Current Sensing Solutions for Power Supply Designers

By Bob Mammano

ABSTRACT

While often considered a minor overhead function, measuring and controlling the currents in a power supply can easily become a major contributor to the success or failure of a design. To aid in achieving optimum solutions for this task, this topic will review the many strategies for current sensing, describe the options for appropriate sensing devices, and illustrate their application with practical design techniques. The distinction between current control and fault protection will be explored and applied to various power supply topologies with emphasis on performance-defining characteristics.

CURRENT SENSING IN POWER SUPPLIES

While it would be easy to classify the design of the typical power supply as a voltage regulation problem, experienced designers recognize that very high up on any priority list of tasks are issues related to the measurement and control of current. And, as it turns out, these are usually where more of the difficulties lie. At the risk of being too philosophical, let me suggest that the measurement of voltage is a "passive" activity in that it can readily be done at almost any place in the system without affecting performance. Current measurements, however, are "intrusive" in that we have to "insert" some type of sensor and, in so doing, run a greater risk of affecting the system we are trying to monitor or control. Which is, of course, justification for this topic in which we will attempt to present a compendium of current sensing devices, techniques and applications as an aid to designers of a broad range of power systems.

There are many reasons for monitoring current in power supplies, and as many or more uses to make of the information once obtained. At least three of these which will be discussed herein, pertain to the use of current sensing for fault protection, for current-mode controlled voltage regulation, and for commanding current as a goal in itself. In all of these current sensing applications, there are many issues facing the designer. Among these include:

- The need for AC or DC current information
- Average, peak, RMS, or total waveform of the current
- Isolation requirements
- Acceptable power losses in the measurement process
- Accuracy, stability, and robustness
- Bandwidth and transient response
- Mechanical considerations
- Implementation cost

Since there has been no published report thus far of any single current monitoring approach which is clearly superior in all the aspects given above, an important task in any new project is to prioritize the requirements as each options will have its strengths and weaknesses in satisfying this list of issues. With these characteristics in mind, let us first look at some of the possibilities in measuring current.

SENSING AND MEASURING CURRENT

RESISTIVE SENSING

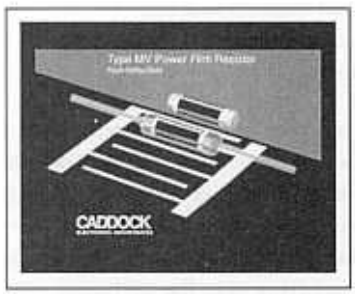
Discrete Resistors for Current Sensing

In almost all cases, current sensing means developing a voltage signal which is representative of the current flowing at the particular place of interest in the circuit. Thus, a current sensing resistor should be considered as a current-to-voltage converter which, in order to perform its function, must be selected on the basis of a set of attributes such as the following:

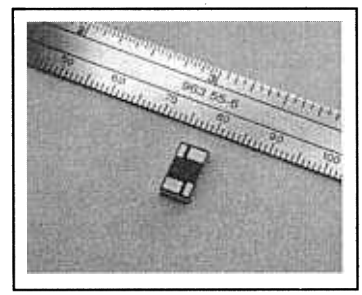
- Low value in order to minimize power losses ($R_{CS}<1\ \Omega$ for this discussion)
- Low inductance because of high di/dt
- Tight tolerance on initial value and low temperature coefficient for accuracy
- High peak power rating to handle short duration high current pulses
- High temperature rating for reliability

Low value resistors in today's market consist of wirewound, thick film, thin film, metal element, and perhaps even other technologies. They come in a wide variety of form factors including axial and vertical through-hole mounted, power and chip surface mounted devices, two terminal and four terminal (Kelvin), on metallic or alumina substrates, and some with integral heat sinks. Representative samples of this variety are pictured in Figure 1. The following discussion is offered as an aid to understanding some of the considerations in selecting and applying these devices to perform the function of current sensing.

