Offline Non-Isolated Flyback Converter Protection

WHITE PAPER

Multifuse® Polymer PTC
Resettable Fuses

ABSTRACT

This paper examines the use of resettable polymer fuses for protecting offline flyback converters. Using a thermal model of the resettable fuse surrounding solder pads and copper to optimize the trip time so that the converter is protected during overloads, there are two potential positions considered for polymer Positive Temperature Coefficient (PTC) resettable fuses in the circuit. One position is directly on the winding and the other position is beyond the control loop. Results are taken from the converter and compared with a simulation.

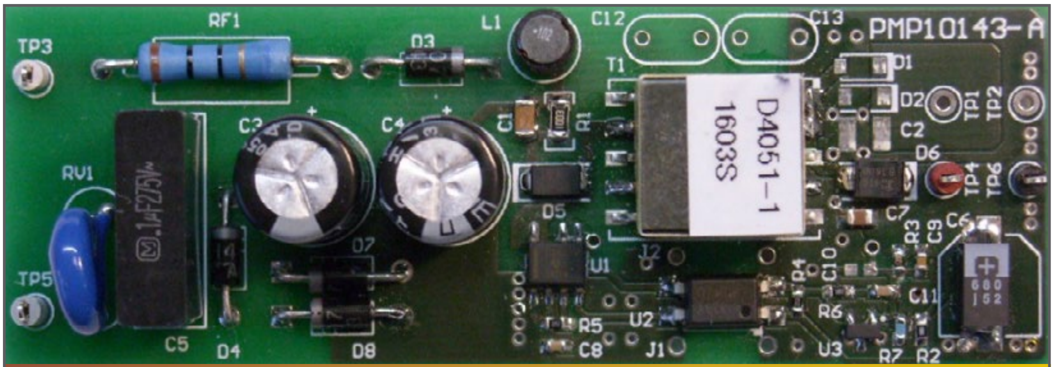

Figure 1. | *Photograph of Converter*

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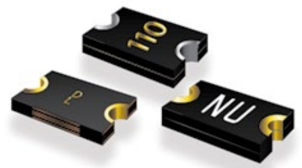

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INTRODUCTION

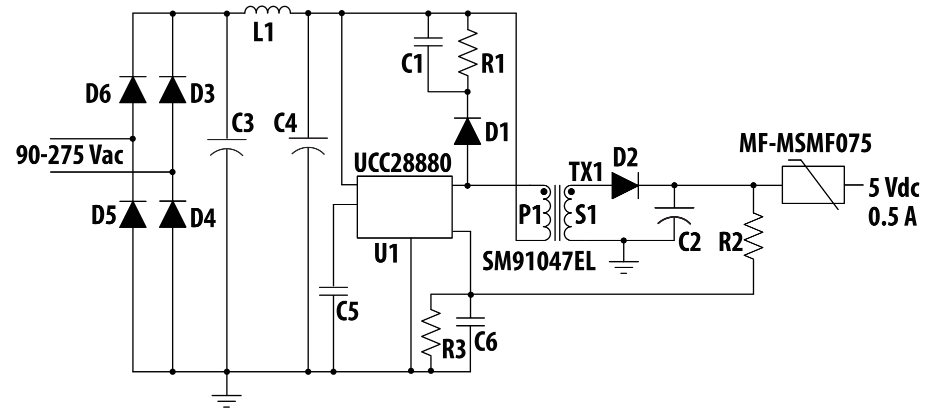


Figure 2. | *Circuit Diagram of Offline Non-Isolated Flyback Converter*

Polymer PTC resettable fuses are used for protecting circuits from overloads, albeit with the following drawbacks:

1. Difference between rated hold current and trip current. Typically, the trip current is twice the hold current with trip times of greater than ten seconds. This paper shows how the trip time can be reduced significantly.

