EETimes Seminar- Circuit Protection for Power Management

Sept, 2017

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Agenda

- **Circuit Protection**
  - **What is it ?**
  - **Where is it used ?**
  - **The Basic Parts**

- **Device Features/Options**
  - **Inrush, Fault, FET SOA Protection, OV, UV etc.**

- **Common Design Errors**

- **Common Test Errors**

Circuit Protection – What is it ?

- Many things with many names
  - Inrush Control
  - Hotswap
  - Hotplug
  - Current Limiting
  - Electronic Circuit Breaker
  - Short Circuit Protection
  - Soft Start
  - Over Voltage Protection (OVP)
  - eFuse
  - Load Power Limiting
  - FET SOA Limiting (Protecting the Protector !)
  - Reverse Current Protection (ORing)

~ the same functions

- Often Required for Agency Rating
  - UL, CSA – North America
  - EN, IEC, (CENELEC) – Europe
  - CCC Mark (CNCA) - China

Circuit Protection – *Where Is It Used ?*

- **Telecom Equipment**

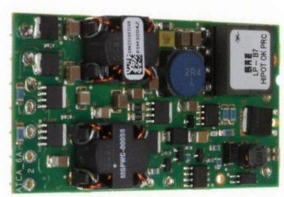
- **Datacenters / Servers**

- **Storage / HDD, SSD, Midplanes**

- **Industrial Control**
  - **24 or 48 V typically**

- **Tower Mounted Antennas**

- **Merchant Power**

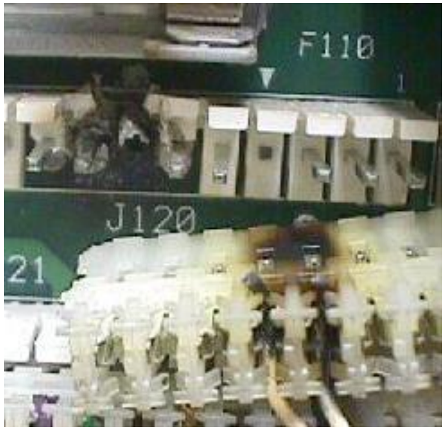


Circuit Protection – What is it ?

- **Circuits designed specifically to….**
  - Prevent Fire ! --“*Keep the smoke in!”*
  - Keep small problems from growing big
    - Minimize damage by quickly isolating failures
  - Prevent potentially disruptive power bus disturbances
    - One small transient can take down/reset an entire system
- ***What Gets Protected ?***

SUPPLY

CONNECTORS

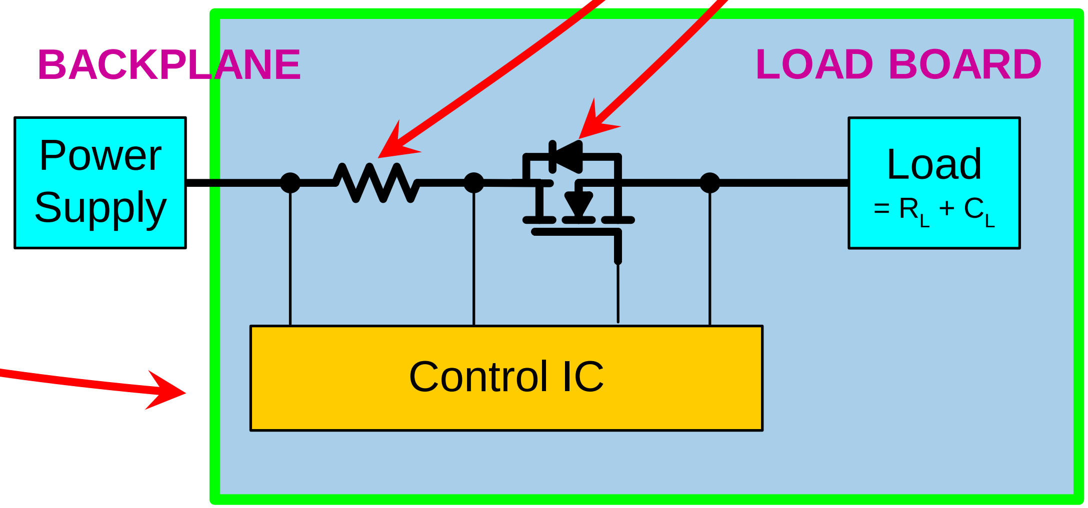


POWER FET

LOAD

Circuit Protection – The Basic Parts

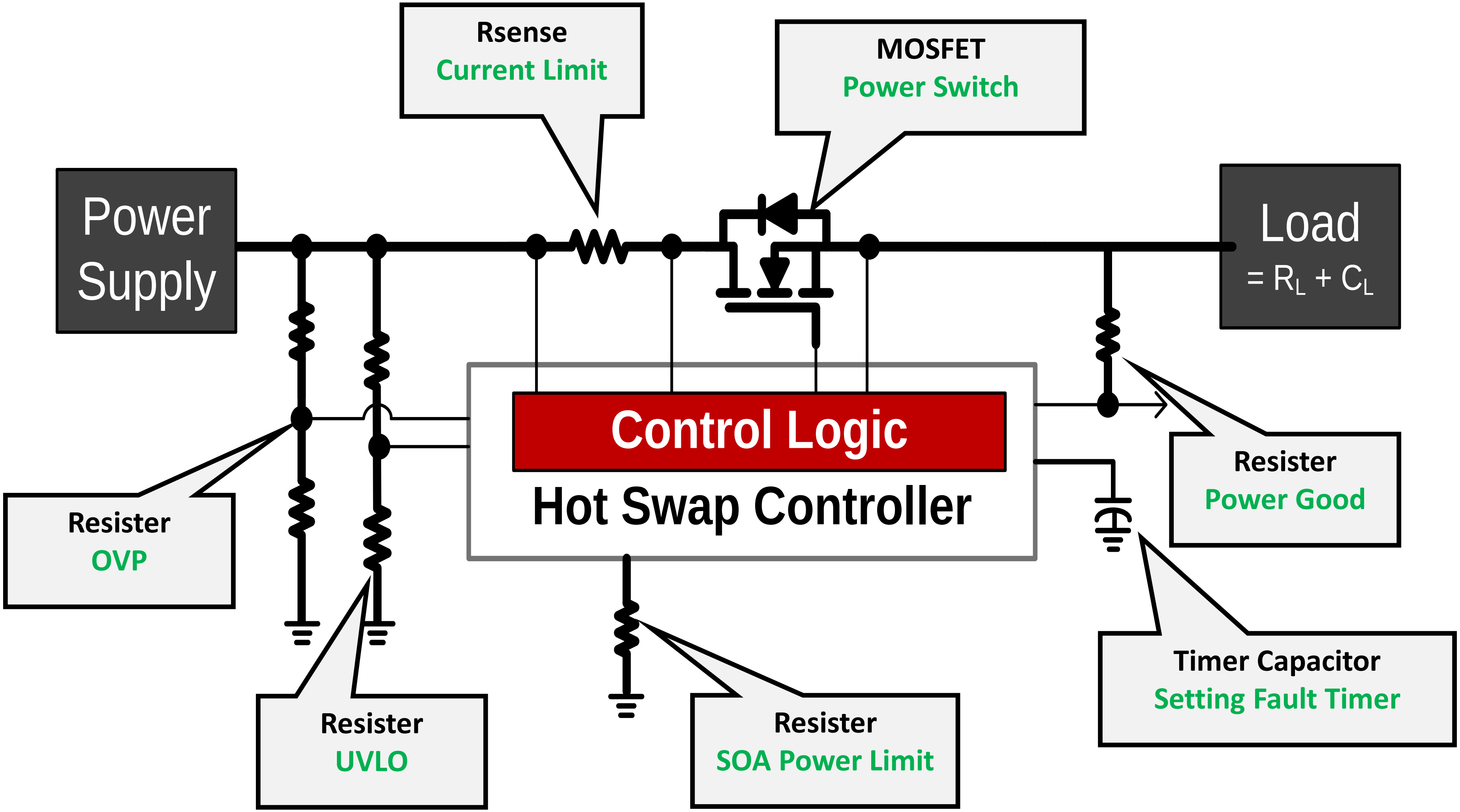
- Most Common Elements
  - Element for modulating current
  - Element for sensing current
  - Element for controlling the FET



- Location..
  - Sometimes on the Load Side of the Connector
  - Sometimes on the Supply Side of the Connector

