Application Bulletin

Implementing Short Circuit Protection

using the RC5036 DC-DC Converter for Pentium® P55/P54

Implementing Short Circuit Protection

Intel currently requires all power supply manufacturers to provide continuous protection against short circuit conditions that may damage the CPU. Fairchild has implemented a current sense methodology to disable the output drive signal to the MOSFET(s) on the switch-mode regulator of the RC5036 when an over current condition is detected. The voltage drop created by the output current flowing across a sense resistor is presented to one terminal of an internal comparator with hysterisis. The other comparator terminal has the threshold voltage, nominally of 90mV. The linear regulator of the RC5036 similarly uses a current sense resistor to disable the output drive when the threshold voltage (45mv typical) is reached. However, no hysterisis is included in the linear regulator. Table 1 states the limits for the comparator threshold for both Switching Regulator and the Linear Regulator.

Table 1: RC5036 Comparator Threshold Voltage

	$V_{threshold}$ Switcher(mV)	$V_{threshold}$ Linear(mV)
Typical	80	45
Minimum	100	37
Maximum	90	53

Switching Regulator

When designing the external current sense circuitry, the designer must pay careful attention to the output limitations during normal operation and during a fault condition. If the short circuit protection threshold current is set too low, the DC-DC converter may not be able to continuously deliver the maximum CPU load current. If the threshold level is too high, the output driver may not be disabled at a safe limit and the resulting power dissipation within the MOSFET(s) may rise to destructive levels.

The design equation used to set the short circuit threshold limit is as follows:

$$R_{SENSE} = \frac{V_{th}}{I_{SC}}, \text{ where: } I_{SC} = \text{Output short circuit current}$$

$$I_{SC} \geq I_{inductor} = I_{Load,\,max} + \frac{(I_{pk} - I_{min})}{2}$$

Where I_{pk} and I_{min} are peak ripple current and $I_{load,\,max}$ = maximum output load current

The designer must also take into account the current $(I_{PK} - I_{min})$, or the ripple current flowing through the inductor under normal operation. Figure 1 illustrates the inductor current waveform for the RC5036 DC-DC converter at maximum load.

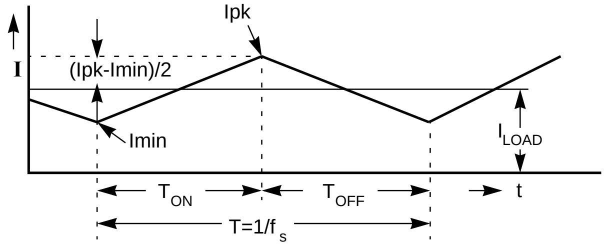


Figure 1. Typical DC-DC Converter Inductor Current Waveform

The calculation of this ripple current is as follows:

$$\frac{(I_{pk} - I_{min})}{2} = \frac{(V_{IN} - V_{SW} - V_{OUT})}{L} \times T_{ON}$$

where:

V_{in} = input voltage to Converter

V_{SW} = voltage across Switcher (MOSFET)=I_{LOAD} x $R_{DS(ON)}$

V_D = Forward Voltage of the Schottky diode

T = 2.8μsec for C_{EXT} = 180pf.

$$I_{SC} = \frac{V_{th}}{R_{SENSE}}, \text{ where: } I_{SC,min} > I_{PK}$$

$$I_{Inductor} = I_{load} + (I_{PK} - I_{MIN})/2$$

For an input voltage of 5V, output voltage of 2.8V, L equals 4.7μH, and a T_{ON} =2.8μsec, the Ipk-Imin/2 current can be calculated as follows:

$$\frac{(I_{pk} - I_{min})}{2} = \frac{(5.0 - 10 \times 0.037 - 2.8)}{4.7 \times 10^{-6}} \times 2.8 \times 10^{-6} =$$

0.545A ~ 0.5A

Therefore, to be able to deliver a continuous 10A of load current, the short circuit detection threshold must be at least 10.5A.

The next step is to determine the value of the sense resistor. Including sense resistor tolerance, the sense resistor value can be approximated as follows:

$$R_{SENSE} = \frac{V_{th,min}}{I_{PK}} \times (1 - TF) = \frac{V_{th,min}}{0.5 + I_{LOAD,MAX}} \times (1 - TF)$$

Where TF = Tolerance Factor for the sense resistor.