2. Sensitivity to ambient temperature, leading to significant derating. The resistance of a resettable fuse at 100 °C can be 220 % of its nominal value at 25 °C. However, high temperature polymer PTCs, are now available and exhibit an increase of 150 % of their resistance which is comparable to typical high power MOSFETs at 100 °C as shown in figure 2.

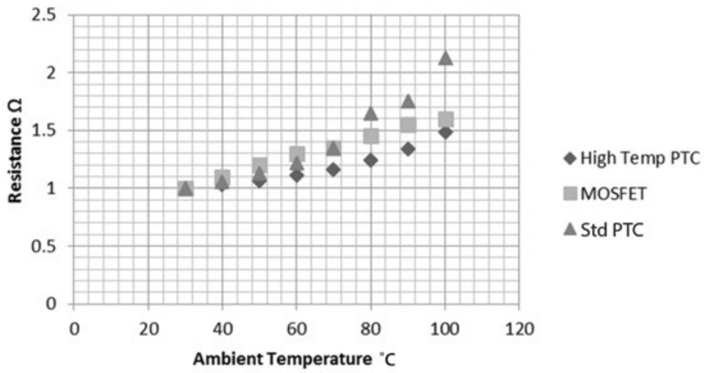
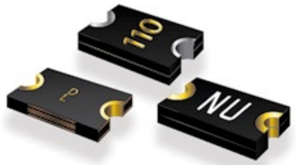


Figure 3. | *Normalized Resistance of a High Temperature PTC and a MOSFET*



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DESCRIPTION OF PTC MODEL

The behavior of a polymer PTC can be modelled using the laws of thermal dynamics. Polymer PTCs react to temperature and will change from low to high impedance at a certain trip temperature. The polymer PTC time to trip depends on the power generated in the component which increases the rate of change of temperature as well as the surroundings which can dampen the rate of change. We can define a polymer PTC as a thermal three-body model consisting of a power source which generates heat in the PTC chip which in turn dissipates through packaging and surrounding solder pads and copper tracks.

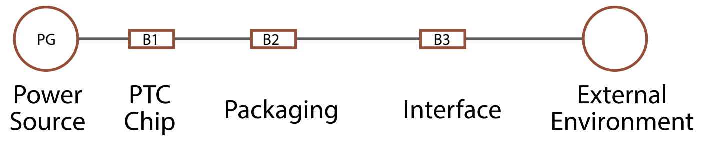


Figure 4. | *Three-Body Thermal Model of a PTC*

The equations for all three bodies B1, B2 and B3 are as follows:

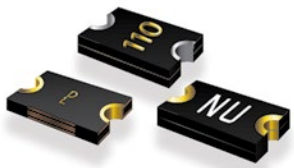
$$\frac{dt_{B1}}{dt} = \theta_{12} k_1 p_G \theta_{12} - k_1 (t_{B1} - t_{B2}) \qquad (1)$$

$$\frac{dt_{B2}}{dt} = \frac{\theta_{23}}{\theta_{12}} k_2 (t_{B1} - t_{B2}) - k_2 (t_{B2} - t_{B3}) \qquad (2)$$

$$\frac{dt_{B3}}{dt} = \frac{\theta_{3A}}{\theta_{23}} k_3 (t_{B2} - t_{B3}) - k_3 (t_{B3} - t_A) \qquad (3)$$

Where:

- θ_{12} is the thermal resistance between bodies B1 and B2
- θ_{23} is the thermal resistance between bodies B2 and B3
- θ_{3A} is the thermal resistance between body B3 and the environment
- p_G is the input power
- t_a, t_{B1}, t_{B2}, t_{B3} is the temperature of the various bodies
- k_1, k_2, k_3 are constants of proportionality



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DESCRIPTION OF PTC MODEL *(Continued)*