Hot Swap Controller Circuit

- Function

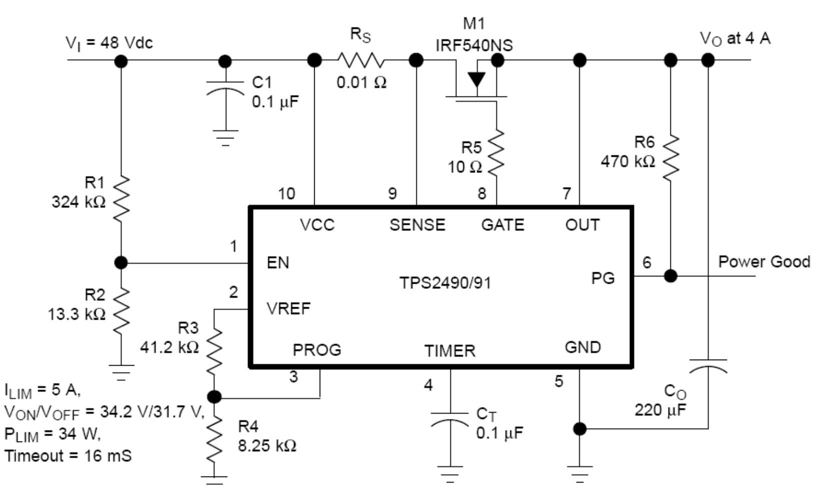


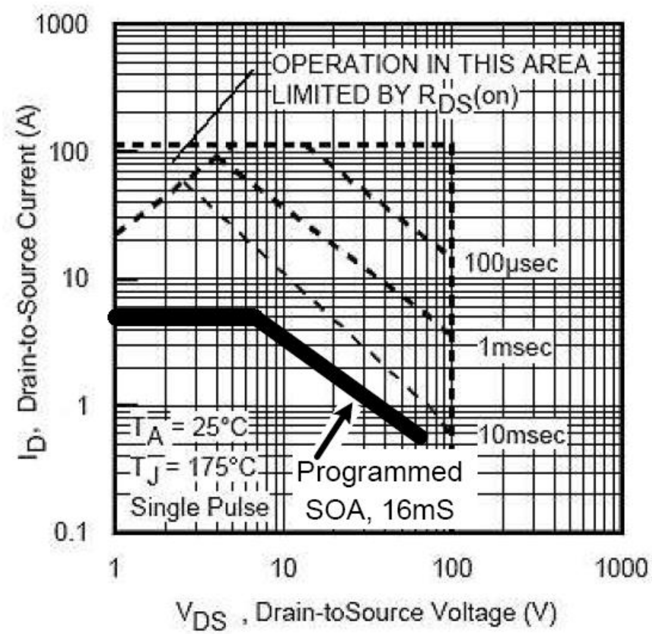
Device Features/Options
Some of the Choices

- **FET - Internal or External**
- **Inrush control - dV/dT, or di/dT**
- **Current Limit - Always, Never, or just at startup**
- **Fault response - Latch off or Retry**
- **Short Circuit Response – Latch Off or Retry**
- **Control - I^2C or Analog Control**
- **Outputs - Power Good, Fault, FET Fault**
- **I_{LIMIT} Accuracy - 20% Standard, 10% Pretty Good, 5% Very Good**
- **FET SOA protection.. Or not**
  - **Allows use of smaller FET and provides very high survivability**
- **Current Indicator Output (IMON) – Analog or Digital Output ?**
  - **Digital Output requires internal ADC and typically includes PIV Monitoring**
- **ORing Control – Linear or Hysteretic**

Device Features/Options
FET SOA Protection

- **One of the least understood but most appreciated features**
- **Allows use of smaller, less expensive FETs**
- **Analog multiplier calculates P_{DIS_FET} in real time and compares result to PROG pin**
- **If P_{LOAD} > PROG then gate drive reduced to lower I_{LOAD} and P_{FET}**

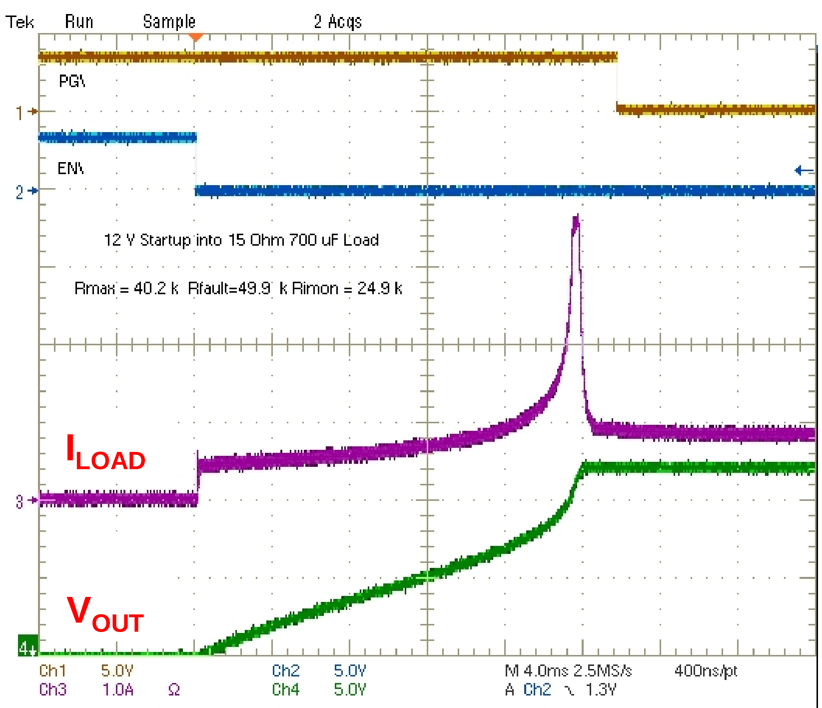




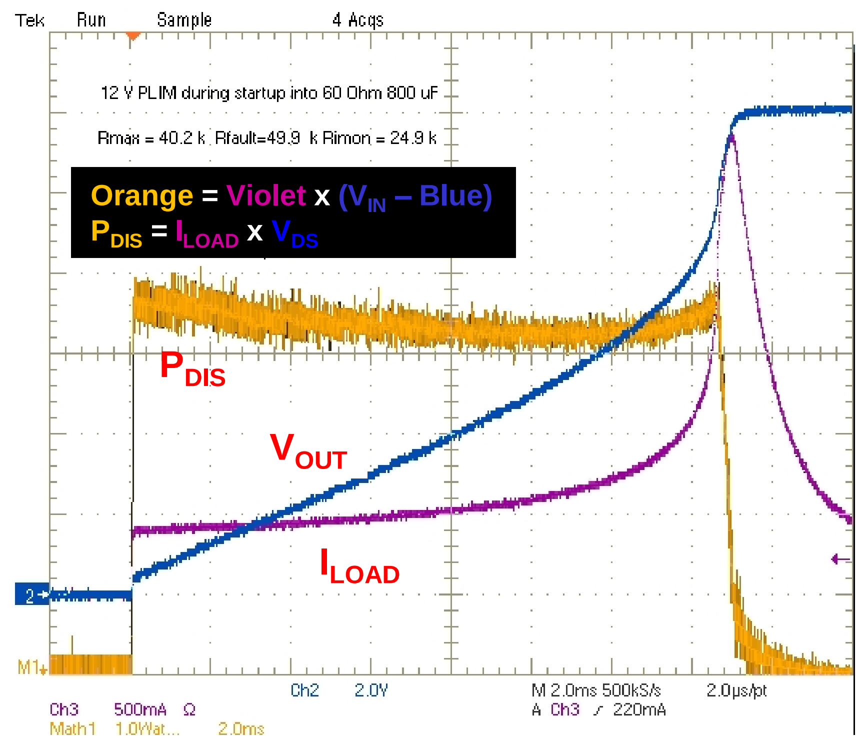
Device Features/Options

FET SOA Protection

- Dynamically adjusts I_{LIMIT} to be approximately proportional to $1/(V_{DS})^2$
- Limits P_{DIS} of fet to programmed limit



TPS2420 Startup into 15 Ω, 700 μF

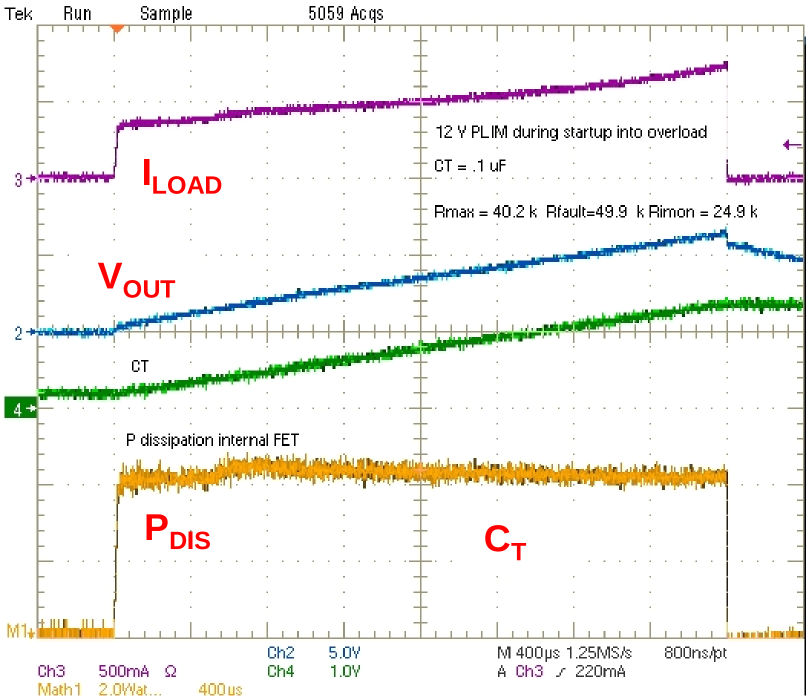


TPS2420 Limits FET P_{DIS} < 5 Watts

Device Features/Options

FET SOA Protection – Startup into overload

- **SOA protection keeps FET safe even when starting up into a severe overload**
- **Fault timer limits T(ime) factor of SOA**
- **Some competitive devices will reduce I_{LIMIT} over a limited range and with limited protection.**



