Application Report
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Basics of eFuses

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ABSTRACT

eFuses are integrated power path protection devices that are used to limit circuit currents, voltages to safe levels during fault conditions. eFuses offer many benefits to the system and can include protection features that are often difficult to implement with discrete components. This application note highlights the challenges and limitations of discrete circuit-protection solutions and discusses how they can be improved with an eFuse. This report also provides an example comparison between eFuse solution and discrete circuit-protection solution for a typical hard disk drive (HDD) application.

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1 Need for Protection and Ways to Achieve

Modern electronic systems are designed with high level of integration to offer superior performance with multitude of functionality. These systems use multi-voltage power distribution to support various types of loads for their proper operation. One of the major expectations is the minimal system downtime during any transient abnormal events such as overload or short-circuit conditions. For example, while hot-plugging a hard disk drive into a storage system, huge inrush current can result in voltage sag on the connected bus and eventually affect other operating loads on the same bus. To overcome this scenario, today's system designers use protection devices to manage inrush, overload, short circuit, and overvoltage events and to guard the sensitive loads for reliable system operation. The key requirement is to bring down the fault currents within the limits and bring the system back to active state once the fault is cleared, without any manual intervention.

Fuses, positive temperature coefficient (PTC) resistors, and active circuit protection are a few of the protection devices with varied capabilities and drawbacks. Fuses are traditionally considered as protection devices used to isolate overload or short-circuit faults from the main system. Although these devices provide protection, the fault current needs to be exceedingly higher than the rating of the fuse with response time ranging from milliseconds to seconds. This makes it extremely difficult to predict the precise overcurrent level at which the fuse will open. A conservative selection on fuse current rating may lead to fuse blowup during inrush current events. In addition, once the fuse blows during an overload event, it has to be physically replaced, which increases system down time and maintenance costs. On the other hand, PTC resistors provide resettable overcurrent protection and, unlike a fuse, these can avoid the physical intervention. However, because they are actuated by the heating effect of an overcurrent load, their reaction time is limited to several milliseconds. Also the ON-resistance of PTC fuse increases after every reset, which raises concerns on achieving repeatable performance over time.

The best way to prevent system downtime is to detect, respond and correct potentially damaging conditions as quickly as possible. As the response of fuse and PTC resistors depends on heating effect (temperature, a lagging parameter) for their operation, many system designers prefer to use a leading indicator, current, to provide effective circuit protection. Both fuse and PTC resistors do not cover many of the protection requirements such as inrush control, overvoltage; reverse current, reverse polarity protections needed in modern electronic systems. The next section describes the active circuit-protection solutions using discrete components and the challenges involved.

2 Discrete Circuit-Protection Solutions

Many of the discrete circuit-protection solutions use a combination of fuses, diodes, MOSFETs, and TVS diodes to meet a specific protection requirement. A typical discrete circuit using a combination of fuse and MOSFET is shown in Figure 1. The protection circuit incorporates inrush current control using P-MOSFET, a series diode to block the reverse current as well as reverse polarity, a fuse for overload or short-circuit protection, and comparator logic to disconnect the power path during undervoltage or overvoltage events. The inrush current limiter avoids voltage sag on the connected bus during hot plug events and helps in optimal fuse-sizing for a precise overcurrent level. However, challenges with current-limit inaccuracies with temperature and slower response still exist. An active current-protection circuit shown in Figure 2 can respond faster to overcurrent faults and provides better current-limit accuracies. However, many of the discrete circuit-protection realizations have the following shortcomings which limit their wider usage:

- Discrete circuits use P-MOSFET as pass FET, which is more expensive than N-MOSFET to achieve the same ON resistance ($R_{DS(ON)}$).
- Discrete solutions are bulky and inefficient. For example, a 2-A load current results in around 1.4-W power dissipation across the diode and corresponding rise in board temperature.
- Discrete circuits do not incorporate thermal protection for the pass FET. So the thermal design is often more oversized than safe operating area (SOA) limits for device protection under extreme cases.
- A discrete circuit needs more components and occupies more board space. More components also raise concerns on protection-circuit robustness and reliability.
- Though the output voltage slew rate is adjustable with RC components, these components must be sized in consideration with the gate characteristic of the pass FET.

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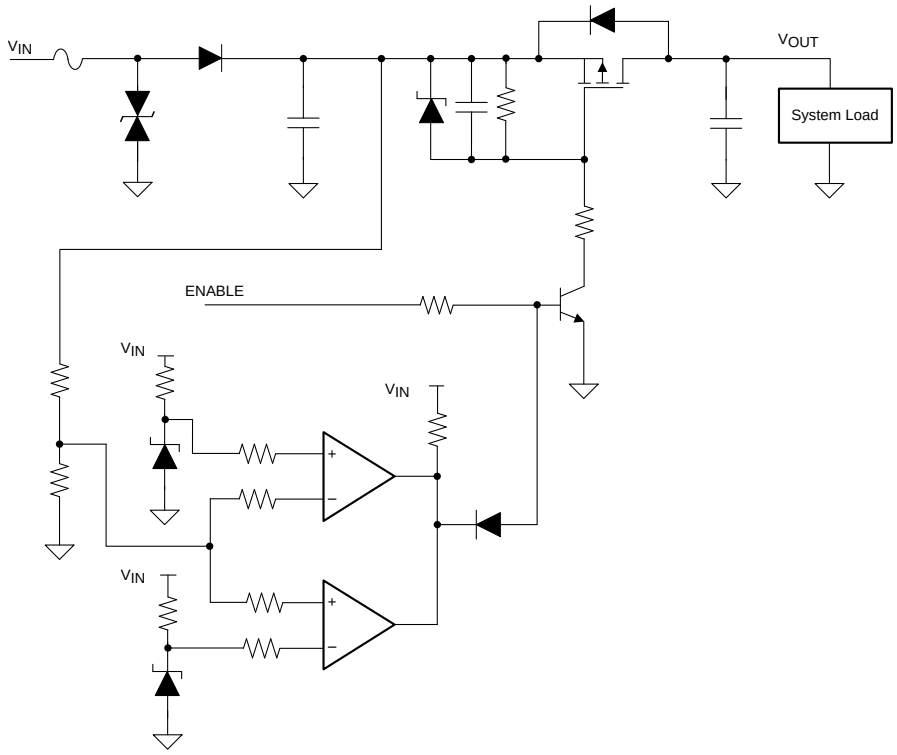

