



Application Report

Low-ohmic sense resistors in automotive systems by Ullrich Hetzler • EDN Europe Magazin 10/2007

For current measurement, two physically very diverse measuring methods have established themselves in certain segments of the market in the last two decades: magnetic current sensors, and shunt-based current measurement. The main advantages of magnetic sensors—among which current transformers and Hall-effect sensors—are that they are potential free and feature low power loss. For this reason, engineers mainly employ these sensors in drive technology and in connection with large currents. Their main disadvantages are comparatively large volume, non-ideal offset and linearity characteristics, and temperature drift.

The pressure to miniaturise and the availability of extremely low-ohmicvalue, virtually error-free resistors coupled with greatly improved data-acquisition systems has led to a revitalisation of the “old” shunt resistor in the past few years and opens up new application possibilities that were unforeseen as little as 10years ago.

The control and regulation of actuators in the vehicle mostly requires currents between 1 and 100A; however, in special cases (e.g. the lambda-sensor heating), there are short-duration currents of 200 to 300A, or even up to 1500A in the case of cranking current. In the area of battery and power management, the situation is even more extreme, since the continuous currents during vehicle operation are between 100 and 300A while, in the idle state, only a few milliamperes must be measured accurately.

BASIC PRINCIPLES

According to Ohm’s law, when detecting current via a resistor, the potential difference is a direct measure of the current. When resistance values are of the order of 1Ω and currents are up to several hundred milliamperes, the arrangement is straightforward. However, the situation changes entirely if currents in a range above 10 to 20 A are involved, because then the power loss ($P=R \times I^2$) in the resistor is no longer negligible. You can attempt to limit the power loss through lower resistance values, but since the measuring voltage is also lowered, the resolution of the evaluation unit often limits the resistance value.

In general, the following applies to the voltage across the resistor: $U=R \times I \times U_{th} + U_{ind} + U_{iext} + \dots$, where U_{th} is the thermal EMF (electromotive force due to a thermoelectric voltage), U_{ind} the induced voltage, and U_{iext} the voltage drop on the power supply.

The error voltages that are not directly due to the current flow can completely distort the accuracy of the measurement; hence the designer should know the causes and should minimise their effects through careful layout design and, especially, by choice of appropriate components.

An electrical resistor can consist of any conductive material. However, such a component is probably not suitable as a current sensor, since the resistance value will be dependent on parameters such as temperature, time, voltage or frequency: $R=R(T, t, P, Hz, U, A, \mu, p, \dots)$.

An ideal current-sense resistor would be completely independent of these parameters; such a component does not, of course, exist. The ideal attributes of a real resistor are listed in Table 1, including tcr (temperature coefficient of resistance), longterm stability, thermal EMF, load capacity, inductance and linearity. Some of these characteristics are essentially material- dependent: component design strongly influences other attributes, and the productionprocess defines certain parameters.

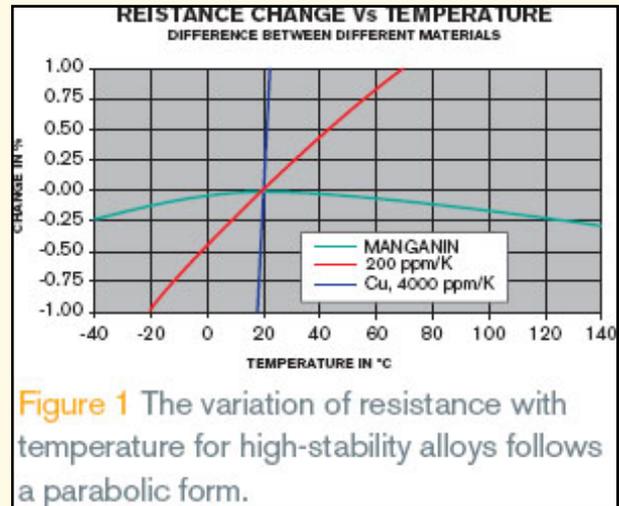
Characteristics/ Requirements	Material	Size	Process
Low tcr	xxx	x	x
High long-term stability	xxx	x	xx
Low thermal EMF	xxx		
Low inductance	x	xxx	
High accuracy			xxx
High load capacity	x	xxx	
Small thermal resistance		xxx	x
4-terminal design		xxx	
Low total resistance		xxx	x
High security	xx	x	x
Low price	x	xx	xxx

Table 1 Critical aspects of a resistor’s performance are strongly or weakly associated with its basic material or the processing it receives.