TPS2420 Startup into overload

Typical Inrush/OCP Design Steps

1. **Select R_{SENSE} to set I_{LIMIT} and $I_{FASTTRIP}$**
   - $I_{LIMIT} = V_{TH}/R_{SENSE}$ - V_{TH} typically 25 – 50 mV
     - Simplest controllers have fixed V_{TH}
     - *High V_{TH} → Better Accuracy but Higher I^2R Losses*
   - Fast trip – (Short Circuit) threshold usually 1.5x -3x I_{LIMIT} Level
2. **Select C_{FAULT} to get desired T_{FAULT}**
   - Set T_{FAULT} long enough to allow all caps to charge (T_{CHARGE}) before time out
     - T_{CHARGE} ~ CV/I (C = Bulk Cap, V = V_{OUT}, I= I_{LIMIT})
   - Set T_{FAULT} as short as possible to limit FET stress during overcurrent events
   - Ensure that T_{FAULT} x V_{IN} X I_{LIMIT} is within SOA curve
3. **Select FET that can withstand T_{FAULT} x V_{IN} x I_{LIMIT} x ~1.5 …..*SOA !!***
4. **Set FET SOA Power Limit on devices so equipped**
   - Design tools available for some devices - check webpage
   - *TPS24700/10/20, TPS2490/1/2/3, TPS2480/1, LM5064/6/7/9, LM25061/6/9*

Common Design Errors

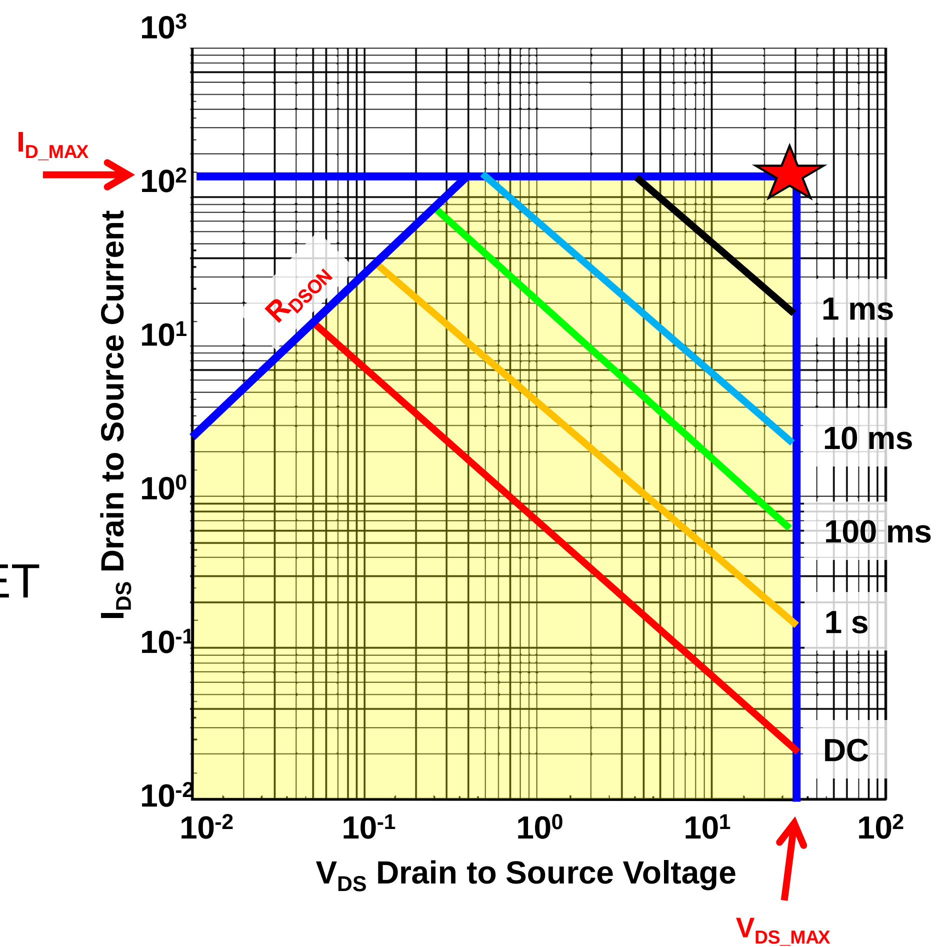
1. ***SOA of FET too Small***

2. ***Layout Issues***

3. ***Inadequate Transient Protection***

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



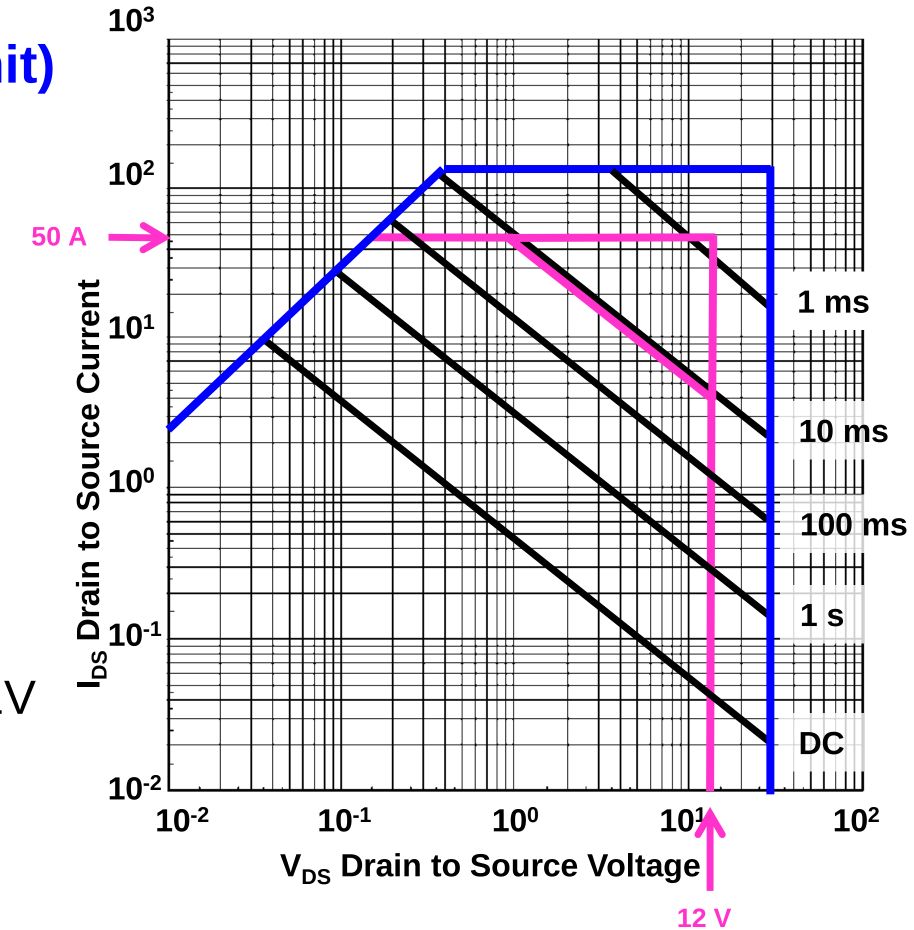
Common Design Errors

SOA of FET Too Small - *Example - 12 V, 50 A Server*

- **Without Power Limiting(current limit)**
  - $P_{MAX} = I_{LIMIT} \times V_{SUPPLY} = 600$ W
  - T_{SOA_MAX} = ~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**

