Current Sensing With a Precision of a Few Parts Per Million Within a Fraction of a Second

Joseph Szwarc

Vishay Intertechnology, Vishay Israel, Holon, Israel 58814

Abstract — **The most precise measuring of electrical current is achieved by the Current Sensing Resistor method. The precision and speed of response to changing current depend on thermal stability of the resistor - its low Temperature Coefficient of Resistance and a related to it Power Coefficient of Resistance. The new Foil resistor technology (Z foil) reduced the TCR to below 1 ppm/°C and special construction reduced the thermal distortion leading to a current detector with a Precision of a few parts per million within a Fraction of a Second.**

Index Terms — **Current measurement, detectors, distortion, resistors, strain, temperature, thermal factors.**

I. Introduction

Of the commonly used methods of measuring the magnitude of electrical current the Current Sensing Resistor method allows the most precise measurement. According to Ohm's law: V = IR the voltage drop measured across a resistor is proportional to the current flowing through the resistor. With known value of the resistance R, the voltage drop sensed on the resistor indicates the intensity of the current flowing through it.

Assuming an ideal resistor which doesn't change its resistance value when there is a change in the magnitude of the current or in environmental conditions like the ambient temperature, the measured voltage drop will yield a precise value of the current: I = V/R. But with a real life resistor, a change in current intensity and in the dissipated power will cause a change in resistor's value which will stabilize after a thermal transient period of a few seconds.

Therefore, the key to a precise and fast measurement of current is the use of real life current sensing resistors which approach, as closely as possible, an ideal resistor, such as is not influenced by the magnitude of the current flowing through it, or by changing ambient temperature, or by any other environmental condition.

II. Resistance Change Due to Changing Ambient Temperature and to Self Heating by Dissipated Power

Real life resistors exhibit two effects of reversible changes of their room temperature value:

- When they are cooled or heated by a changing ambient temperature
- By self heating – due to the changing level of power they have to dissipate (Joule effect).

When a high precision is required, these two effects of a change in resistive element's temperature, ΔT_A due to a change in ambient temperature, and ΔT_{SH} due to self heating, should be considered.

The ambient temperature T_A changes slowly, and all parts of a resistor follow uniformly the change of the ambient temperature, but the effect of the dissipated power is different: The temperature of the resistive element – the active part of the resistor – will change rapidly with the change of the intensity of current. The power it has to dissipate will change as the square of the current intensity and a rapid increase or decrease in current intensity will cause rapid changes in the temperature of the resistive element and in the heat that will be dissipated to the ambient air.

These two effects of resistance changes are quantified by TCR – Temperature Coefficient of Resistance [1]-[3] and by a related to it PCR – Power Coefficient of Resistance (also referred to as "Power TCR")

Resistor's TCR is specified by two values of the relative change of the reference resistance ($\Delta R/R_{REF}$), as measured at a reference temperature T_{REF} using an insignificant level of power, to a resistance R_C or R_H, at a second point of resistor's steady state temperature, T_C or T_H, below or above T_{REF}, divided by temperature difference $\Delta T_C = T_{REF} - T_C$ or $\Delta T_H = T_H - T_{REF}$, respectively. The resulting value of TCR has a unit of ppm/°C (or an equivalent unit of ppm/K):

$$\text{"Cold" TCR: } TCR_C = (R_{REF} - R_C)/(T_{REF} - T_C) \quad (1)$$

$$\text{"Hot" TCR: } TCR_H = (R_H - R_{REF})/(T_H - T_{REF}) \quad (2)$$

In precision resistors using a Ni-Cr alloy for their resistive element the change of TCR with temperature is practically linear and the TCR values of temperature ranges represent also the temperature coefficients at the mid-range points. As a result, the difference between TCR at two extreme points is twice the difference between TCR_C and TCR_H. For instance. in resistors of +/-5 ppm/°C the TCR can change by up to 20 ppm/°C between the two extreme temperature points.