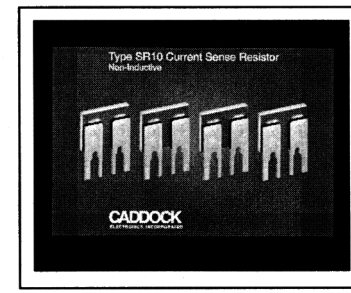
Value - The first criteria in determining a sense resistor's value is often the voltage threshold of the following circuitry which is going to operate on the sensed current information. The simpler IC controllers, for example, will have a defined voltage range for current sensing, or a specific threshold for initiating over-current protection, and the value of the sensing resistor is then uniquely defined by the value of the current to be measured. In more sophisticated applications where some signal amplification is available, the choice would be made on the basis of minimizing the voltage drop across the sense resistor.



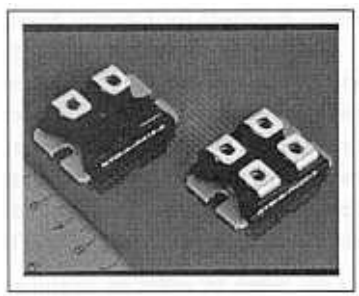
Caddock Electronics' Type MV Power Film Resistor. Design uses interdigitated non-inductive terminations. Power ratings from 1.5W to 10W



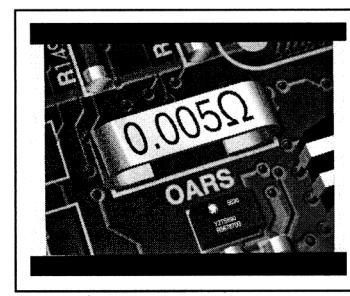
Isotek's PMA, PMD Surface Mount four terminal package, 10mm x 6mm x 1.5mm. Resistance down to 3mΩ, with <30ppm/°C TCR



Caddock Electronics' Type SR10 Current Sense Resistor. Kelvin connection vertical mount 1W non-inductive design. 0.008W to 1.0W, 1% standard tolerance.



Isotek's RTO Heat Sink Base Mount two and four terminal configurations. Uses TO-238 package and screw terminal connections. Rated to 50W with <50ppm TCR and <2nH inductance



IRC's OARS series Surface Mount sense resistor. As low as 5mΩ standard, rated at 1W with <30ppm/°C TCR. Mounting configuration minimizes TCR of copper leads

Figure 1 A sampling of commercially available current sensing resistor products.

This process may be driven by the voltage itself - as in low headroom regulators, for example - or by power loss considerations stemming from either thermal requirements or efficiency goals. In either case, minimizing the voltage drop requires a trade-off study as there is almost always an accuracy or cost penalty incurred. For example, amplifier or comparator input offset voltage variation represents a fixed range of ambiguity which becomes an ever more significant variable as the sense voltage is reduced. Other errors which might not be noticed with higher voltage drops include losses in contacting the sensing resistor and, potentially, even the effects of thermal EMF generation at the connections.

Another important consideration relative to resistor value is the variability of resistor materials chosen by the various manufacturers of these devices. These low values of resistance demand specialized materials and the manufacturers have responded with a wide range of proprietary formulations, all with variations in their characteristics. Even within a particular part type from a particular manufacturer, different resistor values may be made with different materials with resultant differences in performance. This is an important point and will be illustrated further in the discussion which follows.

Power Rating - This parameter is often the driving indicator for selection of the proper technology for a sense resistor. An important part of the power considerations is an understanding of the nature of the current waveform to be experienced. The device may be intended to sense a DC current but may also need to survive - or perhaps even measure - transient peak currents caused from PWM switching, output capacitor charging, inrush current surges, load transients, short circuit peaks, and random externally caused surge currents.

Data on steady state power dissipation capability is most often supplied as a curve giving allowable power rating versus ambient temperature, where the curve is designed to manage the temperature rise in the resistor. Figure 2 gives an example of a typical derating curve for a sense resistor making note of the temperature limitations of the PC board under the resistor and the melting point of the solder used to connect to it. Note that these derating curves are unique to the style of resistor, its value, its material, and its mounting configuration.

