Application Report

SLVAED9–June 2019

# Reducing Power Loss and Overheating During Faults with eFuses

Rakesh Panguloori

## 1 Introduction

Several components inside electronic equipment have an inherent maximum current capacity, which when exceeded, overheats (possibly to an unrecoverable state). Some of the common components are:

- Semiconductor devices
- Passive filters
- Printed circuit board (PCB) traces
- Connectors
- Interfacing cables

This makes current limiting an essential requirement to protect components in almost all systems. Current limiting maintains transient overload currents within the maximum current rating limits. Protecting the power path against faults is crucial but after the fault is cleared, it is also important for the system to recover quickly without manual intervention. This minimizes maintenance costs by reducing visits of technician on-site. All of these drive the fault response of the protection devices as one of the key system level requirements.

- Fuses, also known as a mechanical fuse or melting fuse, are traditionally used as protection devices to isolate overload or short-circuit faults from the main system. While fuses are an inexpensive solution, they need to be physically replaced every time they melt, because they become open and non-operational when a fault occurs. This increases system downtime and maintenance costs.
- Positive temperature coefficient (PTC) resistors eliminate the need for human intervention by providing resettable overcurrent protection. The PTC resistor auto-resets the system from a circuit trip as the temperature cools. However, the ON-resistance of PTC increases after every fault, which raises concerns about achieving repeatable performance over time.
- An electronic fuse or eFuse acts as a "self-healing" device. When it "breaks the path", it automatically turns back on, and attempts to restart the circuit and provides the same robust performance after each overcurrent event.

Figure 1 shows fault response summary of fuse, PTC, and eFuse devices.

| | | | |
|---|---|---|---|
| Fault Response | Open and Non-operational | Self-resets but performance degrades after each reset | Repeatable performance after each reset |
| Manual Intervention | Must | Moderate | Very Low |

**Figure 1. Summary of Fault Response for Fuse, Resettable Fuse, and eFuse**

An eFuse is an active circuit protection device with an integrated FET used to limit currents, and keep voltages at safe levels during fault conditions. For an overload event, the eFuse does the current limit and serves the load until it reaches thermal shutdown. For additional information on how the eFuse protects different types of faults, refer to the *Basics of eFuses Application Report*. An eFuse provides the flexibility to select fault response depending on the type of eFuse. A latch-off version remains in the OFF position and needs power recycle to turn ON again. Figure 2 shows the overload response of the latched TPS259540 device, where the device provides a limited current of 4 A to the output before going into thermal shutdown. A reset at the enable pin is needed to bring the device back into operation. This is different to the latch-off functionality, where an eFuse with the auto-retry function continues to power cycle itself indefinitely until the fault is cleared. As shown in Figure 3, the TPS259541 (auto-retry variant) devices attempts to power cycle after a retry delay of 93 ms and resumes normal operation as soon as the overload fault is cleared.