Resistor's PCR is defined as the relative change from the reference resistance ($\Delta R/R_{REF}$), as measured after application at room temperature of a resistor's rated power P_R, and after achieving a thermal steady state at a temperature which changed by ΔT_{SH}. The PCR is expressed in units of ppm/W.

$$PCR = (\Delta R/R_{REF})/P_R \quad (3)$$

This definition links the nominal value of PCR with the temperature range between room temperature and the steady state temperature of the resistive element after the rated power is applied. This temperature range, of width ΔT_{SH}, has its own

TCR which is different from both the above mentioned TCR_C and TCR_H and which will influence the value of the nominal PCR.

When other levels of power are applied and/or ambient temperature is different from the room temperature, the temperature ranges of self heating will be different and the value of PCR will be influenced by a different TCR. As the TCR changes practically in a linear way with temperature, knowing the TCR_C and TCR_H it is possible to estimate the TCR and the PCR for other service conditions of an ambient temperature T_A and load P [3].

III. Resistors of Low TCR and Low PCR

Low TCR is a must for applications requiring both low TCR and PCR. Additionally, a special design is needed to reduce the difference in' influence of these two factors and to get an essentially zero resistance drift when the current changes and the ambient temperature is below or above the room temperature: The TCR is linked to the change of ambient temperature which usually occurs slowly and therefore it can be assumed that the resistor's resistive element and its substrate are at the same temperature. This is not the case of the effect of self heating by dissipation of power, especially for surface mounted devices.

In this case most of the heat energy is dissipated, through resistor's substrate and its "wrap around" terminations, to a Printed Circuit Board (PCB) to which the resistor is soldered, creating temperature gradients along the path of heat's flow.

Substrate's temperature on the side of the resistive element is higher than on the opposite side, causing a thermal distortion of the substrate and additional thermal strains in the resistive element, leading to a change of resistance. Investigation of thermal distortion's related strain is described in ref. [2].

Calculation of resistance change induced by self heating at a given power level and ambient temperature is more difficult because the value of PCR, as established at room temperature and rated power, changes both with the ambient temperature (due to changing TCR) and with the power level (as the level of self-heating is changing the width of its temperature range ΔT_{SH}). It is easier to assess it by bringing a resistor to a requested ambient temperature and measuring the resistance change when a requested power is applied and steady state resistance value is achieved.

When the self heating effect has to be compared with the TCR effect, it should be expressed in units of ppm/^{O}C, like the TCR. This is done by replacing the load P, in Watts, by the self –heating temperature rise it is causing, ΔT_{SH}, in ^{O}C. This temperature rise can be calculated provided the thermal resistance, R_{TH}, resistive element to ambient air, is known:

$$\Delta T_{SH}, = P \cdot R_{TH} \qquad (4)$$

The difference between the two effects depends on the thermal properties of the resistor. As these two effects are similar (but offset), a reduction of TCR will cause also a reduction of PCR, but if, for instance, they are of opposing signs, a reduction of TCR may cause an increase of PCR.

IV. Additional Strains Caused by Rigid Assembly of the Resistor

When a resistor is assembled by soldering to a Printed Circuit Board, resistor's TCR and PCR are affected by a change in the heat flow and by thermal strains due to mismatch with board's coefficient of thermal expansion and its other mechanical properties.

To preserve resistor's original properties it is therefore preferable to choose resistor types which can be flexibly assembled on a PCB.

V. Thermal Transient at an Increase of Power Versus Cool Down When Power is Reduced

Recording of resistance change when a power is applied and later switched off shows a difference in the two transient periods. During the recorded 45 seconds the power was applied for 22 seconds. The cooling down didn't achieve the original temperature and for the same period of 22 seconds of cooling down the change of resistance was reduced only by about half, see Figure 1.

During the thermal transient period the value of the resistor is influenced by its former temperature.

Figure 1. Continuous recording of $\Delta R/R_{REF}$ during 45 seconds with power applied during the first 22 seconds.