We turn to SPICE models to solve these differential equations. An RC network as shown in figure 5 with a current source I_S has the same differential equations. I_S represents the power generated in the circuit. V_{cth1} represents the temperature on the chip while V_{cth2} represents the temperature on the packaging and V_{cth3} is the temperature on the solder interface. The corresponding differential equations are now:

$$\frac{dV_{cth1}}{dt} = \frac{I_s}{C_{th1}} - \frac{(V_{cth1}-V_{cth2})}{R_{th1}C_{cth1}} \qquad (4)$$

$$\frac{dV_{cth2}}{dt} = \frac{(V_{cth1}-V_{cth2})}{R_{th1}C_{cth1}} - \frac{(V_{cth2}-V_{cth3})}{R_{th2}C_{cth2}} \qquad (5)$$

$$\frac{dV_{cth3}}{dt} = \frac{(V_{cth2}-V_{cth3})}{R_{th2}C_{cth3}} - \frac{(V_{cth3}-V_{ta})}{R_{th3}C_{cth3}} \qquad (6)$$

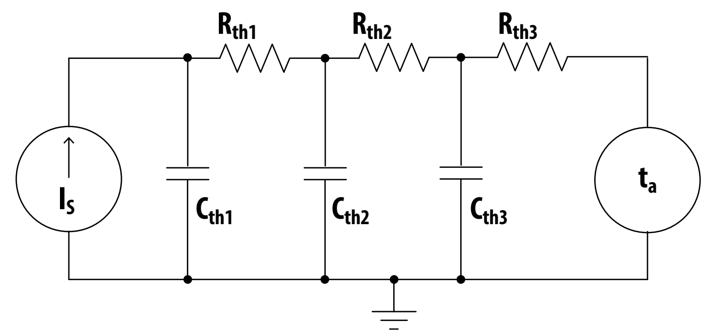
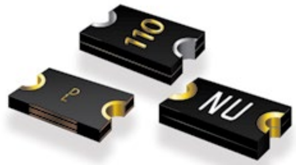


Figure 5. | *RC Network Equivalent of Three-Body Model*



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DESCRIPTION OF PTC MODEL *(Continued)*

We can now use curve fitting to determine the correct vales of R_{th1}, R_{th2}, R_{th3}, C_{th1}, C_{th2} and C_{th3}. The thermal resistance of the system is calculated using the power dissipated by the component, as well as the ambient temperature and the temperature at which the component trips. The thermal resistance is divided between R_{th1}, R_{th2} and R_{th3}.

The model can be used for predicting time to trip and for evaluating the effect of thermal resistance on trip times. Figure 6 shows modelled times for a 0.75 A rated polymer PTC superimposed on the measured times taken from the actual data sheet.

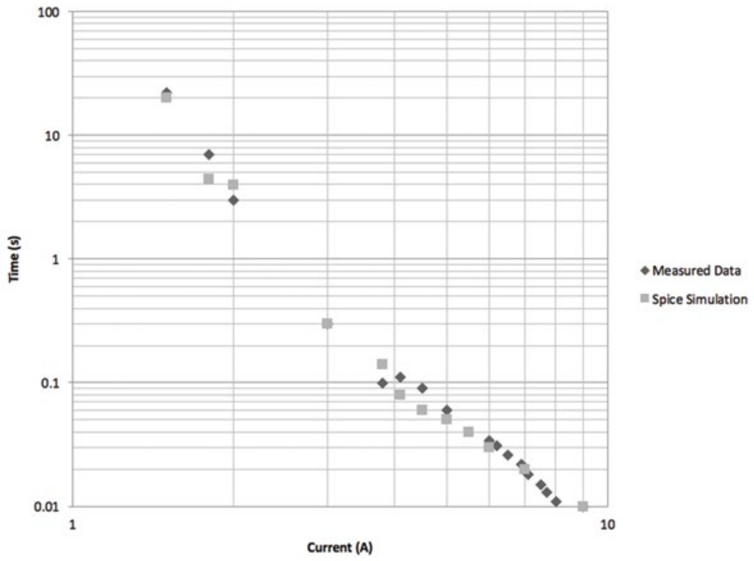
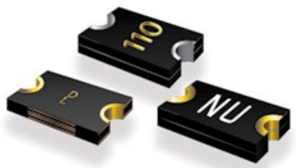