Figure 1. Typical Discrete Protection Circuit

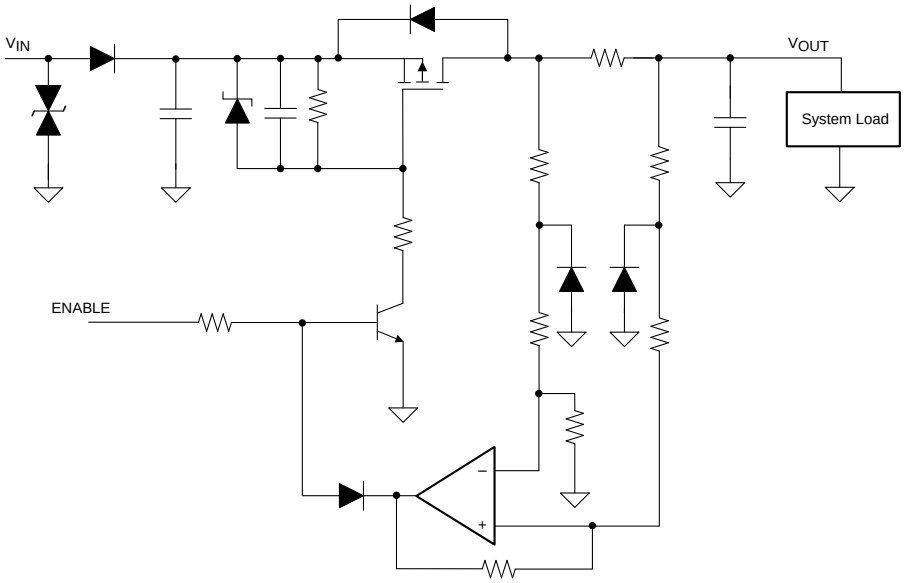

Figure 2. Active Current Protection Circuit Using Discrete Components

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3 What is an eFuse?

An integrated circuit protection solution called “eFuse” can overcome the limitations with discrete circuit protection realizations. An eFuse is an “active circuit protection device with an integrated FET used to limit currents, voltages to safe levels during fault conditions”. It embeds various functions to protect system against inrush current, overcurrent, overvoltage, reverse current, reverse polarity and short circuit faults. The eFuse is more accurate, faster and can ‘repair’ itself without user intervention. Most of the TI eFuses are recognized as *Solid State Overcurrent Protectors* under the UL2367 standard. Also these are certified under safety standard UL 60950 and are safe to use.

Figure 3 shows a block diagram of an eFuse. An understanding of the functionality of various features in an eFuse helps in choosing the right eFuse for a particular application. This section discusses the functionality of each feature the eFuse offers. As shown in Figure 3, an eFuse requires very few external components (resistor R_{ILIM} for current limit setting and a capacitor C_{dVdT} for setting the output voltage ramp rate) resulting in significant board space saving and robust protection when compared to discrete solutions.

