FAIRCHILD SEMICONDUCTOR™

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Application Bulletin

Implementing Short Circuit Protection

using the RC5040/42 DC-DC Converter for Pentium® Pro

Implementing Short Circuit Protection

Intel currently requires all power supply manufacturers to provide continuous protection against short circuit conditions that may damage the CPU. To address this requirement, Fairchild has implemented a current sense methodology to disable the output drive signal to the MOSFET(s) 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 120mV. Table 1 states the limits for the comparator threshold of the Switching Regulator:

Table 1: RC5040/42 Short Circuit Comparator Threshold Voltage

	Short Circuit Comparator $V_{threshold}$ (mV)
Typical	120
Minimum	100
Maximum	140

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:

$$R_{SENSE} = \frac{V_{th}}{I_{SC}}$$, where: I_{SC} = 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 RC5040/42 DC-DC converter at maximum load.

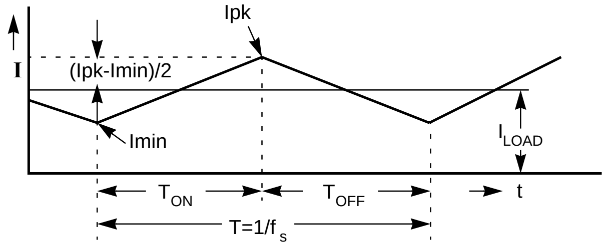


Figure 1: Typical DC-DC Converter Inductor Current Waveform

The calculation of this ripple current is as follows:

$$\frac{(I_{pk} - I_{min})}{2} = \frac{(V_{IN} - V_{SW} - V_{OUT})}{L} \times \frac{(V_{OUT} + V_D)}{(V_{IN} - V_{SW} + V_D)}T$$

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 = the switching period of the converter = $1/f_S$, where
f_S = switching frequency.

For an input voltage of 5V, output voltage of 3.3V, L equals 1.3μH and a switching frequency of 650KHz (using C_{EXT} = 39pF), the inductor current can be calculated at approximately 1A:

$$\frac{(I_{pk} - I_{min})}{2} = \frac{(5.0 - 14.5 \times 0.037 - 3.3)}{1.3 \times 10^{-6}} \times$$

$$\frac{(3.3 + 0.5)}{5.0 - 14.5 \times 0.037 + 0.5} \times \frac{1}{650 \times 10^{3}} = 1.048\text{A}$$

Therefore, for load current of 14.5A, the peak current through the inductor, I_{pk}, is found to be approximately 15.5A:

$$I_{SC} \geq I_{inductor} = I_{Load,\,max} + \frac{(I_{PK} - I_{min})}{2} = 14.5 + 1 = 15.5\text{A}$$

Therefore, the short circuit detection threshold must be at least 15.5A.

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

$$R_{SENSE} = \frac{V_{th,min}}{I_{SC}} \times (1 - TF) = \frac{V_{th,min}}{1.0 + I_{MAX}} \times (1 - TF)$$

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
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	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 for I_{MAX} = 14.5A:

$$R_{SENSE} = \frac{V_{th,min}}{1.0A + I_{MAX}} \times (1 - TF) = \frac{100mV}{1.0A + 14.5A} \times (1 - 29\%) = 4.6m\Omega$$

For a discrete resistor and for I_{MAX} = 14.5A:

$$R_{SENSE} = \frac{V_{th,min}}{1.0A + I_{MAX}} \times (1 - TF) = \frac{100mV}{1.0A + 14.5A} \times (1 - 5\%) = 6.1m\Omega$$

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_{max} (A)	R_{sense} PC Trace Resistor (mΩ)	R_{sense} Discrete Resistor (mΩ)
10.00	6.5	8.6
11.20	5.8	7.8
12.40	5.3	7.1
13.90	4.8	6.4
14.00	4.7	6.3
14.50	4.6	6.1

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 Temerature 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).

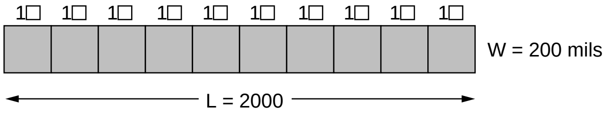


Figure 2. 5.30 mΩ Sense Resistor (10 □)

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.

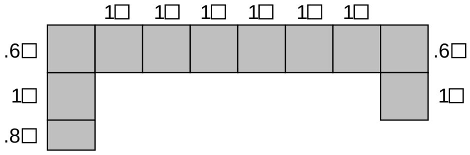
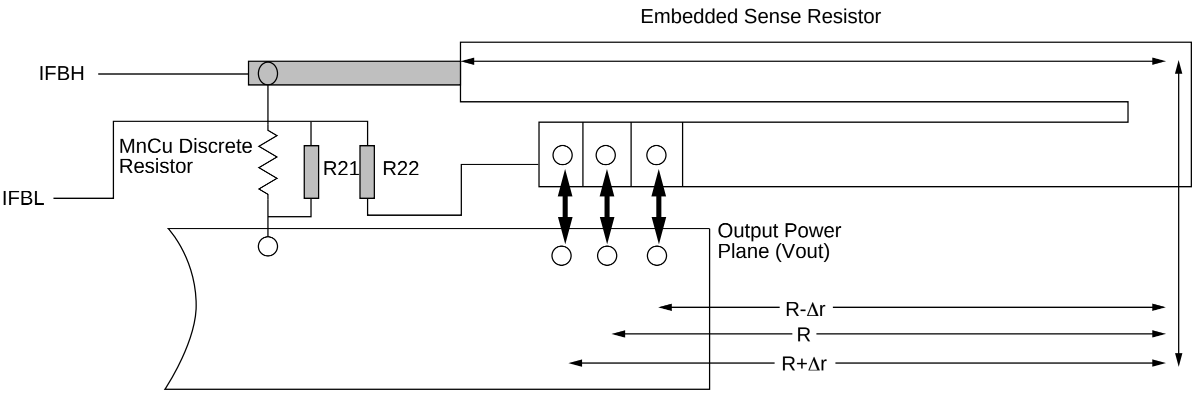


