Shunt Current Measuring up to 800A in the Inverter

In 2005, Siemens Drive Technologies introduced the first large inverter using shunts for phase current measuring and brought it into series production. It wasn't until recently that the power output was extended to 132kW with the new inverter SINAMICS G120 series. Back then, the joint development between Siemens, Semikron and Isabellenhütte laid the foundations for being able to measure currents of up to 800A today. This article looks back at past events and takes a glimpse into the future: how was this technological change successful and what possibilities do future developments have to offer?

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There is nothing revolutionary about the current sensing principle using a low value resistor and an isolation amplifier. It was used for the first time by the first isolation amplifiers from HP and Siemens in electric drive systems 15 years ago. Now, there are systems available from numerous providers, which represent interesting alternatives in terms of both technical requirements and cost, and that offer significantly better cost performance ratio than conventional solutions with current transformers.

Demand for more power as well as increased accuracy, lower construction and mounting space, cost reductions and technological innovation led us to focus again on alternatives to conventional current transformers and develop an integrated and modular concept. This concept can be adapted to all inverters in the entire power range from 100W to 100KW, both electrically and mechanically. The aim was to make technical improvements to the new SINAMICS G120, while at the same time increasing market acceptance by reducing prices.

Figure 2 shows the principle of isolated current sensing using a shunt. The voltage drop on the shunt is converted inside Sigma/Delta (Σ/Δ) transformers into a serial 1 bit data stream. It is transferred by optical, capacitive or magnetical couplers via isolation paths and is integrated into a digital filter (ASIC or μC). A shunt (or a number of shunts running parallel) and a Σ/Δ transformer are required for each output phase that has to be measured. The comparable solution with a current transformer requires the current transformer itself, an A/D converter, as well as an ASIC for each phase.

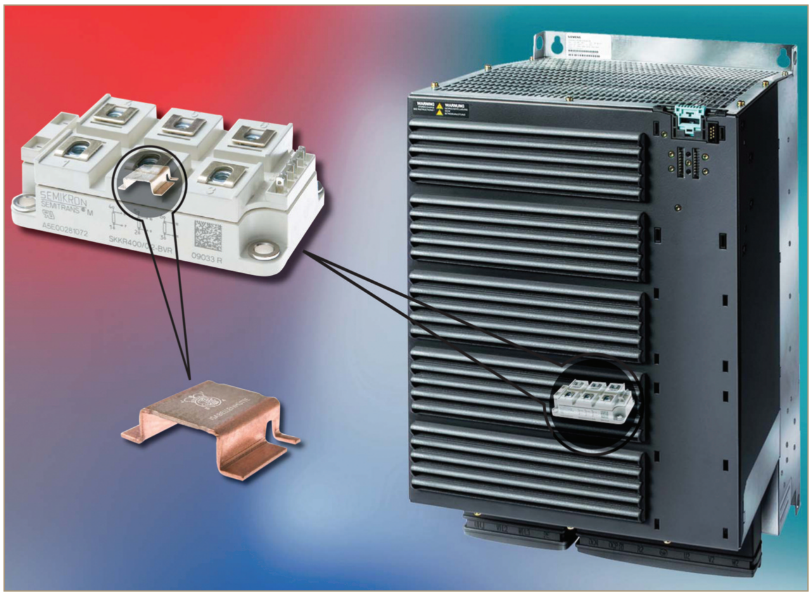

Figure 1: **Isabellenhütte and Semikron act as main suppliers for Siemens Drive Technologies**

At the time, the main development goals and demands on the new solution were as follows:

- Cutting costs in phase current measuring and with a simpler mechanical construction
- Reduced mounting space and weight reduction
- Accounting for power dissipation in the shunt
- Developing a suitable shunt module for high currents
- Increasing the accuracy of the entire system

Cost analysis

Comparing the costs of conventional current measuring (compensation transformer + U/f transformer) to those for shunt measuring, it is evident that shunt

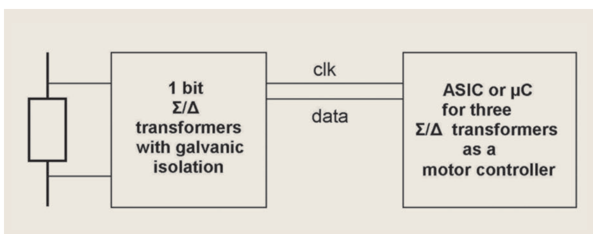

Figure 2: **Basic diagram of current measurement using a shunt**

Output Current (Aeff)	Transformer	Shunt
0…10	100%	~ 45%
10…100	100%	~ 75%
100…250	100%	~ 90%