In response to developments in the area of magnetics, the focus of development efforts in the field of resistive sensors has been to physically optimise the shunt resistor in order to extend the range in which precision current measurements with resistors are practical. Over the same time, semiconductor companies have improved operational amplifier characteristics such as offset, temperature coefficient and noise, which in turn permits designers to employ reduced resistance values in the lower milliohm range, thus largely eliminating the main problem of the high power loss with large currents ($P=RI^2$). However, that gain comes at a price: the relative inaccuracy caused by error voltages (from sources such as interference and thermoelectric voltage, among others) increases at such a rate that low inductance and suppression of thermal EMF become extremely important.

TEMPERATURE COEFFICIENT

Figure 1 shows a typical parabolic temperature curve for resistors manufactured of the Manganin alloy. The material composition alone determines this characteristic, producing resistors with very high reproducibility and very low batch variation. The temperature coefficient (tcr) is expressed in ppm/K and is defined as $tcr = \frac{R(T) - R(T_0)}{R(T_0) \times (T - T_0)} = \frac{dR}{R(T_0) \times 1/R(T_0)}$, where the reference temperature is usually a value of 20 or 25°C. For temperature dependence of this form, it is essential to also state the upper temperature limit that the manufacturer used when specifying the tcr, for example +20 to +60°C. Measurement systems frequently use thick-film resistors in the low ohmic range with tcr values of several 100 ppm/K. The red curve shows the temperature drift for a resistor with only 200 ppm/K; even with this low variation, a temperature change of +50°C is sufficient to exceed the 1% limit: an accurate current measurement is not possible with such resistors. Even more extreme cases include examples of measurement-equipment manufacturers who recommended a copper track on a PC board as current-sense resistor. Because copper has a tcr of 4000 ppm/K (or 0.4%/K), a temperature change of only 2.5°C is enough to exceed the 1% error limit.



THERMAL EMF

A thermoelectric voltage develops on the contact between different materials if it warms up or cools down slightly. This effect is especially important for low-ohmic resistors, since the voltages involved here are generally very small; therefore thermoelectric voltages in the microvolt range can strongly distort the result. Even today, the well-known resistor material Konstantan appears as the basis of wire-wound and punched shunts (shunt resistors stamped from sheet material). Although it has quite a good tcr, its thermal EMF versus copper is extremely high at approximately 40 µV/K. A temperature difference of only 10°C generates an error voltage of 400 µV that adds a 10% error to a measurement of a 4A current using a 1-mOhm resistor. The situation is even more extreme if one considers that depending on the size, the - often neglected- Peltier effect can build up a temperature difference of more than 20°C through reciprocal warming up or cooling down of the contacts (in extreme cases, we have seen a remelting of the solder connection on one side of the resistor). Even with a constant current flow, the build-up of the temperature difference due to the Peltier effect results in a measured total voltage that appears to indicate a non-constant current. After turning off the current, the measurement indicates an apparent current flow that disappears as the temperature differential dissipates. Depending on the design or the resistance value, this error can be as big as a few percent or several amperes. The precision resistance alloys mentioned above thermoelectrically exactly match copper; therefore the metal-to-metal junctions do not develop these voltages. The designer can therefore neglect these effects and, for instance, employ a 0.3-mΩ resistor that delivers a voltage of less than 1 µV—corresponding to 3 mA—immediately after turning off a current of 100A.

