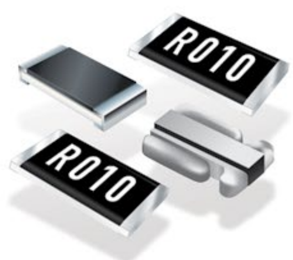
Achieving High Efficiency Automotive System Current Monitoring Using Current Sense Resistors

APPLICATION NOTE



INTRODUCTION

As the automotive industry evolves to manufacture more hybrid and plug-in electric vehicles, the need to provide various high efficiency systems such as electric braking, electric steering and motor control becomes increasingly important in the quest to save battery consumption and reduce energy costs. Current monitoring is highly effective for control and protection purposes in battery chargers, LED lighting and inverter drives in automotive applications such as hybrid and full electric vehicles. To increase efficiency in both AC and DC applications, the electric current in these various systems will need to be monitored for proper feedback controls. Efficiency of these systems can be increased by selecting the proper current sensing feedback devices for the application.

Current sense resistors can be a low-cost solution in terms of space used and ease of integration into the circuit design. Figure 1, for example, illustrates a 3-phase inverter with sense resistors used for measuring current in the windings of a motor.

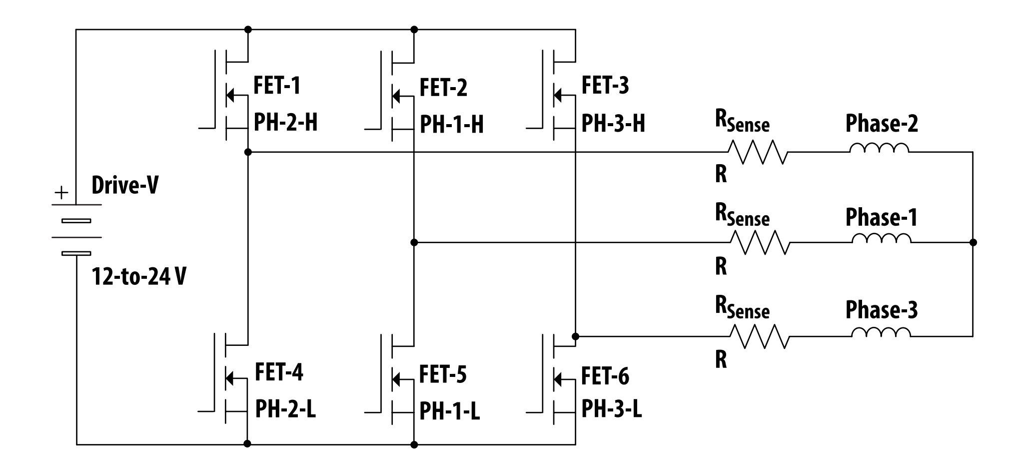


Figure 1. | *3-Phase Inverter Motor Drive Showing Sense Resistors for Measuring Winding Current*

This application note discusses the following topics:

- Overview of different technologies for sensing current
- Location of the sense resistor in a converter
- Thermal calculations needed to select the right resistor
- Sensing strategies

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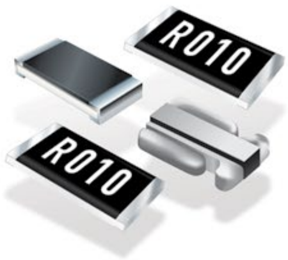

MONITORING THE CURRENT

There are many ways to monitor current including intrusive and non-intrusive methods. Intrusive current monitoring involves placing a device in series with the device being monitored. Non-intrusive monitoring involves placing an inductive or Hall Effect device near the wires supplying current to the controlled device. See the table below for advantages and disadvantages of some current sensing types.

Device	Advantages	Disadvantages	Frequency Range
Current Sense Resistor (CSR)	• Less space required than other options • Lower cost than remote devices • Can be easily integrated into PCB design • Able to measure both DC and AC elements of signal • Good linearity	• Location placement is limited • No circuit isolation • Intrusive to circuit • Requires op-amp or other amplification circuit	No Limit
Hall Effect	• Immune to most environments • Non-intrusive to circuit • Can measure both DC and AC elements of signal	• Higher probability of drift • Sensitive to outside magnetic fields • Must be magnetically shielded in some applications	1 Hz to 100 kHz
Rogowski Coil	• Non-intrusive to circuit • Immune to high DC currents • Easily retrofittable to application • Can withstand high overload currents • Easily removed; good temporary device	• Not viable for production automotive projects • Good only for AC applications • Requires an external power source or large battery pack • Hard to calibrate for reading high and low currents with the same device	~ 20 Hz to 3 MHz
Transformer	• Non-intrusive to circuit • Good for high voltage applications • Widely available • High linearity	• Method causes parasitic resistance (insertion loss) • Not capable of DC current measurement • Accuracy is low • Each device type is limited to high or low current range	~ 40 Hz to 200 kHz