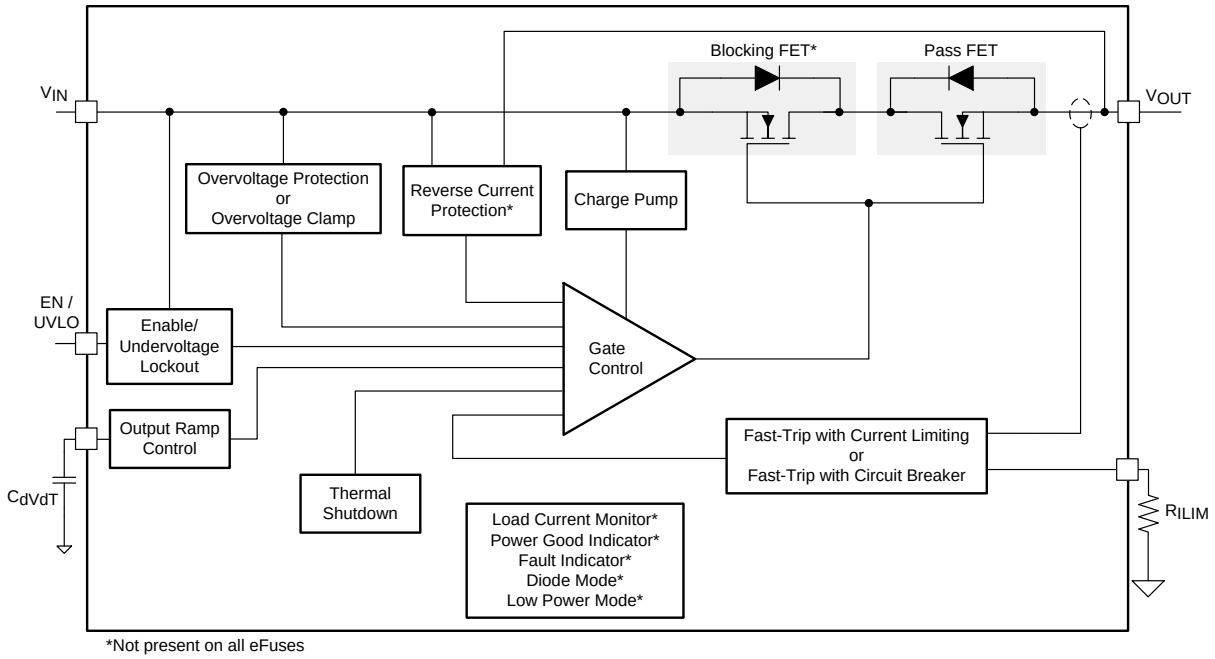

Figure 3. Block Diagram of eFuse

3.1 Inrush Current Control

Inrush currents are a major concern in DC power systems. For example, while hot-plugging a hard disk drive into a storage system, huge inrush current can result due to quickly charging its filter or load capacitor. This huge inrush current with fast slew rate causes voltage sag on the backplane which could affect operation of other connected loads. This problem can be solved by controlling the output voltage ramp rate, thereby limiting the inrush current and disturbance on the backplane. Discrete circuits (Figure 1, Figure 2) use RC components around pass FET for inrush current control, which must be sized in consideration with the gate characteristic of the pass FET and the load. Sometimes, it needs many design iterations to keep inrush current within the desired limit. If the input power is cycled rapidly, the load capacitor gets discharged quickly while the external gate capacitor remains charged and maintains pass FET in the ON condition. This inhibits the current-limiting feature allowing a large current surge when power is restored.

In an eFuse, the output voltage ramp rate is inversely proportional to the C_{dVdT} capacitor value and can be configured easily at the desired rate. The built-in overtemperature protection in an eFuse prevents device failure that could happen due to severe dynamic power stress during startup. Refer to Section 4 for the inrush performance comparison between eFuse and a discrete solution.

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3.2 Overcurrent Protection

When an overcurrent event happens, protection for the downstream circuitry from excessive currents is essential to avoid any potential circuit damage or fire. The active current protection circuit shown in Figure 2 uses an external current sense resistor and a fast comparator for overcurrent protection. This circuit realization often needs tradeoff between accuracy, cost, and power loss. TI eFuses provide active current protection either by limiting the fault current (called current-limiting operation) or by breaking the fault circuit after an overload timeout (called circuit-breaker operation). The latest devices, such as the TPS25942 and TPS25944, offer ±8% current-limit accuracy over the load range of 0.6 A to 5.3 A.

An eFuse with the current-limiting feature limits the output current to a threshold set by an external resistor R_{ILIM}. Figure 4 shows the current-limit response of the TPS25942A eFuse, with the current limit (I_{LIM}) set to 5 A. For an overload condition, the eFuse limits the input current to 5 A until either the overload is removed or the eFuse junction temperature T_J reaches thermal shutdown temperature (typically T_{TSD} = 150°C). Once the eFuse enters thermal shutdown, it either remains in the OFF position (a latch-off version) or attempts to restart after T_J falls below T_{TSD} by 12°C and with auto retry delay (128 ms for TPS25942A, an auto-retry device). It is observed in Figure 4, the TPS25942A makes circuit closure after every thermal shutdown and finally restores to normal condition when the overload fault is cleared. The current-limiting feature is beneficial in applications such as solid-state drives (SSDs), especially if the overcurrent event is temporary and to avoid system downtime.

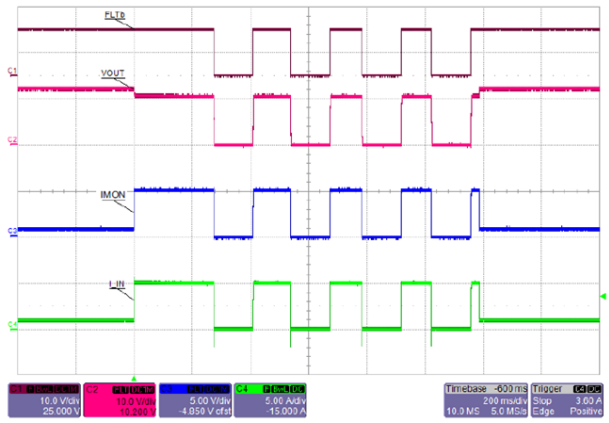

Figure 4. Overload Response of eFuse With Current-Limiting Function

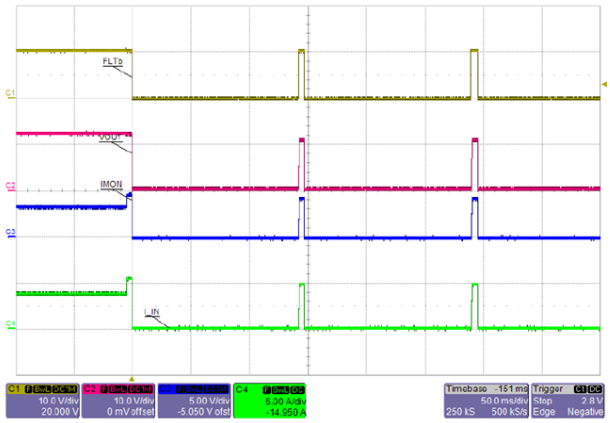

Figure 5. Overload Response of eFuse With Circuit-Breaker Function

For sensitive loads, such as a hard drive in data servers, an immediate power path opening is a safe option in response to an overcurrent fault. An eFuse TPS25944A provides circuit-breaker operation with overload timeout. When the load current exceeds the set current limit of 5 A, the TPS25944A starts the fault timer and breaks the circuit path if the load current does not fall below I_{LIM} before the fault timer expires (4 ms). Figure 5 shows circuit-breaker response of the TPS25944A eFuse, and since the TPS25944A is an auto retry device, it attempts to restart after a circuit-breaker retry delay of 128 ms. The circuit-breaker feature essentially avoids system downtime by allowing pulsed overloads at the output for a fault period interval of 4 ms..

