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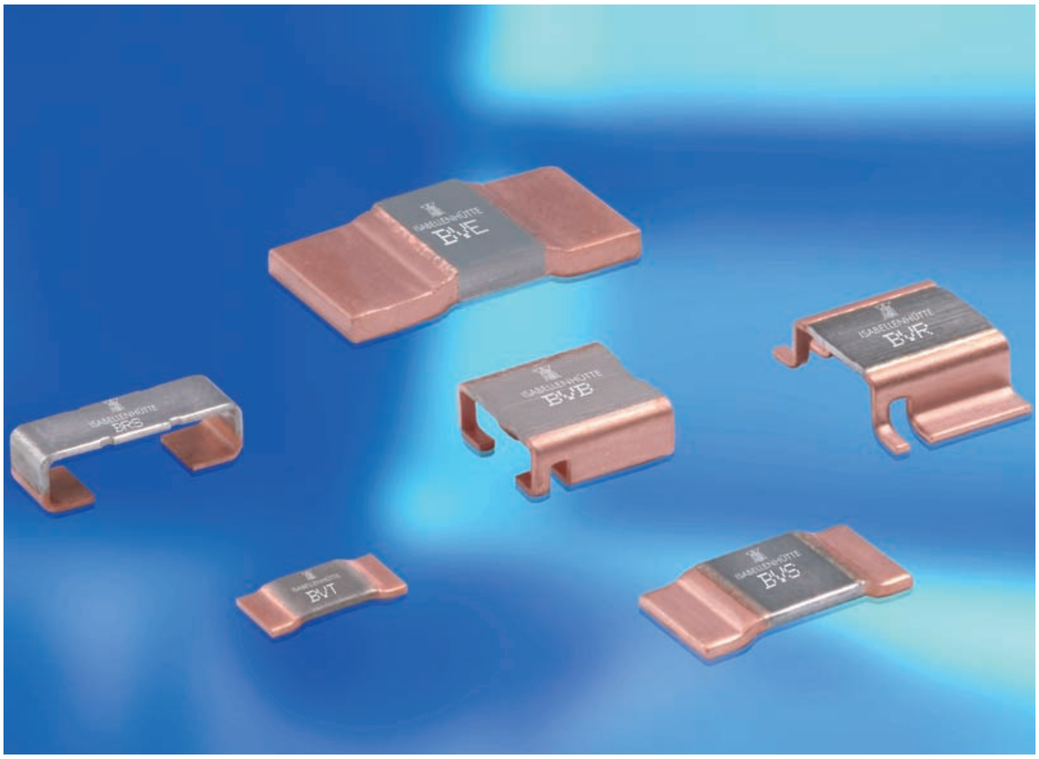
Current sensors in automotive electronics

Revival for the shunt resistor

For decades, the current-sensing resistor, the so-called »shunt«, has been the component of choice for current measurement. Because of continuous design optimization of SMD shunts in recent years, nothing is likely to change in this regard either. This contribution discusses its most important parameters and considerations for the design-in of shunts for current sensing.



Current sensing and its control are increasingly gaining importance throughout the electronics and particularly in automotive electronics sectors since more and more electrical consumers have to be controlled and greater dynamics require higher currents. In addition there is a strong trend to more efficient and economical use of electric energy.

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With the magnetic current sensors and so-called shunts there are, basically two physically quite different measuring methods available having established themselves in certain market segments during the last decades.
Main advantages of magnetic sensors (current transformers, Hall sensors etc.) are the built-in isolated measuring feature and their low power dissipation. This is why these sensors are mainly used in drive technology and for high currents today. Main disadvantages are comparable big

Characteristics/requirements	Material	Design	Process
Low TC	xxx	x	x
Very good long-term stability	xxx	x	x
Low thermal EMF	xxx	x	xx
Low inductance	x	xxx	
High accuracy			xxx
High power rating	x	xxx	
Low internal thermal resistance		xxx	x
Four-terminal technique		xxx	
Low overall resistance		xxx	x
High safety	xx	x	x
Low price	x	xx	xxx