Figure 3: Cost comparison between current measuring method using transformers and shunts

Output Current (Aeff)	Transformer (%)	Shunt (%)
1	7	0.3
10	2	0.8
100	0.3	0.9
250	0.1	0.9

Figure 4: Loss comparison between current measuring method using transformers and shunts

measuring is considerably more cost effective with the same or even increased performance. 90% of modules demanded by the market are in the lower power ranges up to 100A, where the greatest cost savings can be made.

Costs can primarily be saved due to the first step being less sophisticated (transforming current into voltage). The downstream digitisation of the measurement voltage is associated with the availability of new transformers at almost the same cost. Galvanic isolation is not a significant cost factor thanks to the serial transfer of digitised data and is therefore no longer the significant advantage for the compensation transformer that it used to be (see Figure 3).

Lower construction volume

In the power range up to 50A, current can still be carried via the printed circuit board. This means that all measurement value logging from SMD shunts is in comparison to transformers extremely compact and cost-effective. For higher currents, the current has to be carried via bus bars and the higher power loss respective heat generation in the shunt requires adapted construction forms.

The fourth generation of IGBTs has a permissible junction temperature of 175°C. All of its predecessors were rated at 150°C or below. The trend towards higher temperatures – with increased packing density – benefits the shunt sensing process.

Power dissipation

For the current transformers, losses arise in the compensation circuit, load resistor and in the subsequent U/f transformer. The losses in the compensation circuit are mainly independent of the measured current. However, losses in the load resistor and the output stage of the compensation circuit are current dependent.

When measuring with shunts, the power losses in the shunt for a given maximum sensing voltage are directly proportional to the current according to the following equation:

$$P_{v,SHUNT} = I^2 R_{SHUNT} = I * U_{SHUNT}$$

The maximum power dissipation is determined by the voltage range of the Σ/Δ converter, which is at 0.2V for most existing current systems. At 10A, this corresponds to power dissipation of only 2W, which can be handled easily by available SMD resistors. This is different for currents of 300A for instance. A full voltage range of 200mV would already generate 60W per phase, which is the reason that design engineers try to use only half of the converters voltage. Nevertheless, the still considerable output of 30 to 100W can only be handled insufficiently with conventional shunts, which is why the power modules mentioned above were developed based on proven high power modules.

Overall, it is evident that the heat generation in the shunts for low currents is no problem, whereas at the upper end of the current range it needs new solution to get rid of the heat. But nevertheless, the losses in the shunt are only less than 2% of total inverter losses at maximum current. Figure 4 shows a comparison between losses of the old (transformers) and the new measuring method with shunts.

Shunt module

The shunt modules developed by Semikron (module housing) and Isabellenhütte (shunts) for high currents are optimised in terms of TCE (thermal coefficient of expansion), offset, long-term stability and capacity, and therefore meet the above-mentioned requirements almost perfectly. They contain a parallel circuit of up to four precision SMD resistors (see Figure 5) for each phase, which are mounted onto a DCB substrate for better heat dissipation. By using optimum resistors and modified geometry for the DCB layout, a TK of 30ppm/K will be maintained for all modules.

The shunt modules are used by Siemens in all new SINAMICS inverters in the corresponding performance class. Since their introduction, over 100,000 modules have been deployed in industrial applications with big success. Table 1 gives an overview of available Semikron modules.

These RoHS conforming modules are limited to a nominal voltage of up to 690VAC. However, the current load limit for this module form has been reached with the SKKR 800/0.1 model, in spite of adaptations to the plate geometry of the current supplies. The altered plate geometry helped improve the module's robustness and reliability, and the exterior shape remained the same, making integration in the device possible with the same rails.