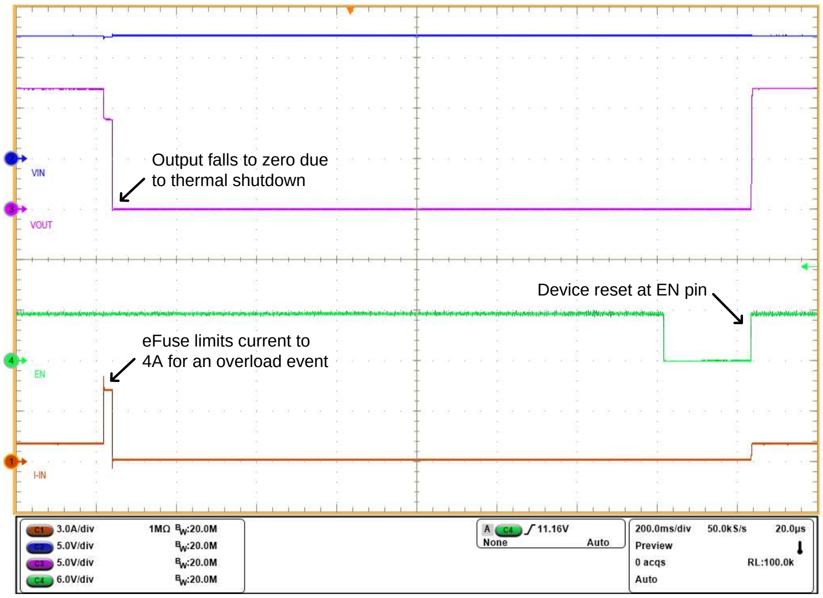



**Figure 2. Latch-off Version of an eFuse (TPS259540) Waits for Power Cycle or EN Cycle**

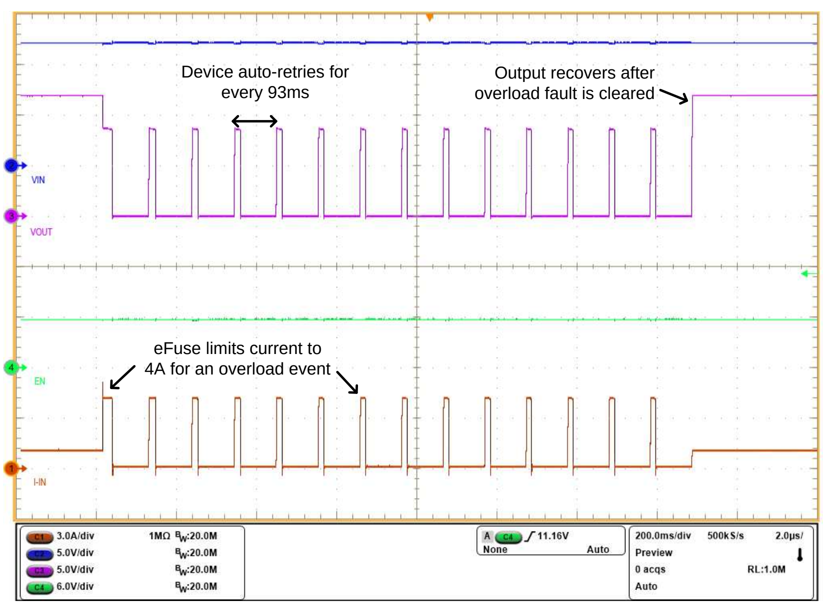
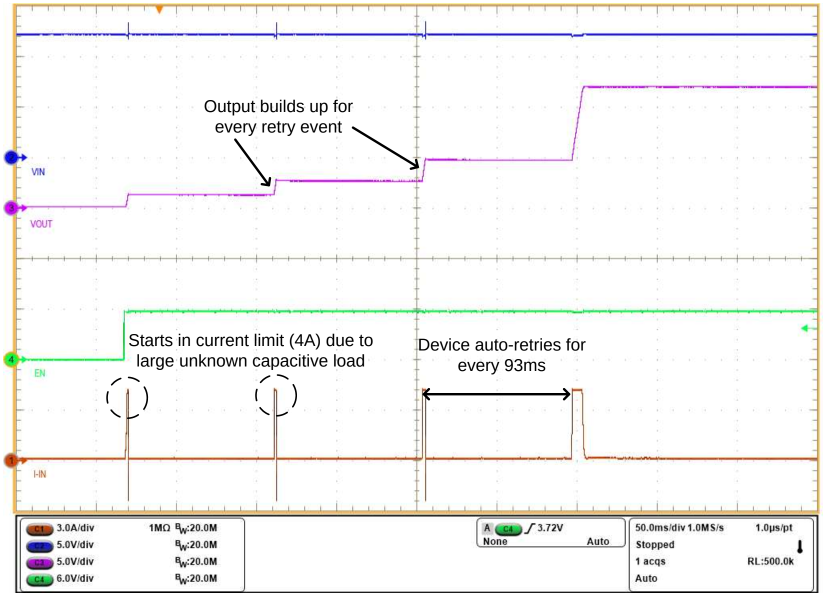



**Figure 3. Auto-retry Version of an eFuse (TPS259541) Continues to Power the Cycle Until the Fault is Cleared**

The auto-retry function is generally preferred in many of the applications to avoid permanent system shutdown for any temporary faults or transients. This allows systems in remote or inaccessible installations to try and recover from faults without need for technician intervention. Another advantage with the auto-retry function is its ability to support unknown loads in a hiccup manner to make a successful start-up. For example, a main board can have several output slots with daughter cards of unknown capacitances. An improper start-up design pushes the device into current limit mode and then into thermal shutdown. However, the auto-retry function can charge the unknown load capacitance in multiple attempts to successfully start up the system, as shown in Figure 4.




$R_{ILM}$ = 487 Ω $C_{dVdt}$ = 3.3 nF $C_{OUT}$ = 2.2 mF

**Figure 4. The TPS259541 Device Starts an Unknown Load in Current Limit Mode**

## 2 Challenges with Indefinite Auto-Retries

The auto-retry function helps to improve the system uptime without the need of manual intervention, but there is a concern in a scenario where the fault is real and persistent. This scenario brings several system-level challenges as discussed in the following sections.

### *2.1 Higher Operating Temperature*

As shown in Figure 3, under a persistent fault, the junction temperature of an auto-retry eFuse hits thermal shutdown threshold (for example, it is 157°C for the TPS259541) in every retry cycle and shuts OFF. Then, the device waits to cool down for thermal hysteresis (typically 5°C to 10°C) and a retry delay interval before attempting next power cycle. Though the auto-retry delay helps to cool down the device, it may not be sufficient to bring the operating temperature to a normal level. Figure 5 shows a thermal image of the TPS2595EVM board during an overload event. The average case temperature of the device reaches ~121°C, and as a result, the average junction temperature of the device reaches close to the maximum recommended value, thus raising concern on the long-term reliability under a persistent fault. This also increases the operating temperature of the PCB and nearby components. Any adjacent power-dissipating components could enhance the problem due to a mutual heating effect and can potentially lead to overheating. Therefore, a limited number of auto-retries or longer retry delay would be needed to avoid this situation.