As the TCR changes with temperature, so the PCR – the Power Coefficient of Resistance will change - it will be different at different ambient temperatures. Figure 2 shows the $\Delta R/R_{REF}$ recording of a Vishay S102C style resistor every 5 seconds during 45 seconds, first half of this period with a load of 0.6W and second half without load, for three ambient temperatures.

The TCR_C (-55^{O}C to +25^{O}C) of this resistor is +2,5ppm/^{O}C; and TCR_H (25^{O}C to 125^{O}C) is - 3.1ppm/°C.

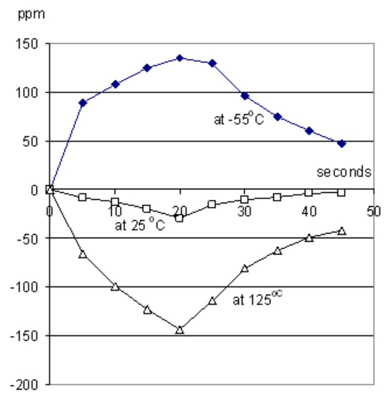

Figure 2. Recording of $\Delta R/R_{REF}$, S102C resistor, pulse 22/45sec, at 3 ambient temperatures: -55^{O}C ,25^{O}C and 125^{O}C.

The three broken lines show the $\Delta R/R_{REF}$ due to self heating at three different ambient temperatures: at -55^{O}C they are large and positive, at +25^{O}C small and negative, and at 125^{O}C large and negative. It indicates the dependence of the PCR from the TCR: the first changes with the second when the ambient temperature changes.

Figure 3 records the same pulse applied to a S102K style resistor, of smaller TCR values, and both positive:

TCR_C = 1.4 ppm/^{O}C
TCR_H = 1.1 ppm/^{O}C

Here the $\Delta R/R_{REF}$ are now all positive and much smaller, following again the smaller and positive cold and hot TCR's.

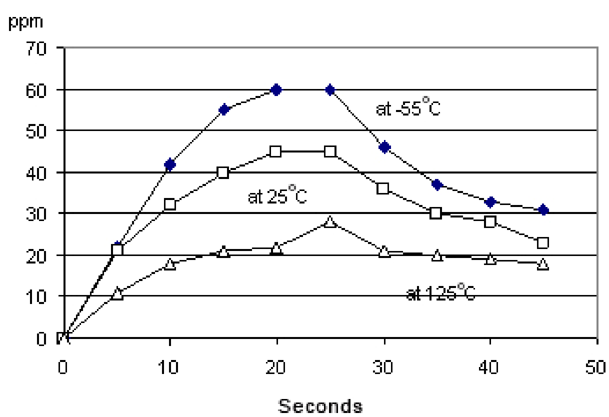

Figure 3. Recording for 45 seconds of $\Delta R/R_{REF}$, S102K style resistor, 0.6W pulse applied for 22 sec, at three ambient temperatures: -55^{O}C ,25^{O}C and 125^{O}C.

VI. Development of Resistors with Low TCR and Low PCR

Manufacturers of precision resistors achieve a low TCR by resistor's design and by matching the physical properties of the resistive element's alloy (alloy's temperature coefficient of resistivity and of thermal expansion and other properties) with substrate's coefficient of thermal expansion.

Two recent technical developments led to the construction of precision foil resistors of extremely low TCR and PCR:

- Introduction of the "Z" foil technology led to foil resistors of TCR below 1ppm/^{O}C over a wide range of temperatures, from -55°C to 125°C.
- Design of a foil resistor with resistive foil elements of equal resistance value on both sides of a ceramic substrate [4] led to a significant reduction of substrate's distortion when the current intensity changed. Now each side of the ceramic substrate absorbs half of the joule energy and the heat flows from the two sides to the center, reducing the temperature gradients.

