

# A Progressive Way to Integrate Current Measurement into Modern Power Electronic Systems

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## Abstract

Modern inverter applications and sophisticated control schemes demand that the current flowing through the load is known exactly. Different measurement strategies can be utilized, each providing specific advantages and disadvantages. Several possibilities are discussed in the paper presented and examined in detail with a focus on mechanical, thermal and electrical aspects. Of special interest is the possibility of higher integration and a solution is presented to achieve high accuracy current measurement with digital output and reinforced insulation.

## 1 Introduction

Current sensors are an inherent part of modern inverter technology and need to fulfill different demands depending on the application. Besides costs the space needed, the mounting technology utilized and the temperature range along with accuracy demands and response time are factors that influence the decision as to what sensor is to be used.

An approach very common in inverter design is the use of current transducers as these components provide some obvious advantages. Sensors range from below 1A to several kA. They can easily be mounted without intrusion regarding the wiring. Depending on the necessary response time Hall Effect sensors are available in both open and closed-loop design with package sizes down to SO8 for open loop transducers [1]. If however short circuit protection and short response times are mandatory, closed-loop systems need to be installed. Due to constructional reasons, these are larger in volume and consume more space. One advantage of Hall Sensors is the galvanic separation they provide though in some cases it is a functional insulation only.

A further magnetic field based current sensor is the so called GMR. GMR means Giant Magneto Resistance and refers to resistors that change their value according to a magnetic field applied. Build into a Wheatstone bridge, these sensors allow the measurement of currents by measuring the magnetic field they cause. The complete insulation and the size of the sensor itself are advantageous. These devices, however, are sensitive to magnetic fields of any kind. Furthermore, if no additional measures are taken, the polarity of the current is lost. Also detrimental is the fact that distance to the wire, mounting position and angle between wire and sensor all influence the measurement.

A more classical method to measure currents is using shunts. The voltage drop across the shunt, caused by the current to be determined, is measured. This so-

lution comes with the least expensive sensor but has two major disadvantages. The sensor does not provide galvanic separation and the resistor causes additional losses. However, from new developments in the areas of shunt technology, interconnection techniques, thermal management and signal processing circuitry it is necessary to reconsider shunts for current measurement in modern inverter designs.

## 2 Current Measurement in Industrial Drives

Integrating current sensors into industrial drives usually is done by mounting the sensor to PCB and add the processing circuitry if necessary. While "off the shelf" Hall Effect sensors already contain the electronic to convert the measured signal into an analog signal with scaled magnitude, this particular circuitry needs to be designed if shunts are used. Shunts can easily be mounted on PCB to measure currents in the range of several amperes. The thermal situation gets difficult, however, if currents in a range of up to hundred amperes occur. Due to the losses caused by the shunt in addition to heat coming from power electronic devices and from the PCB, temperatures beyond the level tolerable for PCB materials could be reached. To prevent this from happening, it is mandatory to place shunts in an area where the power losses can be dissipated easily. While mounting shunts to a heat sink leads to additional wiring and additional space needed, including the shunts into a power module is an attractive alternative [2].

### 3 State of the Art

Today, IGBT-Modules like the FS75R12KE3\_B3 form a full bridge with shunts in the output path. With a value of  $1.2m\Omega$  the voltage drop at 75A is 90mV with a dissipated power of 6.75W per output line. The shunts used have a rectangular shape and in thermal aspects benefit from being soldered to DCB and module base plate in a way similar to the IGBT and diode chips [4]. Though this is a well established technology it shows some noteworthy points that could be improved. From the shape and the size, the resistor used today is comparable to the IGBT mounted inside the module. Thus, it also suffers from the same ageing effects. As also the soldering is similar, there is no possibility to use the area below the resistor. In conjunction with the bond wires necessary to contact the resistor's surface the shunt consumes an area of approximately  $10 \times 15mm^2$  as depicted in Fig. 1 below:

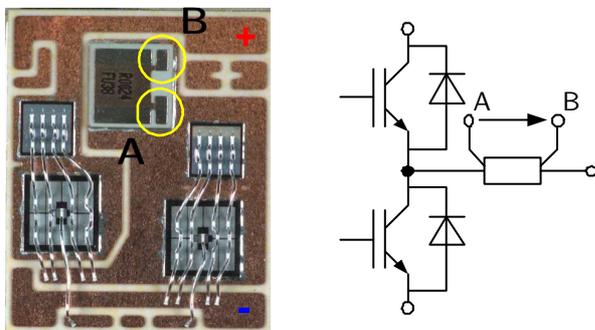


Figure 1: 75A Bridge leg with shunt. Single Module DCB and schematic. Bonds to the shunt not shown for clarity reasons.

The shunt is built in form of a stack consisting of the resistive layer, a carrier layer and a copper layer. After soldering to DCB and base plate the stack appears as shown in Fig. 2: From the similarities with the silicon

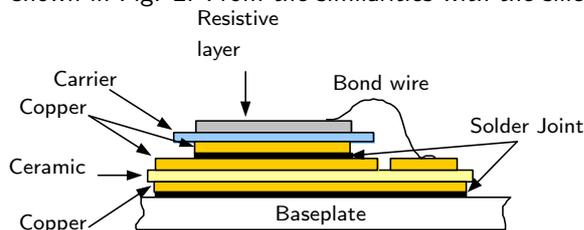


Figure 2: Cross-section of the shunt stack

chip it can be concluded, that power cycling regarding the bond wires could be one destructive mechanism. There also could be delaminating between the resistive layer and the carrier material, the same is possible for the solder joint from copper to base plate.

An improvement would be achieved if

- the solder joint could be removed,
- the necessity of having bond wires could be eliminated
- the resistor consists solely of metal
- the new solution is less expensive or
- the new solution reduces system costs

### 4 New Shunt Development

To eliminate the need of bond wires to carry the main current, a shunt is needed that can directly be connected to DCB-material. Elements providing such a feature are available but these are primarily designed to be used on PCB like common SMD-elements. However, these shunts are inappropriate for integration into power modules as their construction can not withstand the thermal stress. In recent years, manufacturers have developed shunts for higher power ratings predestined to be mounted on IMS or DCB to provide improved thermal properties [5]. Among these, designs with a top hat rail like cross section are most promising. A shunt like this which includes Kelvin Connectors is displayed in Fig. 3 below:

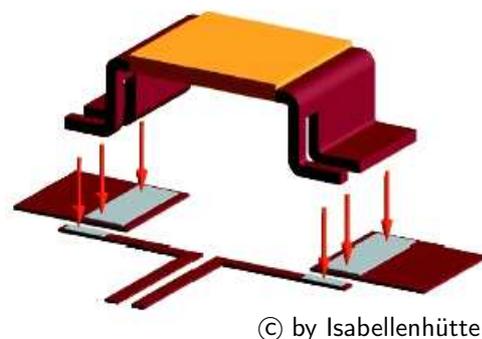


Figure 3: Shunt and appropriate DCB-Layout for soldering

### 5 Improved Interconnections

Still this 4-Wire shunt is soldered to DCB materials and efforts are made to eliminate this kind of connection in future products. Instead of soldering, ultrasonic welding techniques were developed to mount the shunt. This kind of connection comes with several advantages.

The welding process only takes some hundred milliseconds and can be monitored closely. Copious tests were done to determine the quality of the connection as well as the welding process itself. Most noteworthy are excellent mechanical properties of the connection leading to outstanding power- and thermal cycling capabilities. From production point of view no soldering material is needed and no thermal treatment to attach the shunt to the DCB is required. Additionally the mounting procedure takes less time to be completed compared to a soldering process. To achieve a reliable process, a proper sonotrode has been developed that can work as both pick-and-place tool and as welding tool. Fig. 4 shows a sketch of the cross section of the sonotrode after placing the shunt to the position where it is welded as well as the welded shunt itself.