Figure 6. | *Modelled Times to Trip Compared with Data Sheet*



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DESCRIPTION OF PTC MODEL *(Continued)*

If the polymer PTC is mounted on a circuit board, then the third body (B3) would be the output solder pad and connecting track drawn as shown in figure 7 where W1, L1, W2, L2, W3 and L3 represent three separate thermal resistances which form R_{th3}.

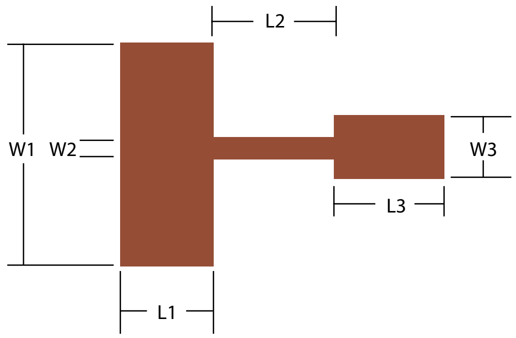


Figure 7. | *Representation of R_{th3} as a Copper Plane*

The thermal resistance θ_{cu} of a copper plane can be expressed as:

$$\theta_{cu} = \frac{L}{W{*}t{*}\beta} \qquad (7)$$

Where β is the thermal conductivity of copper (4 W / (cm °C)).

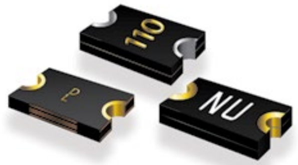
The thermal resistance of a plane as shown in figure 7 of the thickness consisting of a pad plus copper trace can be represented by the following equation:

$$\theta_{plane} = \left(\frac{L1}{W1} + \frac{L2}{W2} + \frac{L3}{W3}\right)\left(\frac{1}{\beta t}\right) \qquad (8)$$

Let θ_{plane} be R_{th3}, as this represents the third body in the thermal model. Assuming we adjust L2 and W2 and assuming $\frac{L1}{W1}$ and $\frac{L3}{W3}$ are much smaller than $\frac{L2}{W2}$, we can express R_{th3} as:

$$R_{th3} = \frac{L2}{W2{*}{*}t\beta} \qquad (9)$$

Hence, R_{th3} can be increased by adjusting W2 downward.



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DESIGN CONSIDERATIONS FOR THE FLYBACK CONVERTER WITH PTC

An offline flyback converter using a UCC28880 monolithic controller was designed to operate in Continuous Conduction Mode (CCM) with 5 V +/-5 % output and a maximum load of 0.5 A from an input voltage range of (90 - 275 Vac). The UCC28880 uses a high voltage MOSFET of 700 V. It switches at 62 kHz and has a typical peak current limit of 0.21 A. The primary inductance was selected based on the fact that the controller has a maximum current at worst-case -40 °C of 0.3 A. The minimum inductance required to keep the power supply in CCM is as follows:

$$L_p = \frac{VDCmin*Dmax}{I_{peak}*FSW} \qquad (10)$$

L_p was selected as 5 mH based on a minimum input of 90 V and a switching frequency of 62 kHz as well as a worst-case peak current of 0.3 A.
The turns ratio N is calculated as:

$$N = \frac{Dmax*VDCmin}{V_{out}*(1-Dmax)} \qquad (11)$$

Being able to operate the controller at the maximum duty cycle of at least 45 % therefore, requires a higher turns ratio but this also increases the stress on the output diode. Secondary detection of the current allows for automatic adjustment of the primary current limit. The controller protects itself from short circuit currents or overloads by entering a “runaway” protection mode, whereby the switching frequency is reduced, allowing the secondary side more time to discharge. Under worst-case conditions, the current limit could be 0.3 A. The rms current in the secondary is given by the following equation:

$$I_{msout} = I*\sqrt{(1-D)} * \sqrt{1+\frac{1}{3}(\frac{\Delta I}{I}}\,)^2 \qquad (12)$$

