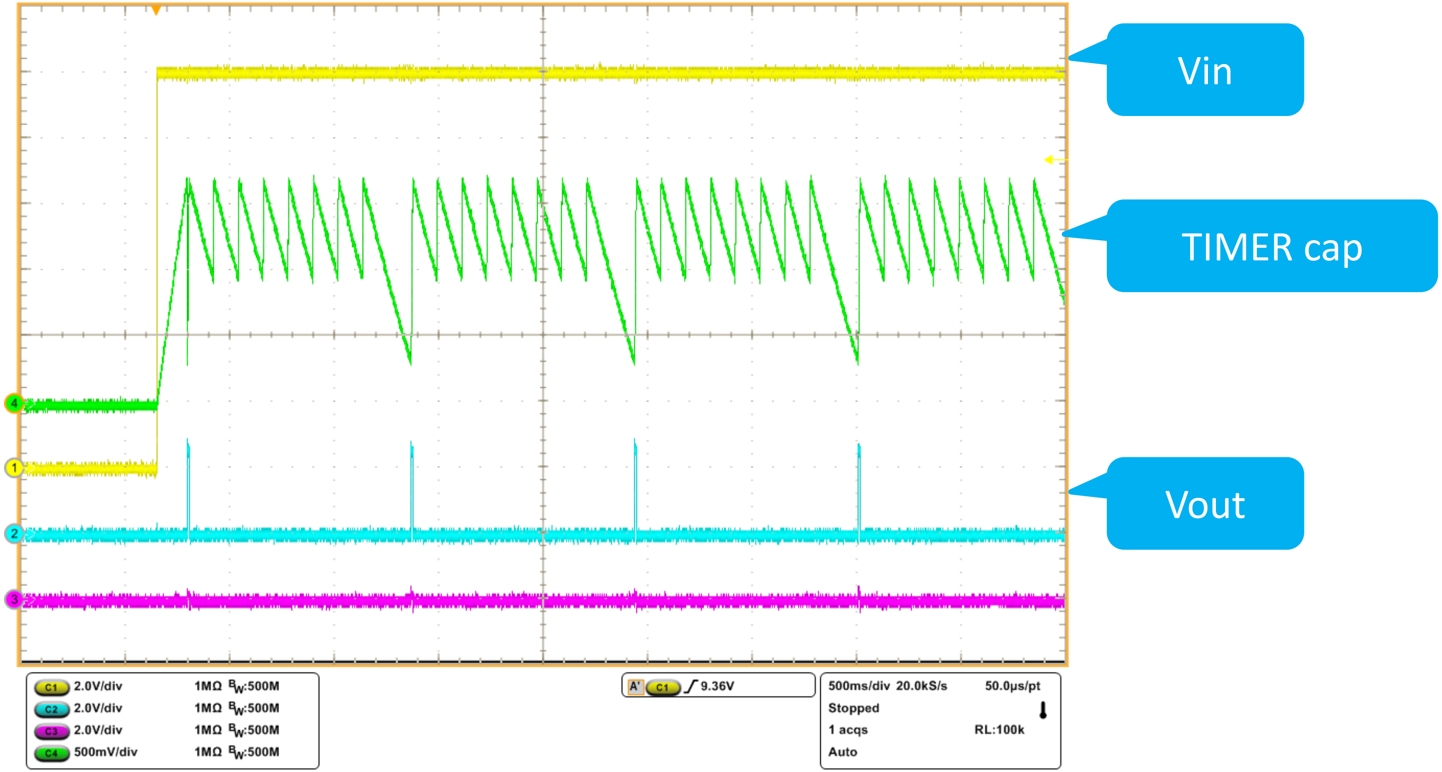
Restart time is typically several seconds
→ set by the timing capacitor C_T
→ circuit will continue to attempt restarts until the fault is removed

2. LATCH-OFF OPTION



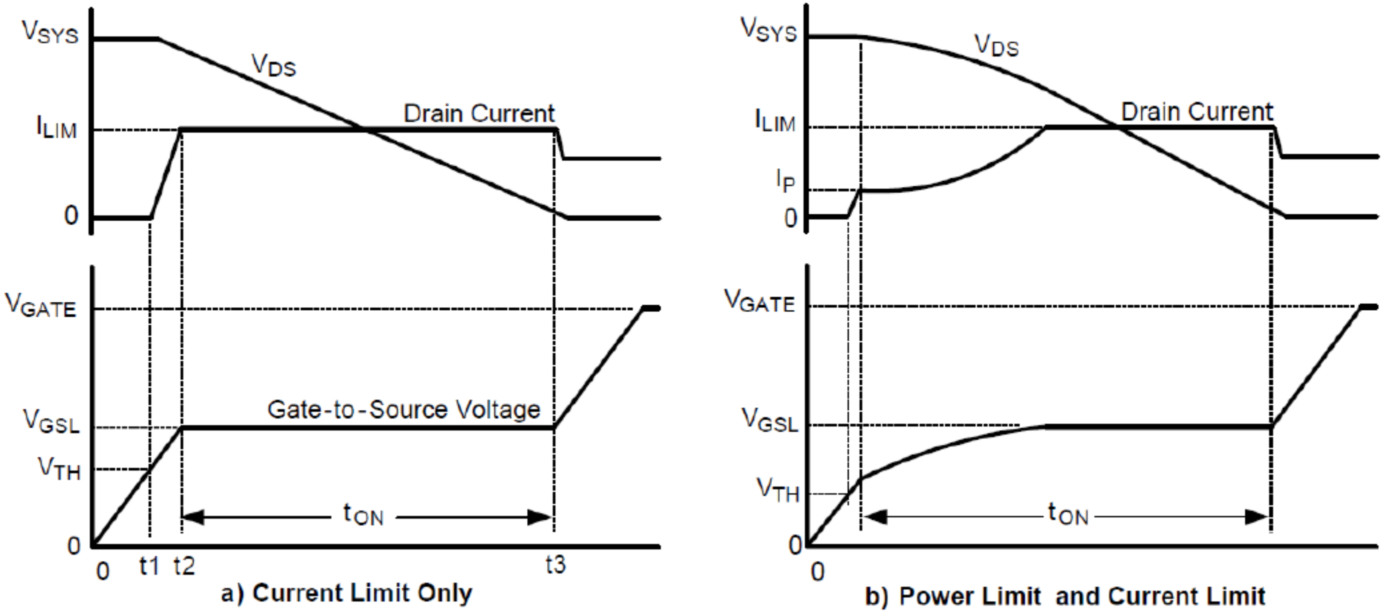
The circuit is restarted by:
→ cycling the input voltage off-on, or
→ by momentarily grounding the UVLO pin