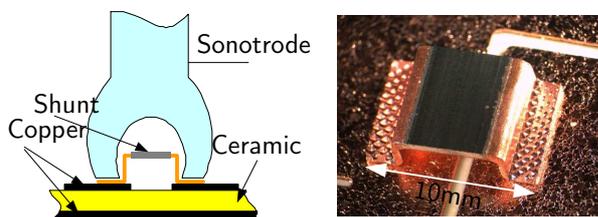


Figure 4: Welding tool and Shunt welded to DCB

To achieve best results with the ultrasonic welding a redesigned shunt that no longer has Kelvin connectors is used. This leads to a highly reliable process and, as described in the following section, did not lead to an unacceptable loss in accuracy.

Measurements revealed that the thermal interface from the shunt to the DCB shows no improvement if soldering is replaced by ultrasonic welding.

The graph in Fig. 5 displays, that a given shunt of  $1.5m\Omega$  reaches almost identical temperatures if a certain current is applied:

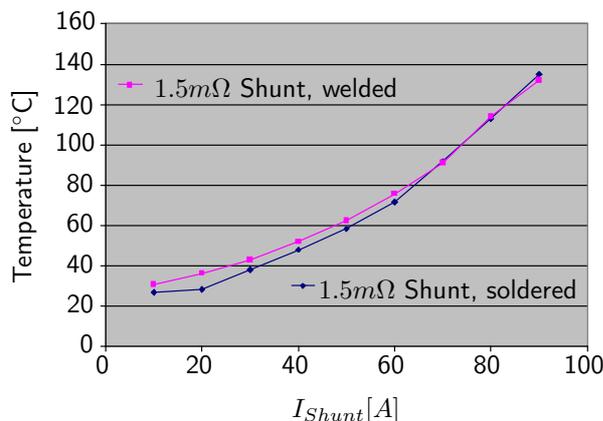


Figure 5: Dependency  $\vartheta_{Shunt} = f(I_{Shunt})$

The ultrasonic welding is supposed to achieve better mechanical stability than the soldered connection.

Thus it is considered an alternative in designs where higher temperatures demand a more robust interconnection.

## 6 Thermal Properties

As the main current flows through the shunt, losses according to  $P_{loss} = I^2 \cdot R_{Shunt}$  occur. The heat developed is the limiting factor in implementing the shunt into a power module for two reasons:

1. The temperature rise has an influence on the shunt value as  $R_{Shunt} = f(\vartheta)$ .
2. The gel inside the module needed for insulation has a maximum rated temperature that may not be exceeded.

The temperature dependency of the shunt value directly influences the measurement accuracy and therefore needs to be minimized. Using proper alloys for the shunt allows for low thermal changes of  $R_{Shunt}$  in a wide temperature range. This is shown in Fig. 6 below for Manganin<sup>®</sup> as resistive material [3]:

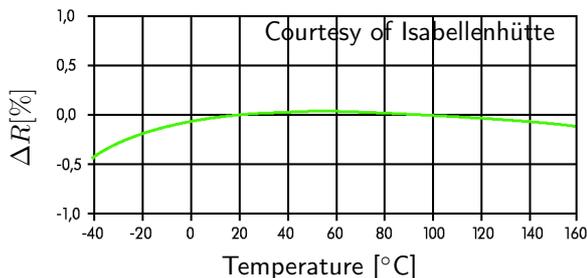


Figure 6: Dependency  $\Delta R_{Shunt} = f(\vartheta)$

Having removed the Kelvin connectors from the shunt the detailed schematic of the sensor changes slightly:

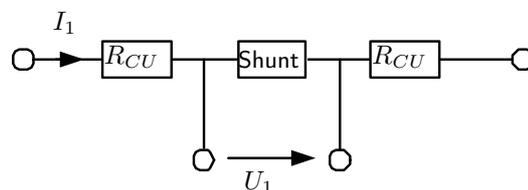


Figure 7: Shunt with Kelvin Connectors

In Fig. 7 the measured voltage  $U_1$  across the shunt is defined by  $I_1$  and the shunt value  $R_{Shunt}$  which only has a low thermal dependency.

In Fig. 8 however, the temperature dependency of the copper connectors adds to the shunt leading to a measured voltage of  $U_2 = I_2(2 \cdot R_{CU} + R_{Shunt})$ .