3.3 Short-Circuit Protection

One of the advantages of an eFuse over discrete solutions is the ability to respond faster for hot-short faults at the output. During a transient short-circuit event, the current through the eFuse increases very rapidly. The current-limit amplifier of an eFuse cannot respond very quickly due to its limited bandwidth. TI eFuses incorporate a fast-trip current comparator, which shuts down the pass FET very quickly when the load current I_{OUT} > fast-trip current threshold $I_{FASTRIP}$. This terminates the rapid short-circuit peak current in less than 200 ns as shown in Figure 8. The fast trip threshold is set to 60% higher than the programmed overload current limit ($I_{FASTRIP}$ = 1.6 × I_{LIM}). After the transient short-circuit peak current has been terminated by the fast-trip comparator, the current-limit amplifier smoothly regulates the output current to I_{LIM} as shown in Figure 7. If during current-limit operation, power dissipation of the pass FET [(VIN – VOUT) × I_{OUT}] exceeds 10 W, there is approximately a 0 to 15% thermal fold back in the current-limit value so that I_{LIM} drops to I_{SC}. Eventually, the device shuts down due to over temperature.

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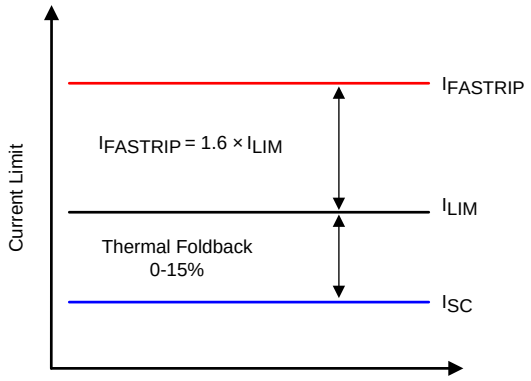

Figure 6. Fast-Trip Current

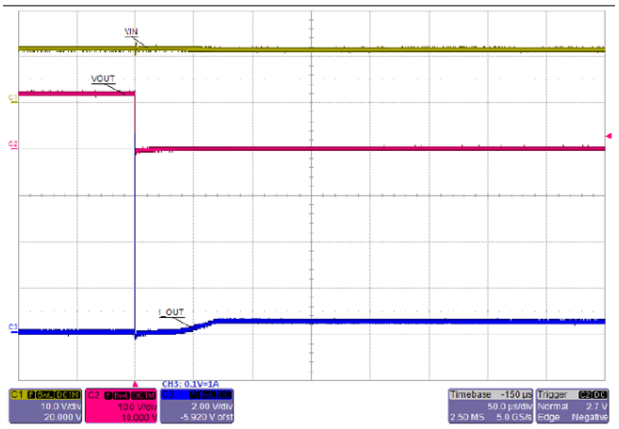

Figure 7. Short-Circuit Response of TPS259241 With I_{LIM} Set to 5 A

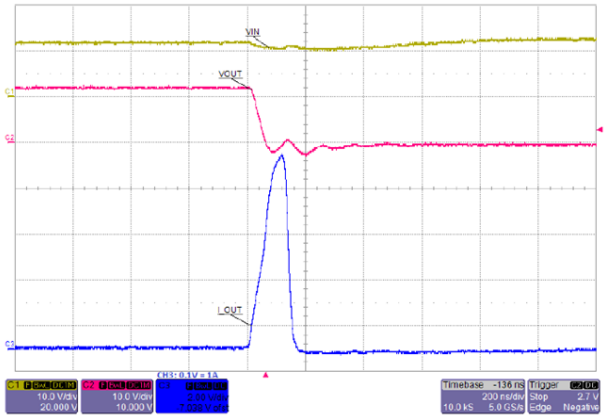

Figure 8. Fast-Trip Comparator Response for a Hot-Short Fault

3.4 Reverse Current Protection

Reverse currents can flow through the system when the voltage at the output is higher than at the input. In applications such as power muxing for redundant power systems or SSD with a large hold-up output capacitor, there is a risk of large reverse currents when the input power is disconnected. The reverse current can damage internal circuitry or system power supplies, if it is not limited. For certain applications such as PLC controller modules, this feature is mandatory to pass 'voltage interruption tests'.

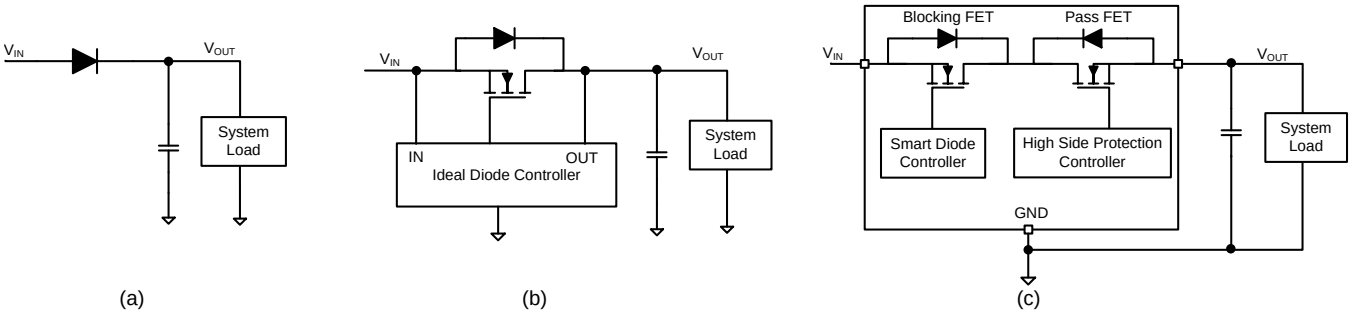

Figure 9. Reverse Current Protection Using (a) Diode (b) External MOSFET and Ideal Diode Controller (c) eFuse

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A series diode can block reverse currents but results in significant power loss in the system which could lower the system efficiency and battery life. An external MOSFET with an ideal diode controller IC (shown in Figure 9(b)) is a more efficient option and also offers flexibility in current support; however, it occupies more board space. TI's TPS2594 family of eFuses integrates blocking FET and a fast reverse comparator to provide true reverse current blocking. When an input power fail condition is detected, the internal FET is turned OFF in 1 µs (typical). True reverse current blocking facilitates simplified efficient power muxing in redundant power systems. For additional information regarding power multiplexing using eFuses, see reference (1).

