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High Bandwidth Magnetoresistive Current Sensors Open up New Possibilities in Power Electronics

The trend to higher switching speeds in order to increase the power density of power electronics is leading to increased demand for high bandwidth current sensors. At the same time there is growing demand for current sensors with low power losses and high insulation strength to satisfy the needs for high efficiency and high robustness respectively. Magnetoresistive (MR) current sensors offer performance benefits compared to more traditional hall-effect based current sensors or shunts.

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The magnetoresistive effect is best known from the read heads of computer hard discs or from magnetic memory (MRAM) applications, but it is also well suited to uses in sensor technology. It has a long history, the anisotropic magnetoresistive (AMR) effect being first discovered in 1857 by Lord Kelvin. The AMR effect occurs in ferromagnetic materials, such as nickel-iron layers structured as strip elements, whose specific impedance changes with the direction of an applied magnetic field. Due to a special structure of the strips the resistance change is proportional to the applied magnetic field over a wide range. This means that by adept design of the sensor structure very small magnetic fields can be detected with very high accuracy.

However, the MR-effect did not experience widespread use until the early 1980s, when the first MR-based read heads were implemented in hard disc drives. The first industrial applications for MR-based sensors followed at the beginning of the 1990s, since when the number of applications has increased dramatically. The applications are not only limited to terrestrial use – MR sensors are used to control the electric drives used on "Curiosity", the Planetary Rover that landed successfully on Mars in August 2012. MR sensors are also used extensively in safety-critical automotive applications, for example in wheel speed sensors for the ABS (anti-lock braking) system or in steering angle sensors for the ESP (electronic stability program) system. The small dimensions, large air gap and high accuracy make MR sensors a good replacement for resolvers or synchros in angle and speed measurement applications.

Figure 1: CMS3000 high bandwidth current sensor (Source: Sensitec GmbH)

The magnetoresistive effect is also particularly attractive in the field of electrical current measurement. The very high sensitivity means that there is no need to use an iron core to concentrate the magnetic field generated by the conductor carrying the current. This means that MR-based current sensors do not suffer from hysteresis and that they have a significantly higher bandwidth. Compared to shunt resistors MR-based sensors have the benefit of galvanic isolation and dramatically lower power losses. This is particularly important in high voltage applications and where overall power efficiency is a major design driver, as the case of electromobility or "more electric aircraft" (MEA) applications.

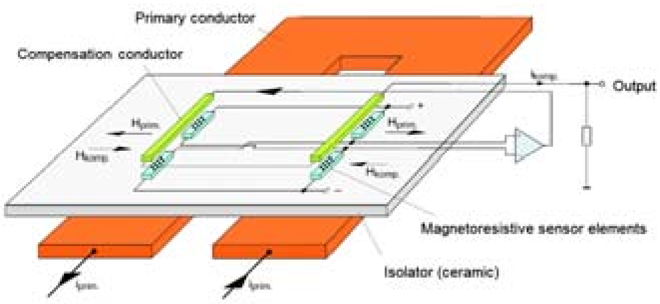

Figure 2: Principle of operation (Source: Sensitec GmbH)

Magnetoresistive current sensing

Sensitec has a long experience of developing MR-based current sensors for industrial applications. The increased demand for compact highly dynamic current sensors generated by recent trends in power electronics for electromobility was the driver for the development of a high bandwidth current sensor (CMS3000) comprising an AMR sensor chip, a signal conditioning circuit and two biasing permanent magnets (Figure 1) [1].

The latter are necessary for maintaining the initial magnetization direction of the AMR structures in the case of overcurrent situations. The permanent magnet material and the AMR-sensitive sensor material are applied onto wafer substrates by a special process and thus can be processed further with standard semiconductor methods, concerning singularization or assembly.

The quantity to be measured is a differential magnetic field, which is the field gradient generated by two currents with opposed current flow directions. For current measurement four AMR "resistors" are connected to form a Wheatstone Bridge. The resistors on the silicon chip are placed so that they constitute a differential field sensor. This is necessary because interference fields can be eliminated this way. Combined with a signal conditioning and processing circuit the chip is assembled onto a ceramic substrate. The primary current conductor has a U-shape, with its straight parallel parts positioned underneath the AMR sensor chip on the other side of the substrate (Figure 2).