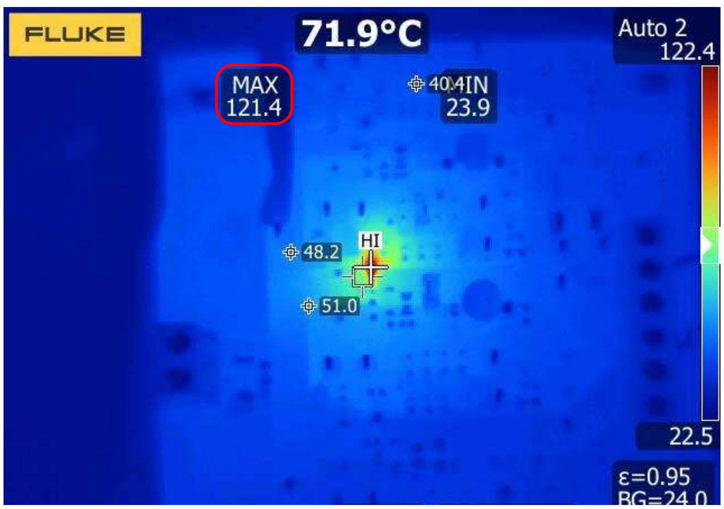
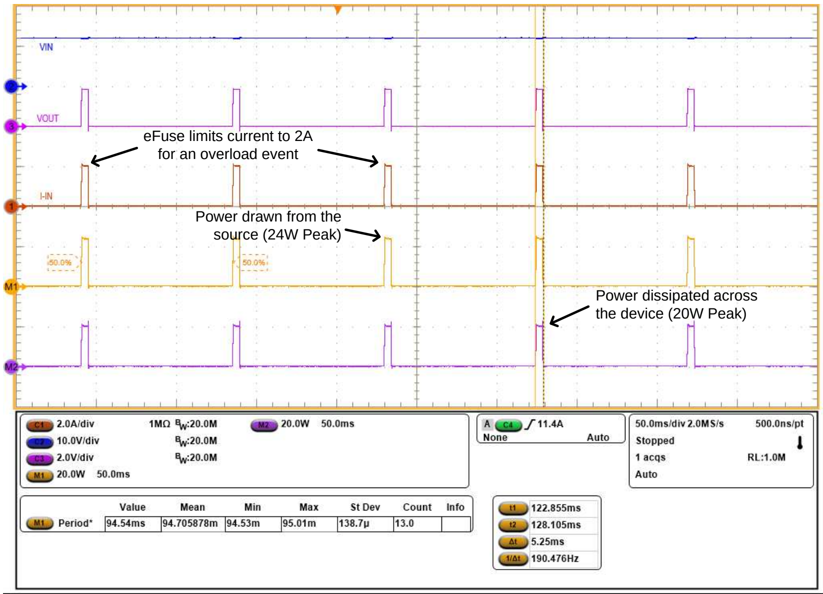



**Figure 5. Case Temperature of the TPS259541 eFuse on the TPS2595EVM Under a Sustained Fault Condition**

### *2.2 Power Loss*

Under sustained fault condition, even though the fault current is limited, it simply gets shunted to ground without being used for any specific work. For example, in case of overload fault with 2 A current limit setting, the device limits the output current to 2 A. The peak power drawn from the input source is 12 V × 2 A = 24 W (refer to Channel-M1 in Figure 6), which causes an average power loss of 24 W × 5.25 ms / 94.54 ms = 1.33 W. Latching-off the device after a limited number of retries or a longer retry delay time minimizes the unnecessary power loss.




$R_{ILM}$ = 1020 Ω    $R_{OUT}$ = 1 Ω    CH-M1 = VIN × I-IN    CH-M2 = (VIN – VOUT) × I-IN

**Figure 6. Power Dissipation Profile of the TPS259541 Under Sustained Overload Fault Condition**

## 3 Techniques to Configure Fault Response

In compact, enclosed systems, where excessive power dissipation and higher operating temperatures are not tolerable, a limited number of auto-retries or longer retry delay would be needed to ensure proper system functionality. There are several techniques to configure the fault response (that is the number of retries and retry delay), which includes the following:

- Discrete components around eFuse
- Using a system microcontroller
- Sophisticated devices that have a digital interface

This section discusses the implementation challenges of these approaches and explains how the integrated auto-retry scheme of the TPS25982 smart eFuse simplifies the design.

### 3.1 Using RC Network

In this implementation (Figure 7), the FLTb and EN pins of the eFuse are connected together and a RC network is used. For a fault, the eFuse asserts the FLTb pin which in turn pulls down the EN pin voltage. As soon as the EN pin voltage drops below the turnoff threshold $EN_L$, the eFuse gets turned off and releases the FLTb pin OPEN. This allows the external $R_{RETRY}$ and $C_{RETRY}$ network to charge from the supply voltage $V_{IN}$ and restart the eFuse once the EN pin voltage reaches the turnon threshold voltage, $EN_R$. The time constant of the RC circuit and the EN pin voltage hysteresis determines the retry delay time. Figure 8 shows the test waveform realizing retry delay of 570 ms. This approach provides a simple solution to configure the time between retries but does not limit the number of retries. So, the unnecessary power loss under sustained fault condition cannot be avoided.