There are several different type of sense resistors. Table 2 describes tolerance, size, power capability, temperature coefficient and cost of various type of sense resistors:

Table 2: Comparison of Sense Resistors

Description	Motherboard Trace Resistor	Discrete Iron Alloy resistor (IRC)	Discrete Metal Strip surface mount resistor (Dale)	Discrete MnCu Alloy wire resistor	Discrete CuNi Alloy wire resistor (Copel)
Tolerance Factor (TF)	±29%	±5% (±1% available)	±1%	±10%	±10%
Size (L x W x H)	2" x 0.2" x 0.001" (1 oz Cu trace)	0.45" x 0.065" x 0.200"	0.25" x 0.125" x 0.025"	0.200" x 0.04" x 0.160"	0.200" x 0.04" x 0.100"
Power capability	>50A/in	1 watt (3W and 5W available)	1 watt	1 watt	1 watt
Temperature Coefficient	+4,000 ppm	+30 ppm	±75 ppm	±30 ppm	±20 ppm
Cost @10,000 piece Quantity	Low included in motherboard	$0.31	$0.47	$0.09	$0.09

Based on the Tolerance in the above table:

For an embedded PC trace resistor and $I_{LOAD,MAX}$ = 10A:

$$R_{SENSE} = \frac{V_{th,min}}{0.5 + I_{LOAD,MAX}} \times (1 - TF) = \frac{80mV}{0.5A + 10A} \times (1 - 29\%) = 5.4m\Omega$$

For a discrete resistor $I_{LOAD,MAX}$ = 10A:

$$R_{SENSE} = \frac{V_{th,min}}{0.5 + I_{LOAD,MAX}} \times (1 - TF) = \frac{80mV}{0.5A + 10A} \times (1 - 5\%) = 7.2m\Omega$$

For user convenience, Table 3 lists recommended Value for sense resistor for various load current using Embedded PC Trance Resistor or Discrete Resistor.

Table 3: R_{sense} for various load current

$I_{LOAD, MAX}$ (A)	R_{SENSE} PC Trace Resistor (mΩ)	R_{SENSE} Discrete Resistor (mΩ)
5	10.3	13.8
6	8.7	11.7
7	7.6	10.1
8	6.7	8.9
9	6.0	8.0
10	5.4	7.2

Discrete Sense Resistor

Discrete Iron Alloy resistor comes in variety of tolerances and power ratings, and is most ideal for precision implementation. MuCu Alloy wire resistor or CuNi Alloy wire resistor is ideal for low cost implementation.

Embedded Sense Resistor (PC Trace Resistor)

Embedded PC trace resistor has the advantage of almost zero cost implementation. However, value of the PC trace resistor has large variations. Embedded resistors have 3 major error sources, the sheet resistivity of the inner layer, the mismatch due to L/W, and the temperature variation of the resistor. For laying out embedded sense resistors one has to consider all three error sources which are described below:

1. ***Sheet resistivity***. For 1 ounce copper, the thickness variation is typically 1.15 mil to 1.35 mil. Therefore error due to sheet resistivity is (1.35 – 1.15)/1.25 = 16%

2. ***Mismatch due to L/W***. Percent error in L/W is dictated by geometry and the power dissipation capability of the sense resistor. The sense resistor must be able to handle the load current and therefore requires a minimum width which is calculated by equation 1.:

$$W = \frac{I_L}{0.05} \qquad \text{(Eq. 1)}$$

where: W = minimum width required for proper power dissipation(mils)
I_L = Load current in Amps

For 15A of load current, minimum width required is 300mils, which reflects a **1% L/W error**.

3. ***Thermal Consideration***. Due to I^2R power losses the surface temperature of the resistor will increase leading to a higher value. In addition, ambient temperature variation will add the change in resistor value:

$$R = R_{20}[1 + \alpha_{20}(T - 20)] \qquad \text{(Eq. 2)}$$

where: R_{20} is the resistance at 20°C,
α_{20} = 0.00393/ °C,
T is the operating temperature
R is the desired value.

For temperature T = 50°C, the **%R change = 12%**.

Table 4 is the summary of the tolerance for the Embedded PC Trace Resistor.

Table 4: Summary PC Trace Resistor Tolerance

Tolerance due to Sheet Resistivity variation	16%
Tolerance due to L/W error	1%
Tolerance due to temperature variation	12%
Total Tolerance for PC Trace Resistor	29%

Design rules for using an embedded resistor

The basic equation for laying an embedded resistor is:

$$R = \rho \times \frac{L}{W \times t} \qquad \text{(Eq. 3)}$$

where: ρ = Resistivity (Ω–mil),
L = Length (mils),
W = Width (mils),
t = Thickness (mils).

For 1 oz. copper, t = 1.35 mils, ρ = 717.86 μΩ-mil, and
1 L/1 W = 1 Square.

As an example, we would like to layout a 5.3mΩ embedded sense resistor.

From Equation 1.
W = 10/0.05 = 200 mils.

From Equation 3.
L(mils) = 0.00530*200*1.35/717.86 = 2000 mils
L/W = 10

Therefore to model 5.30mΩ, one needs W = 200 mils, and L = 2000 mils (see Figure 2).