Furthermore, a compensation conductor is integrated on the chip, with which a magnetic field can be generated close to the resistors. The geometry of the primary conductor defines the measurement range of the current sensor. Based on the output signal from the MR chip, the signal conditioning and processing circuit generates a current I_{comp} in the compensation conductor, which compensates the magnetic field generated by the primary conductor in the plane of the AMR resistors. With this method the signal achieves a high linearity (0.1%) and is largely independent of temperature. This compensation current is directly proportional to the primary current to be measured and is used to generate the output signal from the current sensor.

This "closed-loop" principle results in an extremely compact sensor that is largely insensitive to homogeneous interference fields and temperature changes, with a low power consumption and very high efficiency. The AMR-based current sensor exhibits no hysteresis as observed in iron core based Hall-sensor solutions and no remaining magnetic offset after overcurrent events. Due to the high sensitivity of the AMR sensor chip, a flux concentrator is not necessary.

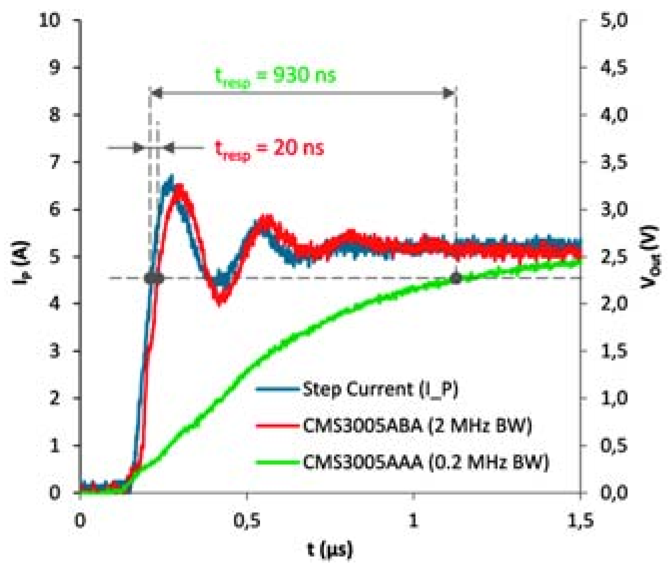

Figure 3: Step response (Source: Sensitec GmbH)

The sensor is designed for high accuracy and very fast electronic measurement from DC up to 2 MHz AC. Contrary to Hall-effect based sensors, the described system enables differential magnetic field measurement by means of an advanced geometry of the magnetoresistive elements. Due to this construction the sensor is immune to homogeneous interference fields and hence needs no magnetic shielding as often required for Hall-effect current sensors.

CMS3000 high bandwidth current sensor family

The key specifications of the CMS3000 current sensor are listed in Table 1. The current sensor is available in 5 different sizes, covering the rated currents 5, 15, 25, 50 and 100 A. All sizes can measure a peak current of up to 3 times rated current. Figure 3 shows the step response of the new current sensor family, compared to a current sensor with 200 kHz bandwidth. The response time is of the order of 40 ns (nano-seconds), which is almost 50 times faster than the previous product generation. The -3dB cut-off-frequency of the new current sensors is well in excess of 2 MHz. There is no frequency derating as experienced with hall-based sensors (at lower frequencies than this). This extremely rapid response can be used to protect power transistors in the event of a short-circuit.

Parameter	Min.	Typ.	Max.	Unit
Supply voltage	± 11.4	± 15	± 15.7	V
Primary nominal current	5	-	100	A
Primary measuring range 1)	15	-	300	A
Nominal current consumption	-	50	60	mA
Upper cut-off frequency (-3dB)	-	2	-	MHz
Response time (s)	-	40	-	ns
Overall accuracy 2)	-	± 1	-	% of I_{PN}
Operating temperature range	- 40	-	+ 105	°C

1) Restricted to 1 s in a 60 s interval.
2) The overall accuracy includes offset, linearity and sensitivity error
Table 1: Key specifications for CMS3000 current sensor

A more detailed description of the principle of operation and the advantages of the CMS3000 can be found in [1].