3.5 Overvoltage Protection

Transient induced voltages or inductive switching can cause overvoltage in the system which lasts from a few hundred microseconds to milliseconds. An eFuse with output voltage-cutoff guards the sensitive circuits from overvoltage by turning OFF the internal FET. The trip point for overvoltage cutoff can be programmable through an external resistor at the OVP pin of eFuse. As shown in Figure 10, the TPS25942x remains active for a nominal 12-V input voltage. When the input voltage exceeds the overvoltage trip point (16.5 V here), the eFuse turns OFF the internal FET causing the output voltage VOUT to fall to zero. The eFuse remains in the OFF condition as long as the input voltage exceeds the set overvoltage trip point. Once the input voltage returns to nominal operating voltage, the device turns back ON and VOUT once again returns to 12 V. The latest eFuse device, TPS2660, protects the load up to 60-V DC *Safe Extra Low Voltage* (SELV) faults and is suitable for industrial applications.

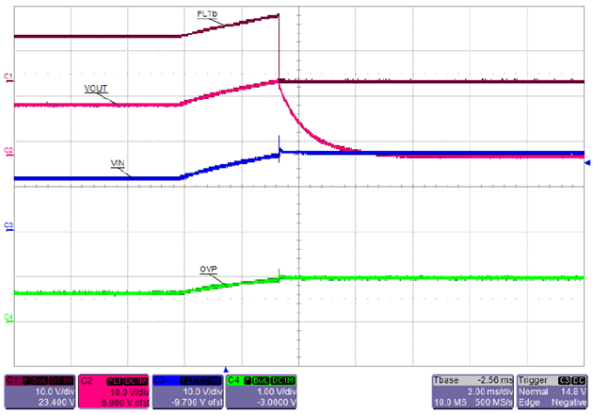

Figure 10. Output Voltage-Cutoff for an Overvoltage Fault

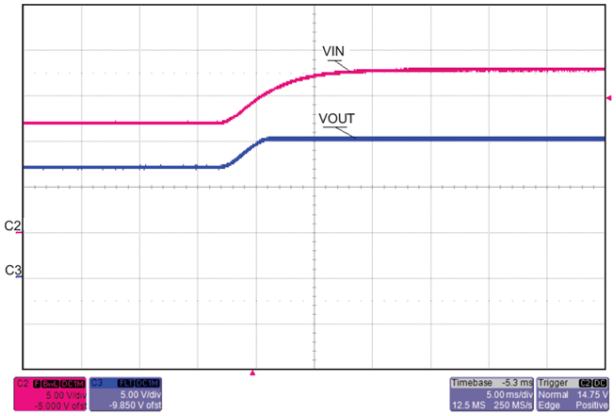

Figure 11. Output Voltage-Clamp during Transient Input Overvoltage

Some of the TI eFuses have an output voltage-clamp (OVC) feature, which keeps eFuse in operation by clamping the output voltage to the nominal voltage. As shown in Figure 11, the TPS25926x eFuse integrates a 15-V output voltage-clamp. When the input voltage exceeds the internal OVC trip point, the internal clamping circuitry activates and limits the output voltage to 15.6 V (typically 15 V). If the transient on the input is only temporary, the eFuse hides the overvoltage fault from downstream circuitry. If the fault lasts long enough to activate the eFuse's thermal shutdown (typically T_J = 150°C), then the fault will still cause the eFuse to turn OFF (similar to output voltage-cutoff).

3.6 Over Temperature Protection

Discrete protection realizations need careful selection of pass FET and thermal design to keep the device in SOA limits under any extreme fault conditions. However, TI eFuses come with inbuilt over temperature protection and gets shutdown if the eFuse junction temperature, T_J, exceeds 150°C (typ). Once eFuse enters thermal shutdown, it either remains in the OFF position (a latch-off version) or attempts to restart (an auto retry version) after T_J falls below T_{TSD} by 12°C and with auto retry delay.

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3.7 Fault Response and Recovery

TI eFuses are available in two versions; latch off and auto retry. A latch-off version remains in the OFF position and needs power recycle to turn ON again. A system with the latch-off version provides more safety by immediately isolating the faulty component but also reduces the system uptime. Figure 12 shows the short-circuit response of the latched device TPS25942L, where the device provides a limited current of 5 A before getting into thermal shutdown. A reset at the enable pin is required to bring the device back into operation. On the other hand, a device with auto retry continues to power cycle itself until the fault is cleared. As shown in Figure 13, the device TPS25942A attempts to power cycle after retry delay (128 ms) and resumes normal operation when short circuit is cleared. Since, over-temperature protection is inbuilt, no special thermal considerations are required for surviving a prolonged output short.