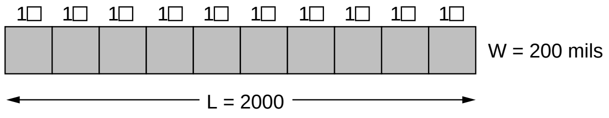


Figure 2. 5.30 mΩ Sense Resistor (10 □)

One can also implement the sense resistor in the following manner. Each corner square is counted as 0.6 square since current flowing through the corner square does not flow uniformly and is concentrated towards the inside edge. See Figure 3.

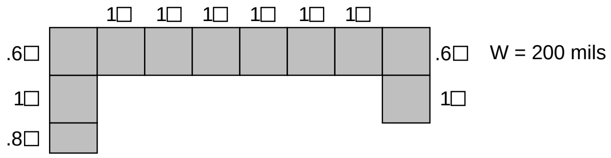
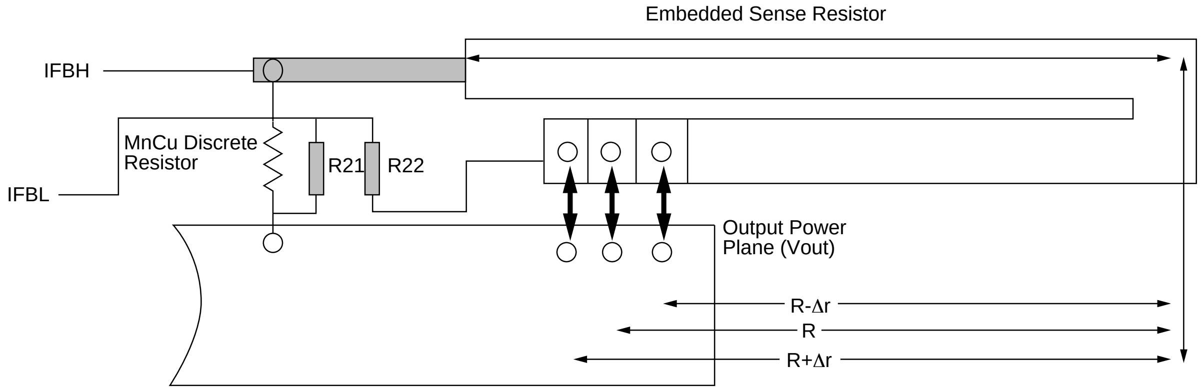


Figure 3. 5.30 mΩ Sense Resistor (10 □)

A design example combining Embedded resistor with Discrete Resistor

For low cost implementation, the embedded PC trace resistor is the most desirable one. However, the wide tolerance (±29%) presents a challenge. In addition, requirement for the CPU changes frequently, the maximum load current may be subject to change. Combining embedded resistor with discrete resistor option may be desirable. A design that provides flexibility, and solution to address wide tolerance is presented below for consideration:



In this design, the user has the option to choose either an embedded or a discrete MnCu sense resistor. In order to use the discrete sense resistor, populate R21 with a shorting bar (zero Ohm resistor) for proper Kelvin connection and also add the MnCu sense resistor. On the other hand in order to use the embedded sense resistor, populate R22 with a shorting bar for Kelvin connection. Also, the embedded sense resistor allows the user to choose a plus or a minus delta resistance tap to offset any large sheet resistivity change. In this design, the center tap will yield 6mΩ, and the left or the right tap will yield 6.7 or 5.3 mΩ respectively.

Short Circuit foldback

During a short circuit condition, the current foldback as illustrated in Figure 5, thus reducing the I^2R power dissipation in the sense resistor as well as the power loss in the MOSFET. This insures against thermal damage due to excessive output currents. For this reason, we will design around the maximum value for R_{SENSE}.

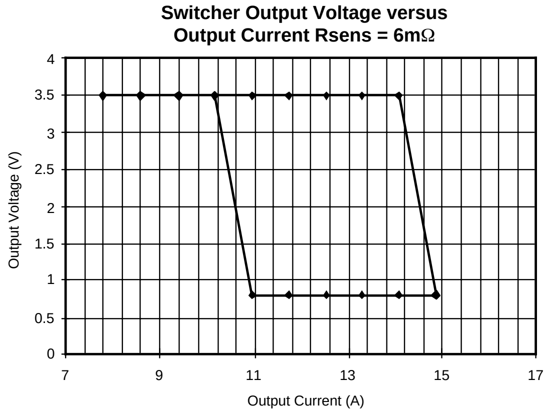


Figure 5, Short Circuit Foldback characteristics for the Switching Regulator

Power Dissipation Consideration During a Short Circuit Condition

The RC5036 controller responds to an output short circuit by drastically changing the duty cycle of the gate drive signal to the power MOSFET. In doing this, the power MOSFET will be protected from being over-stressed and eventual destruction. During the normal operation, the duty cycle is set by the ratio of the input voltage to the output voltage. If the input voltage is 5V, and the output voltage is 2.8V, the ratio of Vout/ Vin is 56%. In a short circuit condition, the duty cycle is dramatically reduced to around 20%. The power dissipated in the MOSFET at normal operation for a load current of 10A, is given by:

$$P_{D,MOSFET} = (I^2R_{ON}) \times (\text{Duty Cycle}) =$$

$$100 \times .03 \times .62 = 1.86\text{W}$$

The power dissipated in the MOSFET at short circuit condition for a peak short circuit current of 15A, is given by:

$$P_{D,MOSFET} = 15^2 \times .03 \times .2 = 1.35\text{W}$$

Thus, the MOSFET is not being over-stressed during a short circuit condition.