Table 1: Effect of material, design and production process on the characteristics of a shunt (the more »x«, the higher the dependency)

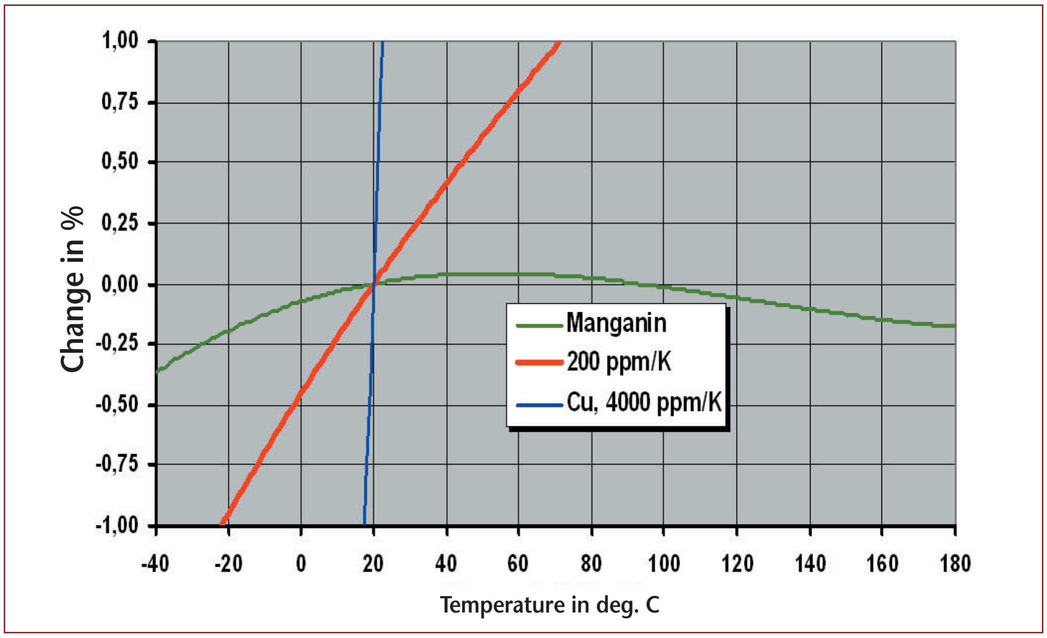


Figure 1 Comparison of temperature coefficient of copper and Manganin®

size, high offset and limited linearity.

The pressure for miniaturisation and the availability of extremely low-value, almost error-free resistors combined with greatly improved properties of OPs and data acquisition systems recently has presented the "old" shunt resistor a revival – in new application fields no one would have thought of even 10 years ago.

The control and regulation of actuators in the motor vehicle usually requires currents in the range from 1 A to 100 A, in special cases (e.g. the lambda probe preheater) currents of 300 A or, with the starter motor, even up to 1500 A for a short time. In the area of battery and power management the situation is even more extreme since continuous currents during vehicle operation are around 100 to 300 A, while only a few milliampere have to be measured in the idle state when the car is parked.

When measuring current with a resistor, the voltage drop, according to Ohm's law, is evaluated as a direct measurand for the current. This is entirely uncritical with resistance values above one ohm and currents of several hundred milliamperes. But the situation changes completely when currents in a range above 10 to 20 A are involved since the power dissipation ($P = R \times I^2$) developing in the resistor generally cannot be neglected any longer. Therefore, the power should be limited by reducing the resistance value, but unfortunately the measuring voltage is simultaneously reduced with the consequence that , the resistance value is frequently limited by the finite resolution and quality of the evaluation electronics. The following equation generally applies to the voltage measured on the resistor: $U = R \times I + U_{th} + U_{ind} + U_{iext} + \ldots$, where U_{th} is the thermal EMF, U_{ind} the induced voltage and U_{iext} a potential voltage drop on the sense tracks of the PC board generated by a small current.

In the case of low currents and low resistance value, these error voltages not produced by a current flow can completely distort the measuring result; therefore the designer should know the origins of the error voltages and minimise their influence by carefully designing the layout and especially selecting suitable components.