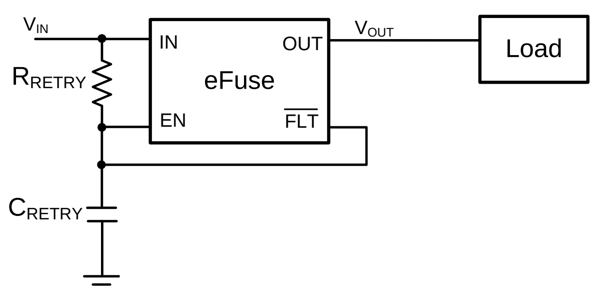
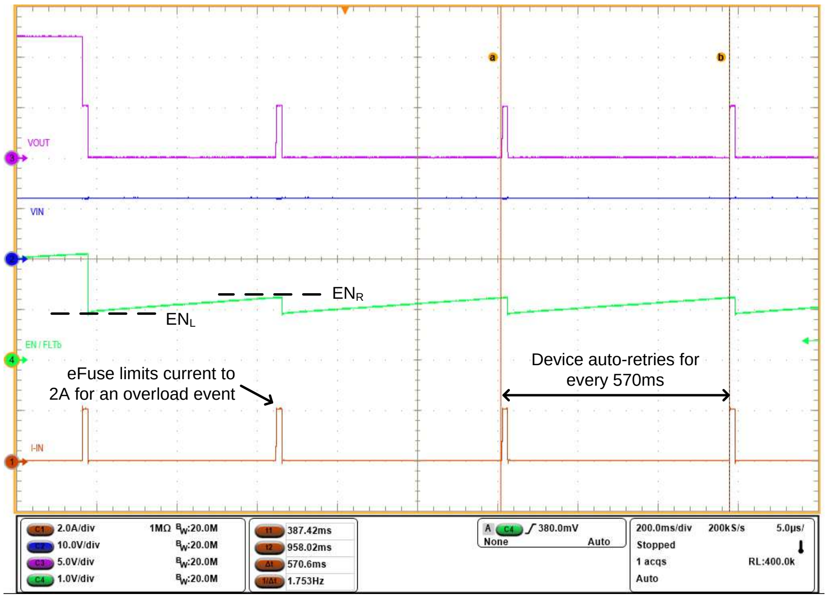



**Figure 7. RC Network Delay at the EN Pin Sets the Retry Delay Time**




$R_{RETRY}$ = 1 MΩ    $C_{RETRY}$ = 1 µF

**Figure 8. Example Test Waveform using TPS259541 to Realize Retry Delay of 570 ms**

## 3.2 *Using System Microcontroller*

Figure 9 shows a block diagram of a typical implementation using a system microcontroller. In this approach, the system prefers to use the latch-off version where the eFuse latches off for a fault and stays off until told to turn back on by the system controller. After the eFuse asserts the FLTb pin, the system can decide on the number of retries and the retry delay interval. For the test case shown in Figure 10, the eFuse is power cycled at the EN pin for four times with 200-ms delay. As the fault still exists, the device is latched-off, indicating the need for technician intervention. This approach is feasible provided the system uses a microcontroller and GPIO pins are available to realize this function, otherwise it adds cost to the solution.