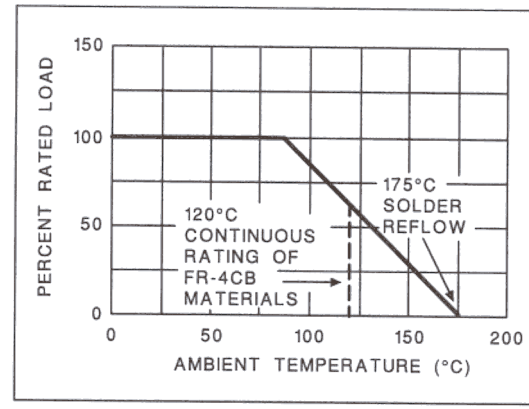


Figure 2 - A typical power derating curve for a current sense resistor

Peak or pulsed power capability is a function of energy (watt-seconds) because it is energy which creates heat, not just power alone. Peak power can therefore be hundreds or thousands of times higher than steady state power as long as the pulse duration is limited. An example of this is shown in the curves of Figure 3 which describe a one-watt surface mount device from IRC which can have a pulse power rating of up to 40 watt-seconds. (Note that the discontinuity in the curve is due to a material change at 0.015Ω.)

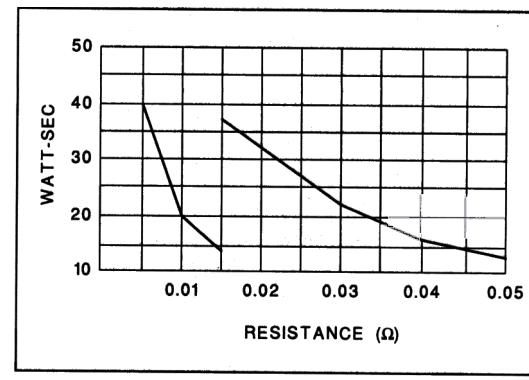


Figure 3 - Pulse-power, or energy rating, for a one-watt IRC resistor series.

Some technologies and package options may limit the surge current rather than the power, due to limiting constraints on leads, wire bonds, or in the case of film devices, the rating of the film itself. This is an area where it is important not to make assumptions but to gather specific data from the supplier of the particular device proposed for use, and then to refine this information with measurements made in the unique environment and mounting arrangement of the proposed application.

Temperature Coefficient of Resistance - The TCR of a sense resistor is an important parameter when accuracy is required. All materials undergo a resistivity change with temperature but this change is different and unique to each. Moreover, it is typically non-linear and - particularly at the higher temperatures - can be either positive or negative as shown in the representative curves of Figure 4. It should be noted that manufacturers have come a long way with this technology and by combining various materials, and using unique processes, can now produce sensing resistors with TCR's as close to zero as most any designer would want. However, when a particular device has a finite and non-linear characteristic, the industry practice is to specify TCR as a linear relationship between specified temperatures, such as 20°C to 60°C, where 20°C is the reference temperature. Since current sense resistors often operate at temperatures substantially above ambient temperature, designers should be wary of TCR specifications which do not provide curves over their entire operating range.

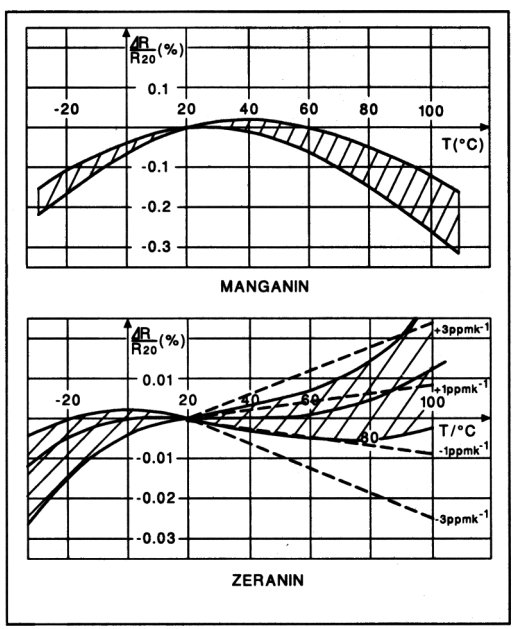


Figure 4 - Variations of TCR with temperature for two different materials produced by ISOTEK.