Since 2005, the sensing limit has increased from 400 to 600A. A higher powered module would require the following:

- Adapting the resistance value of the shunt to higher currents
- New module housing for higher currents
- Stronger power rails
- Reducing lead losses

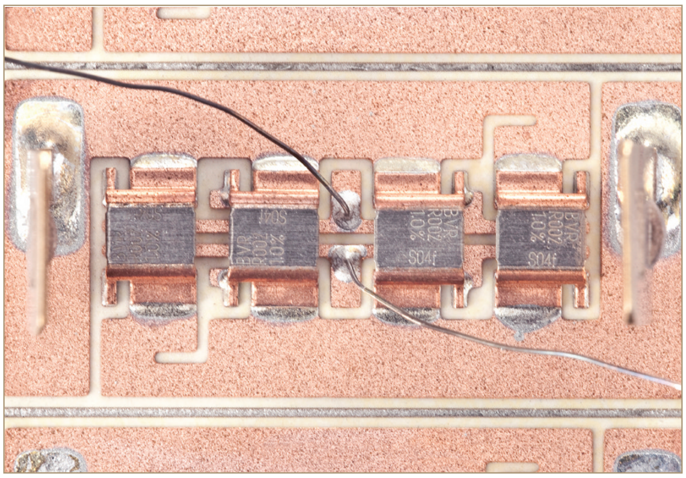

Figure 5: Paralleled circuit with up to four BVR resistors used for each phase

		SKKR 200/0.2	SKKR 300/0.2	SKKR 400/0.2	SKKR 800/0.1
Long-term measuring current (A)	DC (80°C)	100	150	200	400
Max. measuring current (A)	AC	200	300	400	600
Measuring voltage	in mV with max. current	211	211	211	150
P_{tot} for each phase	in W with nominal current	11	16	21	42
P_{max} for each phase	in W with max. current	42	64	85	94
R_{Shunt}	in **mΩ** for each phase	1.06	0.71	0.53	0.26

Table 1: **Overview of available Semikron shunt modules**

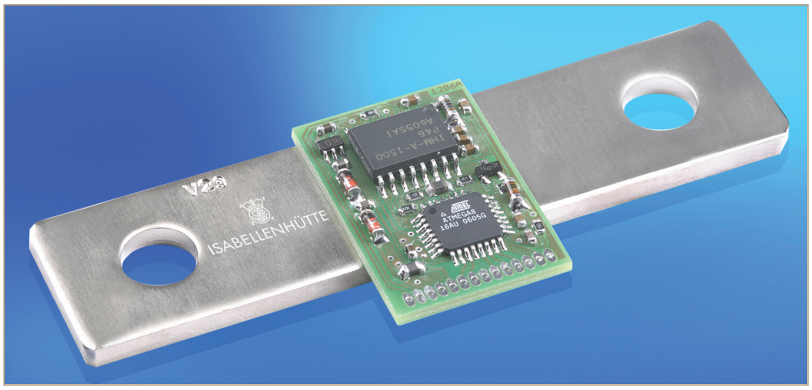

Figure 6: **IMC calibrated sensor module**

- Potential parallel circuiting of modules
- Reducing the voltage output of the transformer.

Additional advantages of these modules include:

- Familiar housing
- It is easier for the construction to integrate the module into an existing concept and potentially add available materials (rails, insulator supports, etc.)
- Customised solutions can be produced relatively quickly.

Measuring accuracy requirements

The quality of any measuring system is determined by the resolution, offset, noise, gain and linearity errors, as well as by temperature and long-term drift. The absolute accuracy of the actual current values has a direct impact on the performance of an inverter or the drive. Using these types of inverters in machine tools permits machining of a surface with a quality better than 0.2μm due to a very low torque ripple.

The resolution is primarily determined by digitisation and is less dependent on the analogous path, as a result of which this issue is not discussed here any further.

Siemens' target for offset errors was <0.1%. Both current measuring methods were able to meet this requirement. With shunt sensing, it is extremely important to select the right resistance value, materials and resistance model. A material that is not adapted thermoelectrically to copper (e.g. constantan) produces a thermoelectric voltage and an offset voltage, which makes it impossible to meet the offset requirement in the temperature range. This error can be avoided completely by using Isa-Weld resistors made from Manganin or Isaohm, where only the offset of the Σ/Δ converter remains.