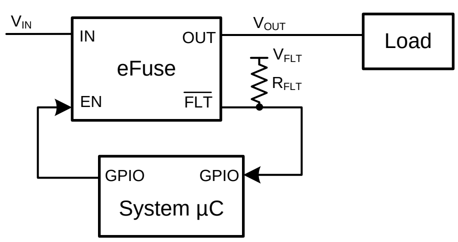



**Figure 9. Using a System Microcontroller to Control Fault Response of the eFuse**

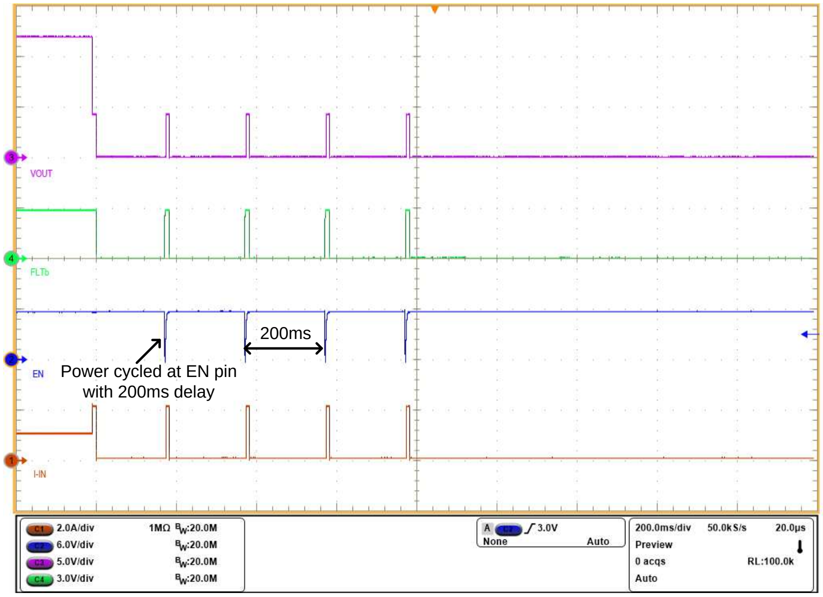



**Figure 10. System Attempts Four Retries with 200-ms Retry Delay Before Latch-off**

### *3.3 Devices with Digital Interface*

Some of the hot-swap controllers such as the LM25066 and LM5066 have digital ($I^2C$™/SMBus™) interface and provides flexibility to digitally configure the number of retries to the following:

- 0
- 1
- 2
- 4
- 8
- 16
- Infinite

The retry counts can be selected by setting the appropriate bits in the MFR_SPECIFIC_09: DEVICE_SETUP (D9h) register. However, the delay between retries depends on the fault timer period which is a function of the system design margin, thus providing controlled freedom on the selection of the retry delay. For more information, refer to the *LM25066 System Power Management and Protection IC with PMBus Data Sheet*.

### *3.4 eFuses with Configurable Fault Response*

The TPS25982 allows the user to configure the system for latch-off (no auto-retry), limited number of auto-retries before latch-off, or auto-retry indefinitely, depending on the system needs. The TPS25982 also provides adjustable retry delay which allows a sufficient cooling period (which is system dependent), and prevents the board from overheating in high ambient temperature installations. Both the auto-retry delay and auto-retry count can be user-programmed using just two low voltage capacitors as shown in Figure 11.

To configure the TPS25982 for a finite number of auto-retries with a finite auto-retry delay, choose the capacitor value on the RETRY_DLY pin, then choose the capacitor value on the NRETRY pin as discussed below.

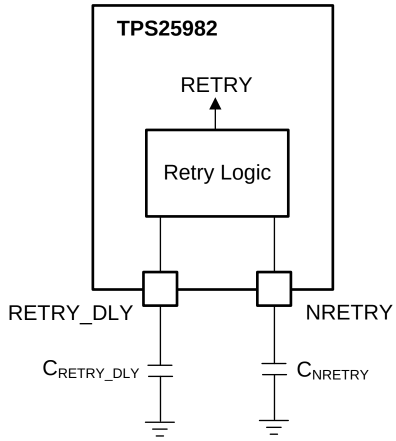



**Figure 11. User Adjustable Auto-Retry Scheme Using Two Capacitors**

### 3.4.1 Setting the Auto-Retry Delay

The time delay between retries can be programmed by selecting capacitor $C_{RETRY\_DLY}$ on the RETRY_DLY pin. The value of $C_{RETRY\_DLY}$ can be calculated using Equation 1.

$$C_{RETRY\_DLY}\,(pF) = \frac{t_{RETRY\_DLY}\,(\mu s)}{46.83} - 4\ pF \tag{1}$$

### 3.4.2 Setting the Number of Retries

The number of auto-retry attempts can be set by a capacitor $C_{NRETRY}$ on the NRETRY pin using Equation 2.

$$N_{RETRY} = \frac{4 \times C_{NRETRY}\,(pF)}{C_{RETRY\_DLY}\,(pF) + 4\ pF} \tag{2}$$

The number of auto-retries for TPS25982 is quantized to certain discrete levels as shown in Table 1. Choose $C_{NRETRY}$ so that NRETRY falls within the range. Use Equation 3 to calculate $C_{NRETRY}$.

$$C_{NRETRY}\,(pF) < \frac{N_{RETRY} \times \left(C_{RETRY\_DLY}\,(pF) + 4\ pF\right)}{4} \tag{3}$$

A TPS25982xx Design Calculator Tool is also available for simplified calculations.