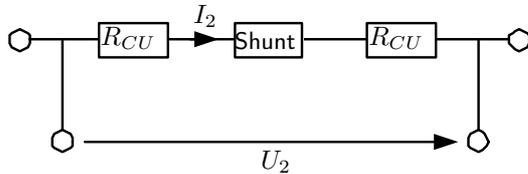


Figure 8: Shunt without Kelvin Connectors

From the shunt geometry the value  $R_{CU}$  can be calculated to be  $11\mu\Omega$  at  $20^\circ C$ . With a linear temperature coefficient  $\alpha_{CU} = 0.0039\frac{1}{K}$  the value changes from  $11\mu\Omega$  at  $20^\circ C$  to  $18.7\mu\Omega$  at  $200^\circ C$  adding a total of  $37.4\mu\Omega$  to the shunt assuming that all the copper reaches  $200^\circ C$ . Observing the shunts operating conditions using a thermographic camera provides an insight into the quality of the connection proposed in this paper. Fig. 9 shows the shunt attached to a DCB on an Econo3 base plate and mounted to a proper heatsink:

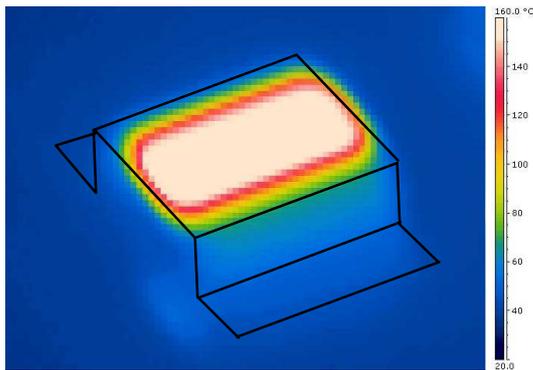


Figure 9: Thermographic picture of the shunt during operation, outline drawn for better overview

The picture is taken with a temperature of  $150^\circ C$  in the center of the shunt and  $40^\circ C$  on top of the DCB. In an application, the base plate temperature is expected to reach  $85-100^\circ C$  leading to a temperature level of up to  $115^\circ C$  for the position the shunt is mounted in. With maximum  $200^\circ C$  allowed for the shunt itself, the copper resistance added to the shunt under these conditions is about  $34\mu\Omega$ .

Using a shunt with a nominal value of  $2400\mu\Omega$  will lead to  $2422\mu\Omega$  at  $20^\circ C$  including the copper and  $2434\mu\Omega$  at  $200^\circ C$  resulting in an increase of less than  $+0.5\%$  which is, due to the thermal properties of Manganin, almost compensated for.

## 7 Galvanic Separation and Signal Processing

Even with the thermal situation improved the main disadvantage of the shunt remains its lack of galvanic separation. However, any equipment that connects the shunt to a microcontroller needs to be designed in a way that it separates control and power electronics. One common way to do so is to have the voltage across the shunt digitized using an A/D-converter that has its supply voltage referenced to the high side voltage. The A/D's digital information is then passed to the control by means of optocouplers. As optoelectronic elements are known to age under high temperature, a further step of optimization would be to improve on this method of transmission. Here, the coreless transformer technology that is already in use in IGBT-Drivers [6] is combined with Sigma-Delta data conversion technology forming an interface to the sensor. The task to be completed by this interface is to read out the electric value, transform it to digital information and transmit this information to the controller level providing reinforced insulation. The schematic for one bridge leg with shunt, high side driver and sigma delta converter both based on coreless transformer technology looks as shown in Fig. 10

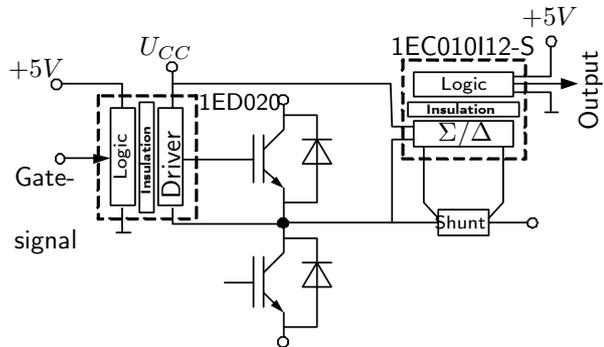


Figure 10: Bridge leg with shunt,  $\Sigma/\Delta$ -Converter and high-side IGBT driver