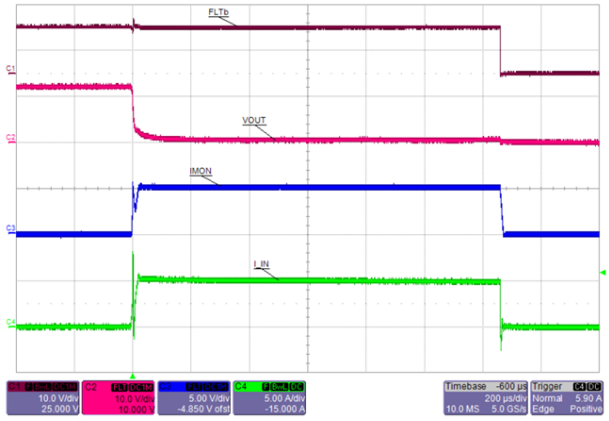

Figure 12. TPS25942L: Latched for Short-Circuit Fault

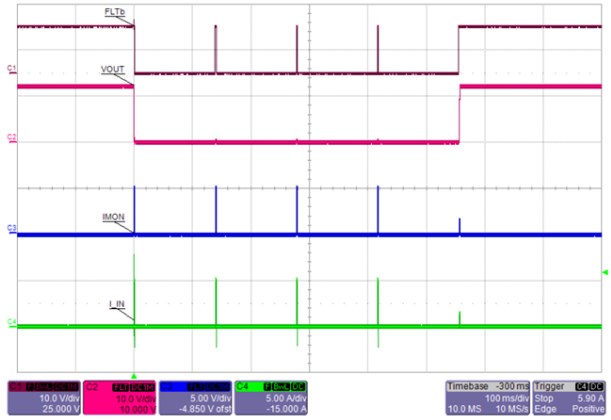

Figure 13. TPS25942A: Auto-Retry and Recovery From Short Circuit

3.8 Input Reverse Polarity Protection

In applications such as PLC systems, the input side needs reverse polarity protection against any field supply mis-wiring. A blocking diode is the simplest means of protecting against reverse polarity connections. Since no control signal is required, circuit complexity and component count are low. On the other hand, the diode dissipates energy all the time due to its forward voltage (V_F) drop, which can cause significant power loss in high-current applications and needs thermal management. Another approach is to use a P-MOSFET, which can be implemented with simpler drive circuitry comprising a Zener diode and a resistor, as shown in Figure 14(b). A P-MOSFET based solution is expensive and has the risk of failure when the input power is removed causing the output capacitor discharge through the fully enhanced P-MOSFET. Another simple solution, shown in Figure 14(c), uses a combination of fuse and TVS diode, where the fuse blows and protects the load against reverse polarity. But after the fault, the fuse needs to be replaced. As shown in Figure 14(d), the TI eFuse TPS2660 integrates a reverse input polarity protection circuit and does not need any external components. The TPS2660 ensures that the device is not functional during reverse polarity conditions and internal FET blocks the reverse current path.

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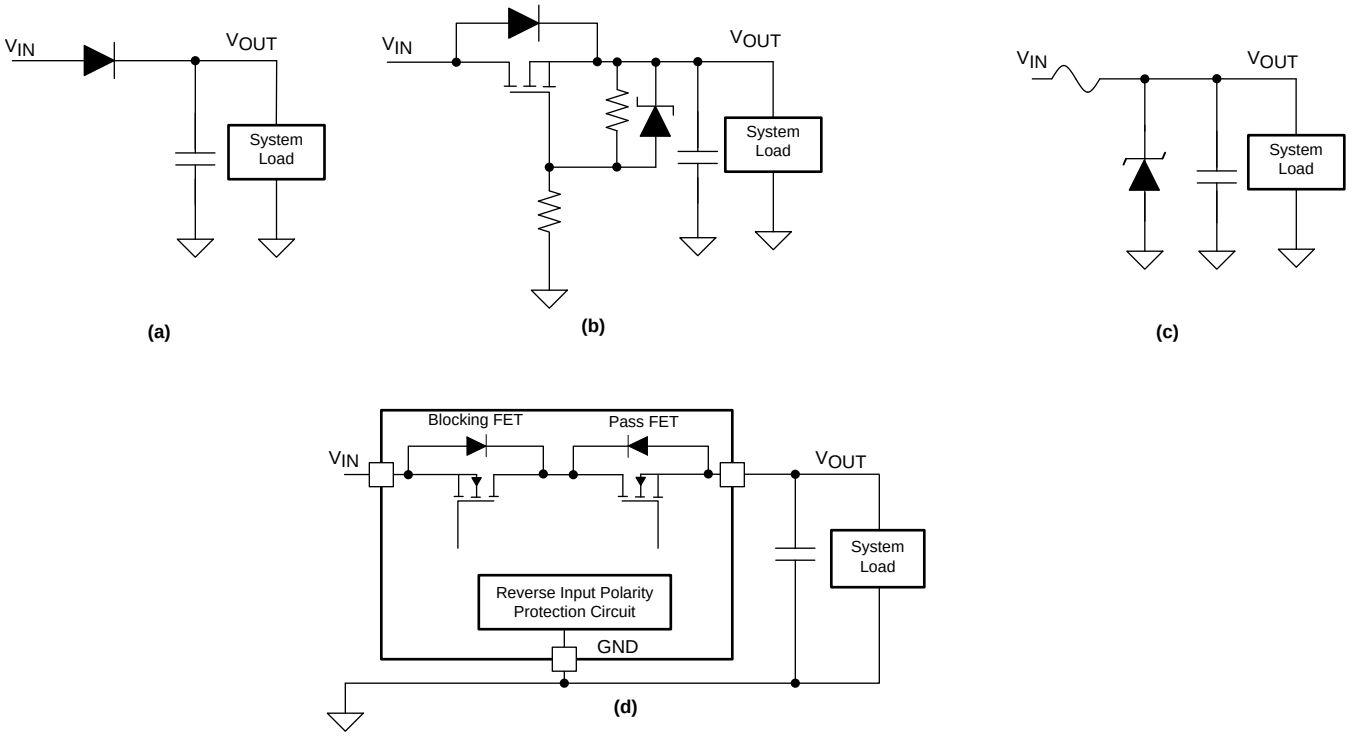

Figure 14. Input Reverse Polarity Protection Using (a) Diode (b) P-MOSFET (c) Fuse + TVS Diode (d) TPS2600 eFuse

3.9 Surge Protection

The TPS2660 eFuse-based surge protection solution (reference (2)) is shown in Figure 15. It requires only a single TVS diode to protect the load from surges. The device does not need any passive wave shaping circuits to reduce the slew rate of the surge. It can handle slew rates as fast as 20 V/µs. Built-in back-to-back FETs and reverse polarity protection circuits effectively block negative voltage that can be generated due to a negative surge. The ±70-V transient absolute maximum ratings of the TPS2660 device enable the use of a single TVS diode for clamping the surge. Overvoltage and undervoltage protection makes sure that the downstream converters are isolated from input when the surge is at peak or valley level. A proprietary high-speed protection algorithm immediately disconnects the output from the input and prevents the surge passing from the input to the output.