**Table 1. NRETRY Quantization Levels for TPS25982**

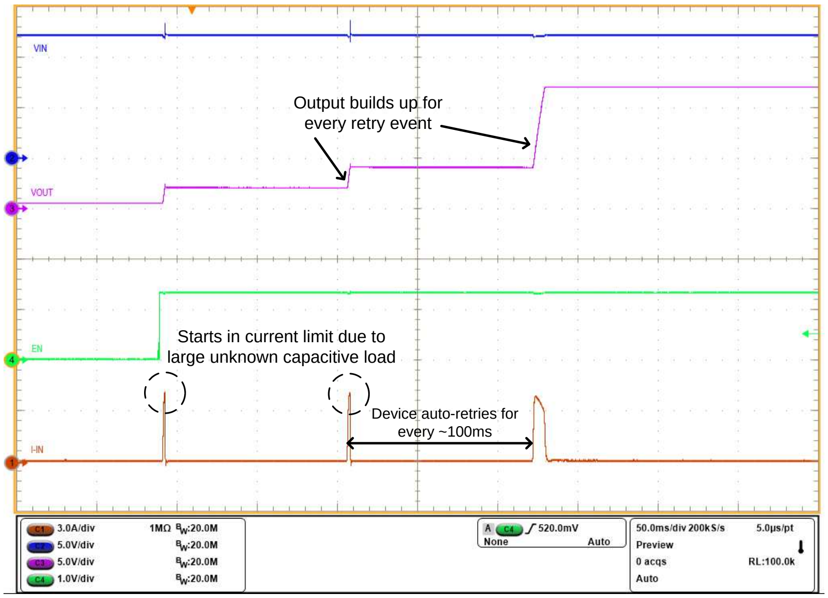
| NRETRY CALCULATED FROM Equation 2 | NRETRY ACTUAL |
|---|---|
| 0 < N < 4 | 4 |
| 4 < N < 16 | 16 |
| 16 < N < 64 | 64 |
| 64 < N < 256 | 256 |
| 256 < N < 1024 | 1024 |

### 3.4.3 Test Results

Figure 12, Figure 13, and Figure 14 show the flexibility of configuring fault response with the TPS25982 device. In this test case, the TPS25982 is configured for four auto-retries with 100-ms retry delay. Figure 12 shows successfully starting an unknown capacitive load in three attempts. If output short exists before enabling the device or output gets shorted in running condition, the device retries only for four times and then latches-off as shown in Figure 13 and Figure 14, respectively. The configurable fault response of TPS25982 provides flexibility to recover from transient faults while avoiding unnecessary power loss and higher operating temperatures under sustained fault conditions.

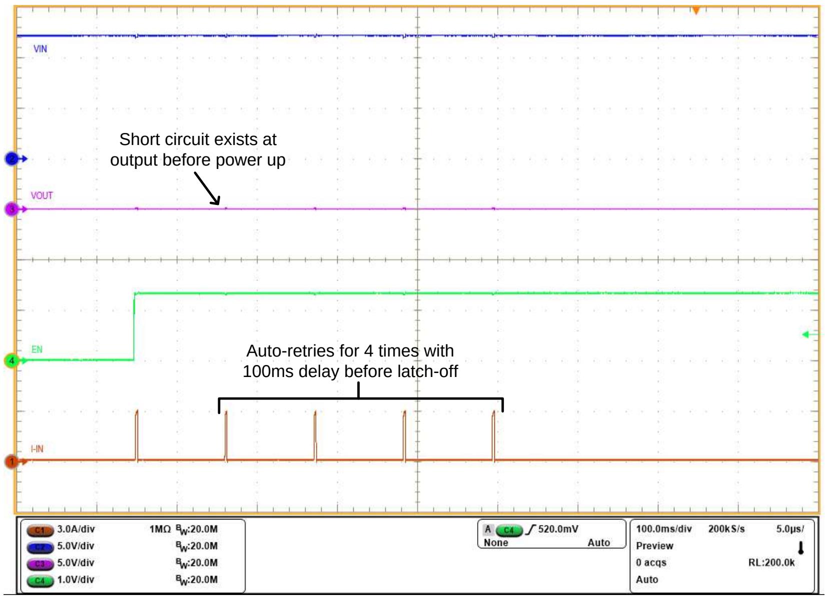
Systems installed in remote or inaccessible locations would require an indefinite retry setting to allow self-recovery from faults. Designing such systems with longer retry delay (for example, 1-sec or higher) would help to maintain lower operating temperatures under a persistent fault. Figure 15 shows the test waveform where TPS25982 retries for every 1-sec until the short-circuit fault at the output is cleared.

Figure 16 to Figure 19 demonstrate the benefits of using longer retry delay. The longer retry delay allows a sufficient cooling period to maintain lower case and board temperatures. Under a sustained short-circuit fault, increasing the retry delay from 100-ms to 1-sec reduces the TPS25982 case temperature from 105.6°C to 61.5°C, thereby enhancing the system life.