LONG-TERM STABILITY

Stability over time is of course extremely important for any sensor, since even after it has been in operation for years, the user still wants to be able to rely on an earlier calibration. This means that the materials of the resistor have to be corrosion-resistant and must not go through any metallurgic transformations during

their lifetime. Measurement elements fulfil these requirements through being composed of homogeneous mixed crystal alloys that the production process anneals and stabilises and that are therefore available in their thermodynamic basic state. Such alloys deliver possible stability values in the ppm/year range, enabling their use as standard resistors and international references.

Figure 2 shows the typical behaviour of a real surface-mount resistor annealed at +140°C for more than 1000 hours. The slight drift of approximately 0.2% is due to the curing of lattice defects that minor deformations during production cause and shows that the components are further stabilised, i.e. are progressively getting better. Since the speed of the drift strongly depends on the temperature, at a lower temperature such as +100°C this effect is virtually non-detectable.

FOUR-TERMINAL CONNECTION

In the case of low-ohmic resistors, the influence of the current terminations is often not negligible, so designs should employ sense terminations to detect the voltage drop directly on the resistor material. A four-terminal connection will allow the measurement system to use only the element itself, R_0 , whereas a simple connection will “see” a total resistance of $R_0 + 2 \times R_{Cu}$ (Figure 3). For example, copper wire of 0.3 mm diameter and 10 mm length adds $R_{Cu} = 2.4 \text{ m}\Omega$; a copper conductor 4 mm 0.2 mm $35 \text{ }\mu\text{m}$ yields $R_{Cu} = 10 \text{ m}\Omega$.

These examples show that very large errors can occur in the case of faulty construction of the resistor or layout errors. The copper connecting wires of the above two-terminal resistor account for 24% of the total resistance of a 10-m resistor, and just a short piece of a PC board copper track of 4 mm length would already distort the resistance by 100%. A trimming process of the total resistor can eliminate the additional resistance of current terminations, but the influence on the tcr is still present.

In the example depicted in Figure 4, the proportion of copper is extremely small at only 2% (as opposed to 24% in the example above) yet the tcr increases from close to zero to about 80 ppm/K. This means that the practice of stating the tcr of the resistance material alone, in the datasheet of a low-ohmic resistor with such a construction, is absolutely unacceptable and nonsense.

Resistors made of electron-beam-welded composite material copper-Manganin copper actually have such a low termination resistance that with a suitable layout, it is possible to revert to a two-terminal resistor again, since a suitable PC-board layout now realises the four-terminal connection. However, during the design of the layout, the designer must be careful that the current flow in the resistor does not touch the voltage connections (sense lines). If possible, the sense lines should be connected to the current terminals from underneath the resistor in form of a micro strip line.

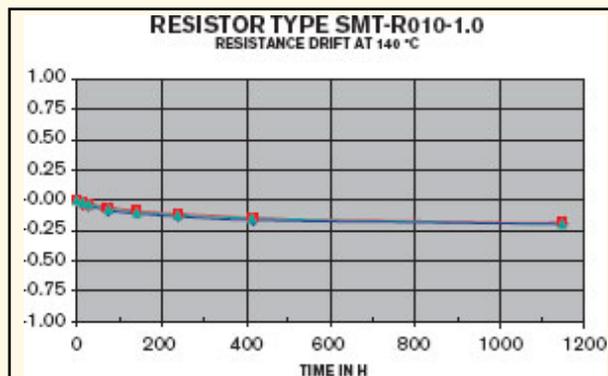


Figure 2 Even under high-temperature accelerated conditions, drift over time is limited to ppm levels.