Basically, an electric resistor can be manufactured from any conductive material. However, such a component is not likely to be suit-

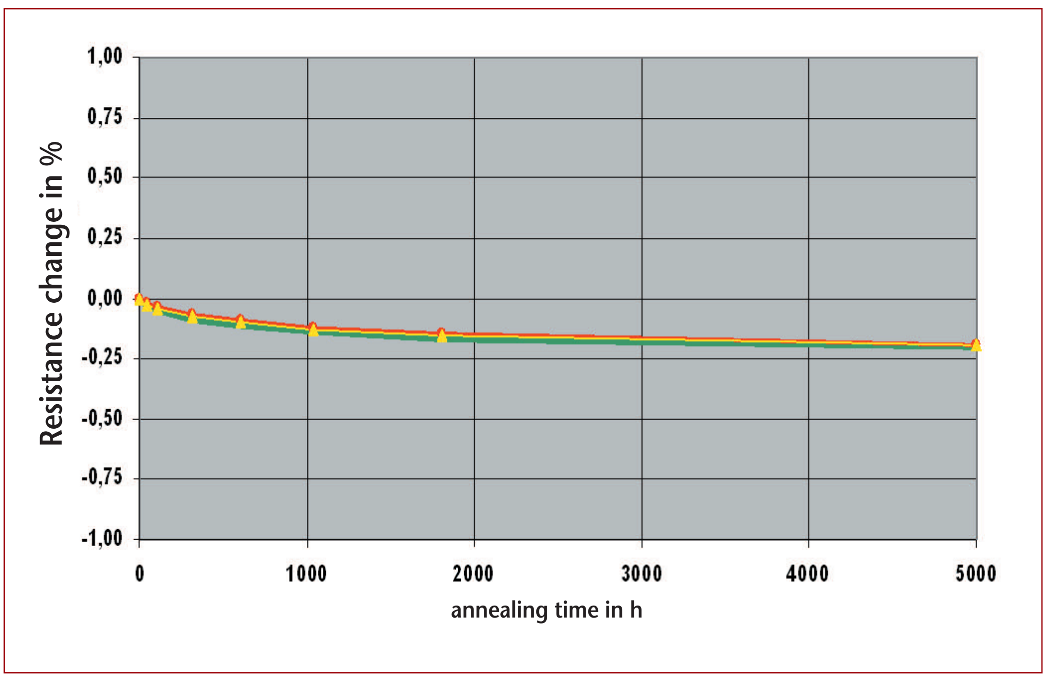


Figure 2: An SMD resistor is annealed for 5000 hours at + 140 deg. C. The low drift shows its superb long-term stability.