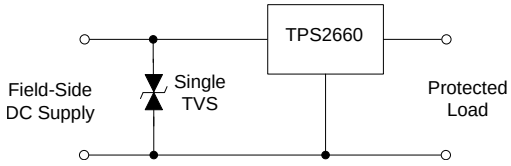

Figure 15. Surge Protection Solution Using TPS2660 eFuse

3.10 Controlled Power Down

When the device is disabled, the output voltage is left floating and power down profile is entirely dictated by the load. In some applications, this can lead to undesired activity as the load is not powered down to a defined state. Controlled output discharge can ensure the load is turned OFF completely and not in an undefined operational state. The BFET pin in the TPS25927x family of eFuses facilitates the quick output discharge (QOD) function as illustrated in Figure 16. When the device is disabled, the BFET pin pulls low which enables the external P-MOSFET, Q_1, for the discharge feature to function. The output voltage discharge rate is dictated by the output capacitor, C_{OUT}, the discharge resistance, R_{DCHG}, and the load.

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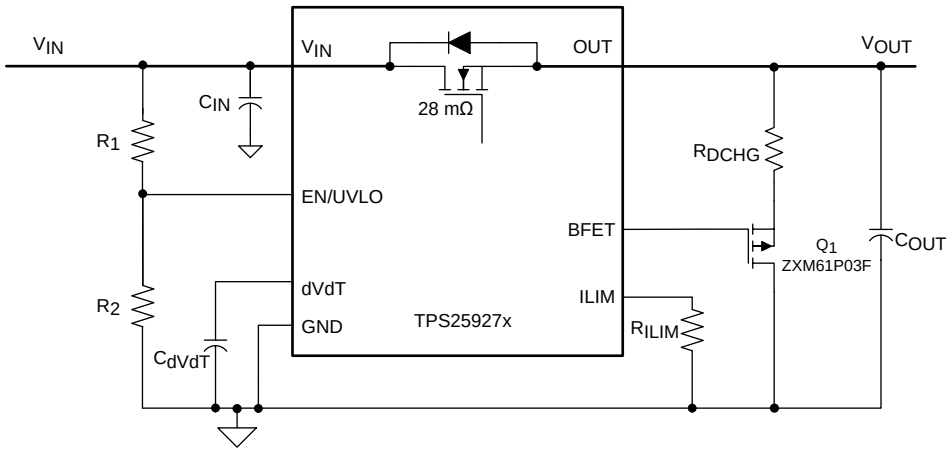

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Figure 16. Circuit Implementation With Quick Output Discharge Function

3.11 UL Certifications

Most of the TI eFuses are UL 2367 (solid-state overcurrent protectors) recognized which would help in designing sections of the system as “limited energy” or “low power” circuits to expedite the UL certification process. Additionally, these devices are also UL 60950 (safe during single-point failure) recognized, which restricts the voltage, current within the circuit limits under any single fault. For additional information regarding benefits of UL recognition, the reader is directed to reference (3).

3.12 Additional Features

3.12.1 Health Monitoring and Reporting

The TPS2594xx family of eFuses provide advanced features such as precise load current monitor, voltage monitoring, and fault flag. The current source at the I_{MON} terminal of the TPS2594xx eFuse is configured to be proportional to the current flowing through the device. A resistor from this pin to GND converts current to proportional voltage, which can be used as a means of monitoring the health of the system.

The power good comparator has an internal reference of $V(_{PGTHR})$ = 0.99 V at the negative terminal and the positive terminal PGTH can be utilized for monitoring of either input or output of the device or any other voltage rail in the system. The comparator output PGOOD is an open-drain, active-high signal, which can be used to indicate the status and control the downstream units for power sequencing. PGOOD is asserted high when the internal FET is fully enhanced and the PGTH pin voltage is higher than internal reference, $V(_{PGTHR})$, eliminating the need for a separate supply voltage supervisor chip.

The FLT open-drain output is asserted (active low) during undervoltage, overvoltage, reverse voltage, reverse current, and thermal shutdown conditions.

3.12.2 Diode Mode

The TPS25942x and TPS25944x family of eFuses incorporate the diode mode feature, where the power path from IN to OUT acts as a non-ideal diode rather than a FET. This feature is useful in power-mux applications to switch over from master to slave supplies and vice-versa smoothly, when two supplies are within a diode drop of each other.

3.12.3 Low Power Mode

The TPS25940 eFuse provides a dedicated DevSleep interface terminal (DEVSLP) to drive the device to low power mode. The DEVSLP terminal is compatible with standard hardware signals asserted from the host controller. When pulled high, it puts the device in low power DevSleep mode. In this mode, the quiescent current consumption of the device is limited to less than 95 μA (typical) and the functionality of several non-critical modes are disabled.

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4 Typical Application Example for Comparison

In this section, a comparison between the eFuse solution and a discrete circuit-protection solution is shown for HDD application. This application requires inrush and reverse current protection while managing holdup capacitor charge at the output. It is observed that the output voltage and the inrush current rises exponentially in the discrete solution and sometimes the discrete solution needs design iterations to limit inrush current in the desired limit.