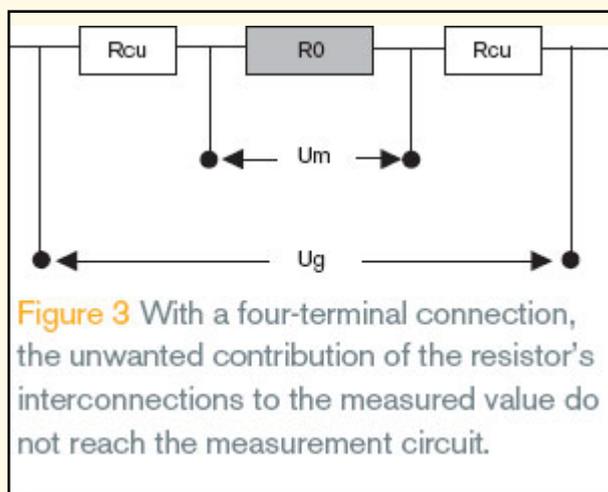


Figure 3 With a four-terminal connection, the unwanted contribution of the resistor’s interconnections to the measured value do not reach the measurement circuit.

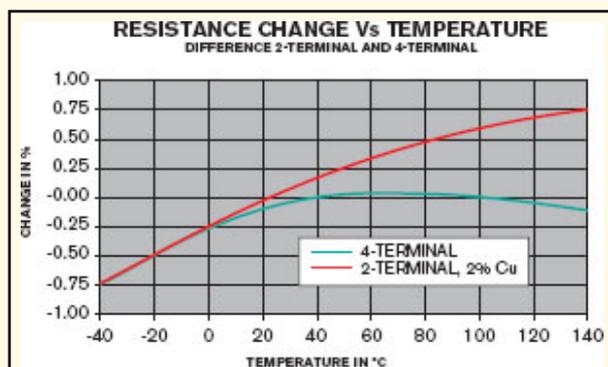
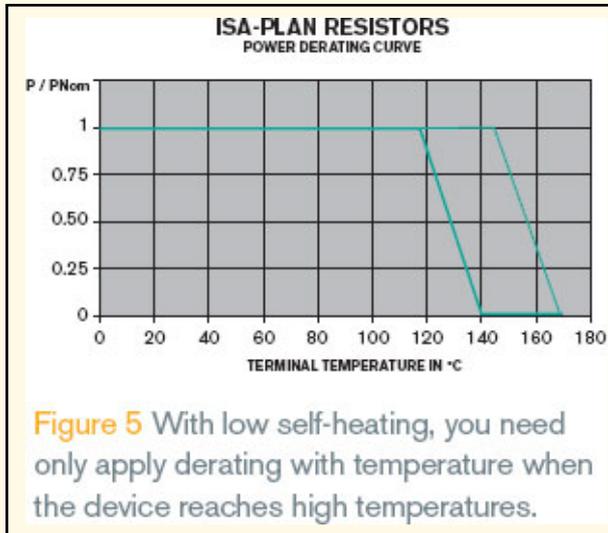


Figure 4 The four-terminal connection allows the measurement system to directly access the signal from the high-stability sensing element.

HIGH LOAD CAPACITY

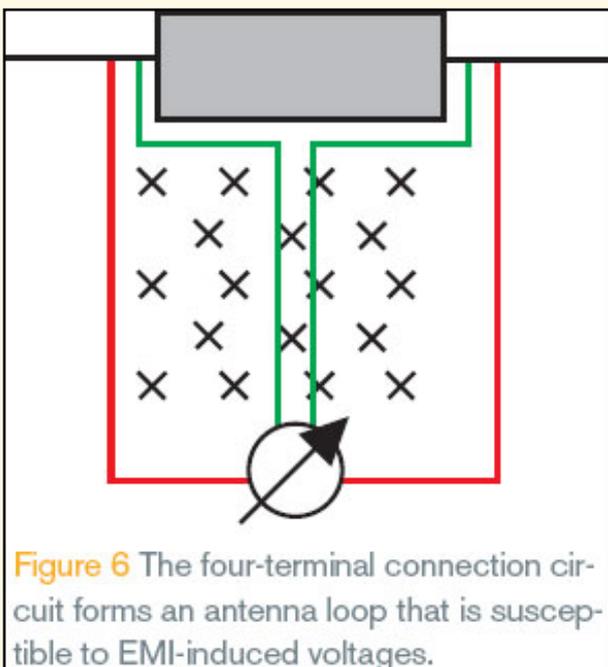
Since the thermal conductivity of resistor materials compared to copper is relatively weak and the resistors mostly use etch-structured foils of a thickness between 20 and 150 μm , it is not possible to dissipate heat via the resistance material into the terminals. An alternative construction employs a thin, heat-conductive adhesive to bond the resistor foil onto a substrate that also has good heat-conductive properties (copper or aluminium). This structure effectively conducts heat to ambient via the substrate and the contacts, which is ultimately reflected in a comparatively very low internal thermal resistance (typically 10 to 30 K/W).