As can be seen, the supply voltage  $U_{CC}$  provided to the driver is the same as the one supplying the converter, the  $+5V$  needed for the logic are identical to the microcontroller's supply. The insulation achieved by using the Coreless Transformer technology qualifies as reinforced insulation.

## 8 Measured Results

A system as shown in Fig. 10 was first set up in the laboratory to evaluate the measurement. The step response from  $I = 0$  to  $I = I_{Nom}$  was recorded using a LeCroy current probe AP015 and the  $\Sigma/\Delta$ -Converter proposed.

The result is displayed in Fig. 11, the current to be measured was turned on at  $t = 0$ . A resolution corresponding to 16bit was chosen. This in combination with the 10Mhz sampling rate leads to  $6.4\mu s$  between two samples. As a sinc3-filter [7] was used in the setup, three steps of delay appear as expected. The final value is approximated within 6 cycles or  $38.4\mu s$ .

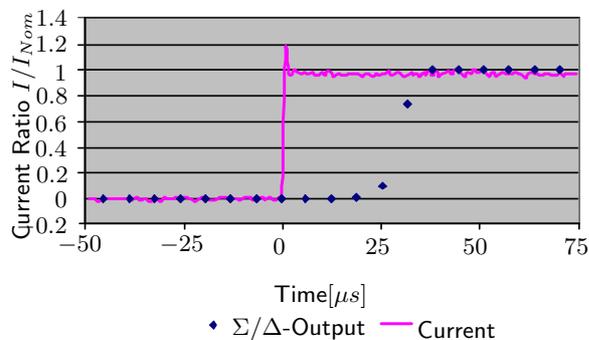


Figure 11: Measured Step Response

It is a feature of the sigma-delta technology that the bit rate can be chosen according to the application's needs. Lower resolution results in faster response but in less accurate measurements as well. Higher resolution provides the more accurate measurement but also increases measurement time. For a modern inverter application it is necessary to determine the instantaneous value of the current within a time corresponding to the inverter's switching frequency. For motor drive applications, this frequency today is up to 20kHz so a response time of the measurement equipment of  $50\mu s$  is sufficient for current control. To be used as a short circuit detection, response times  $\ll 10\mu s$  are mandatory. Though this can not be achieved in form of a measurement, the sigma-delta-technology provides a "workaround". An initial estimate is done in the converter's decimator parallel to the real measurement. If this estimation detects an overcurrent a special signal is generated allowing the user to determine a proper action. In the given example this signal is available about  $2.8\mu s$  after the short circuit occurs. The according correlation is shown in Fig. 12

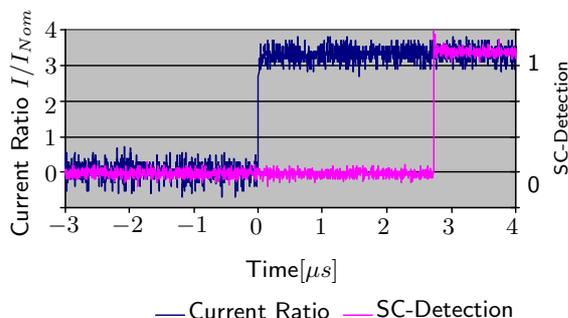


Figure 12: Short Circuit Detection

## 9 Conclusion

New shunts, new interconnection techniques and new signal processing technologies can be combined to form a highly accurate, cost saving current measurement. Improvement also is achieved in thermal design and space requirements due to the integration of the sensor into the power module. Reinforced insulation is provided by coreless transformer technology. The measurement presented in this paper can provide accurate data for regulation purpose as well as information to handle overcurrent situations. Shunt based current measurement remains a very attractive solution for a wide range of power electronic systems.

## References

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