As shown in the table above, current sense resistors provide several advantages for power supply or inverter controller designs. The sensors in contactless technologies are more prone to drift making it difficult to assure tight precision control over wide operating temperatures that are common in automotive applications. Designers are integrating newer digital ICs that are able to distinguish very small signals, which reduce dynamic ranges to less than 30 mV. This leads to an increased demand for resistors that feature lower ohmic values helping to positively reduce power and increase system efficiencies.

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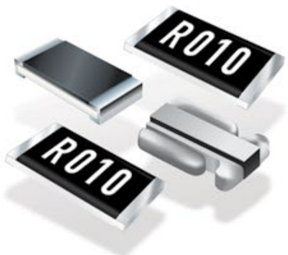


LOCATION OF SENSE RESISTOR IN CONVERTER

Measuring the current in the power inductor in a Voltage Regulator Module (VRM) is done in combination with the output voltage of the VRM controller. Both feedback signals form part of the power supply control loop and are necessary to maintain tight regulation over different loads. The measurement circuit and inductor waveform are shown in Figures 2 and 3. The resistor could be placed on the output side where the signal is quiet and does not require special filtering by the controller. However, the continuous current in the sense resistor generates an efficiency loss which may not be acceptable for the application. Another option is to place the resistor on the upper or lower Field-Effect Transistor (FET) side. The signal is much noisier on this side as a large portion of the current signal conveys no useful information to the controller. However, VRMs normally have a large step down ratio and hence, the resistor is inefficient for a reduced amount of time than on the output side. Another problem when putting the resistor on the upper or lower FET side is the overshoot in the current signal caused by parasitic elements in the converter circuit. This makes reading the signal difficult for the controller.

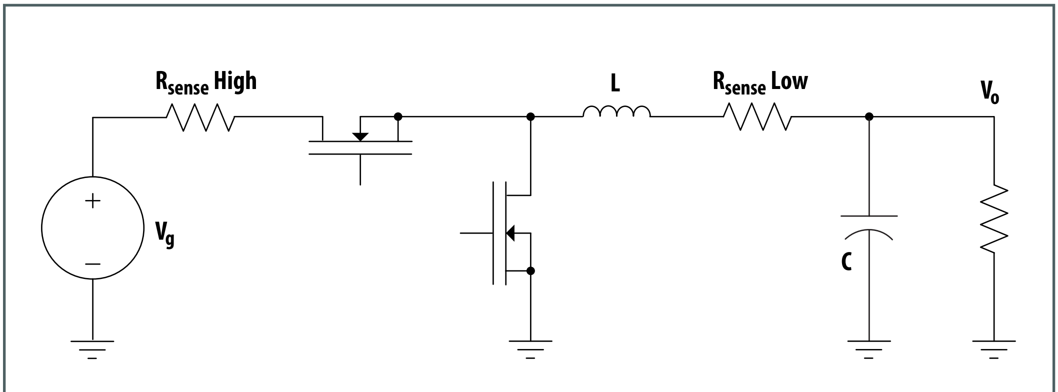


Figure 2. | *Sync Buck Converter with Current Sense Resistors in the High-End and Low-End*