Timer Cap Function – Fault Retry Delay



The hiccup time allows adequate cooling of pass MOSFET

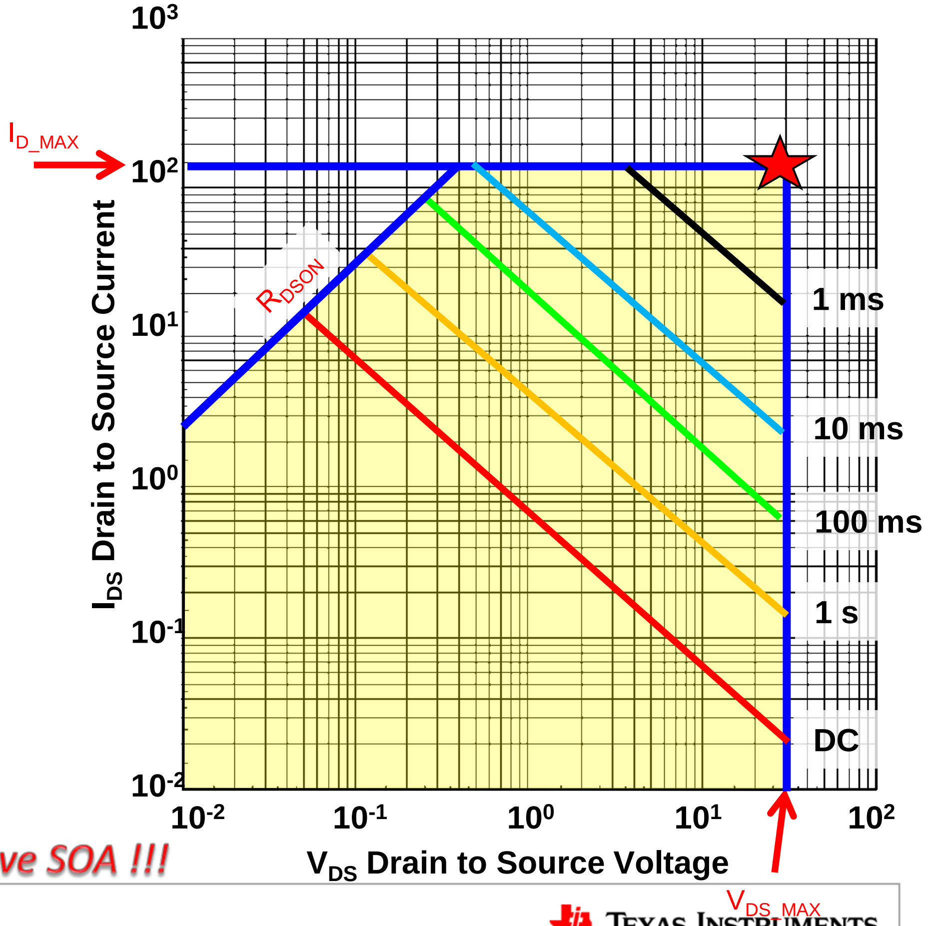
Idealized Typical Startup Waveforms



Common Design Errors SOA of FET Too Small

- **SOA = Safe Operating Area**
  - SOA Chart – Every FET has one
  - Defines Bounds of FET Operation
  - V_{DS_MAX} = Vertical Limit
  - I_{D_MAX} = Horizontal Limit
  - R_{DSON} limits I_D at lower voltages
  - ***Theoretical*** P_{MAX} = 3000 W
- **Fault Time Is Critical**
  - Longer Fault time means bigger FET
  - Shorter Fault Time allows higher peak power
- **Most Stressful FET Events**
  - Startup into short
  - Shorted load while under full load

Putting FETs in parallel does NOT improve SOA !!!

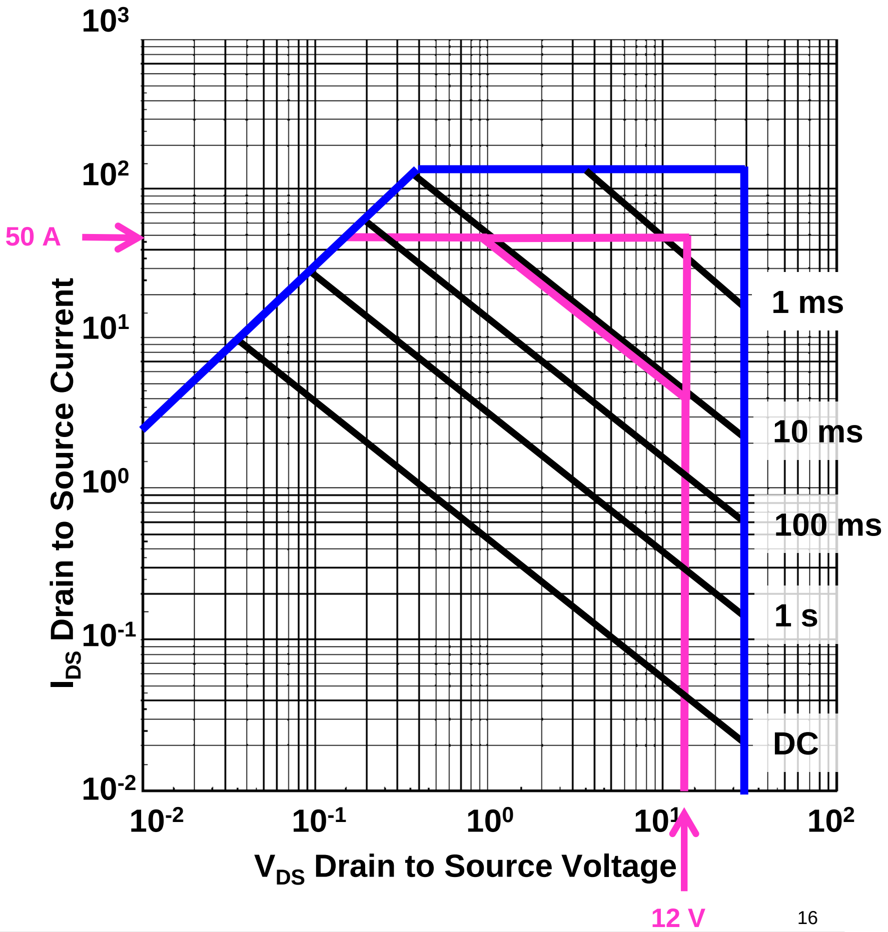


Common Design Errors

SOA of FET Too Small -

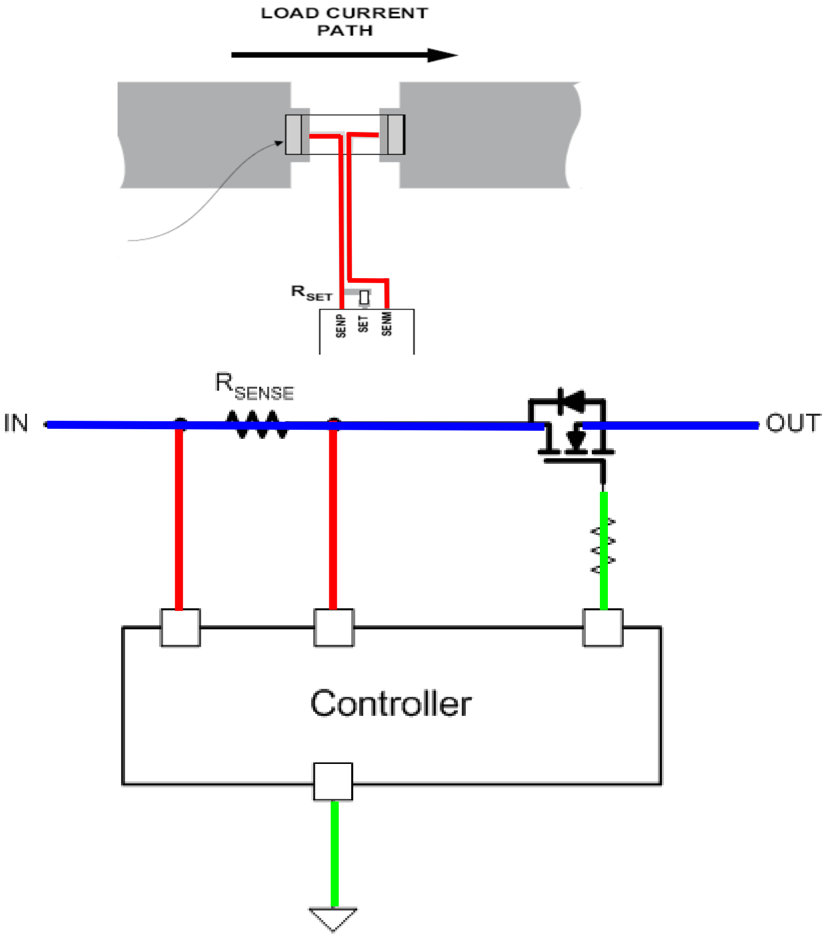
Example - 12 V, 50 A Server

- **Without Power Limiting**
  - $P_{MAX} = I_{LIMIT} \times V_{SUPPLY} = 600$ W
  - $T_{SOA\_MAX} = \sim 800$ us
- **With Power Limiting**
  - $P_{MAX\_LIMITED} = 50$ W
  - As V_{DS} increases I_{LIMIT} is reduced
  - $T_{SOA\_MAX} = 10$ ms
  - Smaller FET can be used
  - @ 50 A will start limiting when $V_{DS} > 1$V
- **Common Error to Pick FET Too Small**



Common Design Errors
Layout Issues –
A Little Stray R Can Make a Big Error

- Critical Kelvin Connections
  - Sense Runs
- Critical Short Run
  - Ground
  - Gate
- High Current Runs
- Poor Kelvin Runs…
  - Inaccurate/variable I_{LIMIT}
- Poor High Current Runs
  - Voltage droop
  - Power loss
  - Overheating



