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
  – \( \frac{dv}{dt} \)
  – \( \frac{di}{dt} \)

• 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

**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.)

TPS2420 going from 3A to 4.2A, Fault timer 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

\[
\text{Fault time} = 27.8 \times 10^3 \times Ct
\]

\[
C_{out} \text{ (max)} = (I_{max} - I_{load}) \times \frac{28 \times 10^3 \times Ct}{V_{out}}
\]
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
The hiccup time allows adequate cooling of pass MOSFET.
Idealized Typical Startup Waveforms

a) Current Limit Only

- $V_{SYS}$
- $V_{DS}$
- $I_{LIM}$
- $V_{GATE}$
- $V_{GSL}$
- $V_{TH}$
- $t_{ON}$
- $t_1$, $t_2$, $t_3$

b) Power Limit and Current Limit

- $V_{SYS}$
- $V_{DS}$
- $I_{LIM}$
- $I_P$
- $V_{GATE}$
- $V_{GSL}$
- $V_{TH}$
- $t_{ON}$
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
  - $R_{DS_{ON}}$ 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**
  - \( P_{\text{MAX}} = I_{\text{LIMIT}} \times V_{\text{SUPPLY}} = 600 \text{ W} \)
  - \( T_{\text{SOA}_{\text{MAX}}} = \sim 800 \text{ us} \)

- **With Power Limiting**
  - \( P_{\text{MAX}_{\text{LIMITED}}} = 50 \text{ W} \)
  - As \( V_{DS} \) increases \( I_{\text{LIMIT}} \) is reduced
  - \( T_{\text{SOA}_{\text{MAX}}} = 10 \text{ ms} \)
  - Smaller FET can be used
  - @ 50 A will start limiting when \( V_{DS} > 1 \text{ V} \)

- **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 \(I_{LIM}\)

• 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

\[
V = L \frac{di}{dt} \quad \frac{di}{dt} \Rightarrow \infty
\]

Positive Spikes at Input to Switch/FET

Negative Spikes at Output of Switch/FET

\[
E = \frac{LI^2}{2}
\]
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

\[ V_{\text{IN}} \quad \text{L}_{\text{PARASITIC}} \quad V_{\text{OUT}} \]

**R_{\text{SNS}}** is small (2-10 mΩ) so it is negligible.
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.

\[ V_{peak} = V_{out} + \frac{L I^2}{C} \]
Input Supply Surge During Test

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

Theoretical Calculation

\[
V_{\text{peak}} = V_{\text{out}} + \sqrt{LI^2 \over C}
\]

\[
V_{\text{peak}} = V_{\text{out}} + \sqrt{100 \text{ nH} \times 5^2 \over 1000 \text{ pF}}
\]

= 105V
Key TVS Specifications

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=25°C)
  - Check RDSON and Package, RthJC
  - Monitor FET temperature with remote Diode (LM25066)

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

- **Power Supply**
  - Load Dump Protection
  - Current Sense Output/Monitoring
  - Current Limiting (Short-circuit/overcurrent protection)
  - Short-to-GND Protection
  - Short-to-Battery Detection
  - Device Temperature Sense Output

- **Load Switch**
  - Soft Start/Controlled Slew Rate
  - Reverse Current Protection
  - Quick Output Discharge
  - Reverse Polarity Protection
  - Overvoltage Protection
  - Undervoltage Protection
  - On & Off
  - Thermal shutdown
  - Fault Flag
  - Supply Voltage Sense Output
  - Output Clamp for Inductive Load

- **eFuse**
  - Power Good
  - Auto-retry/latch-off
  - Auto Turn-On with Reverse Battery

- **Smart High-Side Switch**
  - Auto Turn-On with Reverse Battery

- **Protection**
  - Integrated Watchdog Timer

- **Diagnostics**

- **Load**

Related Websites:
- [www.ti.com/loadswitch](http://www.ti.com/loadswitch)
- [www.ti.com/efuse](http://www.ti.com/efuse)
- [www.ti.com/highsideswitch](http://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 to 15 A
- Size: down to 0.64 mm²
- Package: WCSP, SOT-23, SON, QFN

Applications
- SSD
- Mobile
- IoT
- Laptop
- Car

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 mm²
- Package: SON, QFN, SOIC, TSSOP

Applications
- Power supply
- Server
- Switching

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 mm²
- Package: HTSSOP (PWP)

Applications
- Car
- Workshop
- Industrial

www.ti.com/HighSideSwitch
Load Switch Overview

- **Extend battery life** by reducing standby leakage current. Turn off unused subsystems with load switches: WiFi/BT, LCD, SD Card
- **Save space** and reduce solution size by integrating discrete circuitry into a load switch (2+ FETs with 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.

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

Find more solutions at [www.ti.com/loadswitch](http://www.ti.com/loadswitch)
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

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

### 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

Find more solutions at [www.ti.com/efuse](http://www.ti.com/efuse)
What Is An 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

Input Fuse

Input Transient Snubber

Reverse Polarity Protection

Surge Protector

Alt. Inrush Control

Load Switch for Inrush Control

Over Current & Short Circuit Protection

UV/OV Protection

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

<table>
<thead>
<tr>
<th>Feature</th>
<th>Fuse</th>
<th>PTC</th>
<th>eFuse</th>
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<td>✓ Auto-retry; latch off</td>
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<tr>
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<td>✓ Not damaged by fault</td>
</tr>
<tr>
<td><strong>Time to trip:</strong></td>
<td>✗ Slow trip (s/ms)</td>
<td>✗ Slow trip (ms)</td>
<td>✓ Fast trip (&lt;1.5 us)</td>
</tr>
<tr>
<td><strong>Accuracy:</strong></td>
<td>✗ Needs time to heat up and melt</td>
<td>✗ Current limit depends on ambient temperature</td>
<td>✓ Up to ± 2% current limit accuracy</td>
</tr>
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</table>
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 TPS2660 simplifies 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
- Susceptible to light load oscillation
Hotswap/ORing Controller Combos

Originally developed to control AdvancedMC slots

TPS2456A
Dual 12V Hotswap and ORing Control

TPS2459
Controls 1 AdvancedMC Slot
Internal 3.3 V channel

TPS2458
Controls 1 AdvancedMC Slot
Internal 3.3 V channel

TPS2359
Controls 2 AdvancedMC Slots
Internal 3.3 V channel

TPS2358
Controls 2 AdvancedMC Slots
Internal 3.3 V channel

Internal 3.3 V Channels rated at 150 mA continuous

12V Only

12V & 3.3V

I2C Control

Discrete Control

Single Slot Control

Dual Slot Control

Originally developed to control AdvancedMC slots
Protection Circuits

ORing Controllers

TPS2411
TPS2412
TPS2413
TPS2419
2413 plus Enable

LM5050-2
6 to 75 V, w/ FET Test

LM5050-1
5 to 75 V, w/ AUX Input

LM5051
-6 to -100 V

Click on any part button for hyperlink to overview
## Positive ORing Controller Device Comparison

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