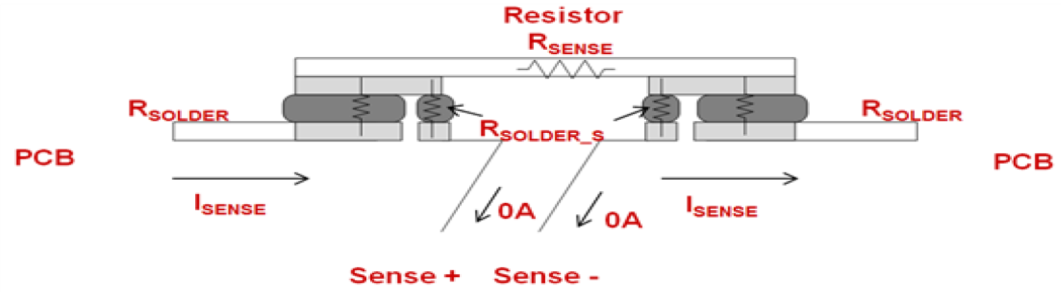


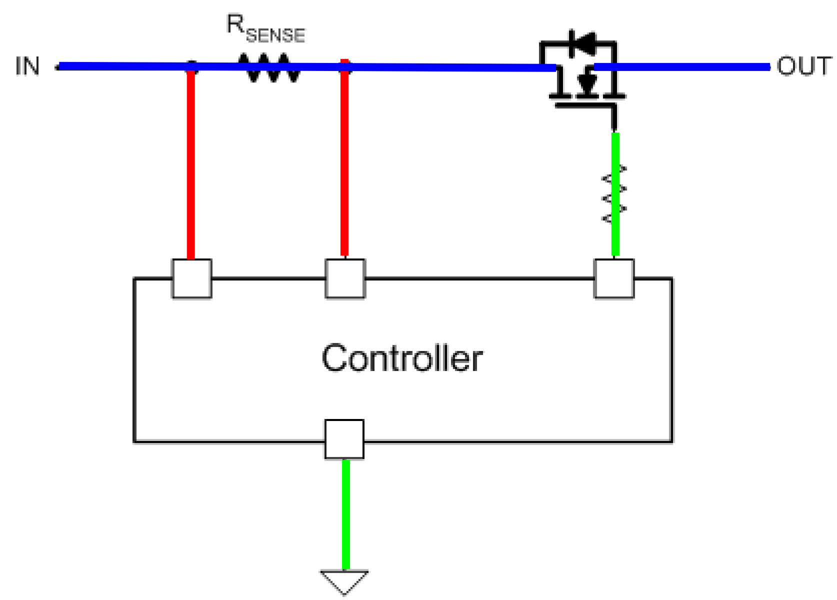
Common Design Errors

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





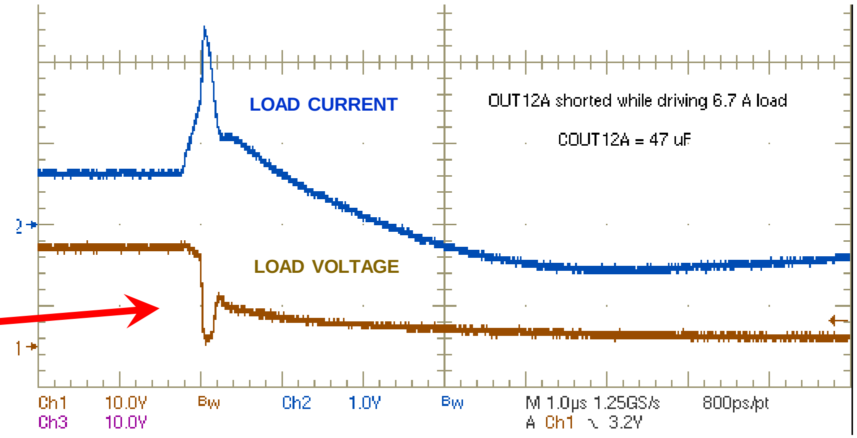
Common Design Errors
Inadequate Transient Protection

- All wires are inductive
- Inductance stores energy $$E = \frac{LI^2}{2}$$
- When the FET turns off, voltage spikes occur

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

Positive Spikes at Input to Switch/FET

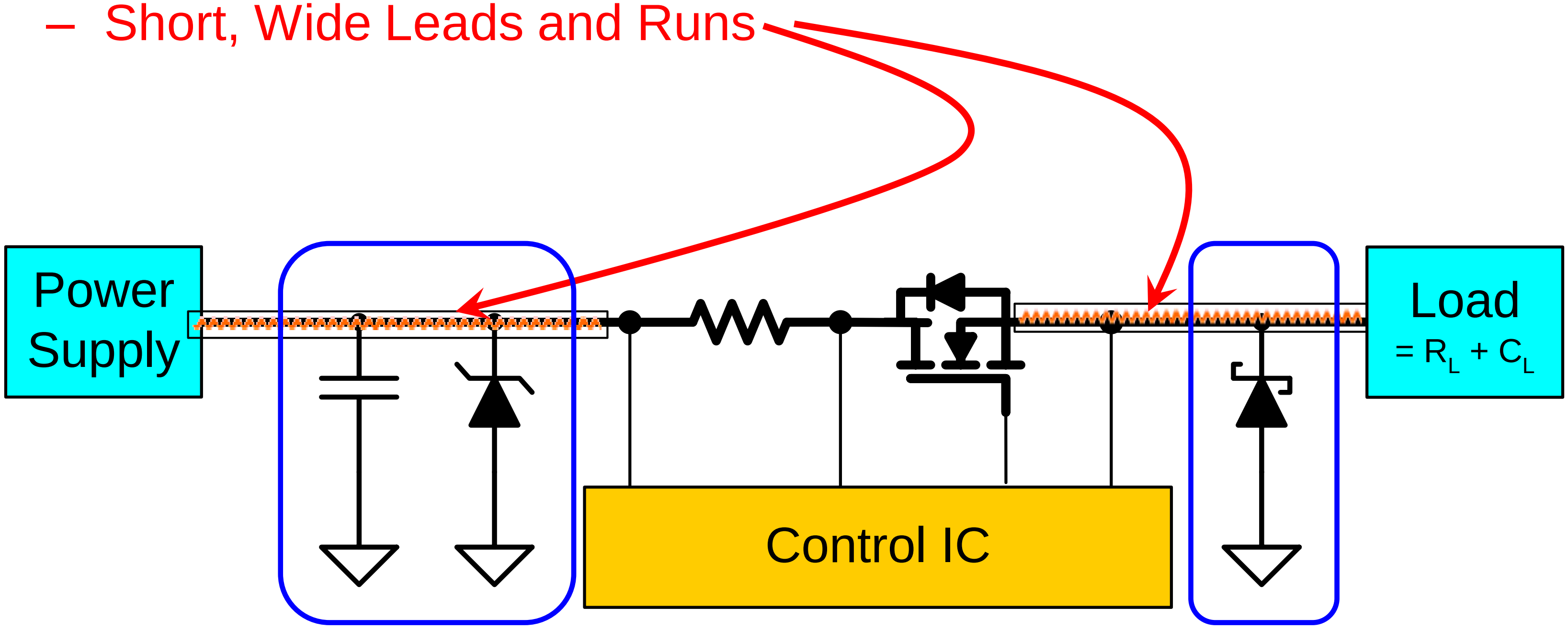
Negative Spikes at Output of Switch/FET



Common Design Errors

Inadequate Transient Protection

- To resolve inductive spikes from supply / load leads
  - Caps and/or TVS at Input to clamp positive spike during hot plug
  - Schottky Clamp output negative spike during output short circuit
  - Short, Wide Leads and Runs



Common Test Error Sources

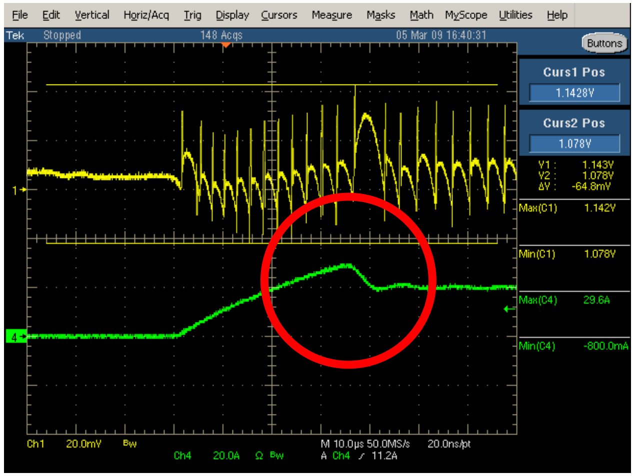
1. ***Electronic Loads***

2. ***Transients From Long Supply Leads***

3. ***Supply I_{LIMIT} Too Low***

Common Test Error Source 1
Electronic Loads

- Electronic Loads
  - Good for DC Loading and Automated Tests
  - Proper Setup Very Important
    - Ex. - Constant Current, Constant Power, Constant Resistance
  - but….
  - Often Have Switch Transients When Stepping Load
    - Transients Can Cause Premature Trip When Measuring I_{LIMIT}

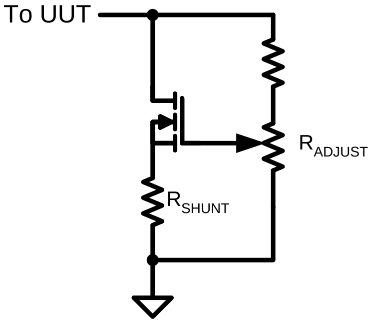


Common Test Error Source 1

Electronic Loads

- For Minimal Transients While Adjusting Load
  - **Method One** - Use Power Resistors as Loads
    - A bit tedious and Old School… but accurate
    - A collection of fixed and variable resistors is best
    - Apply "Last Half Amp" With Small Wire Rheostat
      - Can be effective with eLoads also

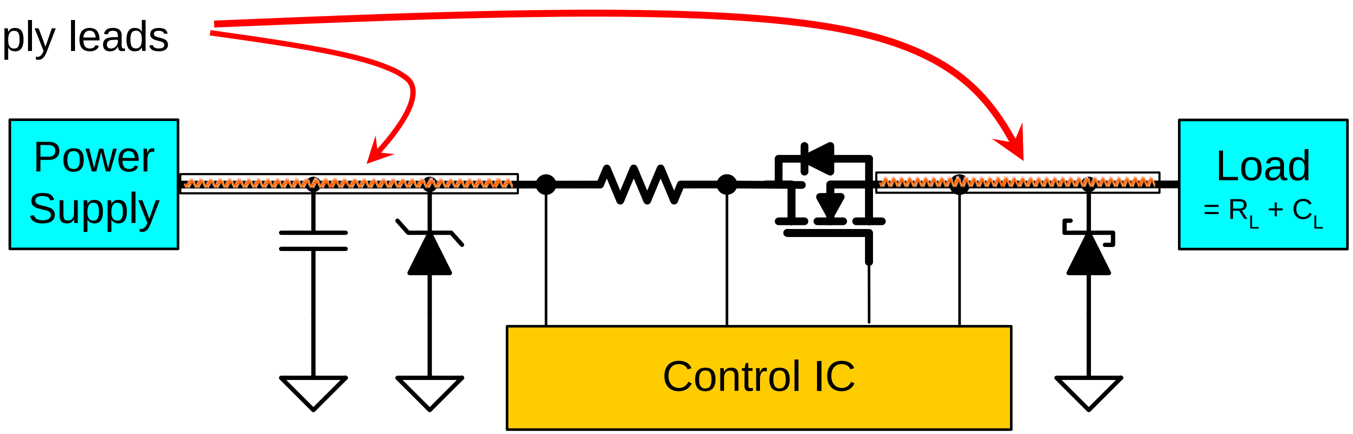
  - **Method Two** - Use Power FET as Load
    - Connect FET and Series Resistor as Load
    - Adjust Potentiometer to vary Current
    - ***Make Sure the FET can Handle the power !!!!***