Common Design Errors Inadequate Transient Protection

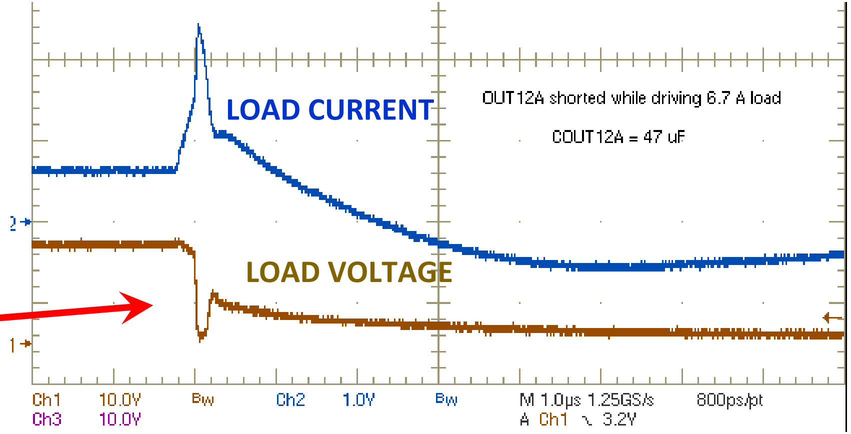
- All wires are inductive
- Inductance stores energy
- When the FET turns off, voltage spikes occur

$$E = \frac{LI^2}{2}$$

$$V = L\frac{di}{dt} \qquad \frac{di}{dt} \Rightarrow \infty$$

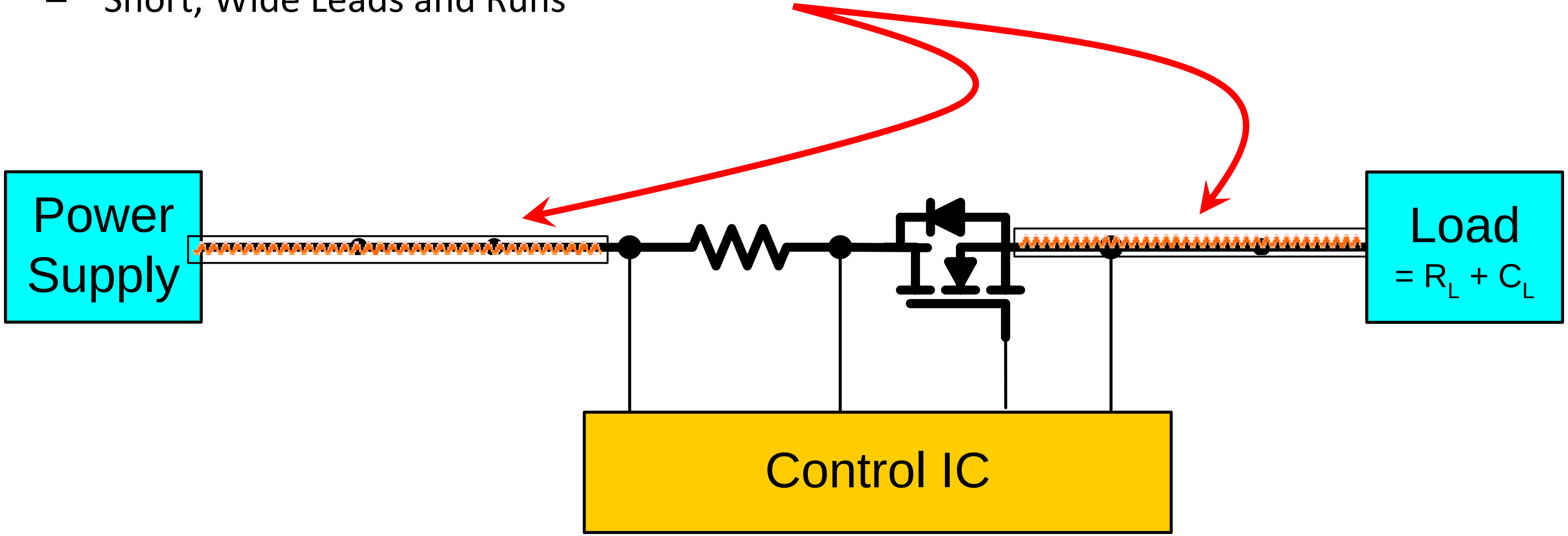
Positive Spikes at Input to Switch/FET

Negative Spikes at Output of Switch/FET

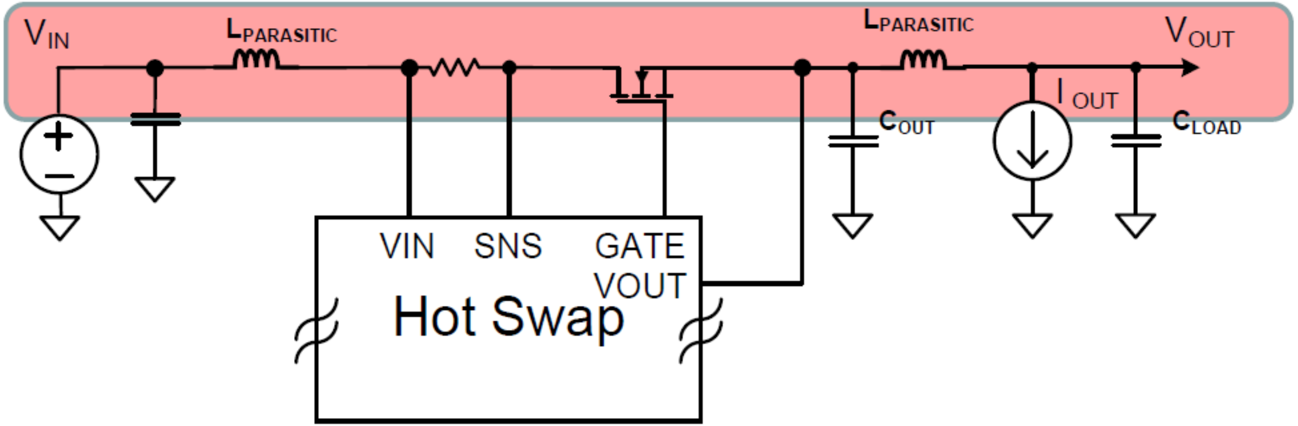


Common Design Errors Inadequate Transient Protection

- To squelch inductive spikes from supply / load leads
  - Caps and/or TVS at UUT Input to clamp positive spike
  - Schottky Clamp across output to clamp negative spike
  - Short, Wide Leads and Runs



Potential Causes for Device Damage



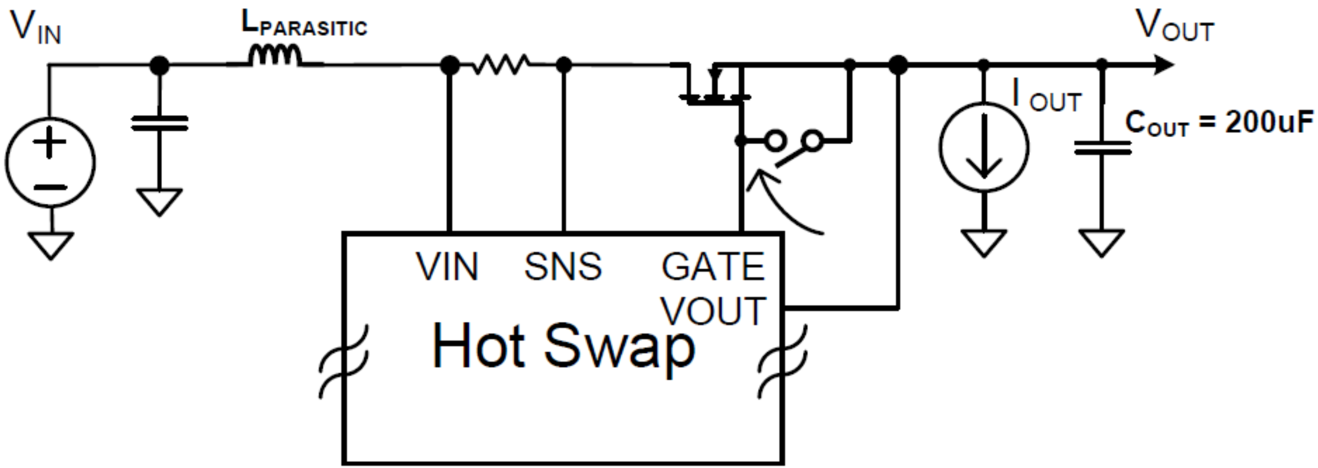
- Parasitic Inductance on the Input and Output of a hot-swap can be detrimental to the reliability and performance of the hot-swap, especially when high currents are involved.