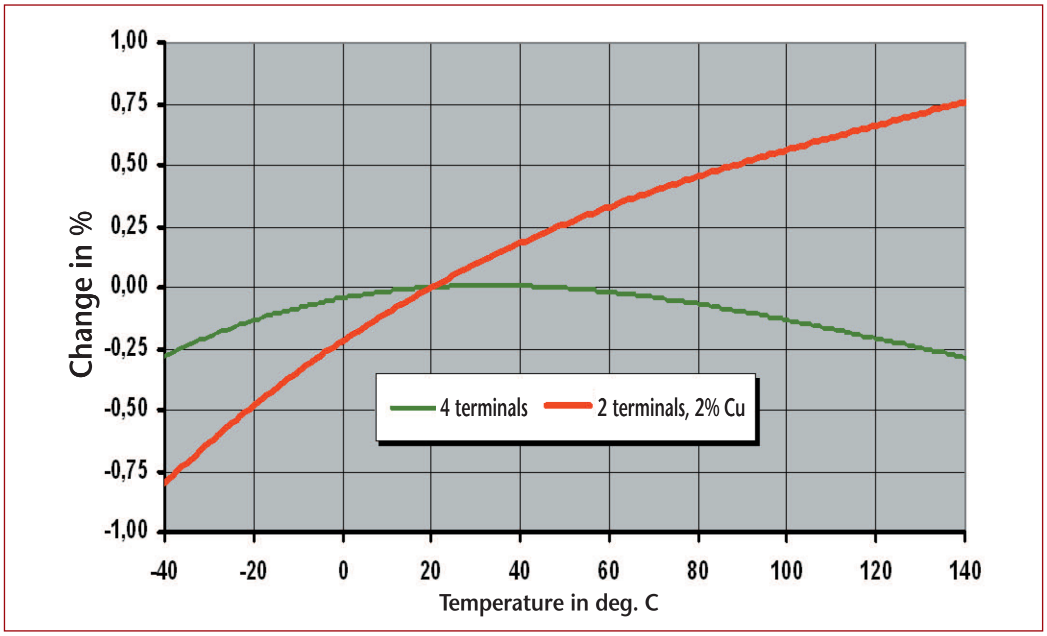


Figure 3: Change of overall resistance over the temperature. The connection technique (4-terminals or 2-terminals) has a significant influence.

able for current measurement since the resistance value will be dependent on parameters such as temperature, time, voltage, frequency etc. Since the ideal current sensing resistor which is totally independent of these parameters obviously does not exist, the real resistance is described by the characteristics such as temperature coefficient of resistance (TC), long-term stability, thermal EMF versus copper, power rating, inductance, linearity etc. indicated in the table. Some of these characteristics are largely material-related while others are more influenced by the design and, yet others, by the production process as shown in Table 1.

Precision resistance alloys

Already in 1889 the company Isabellenhütte developed the precision resistance alloy Manganin®, the characteristics of which have been the basis of precision measuring technology ever since, for instance in standard resistors. The other alloys Isaohm® resp. Zeranin® round off the range of resistivities with 132 μΩ x cm and 29 μΩ x cm in both directions. All these alloys largely satisfy the material-related requirements and have been successfully used for many years by precision resistor manufacturers.

As an answer to new developments of magnetic current sensors, Isabellenhütte, in the last 25 years, pursued the objective of upward expanding the practically utilisable range for precision current measurement with shunt resistors by physical optimisation of the components. Hand in hand with the improvement of offset, TC and noise of operation amplifiers the company succeeded in developing SMD resistors with lower resistance values in the milliohm range so that the main problem of high power dissipation with large currents was largely eliminated. At the same time, the relative error – caused by error voltages (external effects, thermal EMFs etc.) – increases severely, considerably increasing the significance of characteristics such as low inductance and no thermal EMF and TC.