Common Test Error Source 2

Long Supply Leads

- All wires are inductive
- Long Supply Leads can have significant L
- Lab Test Environment Usually Worse Than Final Application !
  - Reason for TVS and diodes on most TI EVMs
- When the FET turns off, voltage spikes occur
- To counter 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
  - Twisted Supply leads



Positive Low Voltage Protection

TI Device Portfolio

PART	Input Range	Package	V_{THRESH} (mV)	SOA Prot.	OV	I2C	PG	Imon Acc.
TPS2420	3 to 20	QFN16 (4x4mm)	Internal FET R_{DSON} typ. = 30 mΩ I_{LIMIT} = ±10% @ 2 A	Yes	No	No	Lo	17%@2A
TPS2590/910		QFN16 (4x4mm)		Yes	No	No	-	na
TPS2421-1/2		SOIC8		Yes	No	No	Lo	na
TPS2592A/B		QFN10 (3x3 mm)	na	No	Yes	No	No	na
TPS2593A/B			Fixed I_{limit}	No	Yes	No		na
TPS24720	2.5 to 18	QFN16 (3x3)	Prog	Yes	Yes	No	Lo	Prog
TPS24710/1/2/3		MSOP10	25 ± 10%	Yes	No	No	l/l/h/h	na
TPS24700/1		MSOP8		No	No	No	Lo	na
LM25066	2.9 to 17	LLP24 (4x5mm)	25 ± 10% 46.5 ± 11.8%	Yes	Yes	Yes	Hi	2.40%
LM25066A/i		LLP24 (4x5mm)		Yes	Yes	Yes	Hi	1.00%
LM25069-1/2		MSOP10	50 ± 10%	Yes	Yes	No	Hi	na
LM25061-1/2		MSOP10	50 ± 10%	Yes	No	No	Hi	Na
TPS2480/1	9 to 26	PW20	25	Yes	No	Yes	Hi	1%
TPS2482/3	9 to 36	PW20	25	Yes	No	Yes	Hi	0.5%

Device Features/Options

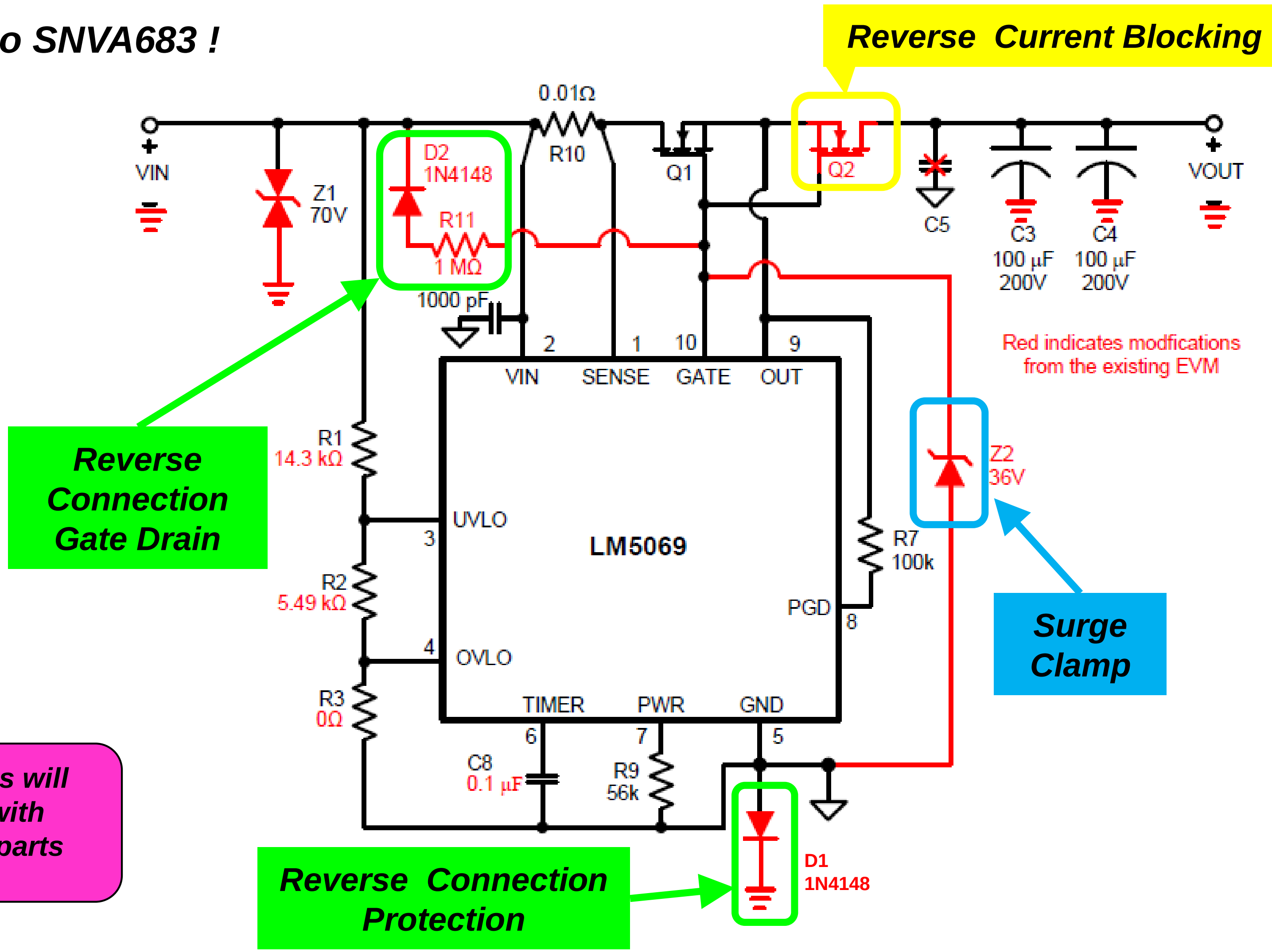
TI IMON Devices vs. Output Type

Part	V_{IN}	Current Monitor Output	**Accuracy** Neglecting external component tolerances
TPS2358/9 TPS2458/9 TPS2456	8.5 – 17 V	$I_{LOAD} = \frac{V_{MON} I_{LIMIT}}{675mV}$	± $4\%_{FS}$
TPS2420	2.8 – 20 V	$I_{LOAD} = I_{MON} x61000$	± 8.2%
TPS2492/3	9 – 80 V	$I_{LOAD} = \frac{V_{MON}}{48 \times R_{SENSE}}$	± 6%
LM25066/A	2.9 – 17 V	PMBus Output	± $2.4\%_{FS}$ / ± $1\%_{FS}$
LM5064	-80 to -18	PMBus Output	± $3\%_{FS}$
LM5066	10 to 80	PMBus Output	± $3\%_{FS}$
TPS2480/1	9 – 26 V	Digital I^2C Output	± 1%

LM5069EVM-627

Reverse Current Blocking, Surge Clamping, Reverse Connection Protection

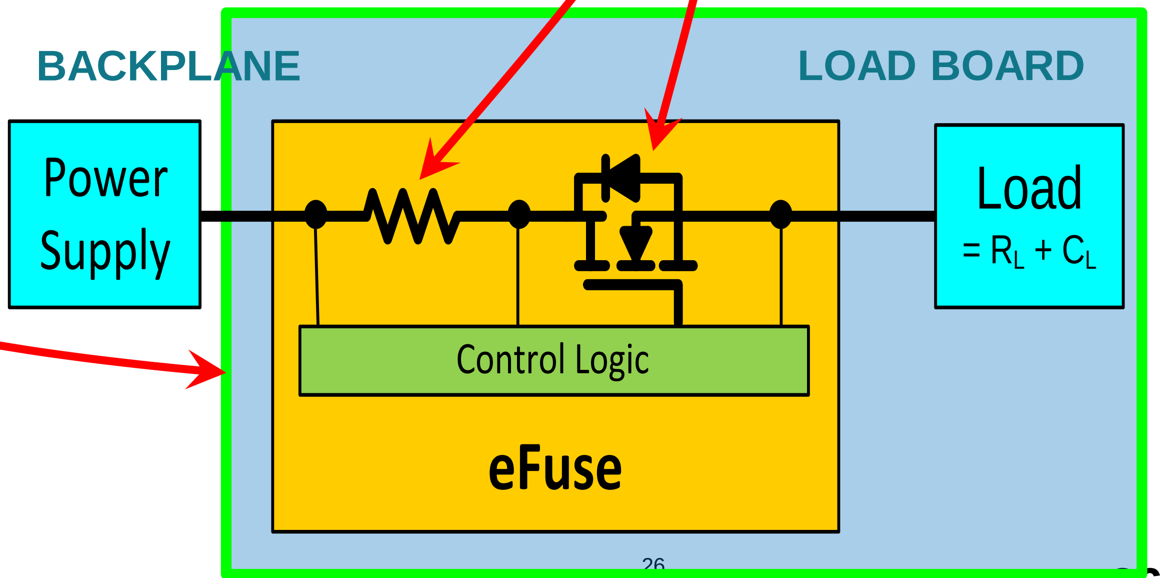
Take me to SNVA683 !