Where I represents the DC value of the current.
The duty cycle during overload will be very low so (12) can be simplified as:

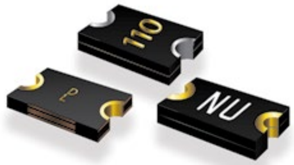
$$I_{msout} = I*\sqrt{1+\frac{1}{3}(\frac{\Delta I}{I}}\,)^2 \qquad (13)$$

ΔI is calculated as 0.2 A on the secondary side. This gives I_{rmsout} = 3.25 A. If we ignore the ripple we can use the following formula:

$$I_{out} = I_{limit}*N*(1-D) \qquad (14)$$

Using (14), I_{out} is 3.4 A.

It is probably excessive to use a diode rated to withstand this short circuit current when the circuit is designed for 0.5 A. The secondary winding would also have to be chosen so it would not overheat during such a short circuit.



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LOCATION OF PTC

A resettable fuse can be placed in two locations as shown in figure 8. In position A, the polymer PTC could be directly assembled inside the winding. The voltage across the polymer PTC in this position will be at least $\frac{VDC_{min}}{N}$ during the on time and V_{out}*N during the flyback time where N is the number of turns and VDC_{min} is the minimum DC input voltage. Therefore, the polymer PTC must be rated to this voltage. During an overload, the polymer PTC will reduce the feedback voltage to zero which in effect creates a potential open loop leaving the output capacitor unprotected.

An alternative location, position B, is located after the control loop and the output capacitor. In an overload situation the controller will regulate as before with the polymer PTC acting as a high ohmic load. Furthermore, the polymer PTC can have a voltage rating equal to the output voltage, which in this case, was 5 V instead of 32 V if connected in position A. Position B, therefore, is judged as being the best location for the polymer PTC.

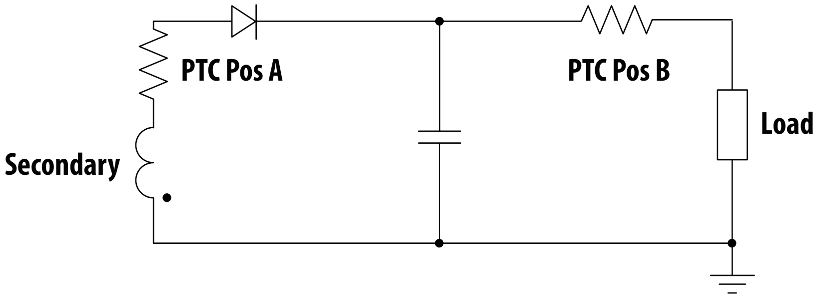
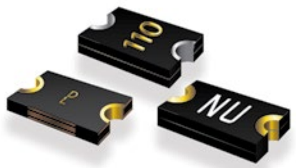


Figure 8. | *Illustration of Two PTC Locations*



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RESULTS AND FINDINGS

The polymer PTC in position B was a surface mount device with a resistance of 0.2 ohms on a board with 70 µm of copper. We can use SPICE to resolve the correct values for R_{th3} and C_{th3} in order to reduce the device's time to trip when it is conducting 1.5 A. Using a track of length of 5 mm, a width of 2.0 mm and the normal thickness for power boards (70 µm), we obtain a value for R_{th3} of 71.4 °C/W. This closely approximates our curve fitting of 69 °C / W for R_{th3}. The time to trip at 1.5 A closely matches the simulation. The overload test was repeated with a track width of 1 mm and the time reduced significantly to 3.5 seconds (figure 9). The thermal resistance was recalculated to have increased to 178.5 °C/W. By stepping the thermal resistance in increments of 60 °C/W in SPICE, we were able to confirm the same measurements as shown in figure 9.