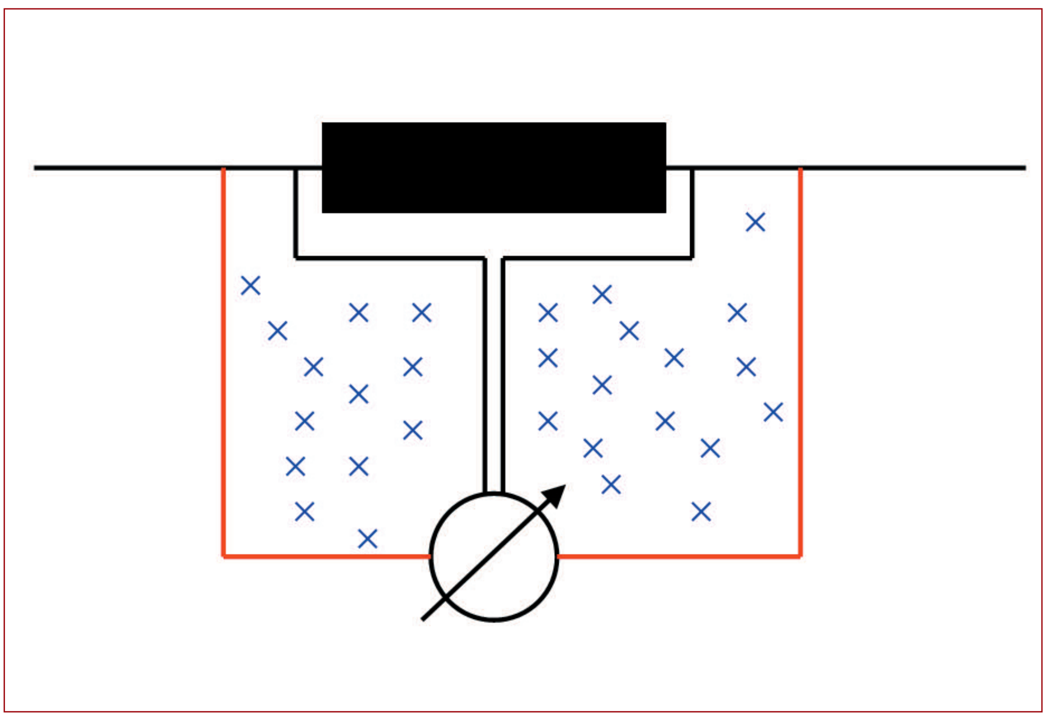


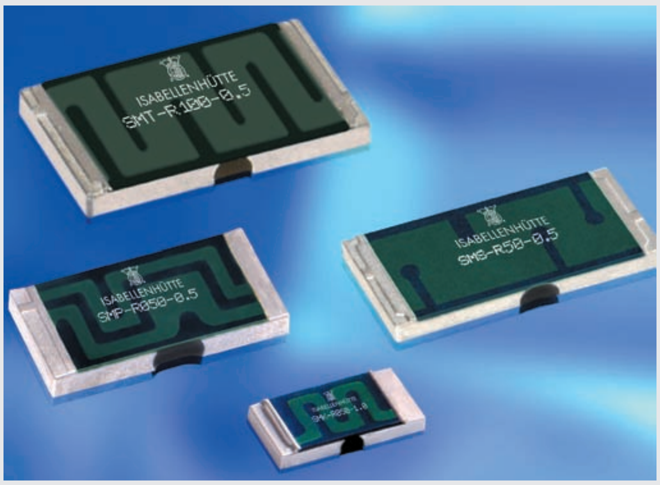
Figure 4: By means of the strip-line technique (black) interference voltages induced by a magnetic field (blue crosses) are minimised.

SMX series

The SMX series utilises a copper substrate which acts as a built-in heat sink, a very low termination resistance and substrate as well. This allows the complete transfer of the Manganin® characteristics to the component and high continuous and pulse power as well as low inductance.

Characteristics:
- Resistance range: 5 mΩ to 2 Ω
- Sizes: 2817, 2512, 2010, 1206
- Power rating: 3 W, 2 W, 1 W, 0.5 W
- Tolerance: up to 0.5%
- Thermal resistance: up to 13 K/W

Application examples:
Gasoline and diesel direct injection, transmission control, light control modules, current monitoring of individual consumers or groups in the vehicle as well as motor control units.

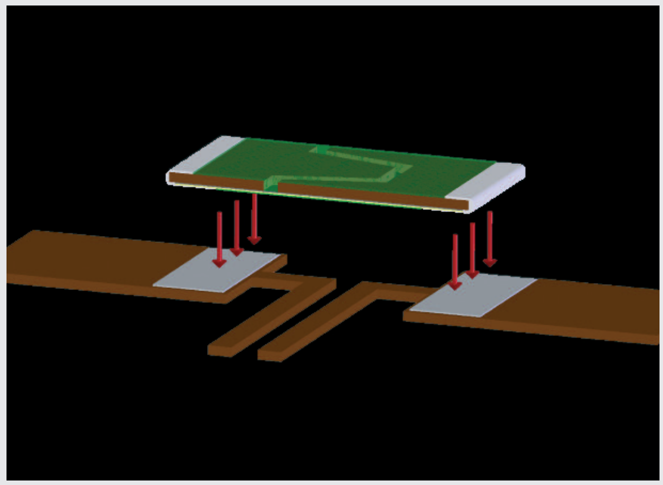


VMX series

The new resistor series VMx by Isabellenhütte brings together performance features that are so far unique in this combination. Depending on component size (versions 0805, 1206, 2010 und 2512), their values range is between 5 mΩ and 2Ω. The resistors are characterised by a comparatively very high power loss, for instance, 3W for version 2512 (at an ambient temperature of 110° C) and a low therminal internal resistance.