These circuits will also work with TPS248x/9x parts

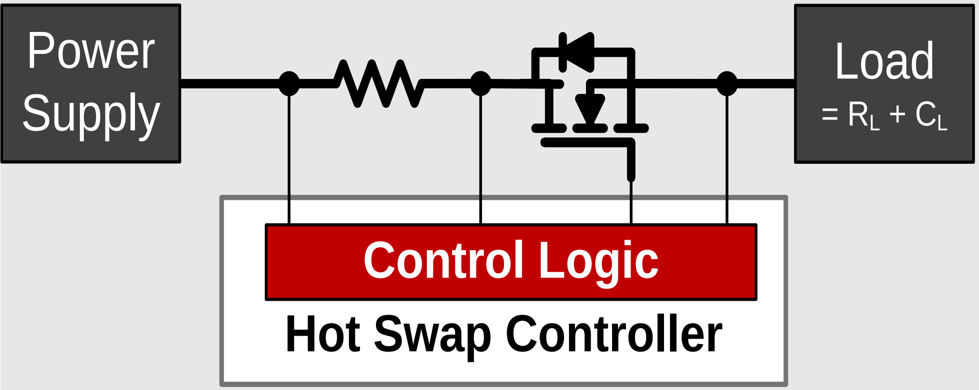
What is an eFuse: Integrated Hotswap IC

- **Most Common Elements:**
  - **Element for modulating current**
  - **Element for sensing current**
    - **(R_{SENSE} shown, usually senseFET)**
  - **Element to control the FET**

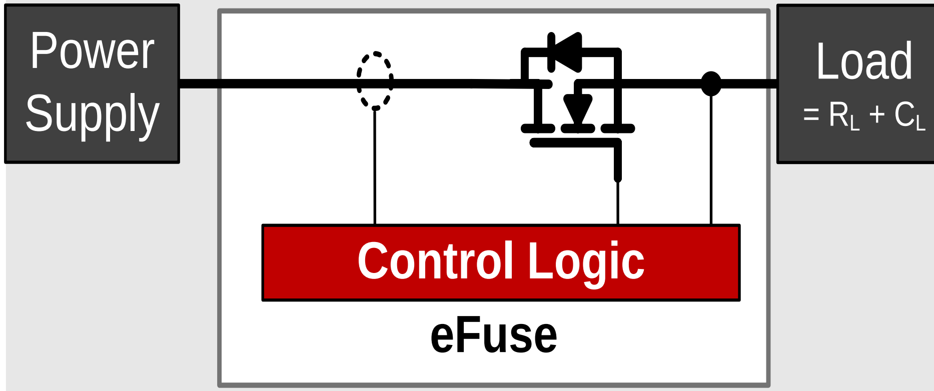


Hot Swap VS eFuse

Hot Swap (Desecrated MOSFET)	eFuse (Integrated MOSFET)



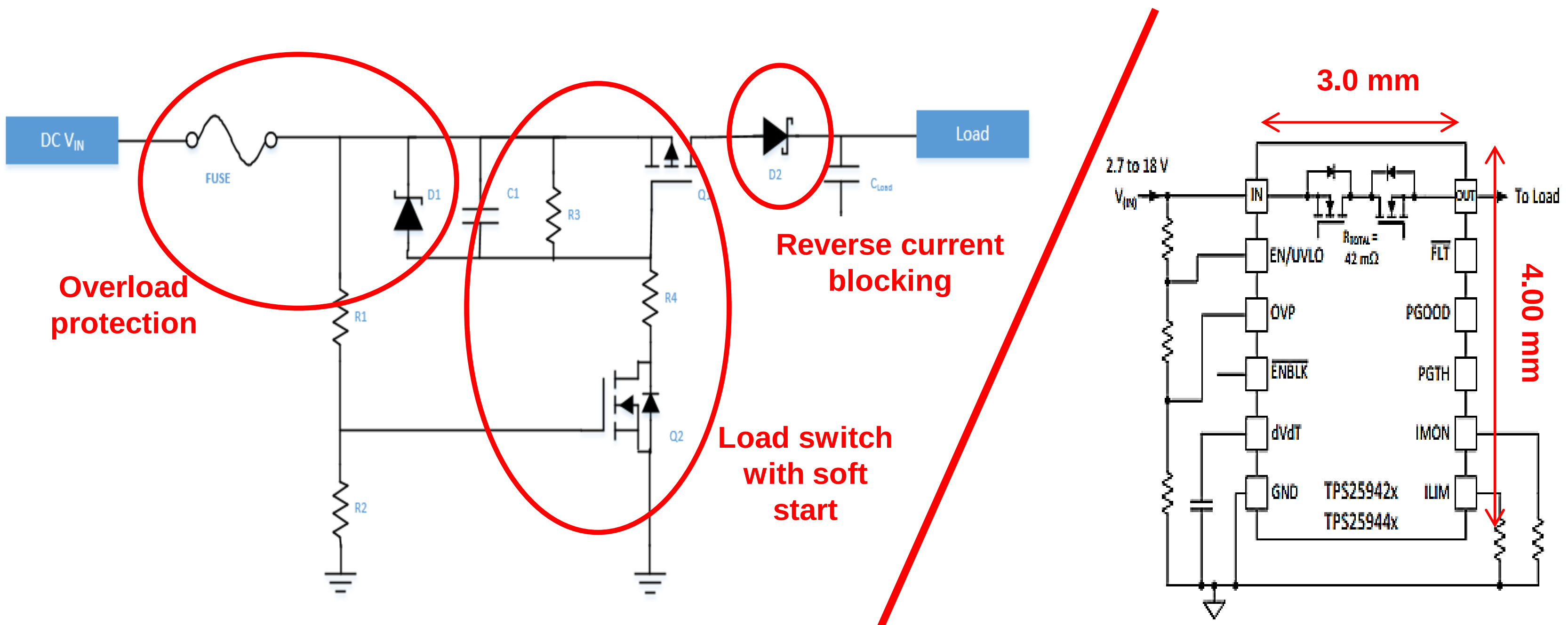
- Flexible R_{DSON} (Designers Choice)
- More feature options
  - No limit on upper current limit
  - Generally more accurate
- More external parts
  - R_{SENSE}, FET
  - Rs, Cs for configuration



- Highly integrated
  - Few external parts
  - Internal FET, Current Sense
  - Thermal protection
  - Matched FET & protection
- Today , support < 10 A (18V)
  support < 55 V (2A)

Discrete Fuse Protection Circuit

Replace all these components…



…with 1 eFuse.

Typical Applications for eFuse

m-SATA SSD

SAS HDD

Enterprise Class SSD

Storage Server Chassis

Set-Top Box
DVD Player
Internet TV

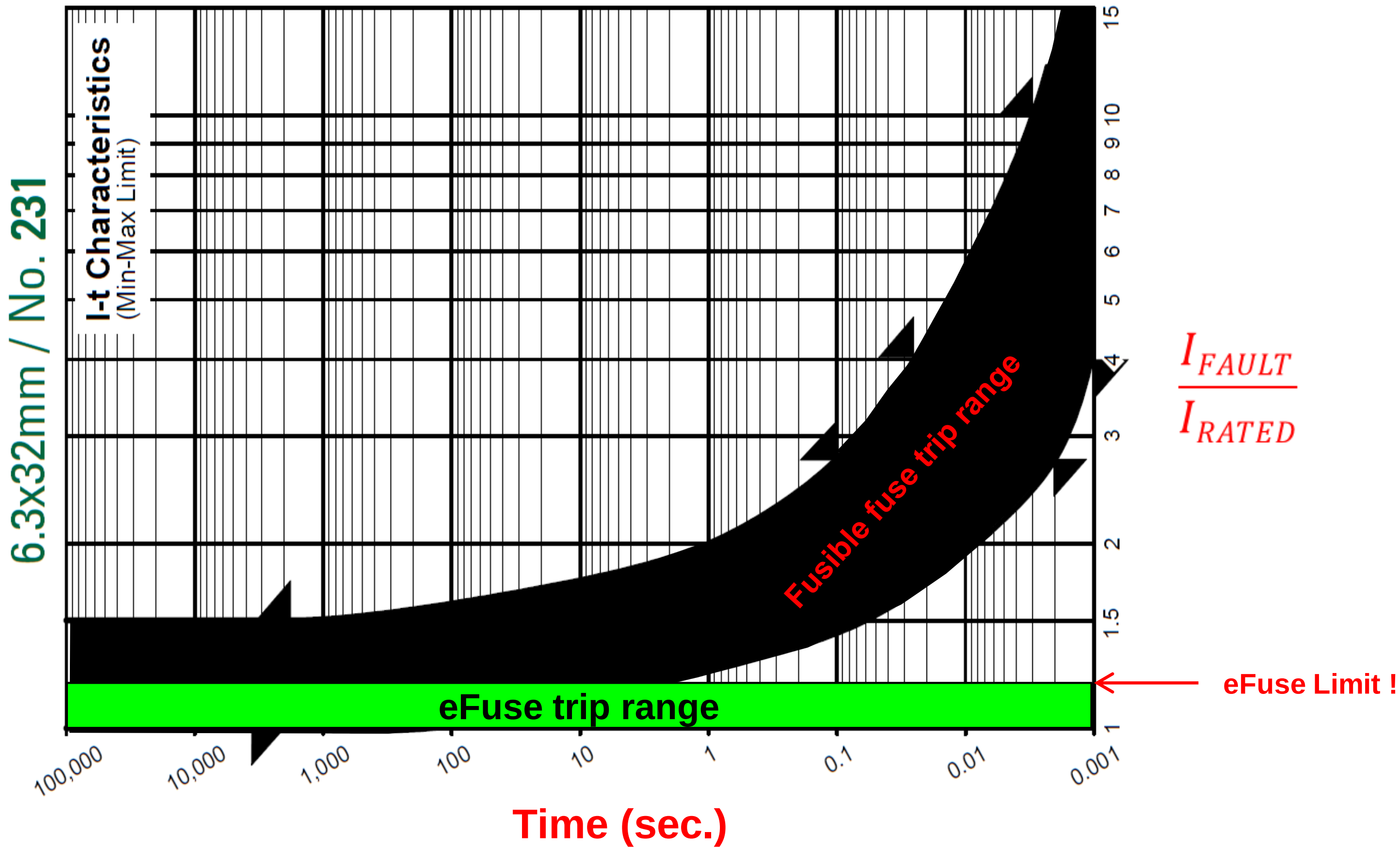
Appliances

Why not use a fuse ?