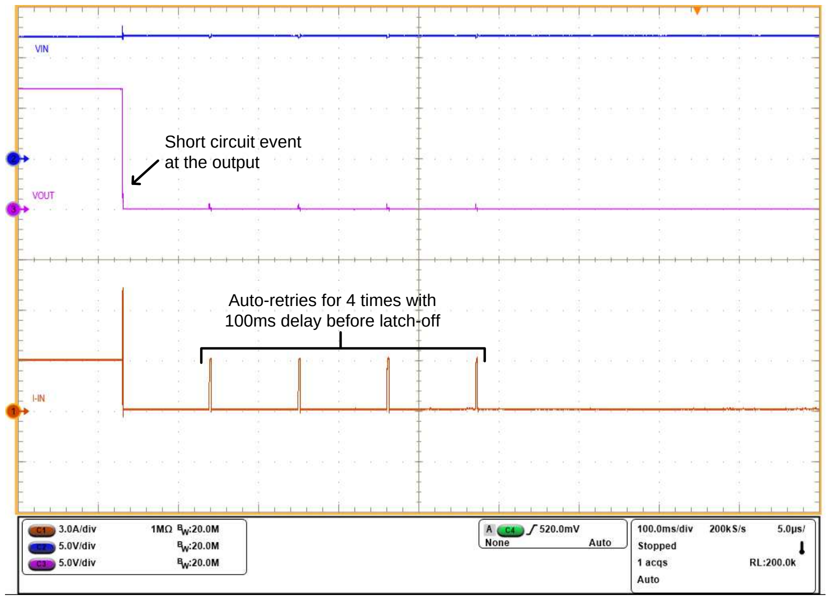

$R_{ILIM}$ = 332 Ω $C_{OUT}$ = 2.2 mF $C_{RETRY\_DLY}$ = 2.2 nF $C_{NRETRY}$ = 2.2 nF

**Figure 12. TPS25982 Starts an Unknown Load Successfully (In This Case, Three Attempts)**



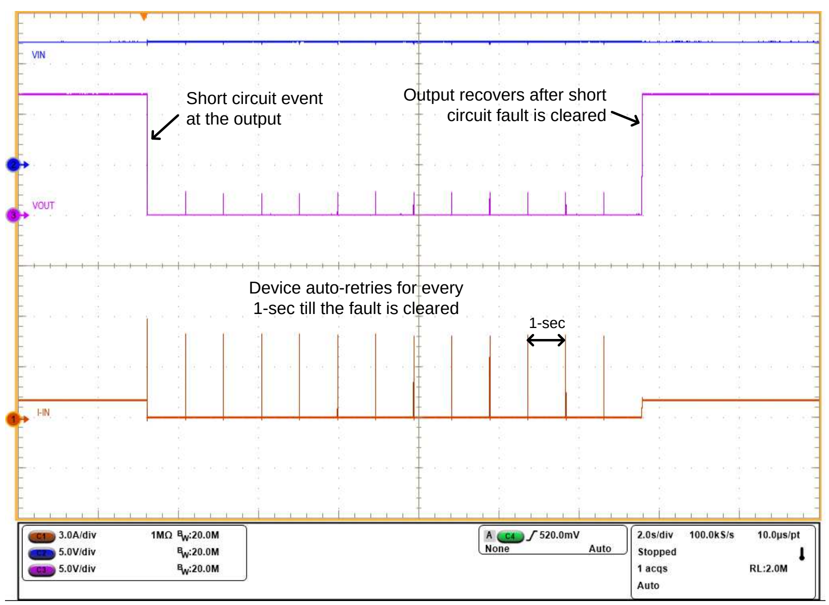

$R_{ILIM}$ = 332 Ω $C_{ITIMER}$ = 4.7 nF $C_{RETRY\_DLY}$ = 2.2 nF $C_{NRETRY}$ = 2.2 nF

**Figure 13. When Enabled into Short, the TPS25982 Attempts Only Four Retries Before Latch-off**



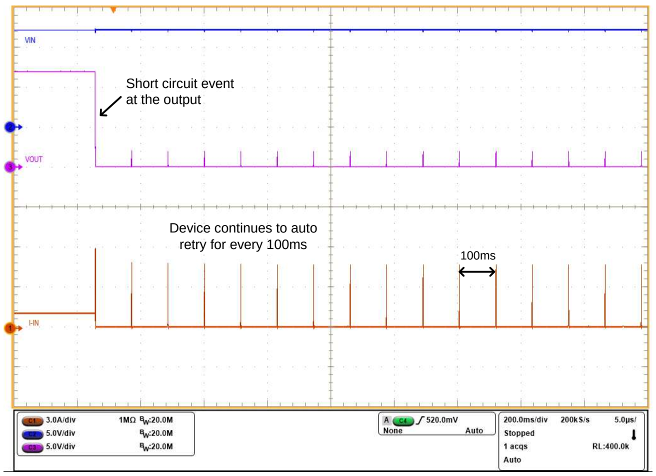

$R_{ILIM}$ = 332 Ω $C_{ITIMER}$ = 4.7 nF $C_{RETRY\_DLY}$ = 2.2 nF $C_{NRETRY}$ = 2.2 nF

**Figure 14. Output Hard Short-Circuit: TPS25982 Attempts Only Four Retries Before Latch-off**




$R_{ILIM}$ = 100 Ω $C_{ITIMER}$ = 4.7 nF $C_{RETRY\_DLY}$ = 22 nF $C_{NRETRY}$ = Short

**Figure 15. TPS25982 Continues to Power Cycle with 1-sec Retry Delay till the Fault is Cleared**




RILIM = 100 Ω, CITIMER = 4.7 nF, CRETRY_DLY = 2.2 nF,
CNRETRY = Short

**Figure 16. TPS25982 eFuse Configured for Indefinite Retires with 100 ms Retry Delay**

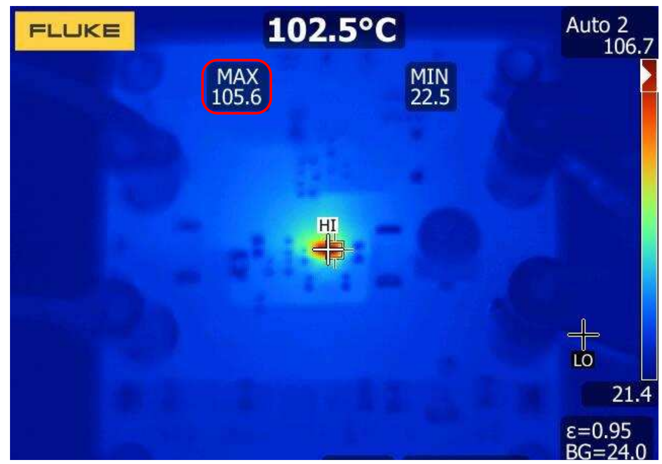
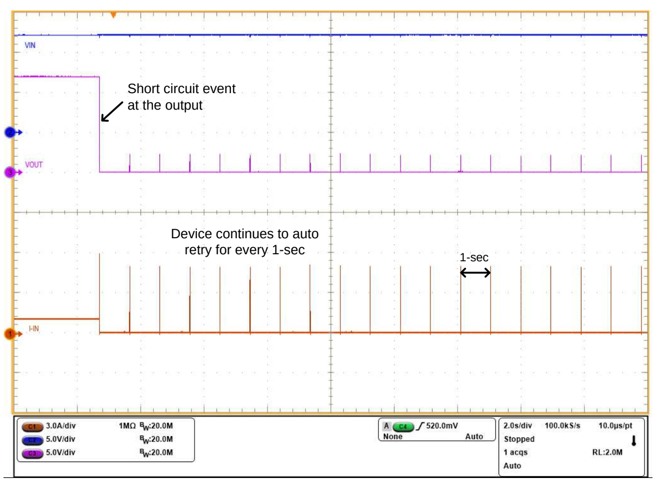



**Figure 17. Case Temperature of the TPS25982 Device Under Sustained Fault with 100 ms Retry Delay**




RILIM = 100 Ω, CITIMER = 4.7 nF, CRETRY_DLY = 22 nF,
CNRETRY = Short

**Figure 18. TPS25982 eFuse Configured for Indefinite Retires with 1-sec Retry Delay**

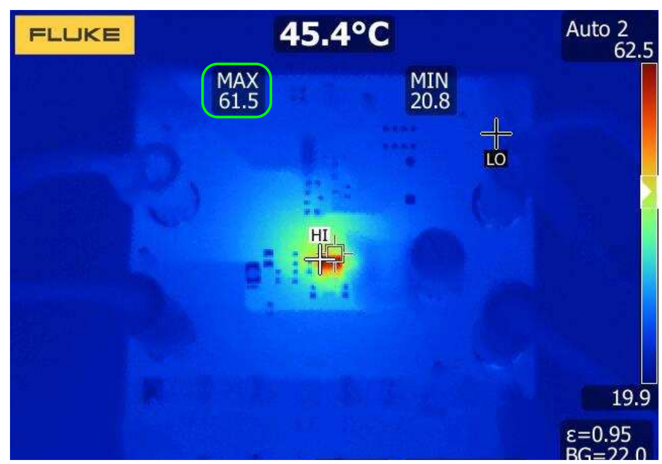