This in turn leads to the resistors being able to cope with maximum power up to a very high terminal temperature; i.e. the derating starts at a very high temperature (Figure 5). At the same time, however, the maximum temperature in the resistor material stays low, considerably improving the long-term stability under load and the tcr-dependent reversible resistor change. In extremely low-ohmic resistors using composite material, the alloy cross-section and hence the mechanical stability is so big that no substrate is necessary. This also means that the thermal conductivity of the resistor material is sufficient to achieve comparatively low thermal resistances. For a 1-m resistor, this is about 10 K/W, and even for a 100- $\mu\Omega$ resistor it is 1 K/W.

LOW INDUCTANCE

Since it is necessary to measure and control switch-mode currents in many of today's applications, the inductance of the shunt or the shunt circuit is very important. Low-inductance SMD resistors employ a flat design with or without closely adjacent meanders. The diamagnetic characteristics of the precision alloys mentioned above, the metallic substrate, as well as the four-terminal connection further contribute to a low inductance.



However, since the sense connectors on the PC board and the resistor form an antenna structure, in which the magnetic field that the current flow generates and other external magnetic fields produce induced voltages, it is especially important to keep as small as possible the area that the sense-track lines enclose. The optimal solution is a strip-line design; i.e. the two lines route to the amplifier as close as possible to each other or even better on two layers congruently on top of each other. As a result of a bad layout (the red lines in Figure 6), this antenna effect can far exceed the influence of the resistor's real inductance.

LOW TOTAL RESISTANCE

At high currents and low resistance values, a four-terminal design is indicated; a popular solution is to punch parts out of a Manganin sheet (Figure 7). This may not be the best solution: although the four-terminal sensor resistor, its tcr and the thermoelectric voltage are favourable, the total resistance is in some cases 2 to 3 times higher than that of the real sensor resistor. The result is a correspondingly higher, often unacceptable power loss and temperature increase in the resistor. In addition, resistor materials are difficult to connect to copper via screw and solder joints, which leads to an increased contact resistance and therefore to further losses.

Employing a construction that punches the resistor out of the composite materials (Figure 8) largely eliminates these errors. The total resistance increases by less than 10%, and the designer can also employ approved copper-copper joining techniques.

AUTOMOTIVE SPECIFICATIONS

For reasons of economy and miniaturisation, SMD designs with resistor values from 200 m Ω are increasingly prevalent for current measurement of up to 100A in vehicles. The following examples illustrate special features and applications. All have in common the two-terminal design and the physically optimised structure that allows an absolutely correct measurement in four-terminal configuration, in combination with a suitable PC-board layout.

For applications such as current measurement in petrol and diesel direct injectors, transmission controllers, high-pressure head-lamp controllers, and engine-management modules, a suitable construction uses a copper substrate that functions as heat sink and electric contact at the same time. This enables the complete transfer of the characteristics of Manganin into the component, a high continuous and pulse power, as well as a low inductance. Resistance range is 5 m Ω to 5 Ω , physical sizes are in the 2816, 2512, 2010, and 1206 outlines, load capacities are from 3 down to 0.5W with a tolerance of up to 0.5%, and thermal resistance is up to 10 K/W.