Figure 3. 5.30 mΩ Sense Resistor (10 □)

A Design Example Combining Embedded Resistor with Discrete Resistor

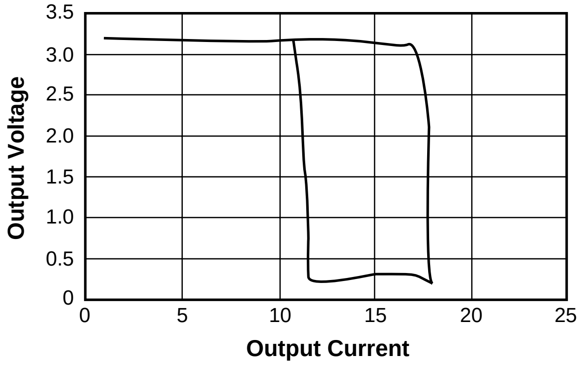
For low cost implementation, the embedded PC trace resistor is the most desirable one. However, the wide tolerance (±29%) presents a challenge. In addition, requirement for the CPU changes frequently, the maximum load current may be subject to change. Combining embedded resistor with discrete resistor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

The following graph illustrates the short-circuit characteristics for a discrete 6.5mΩ sense resistor. The graphs shows first the normal load regulation characteristic, then the inception point of short-circuit, the dynamic impedance as the output voltage collapses, and finally the characteristic as the short-circuit load is released. The initial trip point for short-circuit current is the inception point, which is given by the above-mentioned equations. The actual current achieved when the voltage reaches zero is higher by the dynamic impedance of the short-circuit characteristic. The current point at which the output characteristic once again follows the load characteristic is lower by 6 Amps than the inception point. The reduced current after the release of the short is due to hysteresis built-into the short-circuit comparator. The hysteresis circuit acts to both increase the dynamic impedance once the short-circuit threshold has been achieved and prevent oscillations for loads near short-circuit.



Load current with output shorted to ground

The RC5040/42 provides a constant monitor of the output voltage for protection against over voltage and short circuit conditions. When the output of the converter is shorted to ground, the RC5040/42 will attempt to disable the output drive signal to the MOSFET (V_{CCQP}), resulting in dramatic reduction of the duty cycle to the gate drive of the MOSFET. Figure 5A is the output wave form of the V_{CCQP} for condition when output is shorted to ground, and Figure 5B is the output wave form of the V_{CCQP} for normal operation condition with V_{out} = 3.3V @2A load. Note the duty cycle of gate drive is dramatically reduced under a short circuit condition. This feature of the RC5040 helps protect the MOSFET under fault conditions.

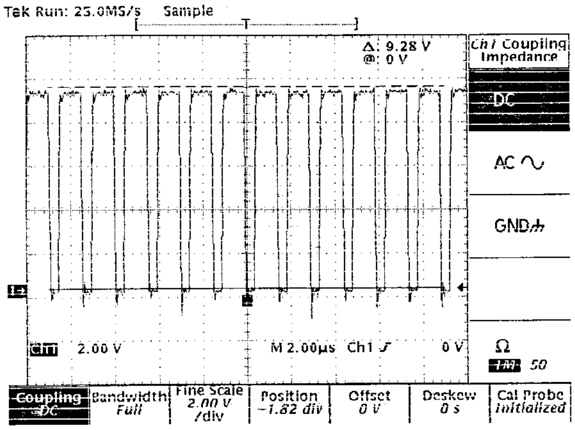


Figure 5A. V_{CCQP} Output Waveform for Output Shorted to Ground

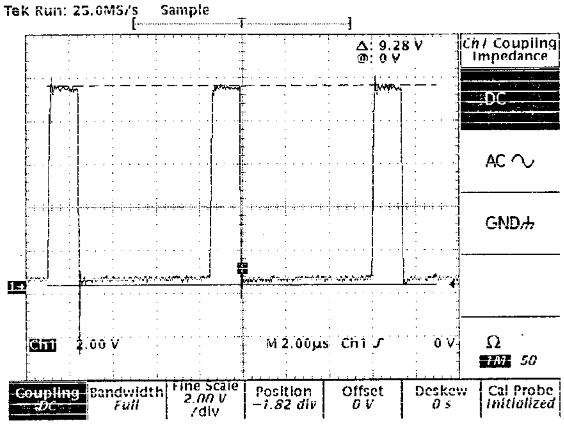


Figure 5B, V_{CCQP} Output Waveform for Normal Operation Condition with V_{out} = 3.3V@2A

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