- By understanding the effects of these inductances, measures can be taken to insure robust operation.

Potential Causes for Device Damage

Input Supply Surge During a Fault

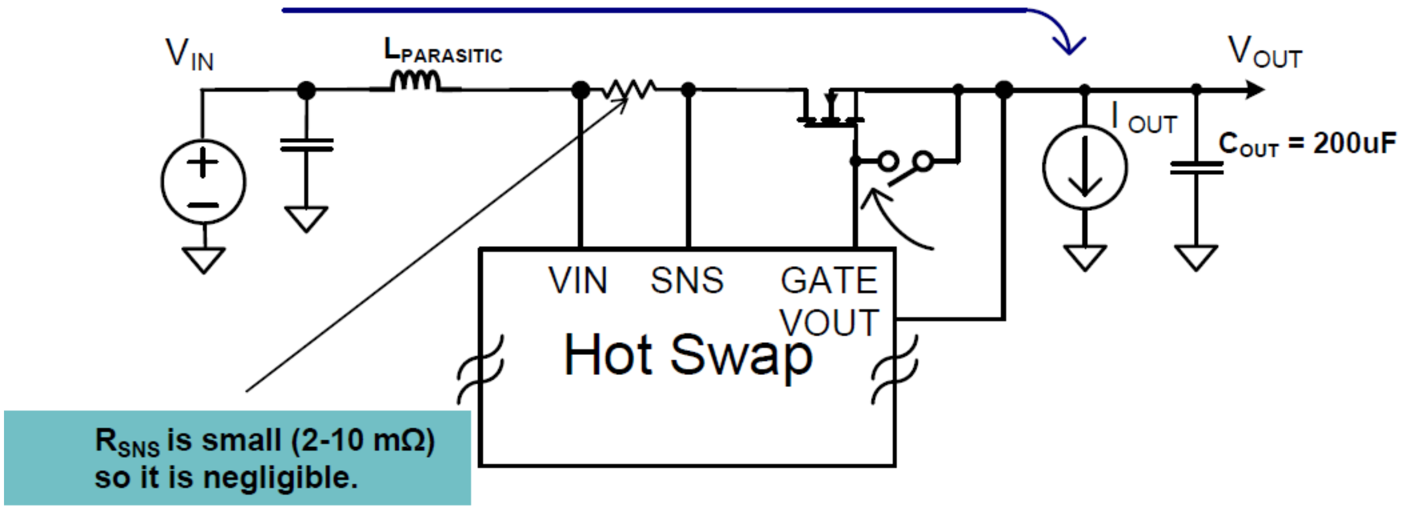
- The classic voltage supply inductive surge problem can cause over-voltages on the input of a hot swap
- Consider the following circuit. It is designed to simulate a circuit-breaker condition on a hot swap.



Input Supply Surge

BEFORE THE GATE IS SHORTED TO VOUT

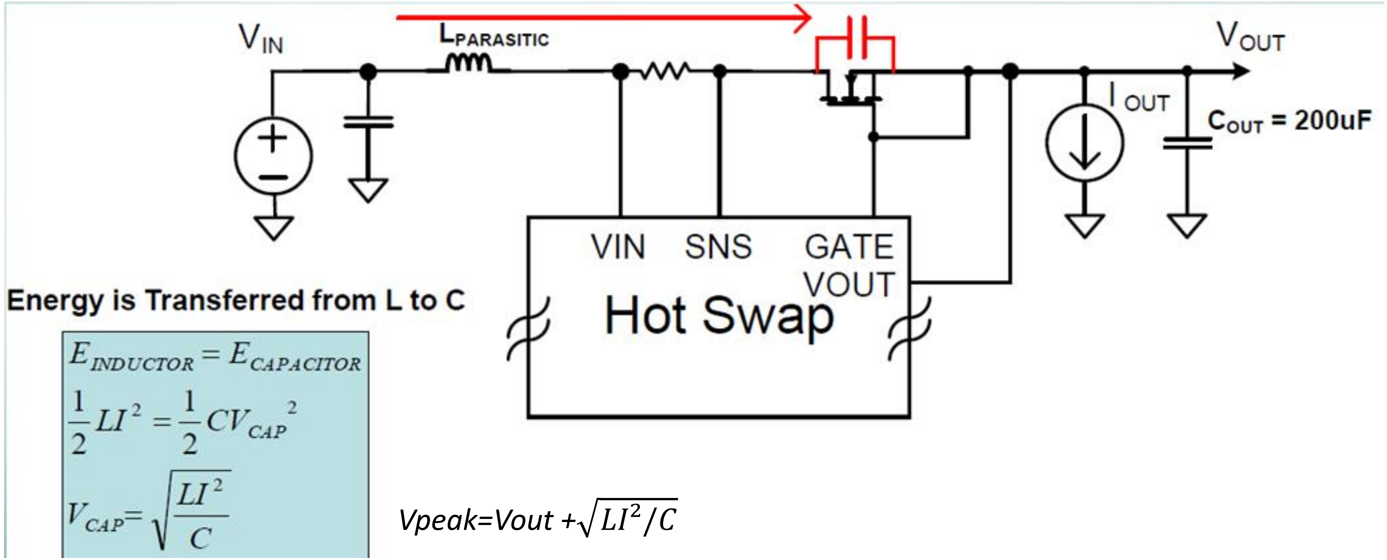
➔ IOUT runs continuously through the pass FET, and LPARASITIC



Input Supply Surge

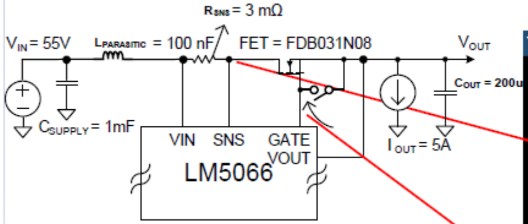
AFTER THE GATE IS SHORTED TO VOUT

- The pass FET stops conducting, and the current in LPARASITIC charges the pass FET capacitance across the FET.



$Vpeak = Vout + \sqrt{LI^2/C}$

Input Supply Surge During Test



V_{PEAK} = 104.8 V
This is greater than ABS MAX!

Theoretical Calculation

$$Vpeak = Vout + \sqrt{\frac{LI^2}{C}}$$

$$Vpeak = Vout + \sqrt{\frac{100\,nH \times 5^2}{1000\ pF}}$$

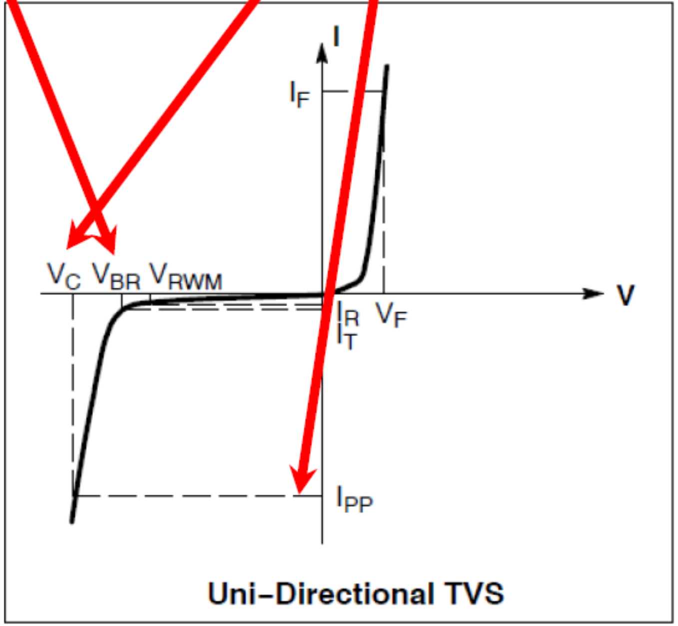
$$= 105\,V$$

Key TVS Specifications

Part Number (Uni)	Part Number (Bi)	Marking		Stand off Voltage V_R (Volts)	Voltage V_{BR} (Volts) @ I_T		Current I_T (mA)	Clamping Voltage V_C @ I_{pp} (V)	Peak Pulse Current I_{pp} (A)	Reverse Leakage I_R @ V_R (µA)	Agency Approval
		UNI	BI		MIN	MAX					
SMDJ5.0A	SMDJ5.0CA	RDE	DDE	5.0	6.40	7.00	10	9.2	326.1	800	X