Characteristics:
- Resistance range: 5 mΩ to 2 Ω
- Sizes: 2512, 2010, 1206, 0805
- Power rating: 3 W, 2 W, 1 W, 0,5 W
- Tolerance: up to 0,5%
- Thermal resistance: up to 20 K/W

Application examples:
Gasoline and diesel direct injection, transmission control, light control modules, current monitoring of individual consumers or groups in the vehicle as well as motor control units.



The most important parameters will be briefly discussed in the following.
Figure 1 shows the typical parabolic shaped temperature dependence of resistivity for Manganin®. Since this characteristic is mainly determined by the material composition, ISA-PLAN® resistors stand out for a very high reproducibility and very low batch variance. The temperature coefficient is expressed in ppm/K and defined as follows: TC = [R(T)-R(T0)]/[R(T0) x (T-T0)].
A value of –20ºC or +25ºC is mostly used as reference temperature T0. If the temperature dependency is a curved graph as in the case of Manganin® it is indispensable to specify the upper temperature used for the TC measurement as well, e.g. TC (20 – 60). In the low-resistance range, thick-film resistors with TC values of several hundred ppm/K are frequently used as well. The red curve shows that with a TC-value of only 200 ppm/K a temperature change of 50 K is sufficient to leave the 1% limit. Accurate current measurement is impossible with such resistors, especially if you consider that for many SMD components the internal heat resistance is of the order of 100 K/W i.e. a power of 1 Watt will increase the temperature by 100 K or change the resistance value by 2 %! The situation is even more extreme when attempts are made to measure with copper resistors etched on the circuit board since copper has a TC of 4000 ppm/K (or 0.4 %/K), i.e. a temperature change of 10 K already produces a drift of 4 %.

Thermal EMF (thermal electromotive force)

So-called thermal EMF will develop at the junction of various materials if slightly heated or cooled down. This effect may act as a significant error voltage when measuring current with low-ohmic resistors since very low voltages must be measured.
The resistor material Konstantan well known from lectures and textbooks is very often used for wirewound and punched shunts even today. Although its TC is quite good, the thermal EMF versus copper is extremely high (however, with approximately 40 µV/K). This means that a temperature difference of 10 K will create an error voltage of 400 µV which corresponds to a current measurement

error of 10 % when measuring a current of 4 A with a 1 mOhm resistor. The situation is even worse when taking into account that the Peltier effect under DC current load is able to build up a temperature difference of more than 20 K (in extreme cases, one-sided desoldering of such resistors has been observed). This in term means that an apparent current change is observed even with constant current flow – due to the appearance of the temperature difference resp. the thermal EMF.
Once the current has been switched off an apparent current flow is measured disappearing with time constant of the temperature change. The above mentioned precision resistance alloys are exactly adapted thermoelectrically to the "copper world" so that these effects are totally negligible. For instance a voltage drop of less than 1 µV (corresponding to 3 mA) occurs over a 0.3 mΩ resistor immediately after a current of 300 A is switched off.
For a sensor, the stability over time of course is highly important since the user will have to depend on the calibration once performed even after years in the application. For the resistance materials this means that they have to be corrosion-stable and do not experience any metallurgically related changes throughout their life cycle. The alloys Manganin®, Zeranin®, and Isaohm® meet these requirements as homogeneous mixed-crystal alloys which are additionally carefully annealed and stabilized and therefore are situated in the thermodynamic basic state. Stability values in the ppm range per year are actually common with these alloys. Figure 2 shows the conditions with a real SMD resistor annealed at +140 ºC for 5000 hours. The low drift of approximately -0.2 % is caused by the healing of residual lattice defects caused by deformations during production and shows that the components further stabilise, i.e. improve over the time. Since the drift speed highly depends on the temperature this effect is barely detectable below 100 ºC.