LOCATION OF SENSE RESISTOR IN CONVERTER *(Continued)*

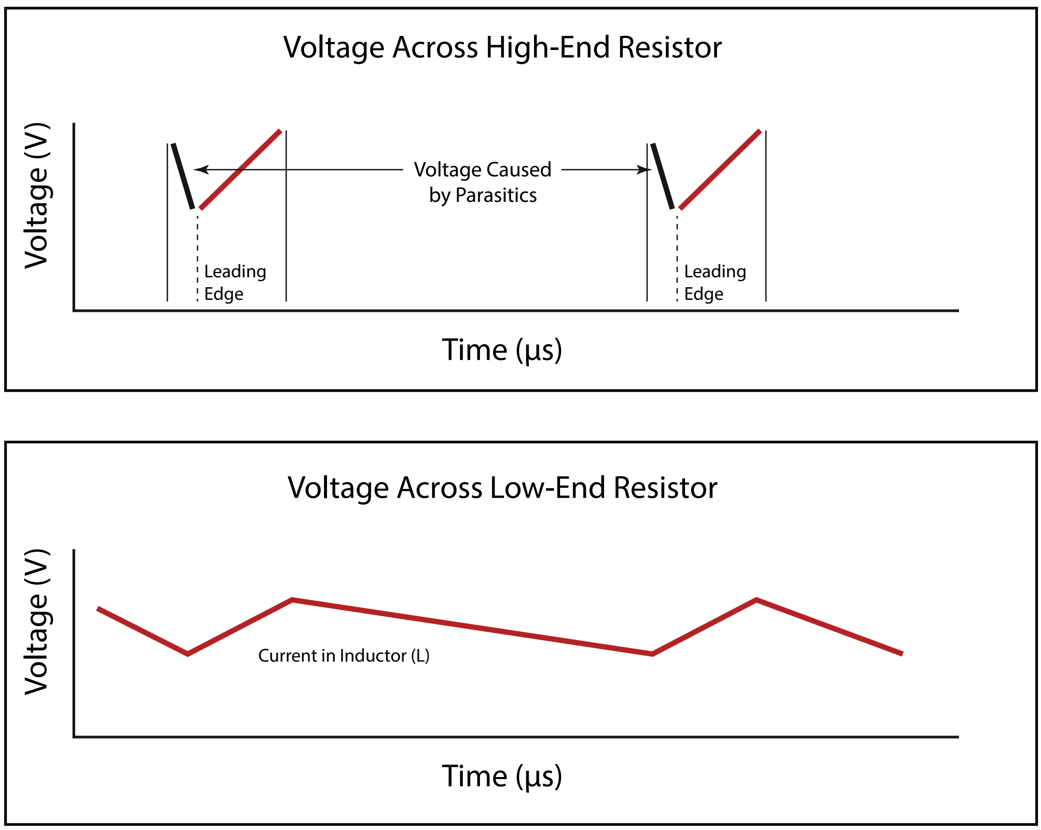
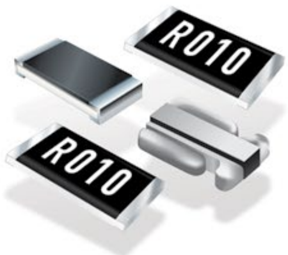


Figure 3. | *Current Waveforms in the Inductor and the High-End Resistor*

Using an example of a synchronous buck converter, it is possible to analyze the efficiency with the sense resistor in both locations. In this example, we will assume the following are the main parameters for this converter with the resistor located after the inductor:

- I_{out} = 30 A_{DC}, V_{out} =5 V_{DC}
- Duty cycle = 20 %
- V_{peak} of controller input = 100 mV
- R_{sense} would be calculated as 3 mΩ
- Power dissipated = 2.7 W at room temperature assuming full power
  This represents an efficiency drop of 1.8 %



LOCATION OF SENSE RESISTOR IN CONVERTER *(Continued)*

The dissipated power under perfect conditions is 2.7 W. Let us assume we select a resistor rated to 4 W, such as the Bourns® Model CSS2H-2512. In order to guarantee reliability and ensure that the MTBF of the component is high, the surface temperature of the device under worst case operating conditions (maximum load at maximum operating temperature) is minimized. This is based on Arrhenius' equation, which states that the time to failure is a function of the absolute temperature. In fact, the MTBF can be doubled if the operating temperature is reduced by 10 °C. The following calculations would be made if the current sense resistor was positioned in series with the high end FET:

- $I_{average}$ = 6 A_{DC}
- R_{sense} = 15 mΩ
- Power dissipated = 0.5 W, which represents an efficiency drop of 0.33 %

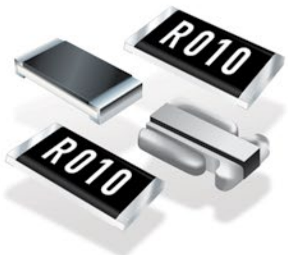
Clearly, there are benefits in efficiency with the resistor located at the high end of the circuit. In order to calculate the surface temperature of the resistor we need to calculate its thermal resistance from the data sheet. We then calculate the thermal resistance of the external environment (solder pads) into which the resistor is going.