1. Ensure VBR is equal to or above max DC operating level
2. Ensure VC(max) at circuit breaker setpoint is less than the pass MOSFET & hot swap controller voltage ratings
3. Higher power rating TVS devices have a sharper knee characteristic

Note: PPP = VC(max)*IPP



Recommended TVS components:

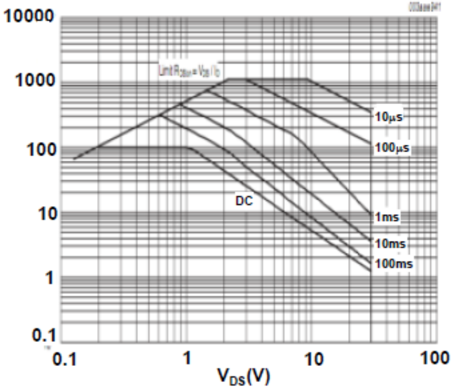
12V rail: Littelfuse 5.0SMDJ15A

±48V rail: Littelfuse 5.0SMDJ60A

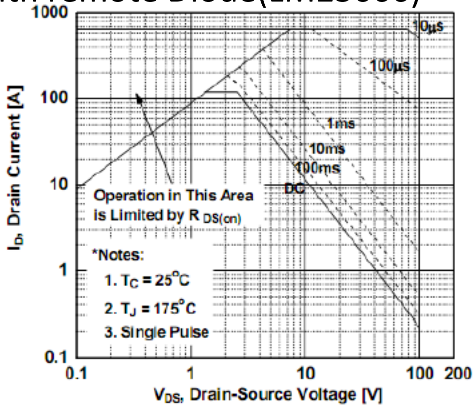
Causes for FET damage

Possible Causes

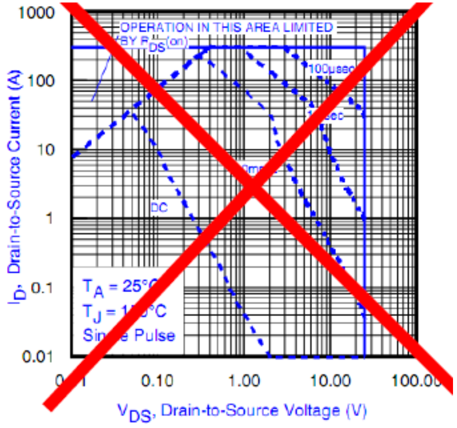
- Improper Power Limit Setting or FET Selection.
  - ➢ Start with 50% derating for desired SOA time
- Improper Timing Capacitor Selection
  - ➢ Set timer to be 20% below desired SOA timeout
- Improper Clamping of input/output Voltage
- Excessive FET temperature (SOA is for TC=25C)
  - ➢ Check RDSON and Package, RthJC
  - ➢ Monitor FET temperature with remote Diode(LM25066)



PSMN1R0-30YLC



FDB047N10 100V



IRF6798 (BAD)

TI Information – Selective Disclosure

IR DirectFETs are not recommended.

Building Blocks for your Design

Load Switch & eFuse

Load Switches

- Power savings and simplify power sequencing
- Protects against inrush current with integrated soft start

eFuses

- Protects against over-voltage, over-current and inrush events.
- Saves board space
- Increases reliability - UL/IEC recognized

Smart High-side Switches

- Increases short-circuit reliability with selectable current limit
- Improves diagnostics with high accuracy current sensing.

Signal Chain

Signal Switches

- Resolves constrained I/O and address conflict
- Improves signal integrity

I²C Solutions

- Isolates signals & simplifies board routing
- Low-power/high-speed technology
- Low-noise audio and THD performance

Voltage Level Translators

Bridges I/O voltage domains between MCU/MPU and peripherals with:

- Low voltage support (down to 0.8V)
- Compact packaging

Circuit Protection

High Performance TVS Diodes

- Protects system from damaging external transients (ESD, EFT, Surge)
- Protects high speed interfaces and sensitive end equipment

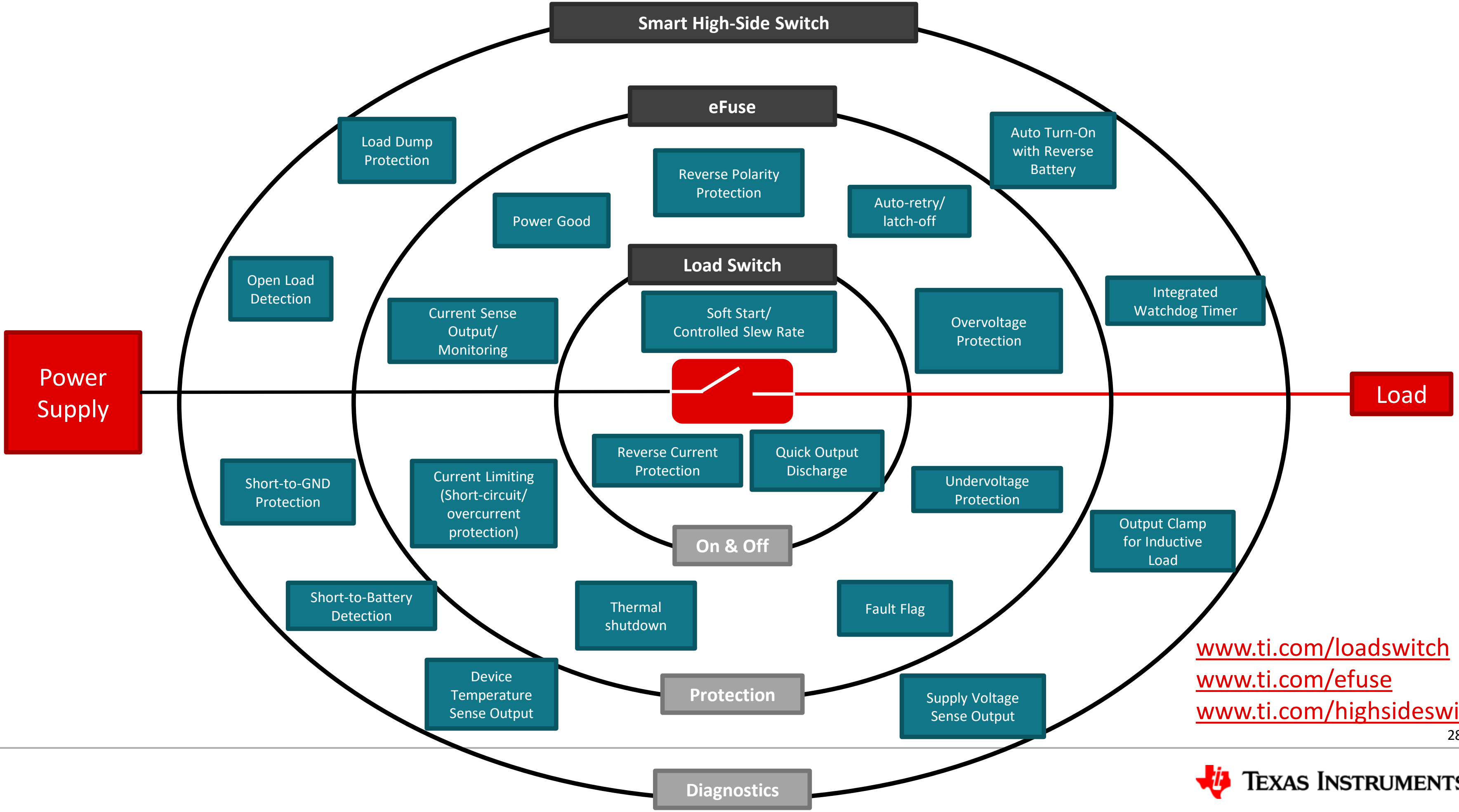
Integrated ESD Protection

- All-in-one protection for many popular interfaces like USB and HDMI
  - ESD, EMI, Current Limit Switch, OVP
- USB Type-C Short-to-VBUS protection for CC/SBU