- Slow
- Inaccurate
- Lossy
- Leave a load unpowered after event

“Fast Blo Fuse ”Trip time vs Current

eFuse vs fuse



- ***Time and trip limit inaccuracies mean bigger power supplies***

Fuses are slow ….even the fast ones

Limits for Pre-arcing Time					
Rated Current	$1.0 \times I_N$ [1]	$1.5 \times I_N$	$2.75 \times I_N$	$4 \times I_N$	$10 \times I_N$
2.00 A ... 16.00 A	> 1 h	< 30 min	2 ms ... 100 ms	1 ms ... 25 ms	< 3 ms

eFuse Performance

- ***I_{LIMIT} is programmable, predictable, and stable over temp***
- ***Bus droop and supply stress reduced by tight over current tolerance***

Fuses are Lossy

- Higher resistance -> more energy -> more heat -> ***higher OPEX***
- ***13x more power lost with fuse !***
  - 800 mV/2A = ***400 mΩ vs. eFuse @ 30 m Ω***
- Lifetime cost of 1 Watt = $2 to $18 (customer supplied numbers)
  - Includes energy cost, distribution infrastructure, HVAC, product life

Little Fuse 231Series

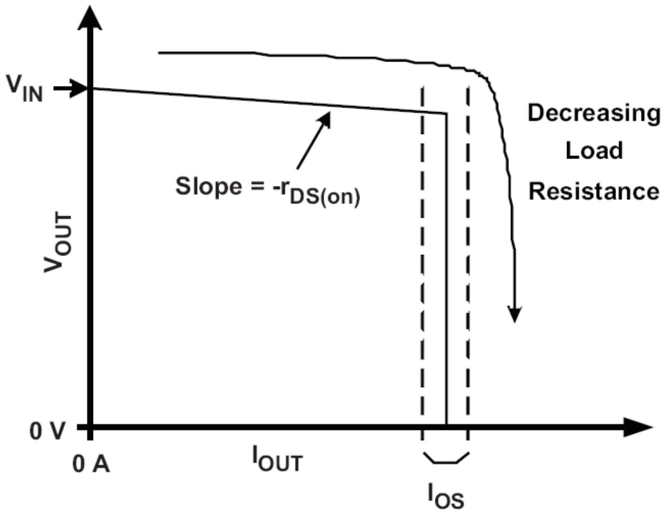
Rated Current	Amp Code	Voltage Rating	Voltage Drop 1.0 x I_N max. (mV)	Power Dissipation 1.0 x I_N max. (W)		Melting Integral 10 x I_N max. (A^2s)
2.00 A	1200	500 V	800	3.0	0.12	0.35
2.50 A	1250	500 V	800	3.0	0.19	0.44
3.15 A	1315	500 V	800	3.0	0.30	0.75
4.00 A [2]	1400	500 V	700	3.6	0.48	1.6
5.00 A [2]	1500	500 V	600	3.6	0.75	2.5
6.30 A [2]	1630	500 V	600	3.6	1.19	5
8.00 A [2]	1800	500 V	600	5.2		10
10.00 A [2]	2100	500 V	500	5.2		20
12.50 A [2]	2125	500 V	500	6.3		38
16.00 A [1,2]	2160	500 V	480	6.3		68

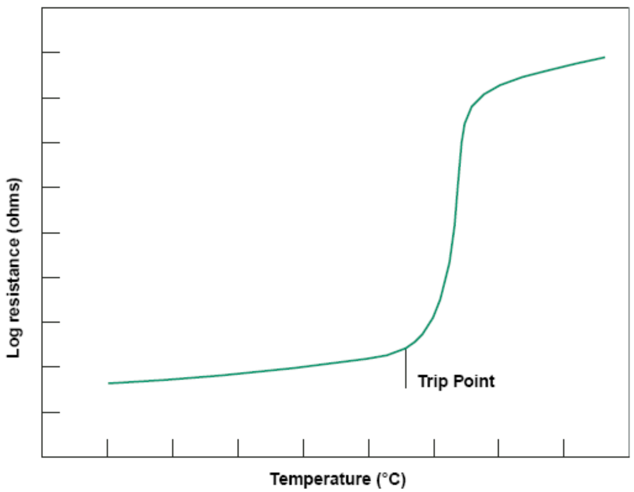
Lower Losses using TPS2590 (30 mΩ)

eFuse vs.Polyfuse

- ***eFuse (USB power switch)***
  - *Current based I_{LIMIT}*
  - *Stable, accurate (20% - 30%) I_{LIMIT}*
  - *Fixed or Programmable I_{LIMIT}*
  - *Repeatable I_{LIMIT0}*
  - *Fast (< 1.5 us typ)*
  - *Wide temp range*
    - *-40 ° to +125 C°*

- ***Polyfuse***
  - *Temp based I_{LIMIT}*
  - *Sloppy, variable I_{LIMIT}*
  - *No Programmable I_{LIMIT}*
  - *R_{ON} Increases with each event*
  - *Slow to trip (several ms)*
  - *Not usable above 85 C°*
  - *Auto –resets after trip event*





Polyfuses (PTC Devices)

Require derating

Temperature Derating Curves Comparing PTCs to Fuses

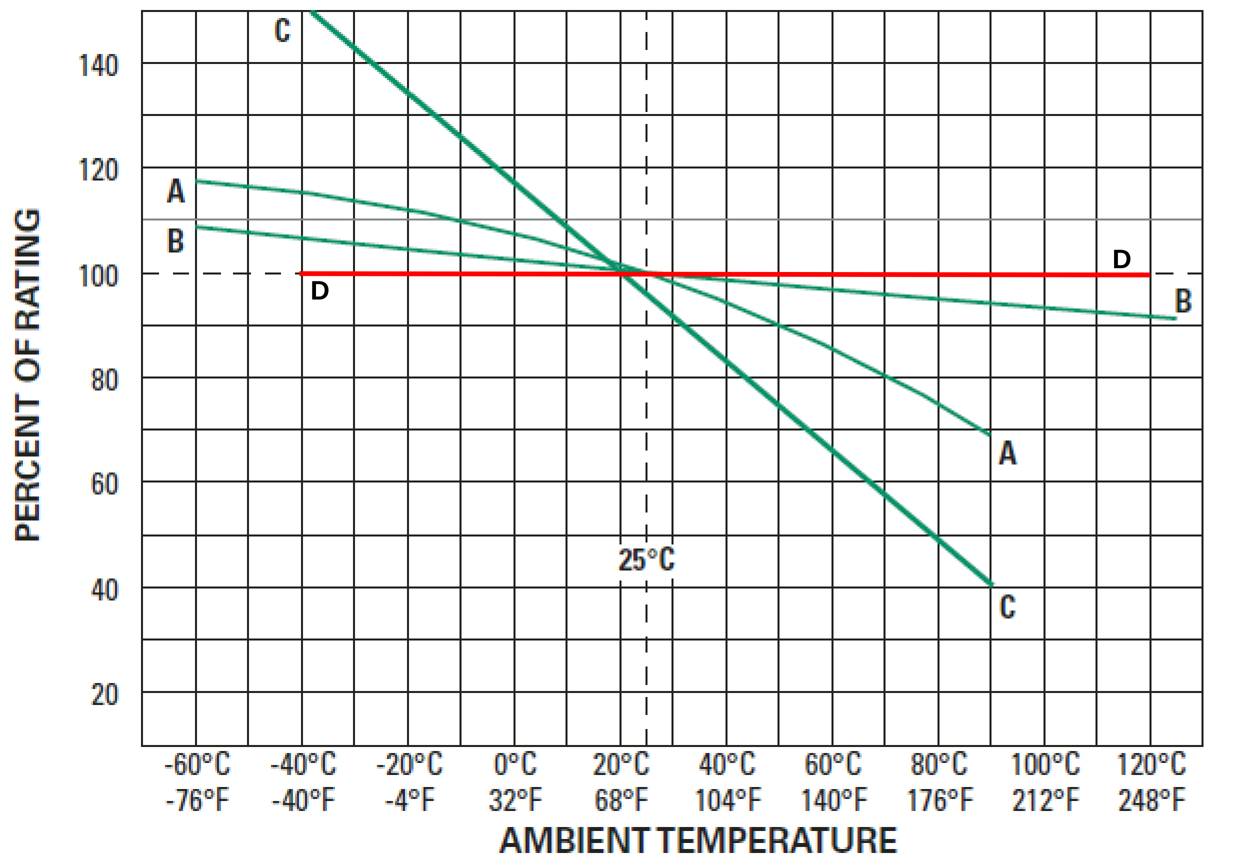
Chart Key

Curve A
Thin-Film Fuses and 313 Series (.010 to .150A)