THERMAL RESISTANCE OF COMPONENT

We assume the data sheet parameters are taken from perfect operating conditions. Therefore, the thermal resistance is as follows:

$$\frac{T_z - T_{max}}{\text{Power}}$$

Where T_z and T_{max} are the zero power temperature and maximum temperature at full power, respectively. R_{th} is, therefore, 25 °C/W.



THERMAL RESISTANCE OF SOLDER PADS

Taking the recommended solder pad dimensions from the data sheet the thermal resistance of the pads is as follows:

$$\frac{L}{\beta * W * t}$$

Where β is 4 W/cm and t is the thickness of copper (70 μm for power boards).

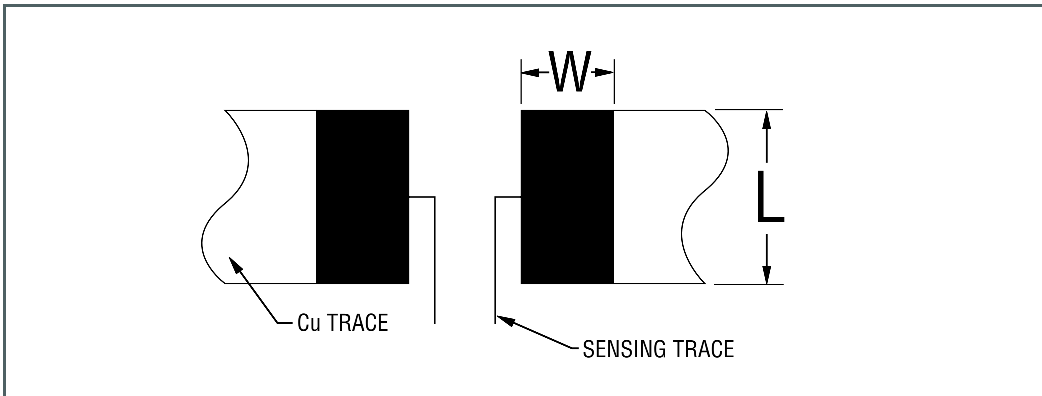


Figure 4. | *View of the Dimensions of a Solder Pad Used for Calculating Thermal Resistance*

Therefore, the thermal resistance of each solder pad is 20 °C/W. There are two solder pads, each contributing to dissipate heat which is similar to two electrical resistors placed in parallel to a current source. The net thermal resistance of the solder pads is, therefore, halved or 10 °C/W. The thermal resistance, therefore, of the system (resistor + surrounding environment) will be 35 °C/W. The increase in temperature at full power will, therefore, be 94.5 °C. This means that the maximum ambient temperature that the component can operate in at full power is 75.5 °C. At higher temperatures the resistor will exceed its designed surface temperatures and as per Arrhenius' equation, its MTBF will decline dramatically.

If the designer's controller can distinguish between the high switching voltage and the relatively small difference between low and peak currents, then a smaller resistor can be used such as the Bourns® Model CRF1206-FZ-R012ELF. The thermal resistance is higher (100 °C/W) according to the data sheet. The solder pads have a resistance of 33 °C/W each. The temperature rise, therefore, at full power (0.5 W) will be 58 °C/W which allows for a higher operating temperature of up to 112 °C.

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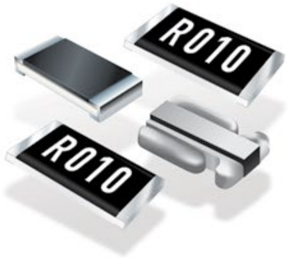

THERMAL RESISTANCE OF SOLDER PADS

The inductance of the component is quite important in this application. The controller will be switching the input voltage at a relatively high frequency across the resistance. The Model CRF1206 Series has a parasitic inductance of less than 5 nH. The voltage induced across the resistor at the start and end of every switching period would be calculated as follows:

$$V = L\frac{d_i}{d_t}$$

In this case, the voltage induced depends on the rise time of the current as the FET turns on. The controller would have to implement a delay whereby it does not read the incoming voltage for a certain period. This is commonly known as the leading edge blanking time. However, the induced voltage cannot be too high or it could damage the controller which is why ultra-low parasitic inductances such as 5 nH are important.