TCR is normally specified in units of parts per million per degree centigrade (ppm/°C) and can be translated into accuracy by using the formula:

$$\Delta R(\%) = (Toperating - Treference) \times \frac{ppm}{10^6} \times 100\%$$

In addition to the TCR of the resistor's element, low-valued sense resistors can experience an additional error caused by the much higher TCR of the copper connections. Copper has a TCR of +3900ppm/°C and to illustrate the impact of this, consider the resistor of Figure 5 which itself has a respectable TCR of 10ppm/°C but with one mΩ of total contact resistance (2Rcu), exhibits a much poorer performance according to the curve shown.

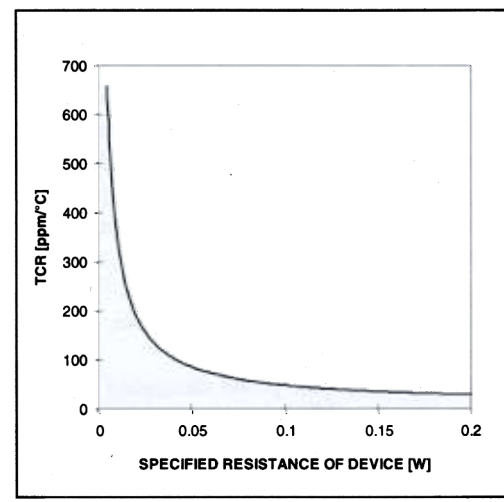


Figure 5 - The impact of contact resistance on total sensed TCR.

Four-Wire (Kelvin) vs. Two-Wire Resistors - A four-wire Kelvin resistor solves this problem (as well as the basic inaccuracy of contact resistance) by eliminating the error of the board trace, the solder connection, and the leads of the resistor itself, by bringing out two Kelvin sense leads as shown in Figure 6. As long as the measuring system presents a reasonably high impedance to the sense leads C and D, then the measured voltage drop is only that of the resistive element, and all the effects of contacting the resistor are bypassed. Clearly, this technique becomes almost mandatory at the higher current levels and many unique package solutions are offered with four contacts (see Figure 1).

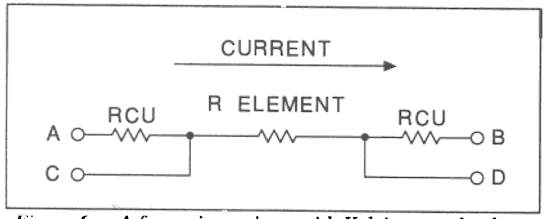


Figure 6 - A four-wire resistor with Kelvin sense leads.

The added accuracy of a four-wire connection comes at an a higher cost, however, as four-contact resistors are more costly, both to manufacture and to install. One economical compromise is to simulate a four-wire connection - as much as possible - with the printed circuit board layout as shown in Figure 7. The patterns are shown for use with either axial or SMD two-terminal resistors, and in either case, the technique is to define a pair of sense leads placed away from the high current path to exclude as much of the contact voltage drop as possible. While this approach is clearly not as good as using a true four-contact resistor, the error - particularly with surface mount metal strip devices - can be extremely small.

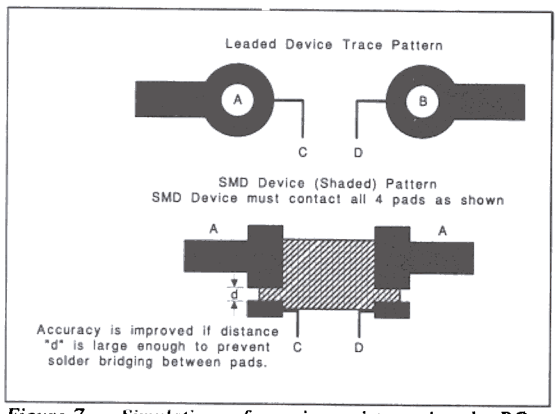


Figure 7 - Simulating a four-wire resistor using the PC board trace.