The Schottky diode has a power dissipation consideration during the short circuit condition as well. During the normal operation of the device, the Schottky diode will dissipate power during the time that the power MOSFET is off. The power dissipated in the diode during normal operation, is given by

$$P_{D,\,Diode} = I_F \times V_F \times (1 - \text{DutyCycle}) =$$

$$10 \times 0.5\text{V} \times (1 - 0.62) = 1.9\text{W}$$

In short circuit mode, the duty cycle dramatically reduces to around 20%. The forward current, in the short circuit condition, decays exponentially through the inductor. The power dissipated in the diode during short circuit condition, is approximately given by:

$$I_{F,\,ending} = I_{sc} \times e^{\frac{1}{L/R}} = 15A \times e^{\frac{2.4us}{5us}} \approx 9.2A$$

$$I_{F,\,ave} \approx (15A + 9.2A)/2 \approx 12A$$

$$P_{D,\,Diode} = I_{F,\,ave} \times V_F \times (1 - DutyCycle) =$$

$$12 \times 0.45 \times 0.8 \approx 4.3W$$

Thus for the Schottky diode, the thermal dissipation during short circuit is greatly magnified and requires that the thermal dissipation of the diode be properly managed by the appropriate choice of a heat sink. In order to protect the Schottky from being destroyed in the event of a short, we should limit the junction temperature to less than 130°C. Using the equation for maximum junction temperature, we can arrive at the thermal resistance required below:

$$P_D = \frac{T_{J(max)} - T_A}{R_{\Theta JA}}$$

Assuming that the ambient temperature is 50°C,

$$R_{\Theta JA} = \frac{T_{J(max)} - T_A}{P_D} = \frac{130 - 50}{4.3} = 18.6°C/W$$

Thus we need to provide for a heat sink that will give the Schottky diode a thermal resistance of at least 18.6°C/W or lower in order to protect the device during an indefinite short.

In summary, with proper heat sink, the Schottky diode is not being over stressed during a short circuit condition.

Linear Regulator

The analysis for short circuit protection of the linear regulator is much simpler than that of the switching regulator. The formula for the inception point of short-circuit protection for the linear regulator is

$$R_{SENSE} = \frac{V_{th,min}}{I_{Load,\,max}} \times (1 - TF)$$

$$V_{th,min} = 37\text{ mV and } I_{load,\,max} = 5A$$

$$R_{SENSE} = \frac{37mV}{5A} \times (1 - 29\%) = 5.3m\Omega \text{ for using PC Trace Resistor}$$

$$R_{SENSE} = \frac{37mV}{5A} \times (1 - 95\%) = 7.0m\Omega$$

For user convenience, Table 5 lists recommended Value for sense resistor for various load current using Embedded PC Trance Resistor or Discrete Resistor.

Table 5: R_{sense} for Various Load Current

$I_{LOAD,\,MAX}$ (A)	R_{SENSE} PC Trace Resistor (mΩ)	R_{SENSE} Discrete Resistor (mΩ)
2	13.1	17.6
3	8.8	11.7
4	6.6	8.8
5	5.3	7.0
6	4.4	5.9

Figure 6 shows the short circuit characteristic for the linear regulator.

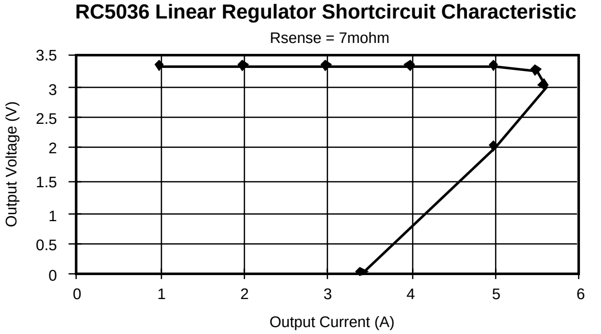


Figure 6. Short Circuit Characteristic for Linear Regulator

Power Dissipation Consideration During a Short Circuit Condition

The output current folds back to approximately 50% of the output peak current during a short circuit condition. The power device is, therefore, not being over stressed during a short circuit condition.

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