The buck configuration shown in Figure 1 uses the FET transistors to do controlled start-ups which limits the inrush current into the output capacitor after switch on. However, inverter drives, for example, which use large DC link bulk capacitors, will have large pulses of current depending on the size of the capacitor. Current sense resistors, therefore, must be able to withstand overloads for shorter periods of time. The metal Model CRE Series current sense resistor line has good load endurance depending on the value of the Model CRE device. Pulse capability of the Model CRE Series 3 W, 5 milliohm device can endure loads of 100 W for 20 ms and a 3 W, 1 milliohm device can handle pulses of 10 watts for up to 2 seconds.

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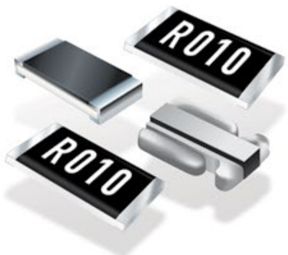


OVERVIEW OF CURRENT SENSE RESISTOR PRODUCT OFFERING

The following matrix summarizes the range of surface mount current sense resistors available from Bourns.

Series	Size (mm)	Power (W)	Resistance	Technology
CRL0805	2.0 x 1.0	0.125	50 mΩ - 9100 mΩ	Thick Film
CRF0805	2.0 x 1.0	0.5	3 mΩ - 20 mΩ	Metal Alloy
CRL1206	3.2 x 1.6	0.25	20 mΩ - 9100 mΩ	Thick Film
CRF1206	3.2 x 1.6	1.00	1 mΩ - 30 mΩ	Metal Alloy
CST0612	1.6 x 3.2	1.00	0.5 mΩ - 2 mΩ	Metal Alloy
CRF2512	6.35 x 3.2	2.00 (1 mΩ - 10 mΩ) 1.00 (15 mΩ - 50 mΩ)	1 mΩ to 50 mΩ	Metal Alloy
CRA2512	6.35 x 3.2	3.00	10 mΩ - 100 mΩ	Metal Alloy
CRE2512	6.35 x 3.2	3.00	1 mΩ - 9 mΩ	Metal Alloy
CSS2H-2512	6.35 x 3.2	4.00	0.5 mΩ - 3 mΩ	Metal Alloy
CSS2H-3920	9.9 x 5.08	12.0	0.2 mΩ - 3 mΩ	E-Beam Metal Alloy
CSS4J-4026	10.16 x 6.6	5.0	0.5 mΩ - 5 mΩ	E-Beam Metal Alloy
CSS2H-5930	14.9 x 7.62	8.0	0.5 mΩ - 3 mΩ	E-Beam Metal Alloy

Bourns® current sense resistors offer resistance values from 0.2 mΩ and powers of 9 W to values of 1 Ω and powers of 0.25 W in metal alloy, e-beam welded and thick film technologies. Bourns' extensive product line meets a wide variety of applications from high current automotive battery chargers to low power battery sensing in consumer applications.

The resistor as shown in Figure 1 can be connected in series with the load. This is known as high side sensing. However, there are other configurations for connecting the resistor illustrated in the following diagrams.

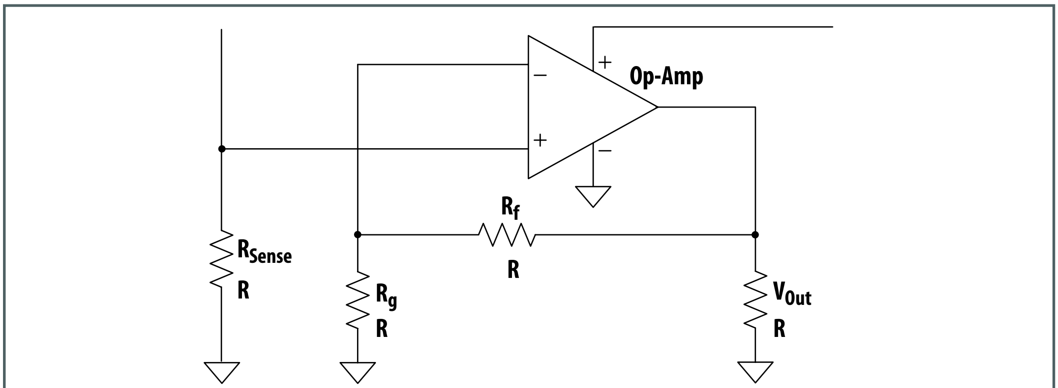
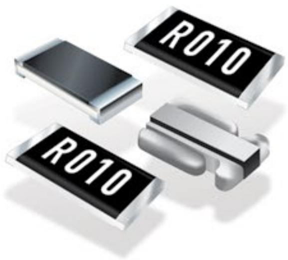