Curve B
FLAT-PAK®, Telelink®, Nano2®, PICO®, Blade Terminal, Special Purpose and other leaded and cartridge fuses (except 313.010 – .150A)

Curve C
Resettable PTCs

Curve D
TPS2420/21, TPS2590/910



Polyfuse Summary

- Slow
- Lossy – 2x regular fuse
- Inaccurate
- Each OC event increases resistance
- Not suitable for high temp.
  - R increases with Temp.-
- Resets after OC event
- Low Cost
- Can provide Safety Agency compliance
  - UL, IEC, CSA

Common Circuit Protection

Fuses	Polyfuse (PTC)	Texas Instruments eFuses
• Physically breaks once tripped, only one time use (Not resettable) • Fast acting / time delay trip • System is offline until fuse is physically replaced	• Temp-based current limit • Auto-resets after fault • Resistance increases with temp and after each fault • Slow response/trip after fault (Several ms) • Time-delay trip only	• High accuracy adjustable current limit (up to ±2%) • Fast trip (<1.5 us typ) • UL recognized devices • Able to auto retry (PTC) or latch off (fuse) after fault • Fault reporting, PG, IMON

eFuses (Integrated FET)

Need more? See Parametric Search:

eFuses (Integrated FET)

	No Reverse Current Blocking	Ext. Blocking FET Driver	Integrated Blocking FET
Over Voltage Protection	**TPS25921A/L** ● 4.5 – 18V, 0.4 – 1.6A, 90mΩ, with +/- 2% Current Limit Accuracy (Existing)	**TPS24750/51** 2.5 – 18V, 12A, 3mΩ eFuse with PG, I_{MON}, Adj. Current Limit (Existing)	**TPS25944A/L** ● 2.7 – 18V, 5A, 42mΩ, Circuit Breaker for Power MUX with PG, I_{MON}, Adj. CL (New)
Over Voltage Protection	**TPS25926** ● 13.8V, 5A, 30mΩ, 15V V_{OUT} Clamp with Adjustable Current Limit (New)	**TPS25924** ● 4.5 – 13.8V, 5A, 28mΩ, 15V V_{OUT} Clamp with Adjustable Current Limit (New)	**TPS25942A/L** ● 2.7 – 18V, 5A, 42mΩ, Current Limiter for Power MUX with PG, I_{MON}, Adj. CL (Existing)
Over Voltage Protection	**TPS25925** ● 5.5V, 5A, 30mΩ, 6V V_{OUT} Clamp with Adjustable Current Limit (New)	**TPS25923** ● 5.5V, 5A, 28mΩ, 6V V_{OUT} Clamp with Adjustable Current Limit (New)	**TPS25940A/L** ● 18V, 5A, 42mΩ, SSD Power Manager with PG, I_{MON}, Adj. Current Limit (Existing)
Over Voltage Protection			**TPS2660** 55V, 2A, 150mΩ, Industrial eFuse with I_{MON}, Adjustable Current Limit (Roadmap)
No OVP	**TPS2420** ● 3 – 20V, 5A, 33mΩ Load Switch with PG, I_{MON}, Adj. Current Limit (Existing)	**TPS25927** ● 18V, 5A, 28mΩ Load Switch with Adjustable Current Limit (New)	
No OVP	**TPS2421-1/-2** ● 3 – 20V, 6A, 33mΩ Load Switch with PG, Adjustable Current Limit (Existing)	**TPS2592ZA/L** ● 4.5 – 18V, 1.7A, 28mΩ Load Switch with Adjustable Current Limit (Existing)	

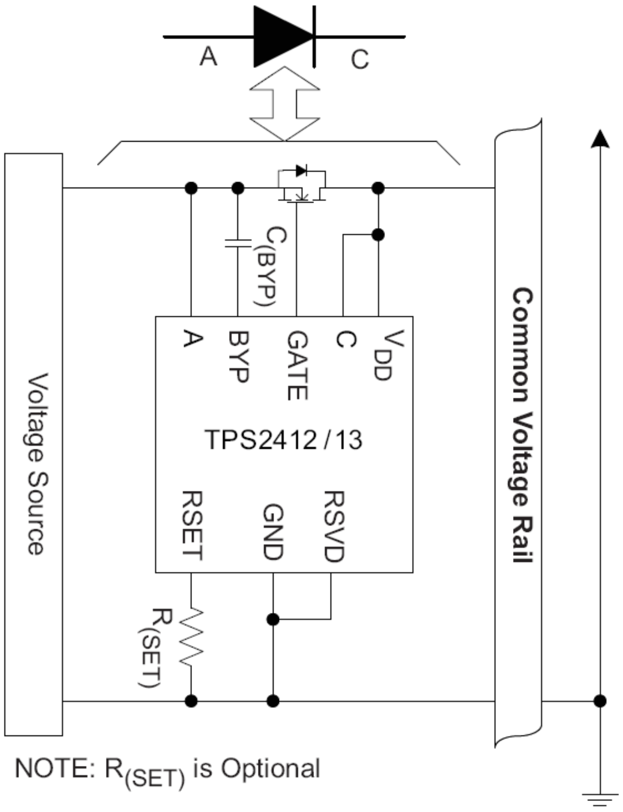
● = UL 2367 Recognized

NEW | EXISTING | ROADMAP

Device Features/Options

ORing Control - What is it and why do it ?

- What is it ?
  - ***Make a FET act like a diode***
    - No more, no less
    - A simple concept
    - A challenge to implement
- Why do it ?
  - Save Energy, $$$
  - Improve PS margin



Device Features/Options

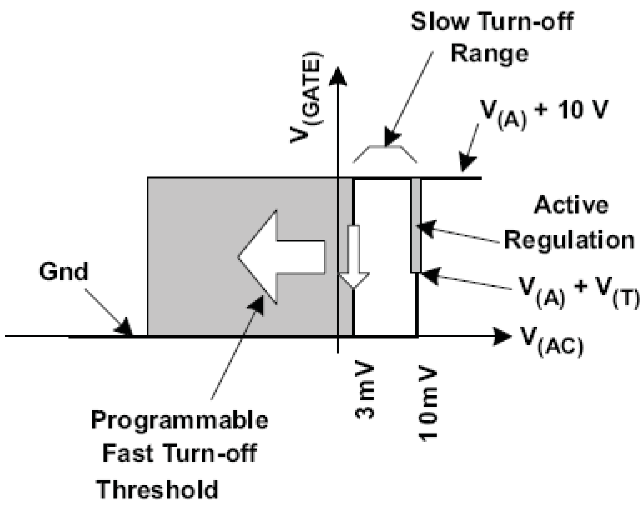
ORing Control –Linear vs. Hysteretic

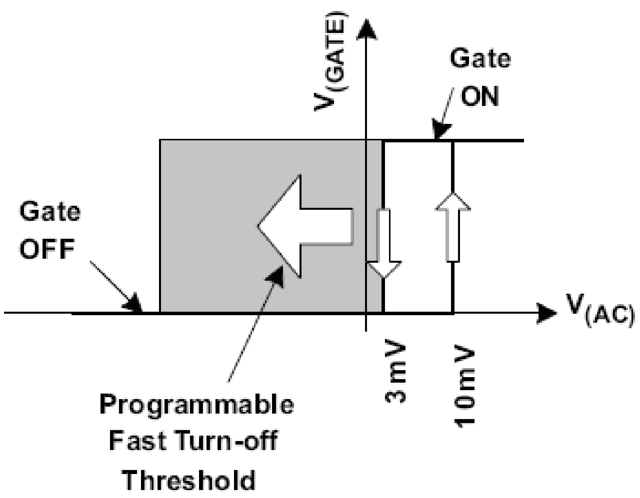
Linear Control

- Regulates V_{AC} (V_{SD}) 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
- More prone to light load oscillation





Oring Control Selection guide

Device	Description	Channels	V_{IN} Range (V)	Enable/ Shutdown	UV	OV	Fault	PG	ORing Linear Gate Drive
TPS2410	ORing FET controller/MUX controller	1	0.8 to 16.5	1H	✔	✔	✔	✔	✔
TPS2411	ORing FET controller/MUX controller	1	0.8 to 16.5	1H					
TPS2412	ORing FET controller	1	0.8 to 16.5						✔
TPS2413	ORing FET controller	1	0.8 to 16.5						
TPS2419	ORing FET controller with OV/enable	1	3 to 16.5	1H		✔			
LM5050-1	Positive HV ORing controller with AUX input	1	5 to 80	L					✔
LM5050-2	Positive HV ORing controller with FET test	1	6 to 80	L			✔		✔
LM5051	Negative HV ORing controller with FET test	1	–6 to –100	L			✔		✔
TPS24740/1/2	High performance hotswap/ORing controller	1	2.5 to 18	1H	✔	✔	✔	✔	
TPS2456/A	Inrush/reverse current controller for dual sources	2	8.5 to 15	2H	✔		✔	✔	✔
TPS2358	Dual 12-V/3.3-V hotswap/ORing controller	2	8.5 to 15	2L					
TPS2359	Dual 12-V/3.3-V hotswap/ORing controller	2	8.5 to 15	Via I^2C					

Thanks You !