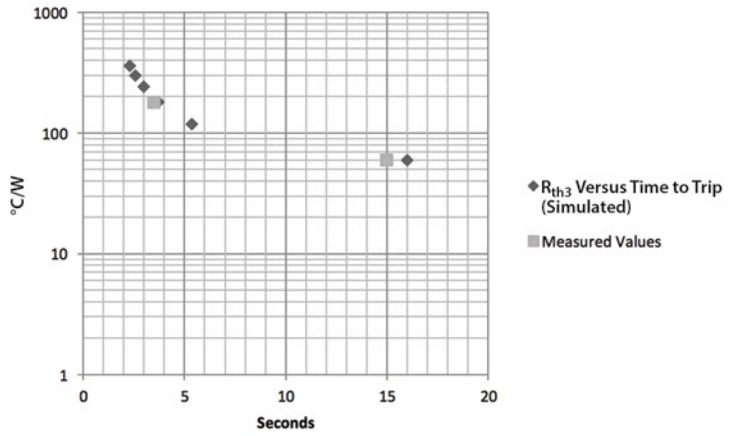
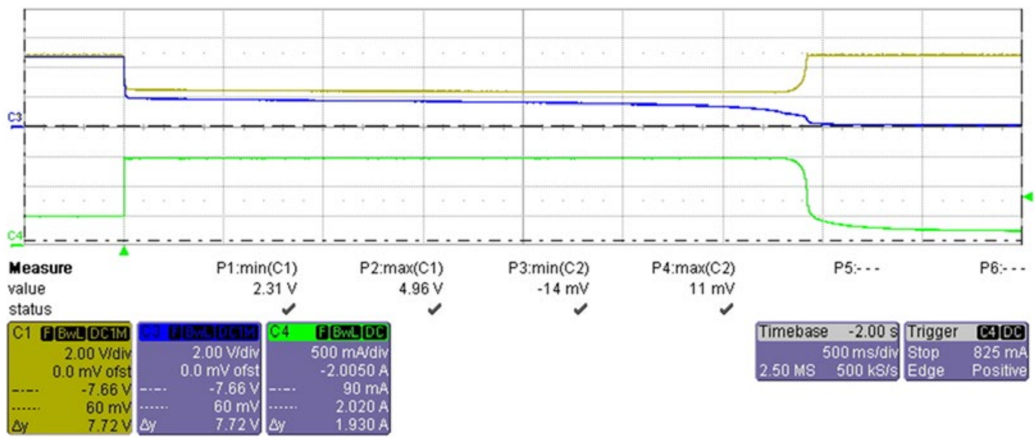


Figure 9. | *Comparison of Simulated Time to Trip Compared with Actual Values*



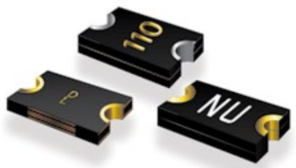
Measure	P1:min(C1)	P2:max(C1)	P3:min(C2)	P4:max(C2)	P5:- - -	P6:- - -
value	2.31 V	4.96 V	-14 mV	11 mV		
status	✓	✓	✓	✓		

C1 F BwL DC1M	[illegible]	C4 F BwL DC
2.00 V/div	2.00 V/div	500 mA/div
0.0 mV ofst	0.0 mV ofst	-2.0050 A
-·-·- -7.66 V	-·-·- -7.66 V	-·-·- 90 mA
······ 60 mV	······ 60 mV	······ 2.020 A
Δy 7.72 V	Δy 7.72 V	Δy 1.930 A

Timebase -2.00 s
500 ms/div
2.50 MS 500 kS/s

Trigger C4 DC
Stop 825 mA
Edge Positive

Figure 10. | *Time to Trip of PTC at 1.5 Amps of Current (Starting from Continuous 0.5 A)*