**Figure 19. Case Temperature of the TPS25982 Device Under Sustained Fault with 1-sec Retry Delay**

## 4 Conclusion

- Auto-retry function is generally preferred in many applications to avoid permanent system shutdown for any temporary faults and to allow systems to try and recover from faults without need for technician intervention.
- However, indefinite auto-retries can lead to higher device case temperature and board overheating in high ambient temperature installations, thus raising concern on long term reliability under a persistent fault.
- Workaround solutions need additional components or sophisticated devices to configure the fault response.
- The TPS25982 smart eFuse provides flexibility to configure the system for latch-off (no auto-retry), limit the number of auto-retries before latch-off, or auto-retry indefinitely as per the system needs, by using just two low voltage capacitors.

## 5 References


1. Texas Instruments, *Basics of eFuses Application Report* (SLVA862)
2. Texas Instruments, *TPS2595xx, 2.7 V to 18 V, 4-A, 34-mΩ eFuse With Fast Overvoltage Protection Data Sheet* (SLVSE57)
3. Texas Instruments, *TPS25982 2.7 V to 24 V, 15-A, 2.7-mΩ Smart eFuse With 1.5% Accurate Load Current Monitoring and Adjustable Transient Fault Management Data Sheet* (SLVSEI3)
4. Texas Instruments, *TPS25982xx Design Calculator Tool*

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265