Paralleling Four-Wire Resistors - Occasionally, when very high power is required, paralleling Kelvin resistors may be an appropriate solution to distribute the heat. When this is done, it is worth noting that ballast resistors must be used in the sense lines to insure that these lines do not inadvertently conduct significantly higher currents than expected. Referring the schematic of Figure 8, and remembering that the whole point of the Kelvin contacts is because of the variability's of the contact resistance, without the ballast resistors, unequal currents through the contact resistances could equalize in the sensing elements by flowing through the interconnected sense lines which typically are not designed for high currents. The lower the Kelvin resistor value, the higher the error introduced by mismatched connections. The ballast resistor should be on the order of 1000 times the element resistance and can have a low power rating since its presence insures that any currents in these leads will be quite small.

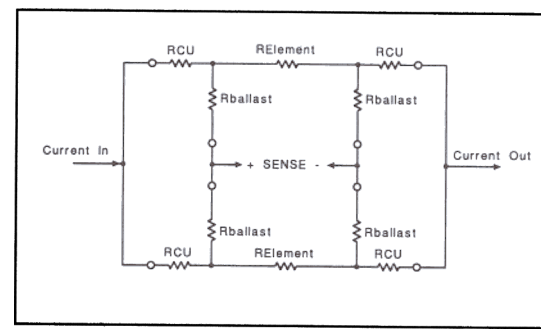


Figure 8 Using ballast resistors when paralleling Kelvin resistors.

Self-Inductance - A low inductance type of resistor becomes extremely important in any application where the current waveform can exhibit a high di/dt - an issue inherent in most switching power supply circuits. Any inductance in the resistor, when ex-

posed to a high current slew rate, will result in an inductive "step" voltage superimposed upon the sense voltage as shown in Figure 9. This may merely contribute an error or, more commonly, prematurely trip an overload-detecting comparator, or ring below ground and latch up the sense circuitry. Most sense resistors on today's market are manufactured with "non-inductive" techniques but it should be remembered that this is a subjective term and, the higher the current, the less inductance it takes to create problems.

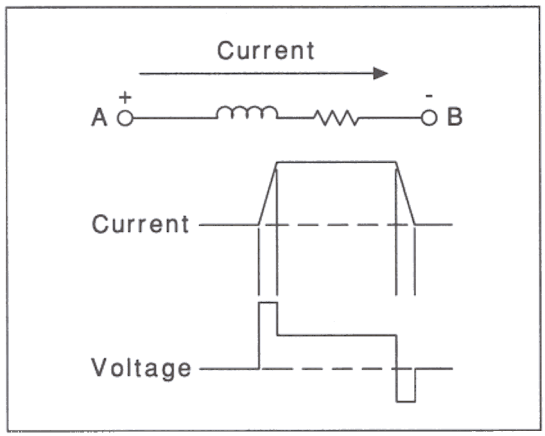


Figure 9 - Resistor inductance combined with high di/dt can cause voltage spikes.

Current Sensing With a Copper Resistor

Rather than add a separate component for current sensing, there is certainly an incentive for using the copper trace in a printed circuit board as a low-value resistor for this purpose. If we can accomplish this, not only will we - of necessity - suffer a smaller voltage drop and associated power loss, but now sensing current comes for free, saving all the costs associated with buying and installing a discrete resistor. But of course, there are difficulties, most notably that the resistance of copper is VERY low, meaning that the signal voltage will either be so small as to require relatively challenging amplification, or that the length of this resistor may add cost due to the PC board area required. This area usage is also impacted by the tolerances required of the resistor's value. While a narrow resistor pattern would decrease the length and thus also the area, PCB etch tolerances usually dictate a minimum width of 0.015 to 0.025 inches. Another difficulty is that copper has a temperature coefficient of 0.39 % / °C, meaning that the voltage drop for a given current will increase some 20% for a 50 °C temperature rise. However, for those applications where this technique is appropriate, the following design data is provided [1]:

The resistance of a metal path at a given temperature is governed by the equation:

$$R(T) = S(T)\frac{Length}{Width \times Thickness}$$

where S(T) is the basic resistivity of the material. For the normal copper used in PCB technology, its value is

$$S = 1.7241 \times 10^{-6}\ \Omega\text{-cm at } 20°\text{C}$$

and the more complete description is

$$S(T) = 1.7241 \times 10^{-6}\left[1 + 0.0039(T - 20)\right]\ \Omega\text{cm}$$

Since PC boards use sheet copper of a known thickness, it is helpful to divide the resistivity by the thickness (in centimeters) to obtain a Sheet Resistance, Rs, which now has the units of Ohms per square. The advantage is that now the resistor's design can be done in only two dimensions - length and width - which are the dimensions that the designer can control. For one-ounce copper, the thickness is typically 0.0036 cm, and the 20 °C value of a given resistor then becomes:

$$R(\text{in milliohms}) = 0.4789 \times \frac{length}{width}$$

where length and width can be in any units as long as they are the same. And, of course, two-ounce copper is twice as thick, so Rs is half the above value. Note that, as mentioned above, dimensional tolerances directly affect the resistor's value. Edge control of the PC etch process will usually define the minimum acceptable width, and one must always insure that a cost-cutting buyer doesn't allow a thinner copper sheet midway through a production cycle.

The use of a low value sense resistor implies that the current in the resistor may be quite high. A cop-

per etch on a PCB will self heat due to the power dissipated by the resistor. This temperature rise above ambient can be determined from the current and the total resistor area by using guidelines from MIL-STD-275E [2]. This information was used to generate Table 1 which provides the required dimensions for a 1oz PCB resistor given a maximum current and desired voltage drop. This data assumes a temperature rise of 30 °C above an ambient temperature of 60 degrees.

	Desired Voltage Drop			
	10mV	25mV	50mV	
AMPS	PCB Etch Length (in)			Width (in)
1	0.162	0.405	0.810	0.010
2	0.243	0.608	1.215	0.015
3	0.405	1.013	2.025	0.025
4	0.648	1.620	3.240	0.040
5	0.891	2.228	4.456	0.055
6	1.053	2.633	5.266	0.065
7	1.377	3.443	6.886	0.085
8	1.701	4.253	8.506	0.105
9	2.025	5.063	10.126	0.125
10	2.430	6.076	12.152	0.150
11	2.754	6.886	13.772	0.170
12	3.078	7.696	15.392	0.190

Table 1 - Dimension solver for given current and voltage based on allowing a 30 °C temperature rise above a 60 °C ambient.

Using an IC Leadframe as a Current Sensing Resistor

There is another approach to using copper as a current sensing resistor, exemplified by Unitrode's proposed UCC3926 Integrated Current Sensor, illustrated with the simplified block diagram of Figure 10.

This product takes the tack of integrating the sensing resistor with the amplification and level shifting circuitry normally required to develop a usable current signal. Since low-value resistance is not readily compatible with IC processing, a specially designed copper leadframe shown in Figure 11 is used to form the resistor. While the current to be measured must now pass through the IC package, the design of the sensor and it's signal-conditioning circuitry as an integrated product allows several benefits as listed below:

The custom leadframe design allows the safe conduction of as much as 20 Amps with a maxi-

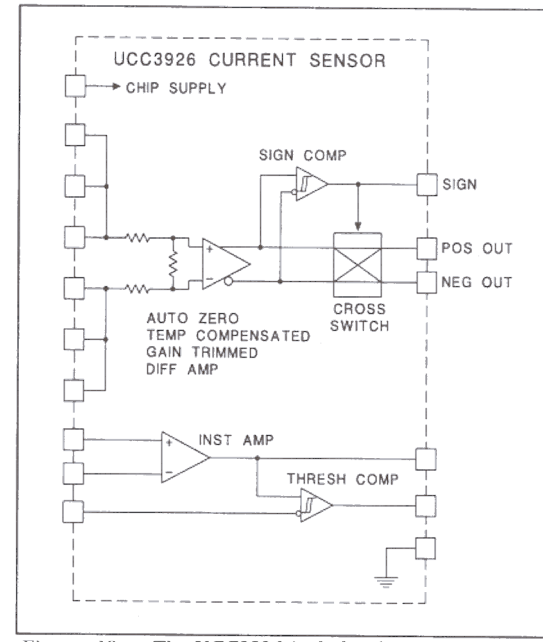


Figure 10 - The UCC3926 includes the current sensing resistor and the signal-conditioning circuitry together in a single IC surface-mount package.