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RESULTS AND FINDINGS *(Continued)*

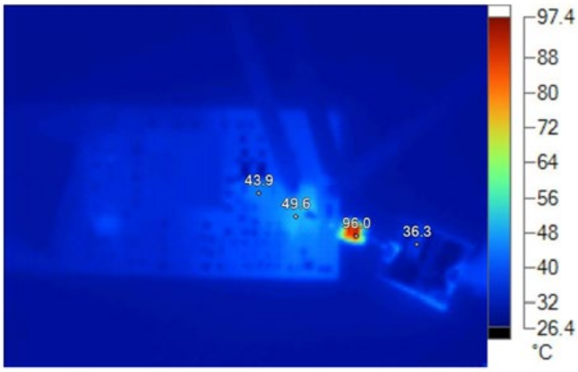


Figure 11. Thermal Image of Board during Short Circuit Test

The board with the polymer PTC was connected to a 33 mF capacitor. The capacitor charged in 0.3 seconds with a load of 0.5 A (figure 12). A power supply of similar output voltage and current (5 V at 0.5 A) without a polymer PTC for protection but with integrated secondary overcurrent protection was also connected to the capacitor. The secondary current limit was set to 0.65 A. Figure 12 also shows that the protection circuit remains tripped in this condition due to the very high initial charging currents. These currents are not long enough in duration to trouble the polymer PTC. This short experiment illustrates one benefit of the polymer PTC for circuits charging super capacitors.

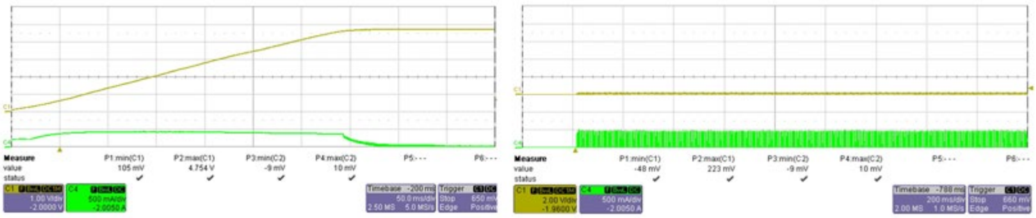
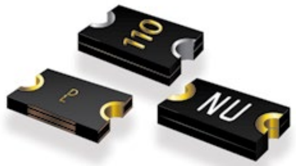


Figure 12. Charging Voltage of 33 mF with PTC and with Secondary Overcurrent Protection



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CONCLUSION

A polymer PTC resettable fuse can be used to provide short circuit protection to a flyback converter. It is possible, using thermal dynamics, to model the polymer PTC and the environment to calculate the required external copper traces to obtain the necessary trip time. High temperature polymer PTCs demonstrate a comparable resistance drift over temperature to MOSFETs and could be considered for circuits where there is not a secondary overcurrent protection mechanism or where the initial inrush is too much for the in built short circuit protection circuit. The best location for the polymer PTC is on the output after the control loop. Putting the polymer PTC on the secondary, can leave the circuit vulnerable to open circuit conditions.

REFERENCES

Advanced Power Technology. Power Mosfet Tutorial, Application Note APT-0403. Rev B March 2, 2006

Bourns Electronics. MF-RHT Series PTC Resettable Fuses Data Sheet, Rev. H, 11/14

Erickson, Robert W. and Dragan Maksimovic. Fundamentals of Power Electronics Springer Science and Business Media, LLC 2001

Gupta, Milind. Use thermal analysis to predict and IC's transient behavior and avoid overheating Maxim Engineering Journal, Volume 68, pages 9-15

Texas Instruments. AN-2020 Thermal Design By Insight, Not Hindsight, SNVA419C–April 2010–Revised April 2013

Texas Instruments. UCCC28880 High Voltage Switcher for Non Isolated AC/DC Conversion, SLUSC05A – July 2014–Revised October 2014

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