As a result the resistors based on Z foil exhibited now both a very low TCR and a very low PCR

Figure 4 is the recording of a transient relative resistance drift versus time for three samples of resistors when a pulse of power is applied at room temperature for 9 seconds. It shows the typical behavior of representatives of three resistor production technologies commonly used in electronic circuits.

A load of 0.3W was applied to size 1206 chips:

- Thick film chip, with a positive TCR_H of about 42ppm/°C, stabilized at a steady state (out of the shown recording) with resistance change about +2000 ppm.
- Thin film chip of a low TCR_H - about minus 4 ppm/°C - changed by -140ppm after 9 seconds of applied power
- Bulk Metal Z-Foil (BMF) applied on ceramic substrate's two sides, of TCR_H of -0.1 ppm/°C, changed negatively up to minus 2ppm during the first second and by plus 5ppm after 9 seconds. A group of 5 such chips showed changes below 10ppm.

Note: Recordings of chip sizes 0805 to 2512 showed thermal time constants (time to achieve 63% of steady state value) to be between 1and 10 seconds, depending on the chip's size, resistor's construction and mode of assembly.

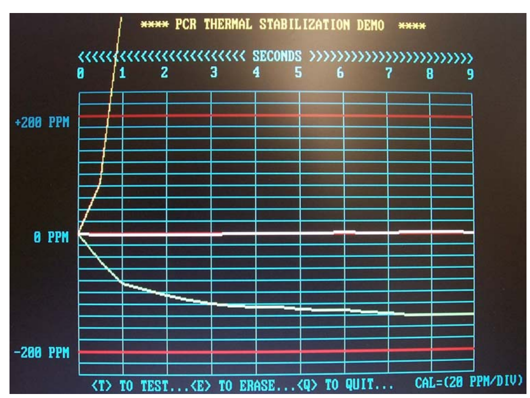

Figure 4. 9 seconds recording of 3 thermal transients - comparison of 3 technologies: Thick film (top). Thin film (bottom) and Double Sided Z foil (center)

VII. Conclusions

High precision current sensing can be achieved by use of resistors which are not influenced by a change of their temperature - whether it is due to changing ambient temperature or to self heating by the power they dissipate.

The coefficients which specify the change of resistance with the change of resistor's temperature, TCR and PCR, are not constants and therefore the resistance changes are not proportional to the change in temperature

For precision current sensing applications imposing requirements of precision (between 1% to 0.01% and better) and of a specific fast transient behavior it is recommended to specify the Temperature Coefficient (TCR), the service temperature range and the response to application specific loads, increasing and decreasing, in terms of allowed resistance change and time it takes to achieve a requested closeness, in ppm, to the steady state resistance value.

As the resistance value and thermal transient's parameters change with ambient temperature, testing is recommended, according to the service temperature range, at room temperature and at two application's extreme temperatures.

It is possible to achieve a high precision of current sensing and a significant reduction of duration of the thermal transient period by using resistors of very low TCR over a wide range of temperatures and of a construction which minimizes the thermal distortion at self heating.

Foil resistors technology using the Z foil with its very low TCR and special double sided resistor construction show the best results achievable so far.

Acknowledgements

The author would like to thank the following persons for their help in preparation of this paper

Dr. Felix Zandman of Vishay Intertechnology for initiating and supervising this work

Richard Zuratt of Vishay Intertechnology and

Ilya Aronson of Vishay Israel for performing the tests described in this paper

References

[1] F. Zandman et al. "Resistor Theory and Technology", Scitech Publishing, Inc, 2002. pp 26, 53-74, 113-114, 261-262

[2] R,B. Watson et al. "Effects of Material Properties and Heating/Cooling Rate on Strain Gage Thermal Output Observations", *ICBM12- 12th International Conference on Experimental Mechanics*, August/September 2004

[3] F. Zandman and J. Szwarc "Non-Linearity of Resistance/ Temperature Characteristic" Vishay Intertechnology, http://www.vishay.com/docs/60108/nonlinea.pdf

[4] High Precision Power Resistor - United States Patent # US 7,154,370 B2 December 2006