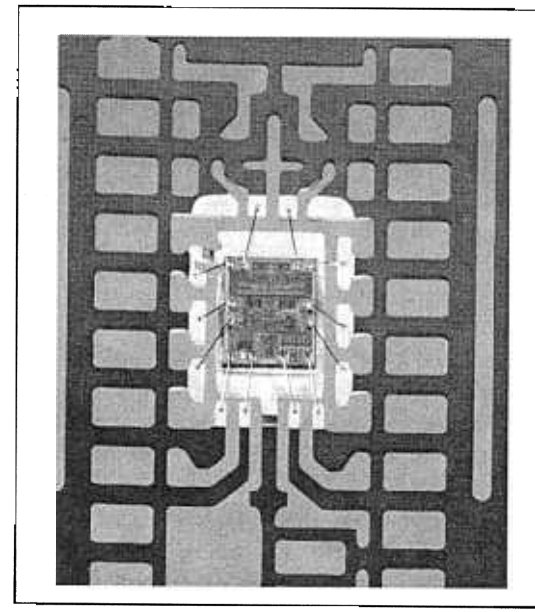


Figure 11 - A specially-designed leadframe for the UCC3926 forms the current sensing resistor.

mum total voltage drop of 30 millivolts, significantly minimizing both power loss and internal heating.

The leadframe resistor voltage drop is measured with Kelvin contacts provided by internal bonding wires.

A chopper-stabilized, high-gain, auto-zero amplifier is included to deliver a 0.5V signal from a 15A input current. The common-mode range of the sensor can be either at ground or at a positive voltage rail of up to 14V. Sensed current can be bi-directional.

The amplifier is trimmed after assembly to cancel the effects of both resistor tolerances and gain, as well as packaging induced shifts. This product is specified to measure current with an accuracy of ±2%.

The amplifier has built-in temperature compensation for the TC of the copper resistor and will tend to track any self-heating as the chip is mounted in the same package.

Using FET Drain-Source Resistance as a Sensor

With the successful utilization of power MOSFETs as the switching devices for the current we wish to monitor, and the recognition that a FET is a majority-carrier device with a fairly linear on-resistance, the prospect of using the Rds(on) of the FET as the current sensing resistor has gained recent interest. An illustration of this approach is shown in Figure 12 which shows a portion of the Unitrode UCC3582, a simple synchronous buck regulator, in which short circuit protection is provided without the need of a separate current sensing resistor. With this device, the drain-source voltage of the external high-side switch is monitored during the on-time of the switch, and a voltage greater than 450 mV will initiate pulse-by-pulse current limiting. While this is a very low-cost solution, one must recognize that the actual current threshold will vary with unit-to-unit variation of FET parameters, gate drive amplitude, and temperature. While these tolerances are probably too great to allow this technique to be used for accurate control, it may be perfectly acceptable if the only issue is survivability in a fault condition.

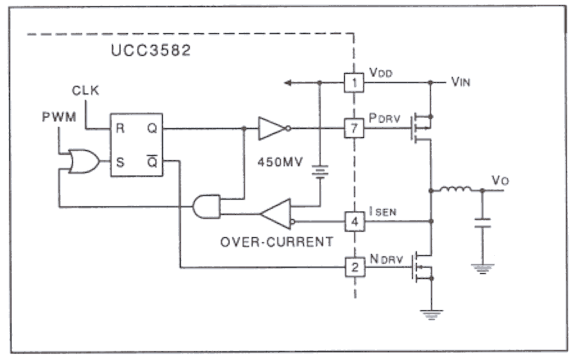


Figure 12 - The UCC3582 eliminates the need for a separate current sensing resistor by using the Rds(on) of the FET.