Table 1. Design Parameters

Design Parameter	Value
Input voltage range, VIN	12 V
Undervoltage lockout set point, V(UV)	10.8 V
Load capacitance, C_{OUT}	2 × 1800 µF
Load at start-up, $R_{L(SU)}$	10 Ω
Current limit, I_{LIM}	1.5 A

Table 2. Comparison Table

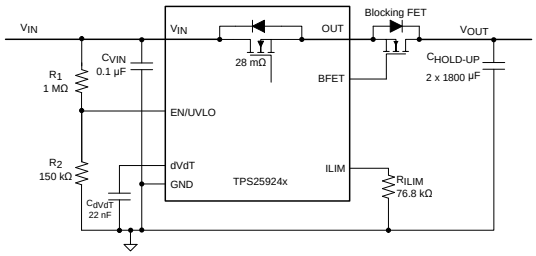
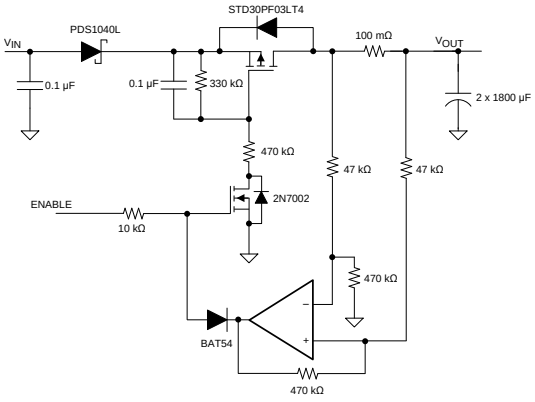
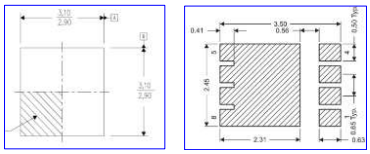
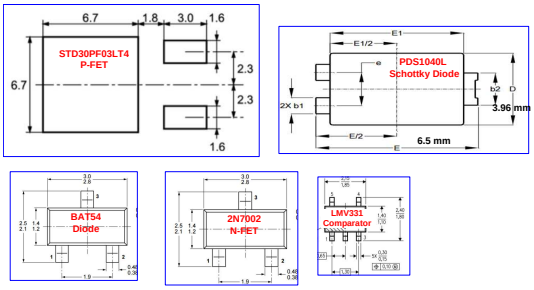
	eFuse Solution: TPS259241+ External Blocking FET	Discrete Circuit-Protection Solution
Circuit Schematic	 Copyright © 2016, Texas Instruments Incorporated	 Copyright © 2016, Texas Instruments Incorporated
Total no. of Components	7	15
Area Occupied by Semiconductors	Approximately 20 mm^2 TPS259241 eFuse CSD16411 N-FET 	> 100 mm^2 
Steady State Power Loss at 1-A Load	38 mW	0.488 mW

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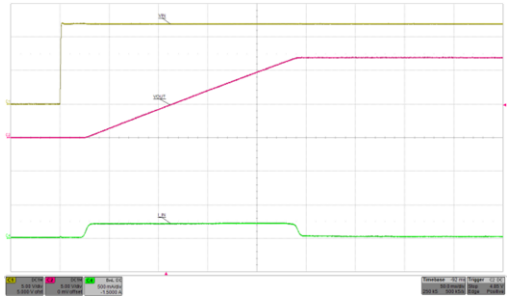
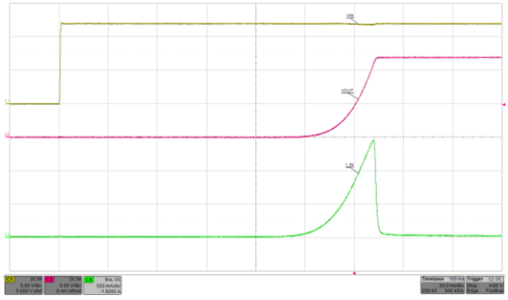
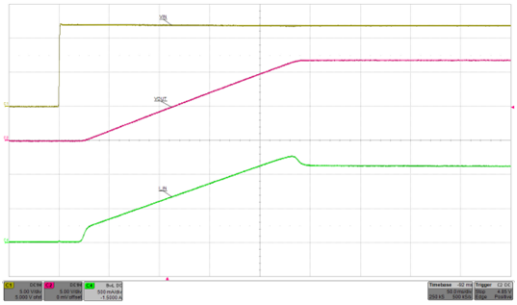
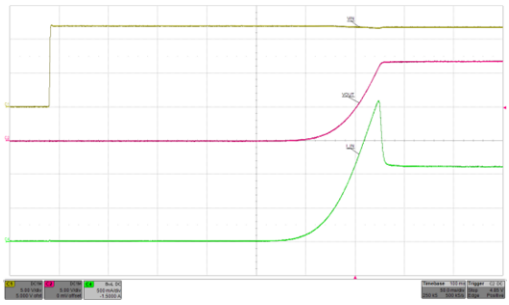
Table 2. Comparison Table (continued)

	eFuse Solution: TPS259241+ External Blocking FET	Discrete Circuit-Protection Solution
Inrush Performance with $R_{L(SU)}$ = OPEN		
Inrush Performance with $R_{L(SU)}$ = 10 Ω		

5 Conclusion

Modern electronic systems need more than one type of protection. Though each of the protection requirements can be met with discrete components, the solution needs more board space, is less efficient, more expensive, and inferior in performance than TI's integrated circuit protection solution "eFuse". The eFuse is more accurate, faster, and can 'repair' itself without user intervention. Most of the TI eFuses are recognized as *Solid State Overcurrent Protectors* under UL2367 standard. Also these are certified under safety standard UL 60950 and are safe during single point failure.

6 References

1. *Power Multiplexing Using Load Switches and eFuses* (SLVA811)
2. *The TPS2660 Simplifies Surge and Power-Fail Protection Circuits in PLC System* (SLVA833)
3. How to save time and money with low power circuits (https://e2e.ti.com/blogs_/b/industrial_strength/archive/2015/10/23/low-power-circuits)

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Revision History

Changes from Original (December 2016) to A Revision	Page
• Changed title of the *Application Report* to Basics of eFuses	1

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