The requirement for gain errors (deviation between phases) is <0.9%. In addition to the accuracy of load resistors, the exact number of turns of compensation winding in a current transformer is critical, while for shunt measuring, the accuracy of the shunt and that of the Σ/Δ transformer plays a significant role. However, when comparing these errors in a performance test, temperature and resistance drift over time is more important than complete accuracy. The Isa-Weld resistors deliver

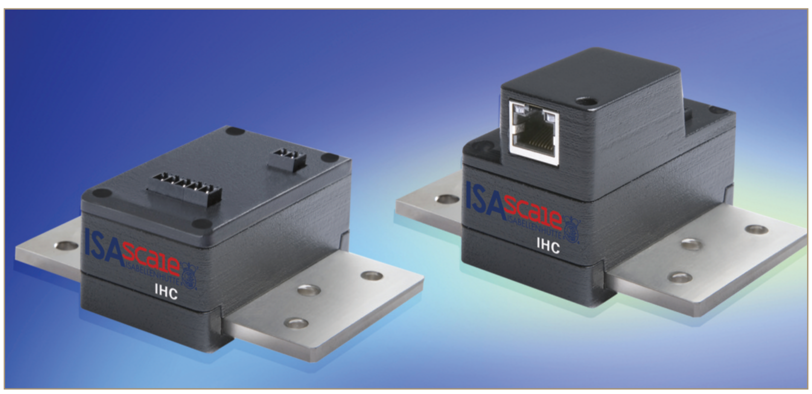

Figure 7: **IHC measuring module with galvanic isolation for currents up to 2000A**

optimum values for these measurements and comfortably meet the requirements.

Both methods can meet the requirements for linearity without any special measures being taken. However, shunt measuring still has a lot of unused potential in this respect.

New developments and outlook

In spite of the advantages shunt current sensing has to offer versus current transformers and other magnetic measuring methods, there are still limitations in the power output over 600A as a result of extremely high power generation within the shunt. Parallel connection of numerous modules may solve the heating problem, thanks to the linear dependency of power dissipation on the current output. However, this solution is not ideal because of the space requirement and cost aspects. Power dissipation of 30 to 100W just for the measurement cannot be justified in the long-term, particularly as the trend towards using electric energy economically is becoming continuously stronger.

That is why further considerable improvement and innovation in measuring technology are inevitable for shunt measuring applications in other sectors, such as automotive technology or solar technology. The interesting market volume and the achievable margins have triggered a real flow of ideas in the area of isolated Σ/Δ converters. In addition to galvanic isolation via optocouplers, transformers based on magnetic or capacitive couplings are now available from several manufacturers. This competition has led to a significant reduction in prices and an improvement in the product's characteristics. The next aim will be to reduce the input voltage range (200mV = >50mV = >20mV) while maintaining the same accuracy. This would offer the advantage that power dissipation could be reduced by up to one order of magnitude, while the solutions be even more compact with lower cost. An example of a solution from Isabellenhütte: the calibrated sensor module for direct measurement of +/-300A current, voltage and temperature with a communication via an isolated digital interface (see Figure 6).

The number of semiconductor manufacturers for Σ/Δ converters will continue to increase if the requirement for isolation is dropped, and costs will come down due to reduced complexity of the product and increased sales. Galvanic isolation of the digital signals via just a single coupler can be very cost-effective if the clock and data are transferred together in Manchester code.

It goes without saying that the requirements on the overall design will also increase. In an effort to eliminate interferences from the strong alternating magnet fields, the Σ/Δ converter will have to be mounted right next to the shunt, or even together with the shunt, which in turn, also reduces size and cost. These types of modules with an integrated current sensing (200mV converter) have already been introduced. In this case, high power dissipation results in unnecessarily large and expensive solutions. Figure 7 shows the IHC measuring module with galvanic isolation for currents up to 2000A.

It is likely that new semiconductor developments in downstream electronics will also contribute to this technology becoming more widely used in the drive technology and solar technology sectors. Motor controllers are currently being prepared, which are able to directly process the data streams of all three shunts (three phases) and convert them into a digital 12 to 14bit signal with a higher sampling rate. The measurements can be triggered at a given time after the switching edge of the power transistors and a rapid over-current signal is generated.

Given the lower power dissipation in the shunt, the module will become considerably smaller in the long-term (possibly even be separated for each phase) and will directly contain the Σ/Δ converter and additional electronics. Furthermore, directly mounting the transformer or the circuit board onto the shunt is a practical way of avoiding interferences.

Isabellenhütte has launched a number of preliminary developments in this direction. Prototypes for these types of solutions are available on request.