Automotive ESD Protection

- AEC-Q100, AEC-Q101
- Short-to-Battery/Ground
- Over Current Protection

Load Switch, eFuse & Smart High-Side Switch



www.ti.com/loadswitch
www.ti.com/efuse
www.ti.com/highsideswitch

Load Switch, eFuse & Smart High-Side Switch

Load Switches
Power Distribution & Savings

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

Parameters
- **Ron:** 4 - 435 mΩ
- **Vin:** 0.65 - 6.0 V
- **Imax:** up to15 A
- **Size:** down to 0.64 mm^2
- **Package:** WCSP, SOT-23, SON, QFN

Applications



www.ti.com/LoadSwitch

eFuses
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

Parameters
- **Ron:** 3 – 150 mΩ
- **Vin:** 2.5 – 55 V
- **Imax:** up to 12 A
- **Size:** down to 9 mm^2
- **Package:** SON, QFN, SOIC, TSSOP

Applications



www.ti.com/eFuse

Smart High-Side Switches
Diagnostics & Protection

Benefits
- Increased reliability against short-circuit
- Accurate, real-time load diagnostics
- Robust solutions withstands automotive requirements – AEC-Q100/ISO

Parameters
- **Ron:** 4 mΩ – 1 Ω
- **Vin:** 3 - 40 V
- **Imax:** up to 90 A
- **Size:** down to 32 mm^2
- **Package:** HTSSOP (PWP)

Applications

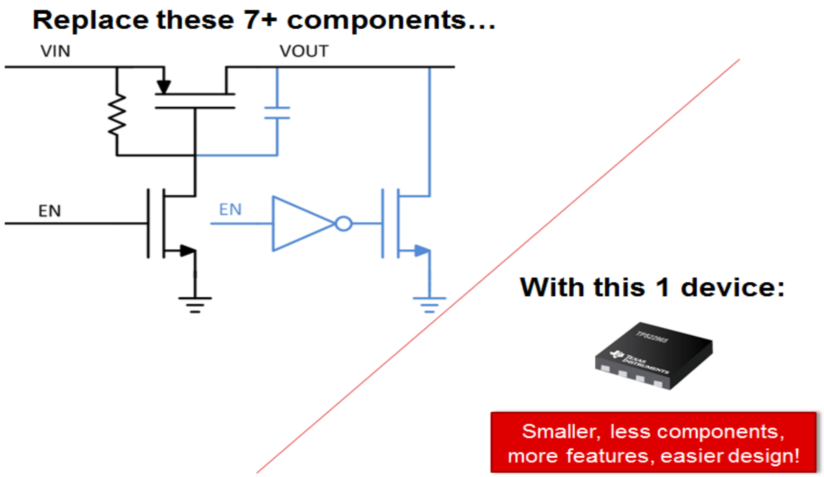


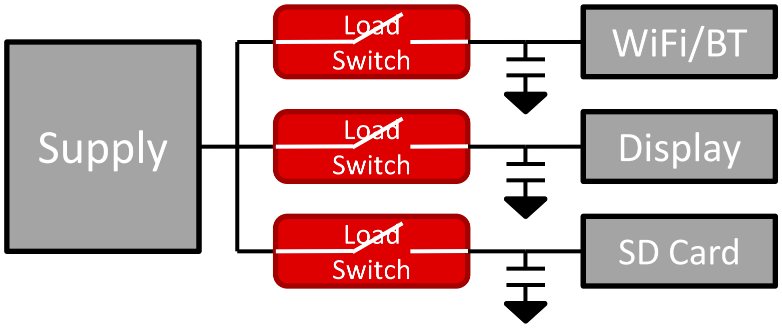
www.ti.com/HighSideSwitch

Load Switch Overview

- **Extend battery life** by reducing standby leakage current. Turn off unused subsystems w/load switches: WiFi/BT, LCD, SD Card
- **Save space** and reduce solution size by integrating discrete circuitry into a load switch (2+ FETs w/Resistors & Capacitors)
- **Simplify power sequencing** by implementing point of load control with load switches. Power on/off each rail with GPIO
- **Mitigate inrush current damage** to the system with integrated "Soft Start" slew rate /rise time control.

Load Switch	Features
TPS22975	5.7V, 6A, 16mΩ, Adjustable Soft Start/ Rise Time (CT), Quick Output Discharge (QOD), Thermal Shutdown, QFN-8 pkg (0.5mm pitch)
TPS22990	5.5V, 10A, 3.9mΩ, Adjustable Soft Start/ Rise Time (CT), Quick Output Discharge (QOD), Integrated Power Good (PG), QFN-10
TPS22918	5.5V, 2A, 52mΩ, Adj. Soft Start/ Rise Time (CT), Configurable Quick Output Discharge (QOD), leaded SOT23-6pin, AEC-Q100 Available
TPS22915	5.5V, 2A, 38mΩ, Fixed Soft Start/ Rise Time, Optional Quick Output Discharge (QOD), 0.78mm x 0.78mm WCSP-4 (0.4mm pitch)
TPS22976	5.7V, 6A, 2-channel, 16mΩ, Adjustable Soft Start/ Rise Time per channel (CT1 & CT2), QOD, Thermal Shutdown, QFN-14 package



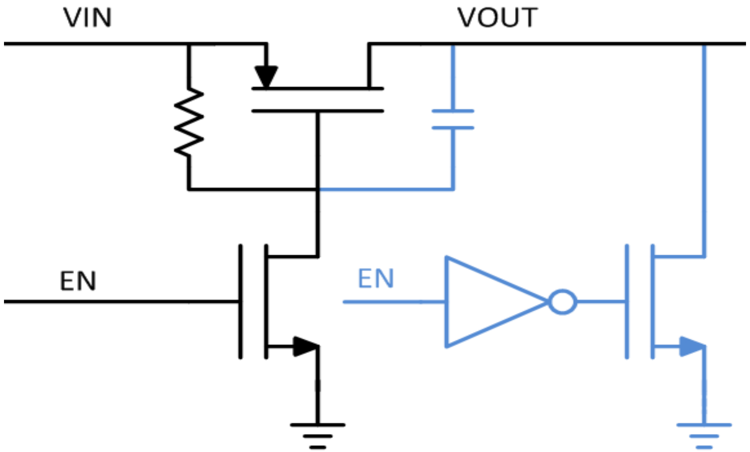


Manage power distribution for subsystems

What Is A Load Switch?

Load Switch

Load switches are electronic relays used to turn on/off power supply rails.



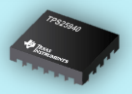
- Space Savings
- Reduced Inrush Current
- Extended Battery Life
- Broad Portfolio

eFuse Overview

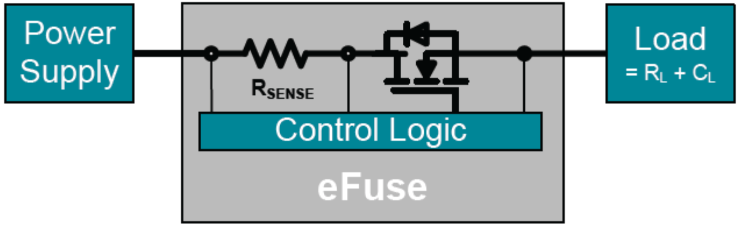
- **Integrated FET & current sense** an active circuit protection device that commonly replaces fuses and Polyfuse/PTC
- **Prevents failure** during hot-plug/swap by protecting against under/over-voltage, over-current, and inrush events
- **Save Space** and reduced solution size by integrating discrete protection circuitry
- **Faster Time to Market** and increased reliability through UL/IEC recognition

eFuse	Features
TPS2660x	60V, 2A, 150mΩ, ILIM,CT pin, RCB, ISNS, RPP,OVP HTSSOP
TPS25940/2/4	18V, 5.2A, 42mΩ, ILIM, CT pin, RCB, ISNS, OVP, QFN
TPS25921A/L	18V, 1.6A, 87mΩ, ILIM, CT pin, OVP, SOIC
TPS25925x/6x	18V, 5A, 30mΩ, ILIM, CT pin, OVC, SON
TPS25923x/4x/7x	18V, 5A, 28mΩ, ILIM, CT pin, OVC,BFET, SON