Connection technology

With low ohmic resistors the influence of the connection leads on the resistance value and its TC cannot be neglected in many cases. Therefore, the sense voltage should be measured via two additional terminals which are connected directly on the resistance material. A PC-board track with a dimension of 4 mm x 0.2 mm x 35 µm (L x W x H) has already a resistance value of 10 mΩ, which means that this copper part in the measuring circuit would already distort the resistance by 100%. Although this additional resistance of the feeds could be eliminated by trimming it can severely distort the TC of the overall resistance as shown in Figure 3. This highlights the effect of unsuitable design of the resistor or the layout. Even if the copper component influence is extremely small with only 2% in the example from Figure 3 the TC increases from almost zero to approximately +80 ppm/K. This means that the frequent practice of indicating the TC of the resistance material used is absolutely impermissible for the component without testing.
As resistors made of electron-beam welded composite material Cu-Manganin®-Cu actually do have such a low feed resistance, a two-terminal resistor can be used again with a suitable layout since the interaction of layout, soldering and resistor realises the four-terminal connection. However, care must be taken with the layout to prevent the current flow in the resistor from touching the voltage connections (sensing lines).
Since the heat conductivity of the resistance material is relatively poor compared with copper and thin foils of resistance materials are generally used, heat conduction via the resistance material is not possible. With ISA-PLAN® resistors the resistance foil is therefore bonded with onto a good heat-conducting substrate (copper or aluminium) using a thin heat-conductive adhesive. This results in a very effective heat conduction from the resistance material to the substrate and out to the PC-board via the solder joints. Finally this effect is reflected by the extremely low internal heat resistance if compared to similar components (typically 10 K/W to 30 K/W).
As a result, the resistors can be powered with full load up to a very high junction temperature, i.e. the derating curve starts at a very high temperature. Nevertheless, the maximum temperature in the resistance material is kept low considerably improving long-term stability under load and reversible resistance change due to the TC.
With the extremely low resistance designs made from composite material the large Manganin® cross section and consequently the high mechanical stability ensure that no substrate is required. The heat conductivity of the resistance material is also adequate in this case to achieve comparatively low heat resistance. For the 1 mΩ resistor this is approximately 10 K/W and even 1 K/W for the 100 µΩ resistor.

Low inductance

Since switch mode currents have to be measured and controlled in many applications today the inductivity of the shunt is gaining more and more importance. The special low-inductance flat design of the ISA-PLAN® and ISA-WELD® resistors without or with narrowly spaced meanders and the diamagnetic property of the precision alloys, the metallic substrate and the four-wire connection further contribute to the improvement. However, the sensing lines together with the resistor form an antenna structure which picks up the magnetic field change caused by the current flow and other external magnetic field changes as an induced interference voltage. For this reason it is very important to keep the area enclosed by the resistor and the sense tracks on the PC-board as small as possible. A strip-line technology design is ideal, i.e. both lines are routed to the amplifier in parallel as narrow as possible to each other or congruently positioned on top of each other at two layers (Figure 4). With incorrect design (red lines) this antenna effect is able to exceed the influence of the genuine inductance of the resistor by orders of magnitude.

Although a four-terminal design is advisable with high currents and low resistance values, the often used punched resistors from a Manganin® sheet for instance is not the best solution. TC and thermal EMF of the four-terminal current sense resistor are OK but the overall resistance and thermal resistance may be two to three times higher than the actual current sense resistor. Consequently, higher and often impermissible heating effects in the resistor. Additionally, resistance materials are sometimes difficult to connect to copper by screw connections or soldering because of high, non reproducible contact resistance and resp. bad wetting of the resistance material.

These drawbacks have largely been eliminated with the ISA-WELD® resistors punched from electron-beam welded Copper-Manganin®-Copper composite material. The lead resistance is nearly zero due to the bulk copper terminal which means that the overall resistance is very close to the four terminal resistance. In addition, the customer can use well established and proven Cu-Cu connection techniques.

For reasons of costs and miniaturisation SMD versions with resistance values from 300 µΩ are increasingly used for current measurement up to 100 A in motor vehicles. For the automotive industry Isabellenhütte for instance has created the series SMX, LMX and BVX. All of them have a two-terminal design and a physically optimised structure in common. Together with an optimised PC-board layout totally correct four-terminal measurement is possible without any influence of the termination nor the contact resistance of the solder joint.

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