Figure 5. | *Low Side Current Sensing*



OVERVIEW OF CURRENT SENSE RESISTOR PRODUCT OFFERING *(Continued)*

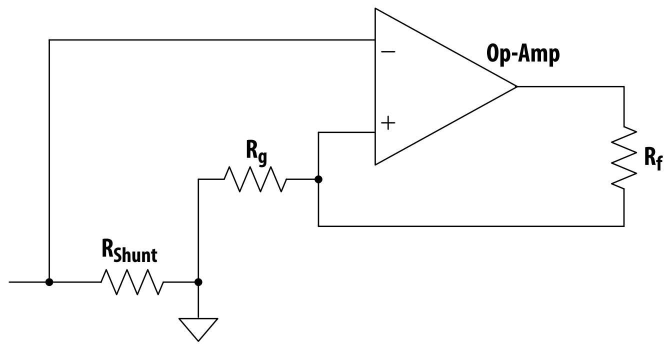


Figure 6. | *Low Side Current Sensing - Kelvin Configuration*

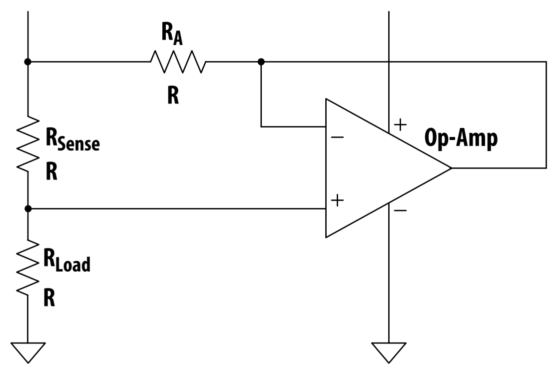


Figure 7. | *High Side Current Sensing*

SENSING STRATEGIES

High Side Current Sensing: In this style of sensing, a Kelvin configuration is used for monitoring current in applications such as single and 3-phase DC motors and large loads. The circuitry can be located in line with the load-driving FETs and monitored with any type of amplifying circuit. The additional circuitry can be easily added to the motor drive design. Two-pin current sense resistors can also be located either on the PCB or at the load for remote current sensing applications.

Low Side Current Sensing: In high-power current sensing applications, a typical circuit will require a Kelvin configuration or 4-pin current sense resistor as well as a common-mode zero-drift Op-Amp. These sensing circuits can be used for monitoring loads in both negative and positive DC voltage applications. For low power current sensing a 2-pin device can be used along with a non-inverting Op-Amp. This type of circuit is used for battery charge monitoring for smaller devices, such as alarm panels, power tools or various Uninterruptible Power Supplies.

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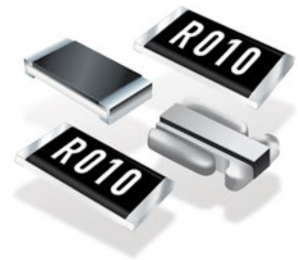

CONCLUSION

While there are several good methods for sensing current, this application note has shown that current sense resistors are ideal solutions for today's automotive power supplies, inverters and battery charging systems. As explained, it is important for the designer to carefully consider the operating conditions and the location of the resistor when selecting these components.

Bourns continues to innovate its resistor product offering. A good illustration is the addition of e-beam welded metal alloy sense resistors. These resistors can be used in high current applications such as automotive or industrial systems. Delivering the right current sense resistor for a given application, Bourns® products range from thick film chips with low power and high resistance values to metal alloy high power ultra-low ohmic resistance values.

ADDITIONAL RESOURCES

Please contact your local Bourns Application Engineer or Bourns Sales Representative for additional information.
Visit Bourns online at:

www.bourns.com

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Email americus@bourns.com

EMEA: *Tel* +36 88 520 390
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