	Fuse	PTC	eFuse
After Fault:	× Broken after fault	✓ Auto-retry	✓ Auto-retry; latch off
Reliability:	× Must be replaced	× R_{ON} increases after fault	✓ Not damaged by fault
Time to trip:	× Slow trip (s/ms)	× Slow trip (ms)	✓ Fast trip (<1.5 us)
Accuracy:	× Needs time to heat up and melt	× Current limit depends on ambient temp.	✓ Up to ± 2% current limit accuracy

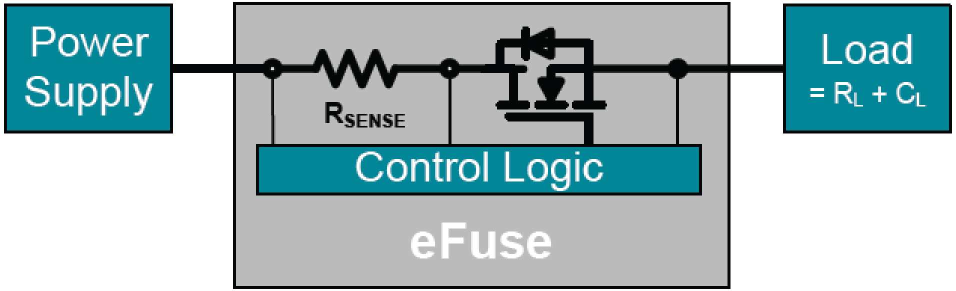


Highly Integrated Protection Features

What Is An eFuse?

eFuse

An active circuit protection device with an integrated FET to control load current



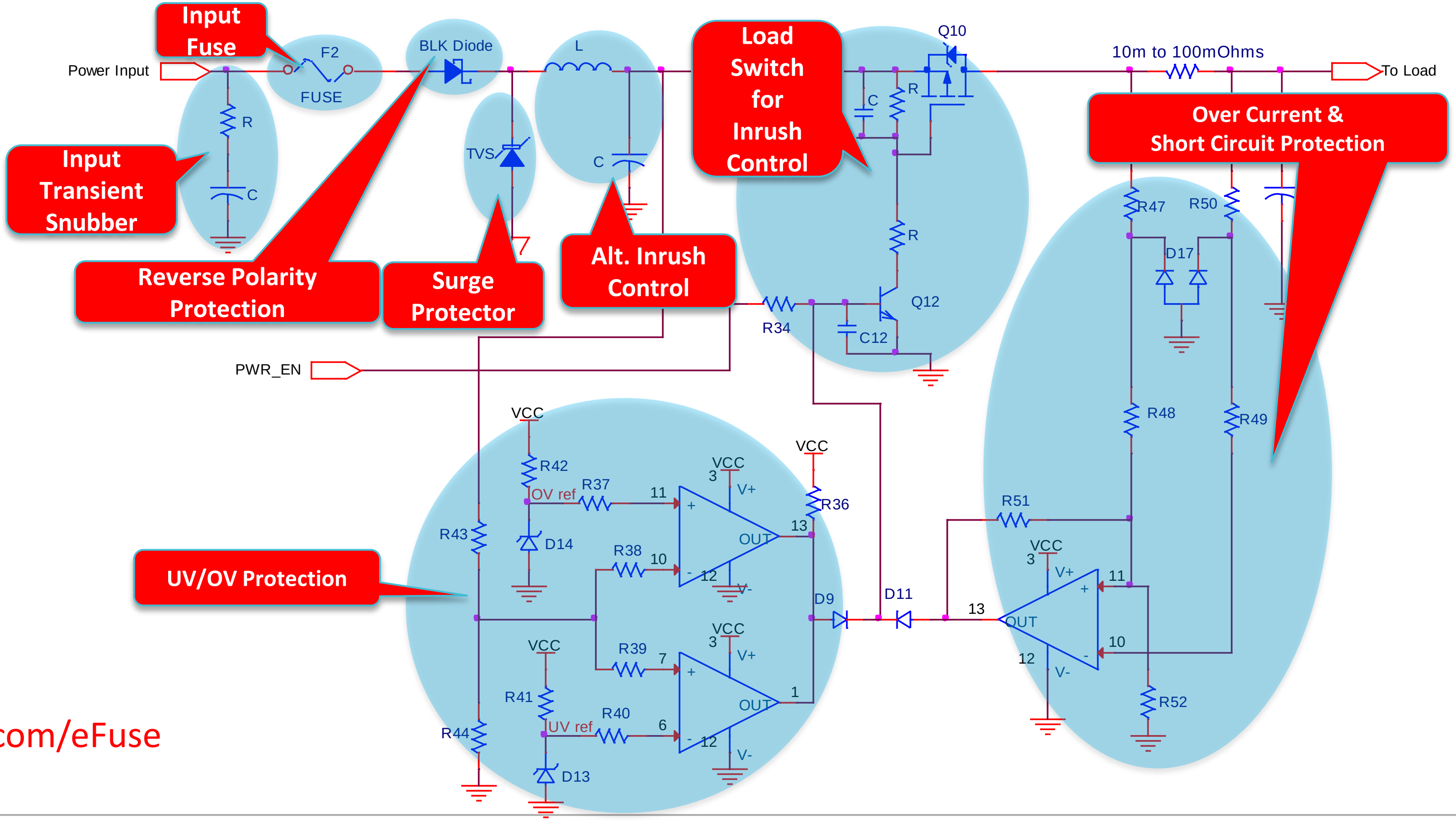
Integrated Advanced Circuit Protection

Stable, Reliable Current Limit & Short Circuit

Reduced Inrush Current

UL Recognition: 60950 & 2367

Integration

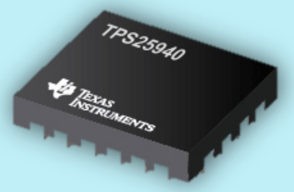


ti.com/eFuse

eFuse Features

Adjustable Current Limit, Inrush	✓ More flexibility in System design
Short Circuit protection	✓ Very fast (<200nS)Robust protection of system during short circuit situations
Over & Under Voltage protection	✓ Programmable OVP & UVLO help eliminates supervisory circuits
Reverse Current & I/P Voltage Protection	✓ Protects against miswiring {Reverse polarity i/P} ✓ Reserves holdup capacitor charge during power failure (Last Gasp) ✓ Addresses Power Muxing system challenges
Status output pins	✓ PG signal provides sequencing in the application ✓ Fault intelligence provided to the micro controller etc ✓ Real Time Analog Load current monitor

eFuse vs. Fuse vs. PTC



	Fuse	PTC	eFuse
After Fault:	× Broken after fault	✓ Auto-retry	✓ Auto-retry; latch off
Reliability:	× Must be replaced	× R_{ON} increases after fault	✓ Not damaged by fault
Time to trip:	× Slow trip (s/ms)	× Slow trip (ms)	✓ Fast trip (<1.5 us)
Accuracy:	× Needs time to heat up and melt	× Current limit depends on ambient temperature	✓ Up to ± 2% current limit accuracy

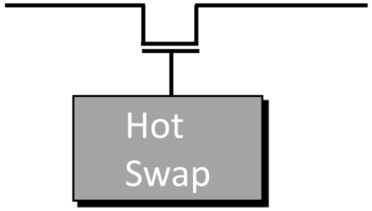
For More Information On eFuses & Load Switches:

Please visit: ti.com/efuse & ti.com/loadswitch

App Notes

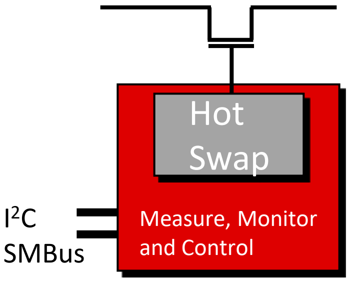
- Basics of Load Switch
- Fundamentals of On-Resistance in Load Switches
- Achieve 20A Circuit Protection and space Efficiency using Paralleled eFuses
- The TPS2660simplifies Surge and Power Fail Protection Circuit in PLC Systems
- Soft Startup of Brushless DC Fan with TPS25924 eFuses