An alternative format for flip-chip assembly—a two-terminal design—offers extremely low ohmic values starting at 1 m Ω . Below 3 m Ω , the design uses no substrate: for higher values, an insulated aluminium substrate lying on top serves as a carrier material and a heat bridge that carries the heat efficiently out of the resistance material to the contacts. In this format, the resistance range is 1 m to 0.5 Ω , outlines are 2512, 2010, 1206, and 0805, load capacity is 2 to 0.25W at 1% tolerance, and thermal resistance is up to 15 K/W. You might use these in ignition-control modules, transmission controllers, engine-management modules, window lifters or pulsed actuators.

Applications may include switch-mode current regulation and PWM power controllers with special requirements: for example, measuring up to 100A for a radiator fan; operating at up to +140°C ambient for an interior blower fan; the need to operate at EMV Level 5 for an electric oil pump or with an efficiency of 94 to 98% for an electric water pump; or to offer full motor protection—for all cases, a further format is available.

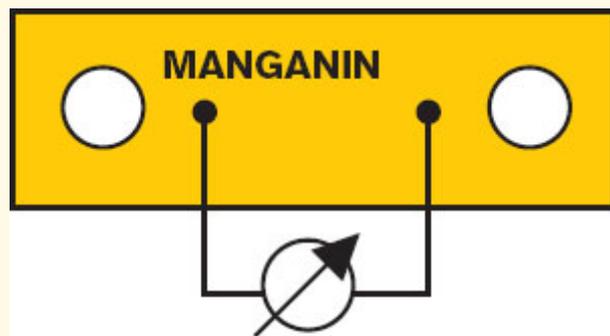


Figure 7 A single-piece resistor cut from sheet alloy is a simple approach to a low-ohmic sense element.

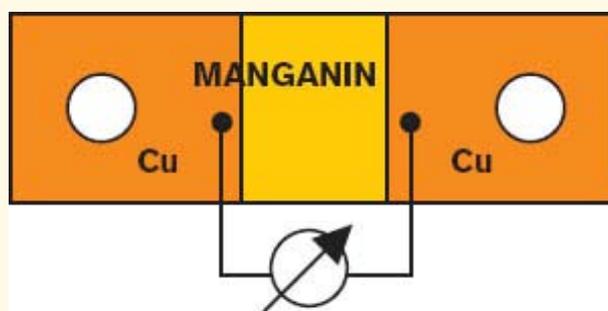


Figure 8 This construction presents copper connections to external circuitry, reducing errors and simplifying interconnection.

This is also an surface-mount resistor, but in this case punched out of composite material and suitable for high-current applications for assembly either on the circuit board or on DCB (direct-copper-bonded) or MIS (metal-insulator semiconductor) substrates, or for welding into lead frames. It spans $100\mu\Omega$ to $4\text{ m}\Omega$ in resistance, with a load capacity up to 5W at 1% tolerance, and has thermal resistance of up to 2 K/W .

DATA-ACQUISITION SYSTEM

There is an increasing number of applications in vehicles that require the highly dynamic, accurate and high-resolution measurement of currents of several hundreds to over 1000A and at the same time a good resolution in the milliamperere range. Examples for this are battery and power management in passenger cars and trucks as well as current measurement in electric and hybrid vehicles.

An ASIC specific to this application comprises a complete four-channel data acquisition system to measure extremely low voltages on shunt resistors. With a 16-bit resolution and many special functions, this absolutely offset-free converter, in conjunction with a low-ohmic resistor made of composite material, comes very close to the ideal current sensor. On the one hand, it can measure currents up to 1500A with high dynamics, linearity, and resolution; but on the other hand, it achieves a resolution of few milliamperes for a low sampling rate. The ASIC only requires one supply voltage of $\pm 5\text{V}/3\text{ mA}$ and can still measure bipolar signals even below its own supply voltage. In addition to the current measurement, a voltage or temperature measurement is available at the same time.

With a special resistor of $2\mu\Omega$, this system can even measure currents of up to $10,000\text{A}$ at a resolution of less than 1A and thus advances into an area that has up to now been the exclusive domain of converters.

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