Using the Inductor as a Sense Resistor

Another interesting circuit idea for measuring current without a discrete sensing resistor has been proposed by Pacholok [3] and is particularly appropriate for low voltage power converters where a voltage drop of several hundred millivolts for current sensing would represent a significant efficiency loss. This approach, illustrated with a boost converter circuit in Figure 13, recognizes that the voltage drop across a power inductor consists of two parts:

1. $V_L = L\frac{dI}{dt}$

2. $V_R = I \times R$

where the "R" is the copper resistance of the inductor's winding. These two voltages add to form the total voltage across the inductor, VT. By adding a closely coupled second winding with an equal number of turns, but with minimal current loading, this winding will have only VL across it. By then summing the voltages from the two windings such that the VL terms cancel out, one is left with only VR, a voltage determined by the inductor current, and the appropriate signal for a current-mode control loop. A simple current mirror circuit will convert this differential VR term to a single-ended, ground-referenced signal compatible with the current sensing pin of a UC3842 or similar device.

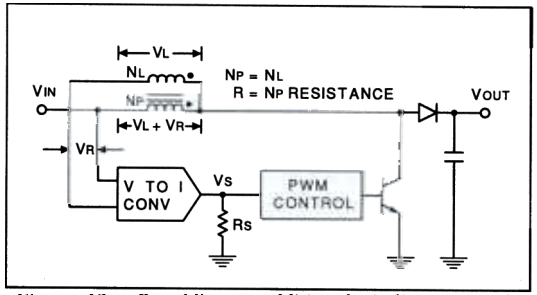


Figure 13 - By adding an additional winding, the IR drop in the inductor can be used for current sensing.

While this technique has saved the power loss and cost of an additional current sense resistor, recognize that the resistance which is used is the copper wire in the inductor and the temperature coefficient of copper's resistivity applies. There may also be some inaccuracies as the current signal is a small voltage derived as the difference between two much larger voltage signals.

MAGNETIC SENSING DEVICES

Ever since it was discovered that a current flowing in a conductor generated a magnetic field, there were techniques developed to use that field as a way of measuring the current which created it. It should be obvious that one of the more significant benefits of using magnetic coupling for sensing current is the electrical isolation which this achieves. Clearly, the most popular and practical application of this approach is embodied in the current sensing transformer, but before discussing this component, it may be useful to review some other techniques which have been used to determine a current's value from its associated magnetic field.

The Rogowski Coil

One of the earliest current transducers was the Rogowski Coil, first described in 1912 and illustrated in Figure 14. [4][5]

This device consists of a single-layer coil, uniformly wound on a non-magnetic core which is either flexible or formed into a circle which surrounds the conductor of the current to be measured. The terminal voltage of this coil will be

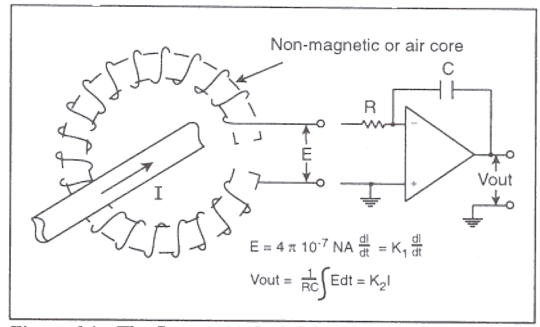


Figure 14 - The Rogowski Coil delivers a terminal voltage proportional to the rate-of-change of the current passing through its loop.

$$E = \mu oNA\frac{dI}{dt}$$

where μ o is the permeability of free space, N is the number of turns/meter of the coil, A is their cross-sectional area in square meters, and I is the current passing through the loop. This expression for the voltage can then be written as

$$E = K_1\frac{dI}{dt}$$

with K1 now defined as the coil sensitivity with units of Volt-sec / Amp.

To reproduce the current waveform as a voltage, an integrator such as shown in the above figure will generate

$$Vout = \frac{1}{RC}\int$$

if we define K2 as K1 / RC.

Practical implementations of this technique typically also incorporate a low-frequency roll-off to eliminate thermal noise and drift. Since the transducer is not able to reproduce the DC component of the current, it operates in a manner similar to the AC input of an oscilloscope.

The major benefit of a Rogowski Coil is that since the core is effectively air, there is no magnetic material to saturate and the coil's output remains lin-