System Protection & Management Options



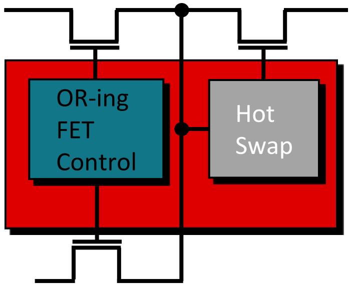
Inrush Current and Fault Protection

- Highly reliable hot swap cores
- Power limiting protects MOSFETs



I2C/SMBus System Management

- Integration of hot swap and digital system power management for system diagnostics
- PMBus support



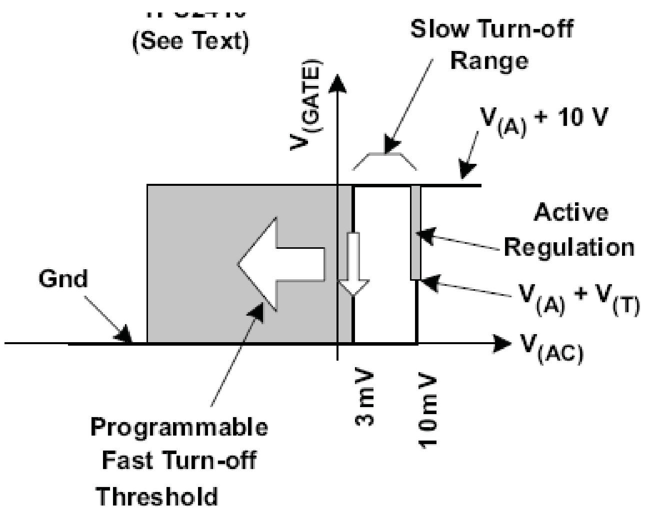
Multi-function Integration

- Integration of key analog cores for additional PCB area savings

ORing Control (Linear v. Hysteretic)

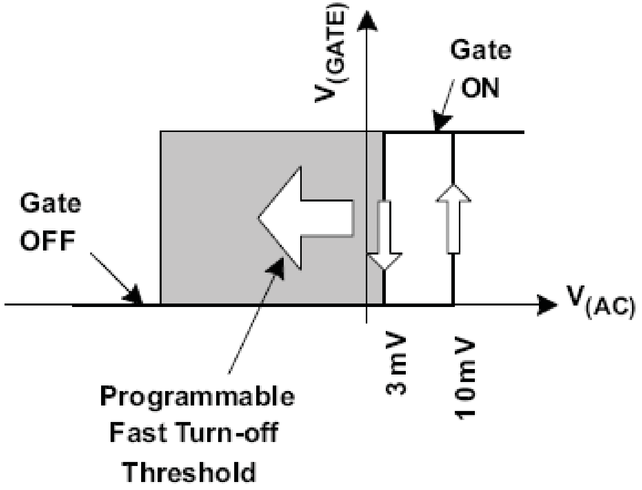
Linear Control

- Regulates V_{AC} to 10 mV
- Reverse current less likely
- May not like reactive loads

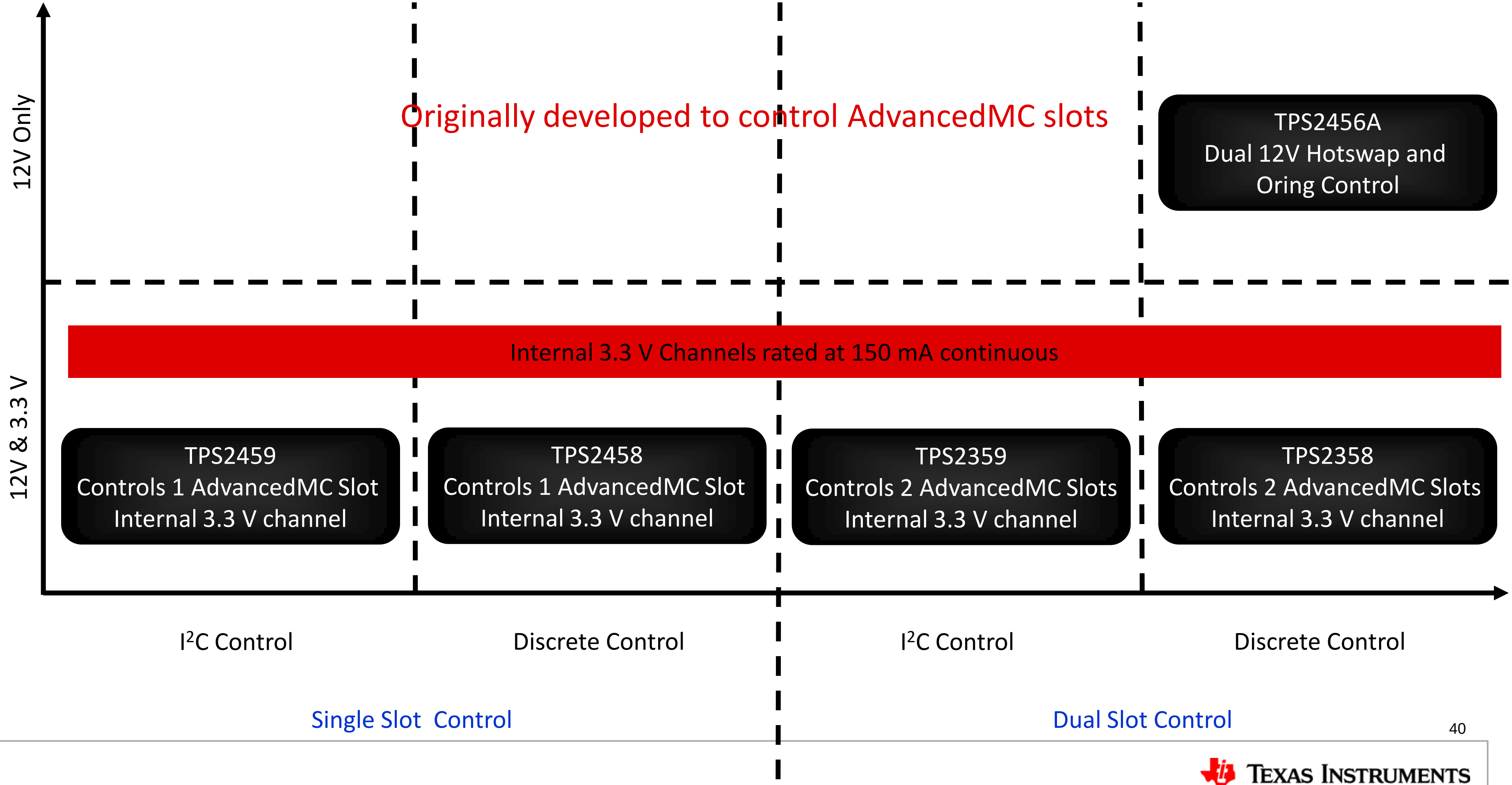


Hysteretic Control

- FET on if V_{AC} > 10 mV
- FET off if V_{AC} < 3 mV
- Fast off if V_{AC} goes negative
- **Less sensitive to reactive loads**
- **Suceptible to light load oscillation**



Hotswap/ORing Controller Combos



Protection Circuits ORing Controllers

Click on any part button for hyperlink to overview

	Low Voltage Full Featured ORing Control	Low Voltage Simple OR-ing FET Control	High Voltage OR-ing FET Control
Positive V Hysteretic Control	TPS2411	TPS2419 2413 plus Enable TPS2413	
Positive V Linear Control	TPS2410	TPS2412	LM5050-2 6 to 75 V, w/ FET Test LM5050-1 5 to 75 V, w/ AUX Input
Neg V Linear Control			LM5051 -6 to -100 V

Positive ORing Controller Device Comparison

PART	$V_{OPERATING}$	Package	AUX Input	FET Test	Control Type	I_{GATE} uA	V_{TH} FAST SHUTOFF mV
LM5051	-6 to 100	SOIC8	No	Yes	Linear	280 - 950	-45
LM5050-1	5 to 75	TSOT23-6 Thin	Yes (VS)	No	Linear	12 - 41	-28
LM5050-2	6 to 75		No	Yes			
TPS2410	0.8 – 16.5	TSSOP14	Yes (VDD)	Yes	Linear	290	Adjustable -3 to -200
TPS2411				Yes	Hysteretic		
TPS2412		TSSOP8		No	Linear		
TPS2413					Hysteretic		
TPS2419			No		Hysteretic		

Thank you.