Application Example: DC/DC converter for aerospace

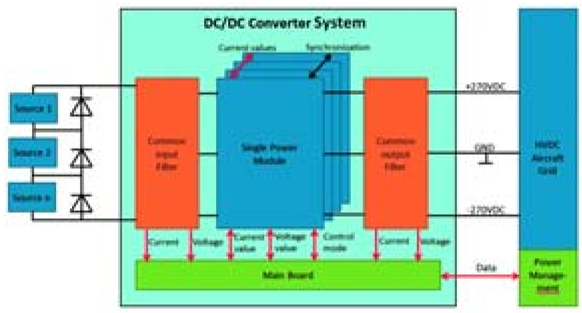

Figure 4: Block Diagram DC/DC Converter
(Source: EADS Innovation Works)

An area of particularly dynamic development in power electronics is in the field of "more electric aircraft". These developments have the primary objective of reducing CO_2 emissions and also reducing noise emissions. One specific project, undertaken by a leading German aerospace supplier, concerns the replacement of the turbine driven auxiliary power unit (APU) by means of a green energy source, such as a fuel cell. The fuel cell provides energy to a high voltage DC power distribution grid, which offers the additional potential benefits of higher efficiency, reduced complexity and significant weight savings compared to the state of the art. A high voltage DC grid is already standard in military aircraft and has been introduced for the first time for passenger aircraft on the Boeing B787 Dreamliner. There are several methods of supplying such a grid, either by AC generators, or by DC sources such as fuel cells or batteries. In order to connect these different kinds of sources to the same grid DC/DC converters are necessary [3]. Figure 4 shows the block diagram of a new DC/DC converter based on a cascaded buck boost topology [4].

A further innovative feature of the new design is the use of low voltage sources connected in series, in order to provide a high level of fault tolerance. As shown in Figure 5 and Figure 6 the converter consists of several identical single power modules (SPM), each of which features CMS3050 current sensors, with a rated current of 50 A. The switching frequency of the converter is 200 kHz and the CMS3000 allows the inductor current signals to be measured in the middle of the rising edges. This reduces the impact of the switching edges of the power switches. The extremely high bandwidth of the MR-current sensors also provides short-circuit protection for the converter.

Laboratory tests of a single power module (Figure 7) have demonstrated an efficiency of up to 96 % for a power range from 0.7 to 4 kW. The weight of the complete DC/DC converter is expected to be just 10 kg.

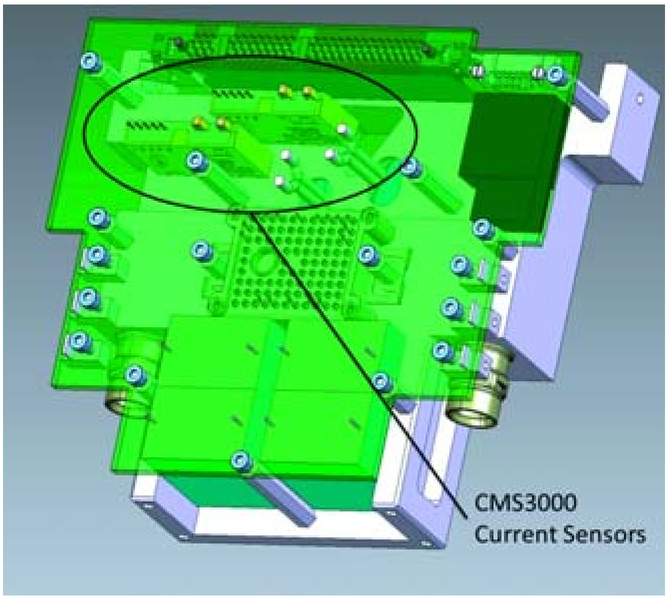

Figure 5: Single Power Module (Source: EADS Innovation Works)

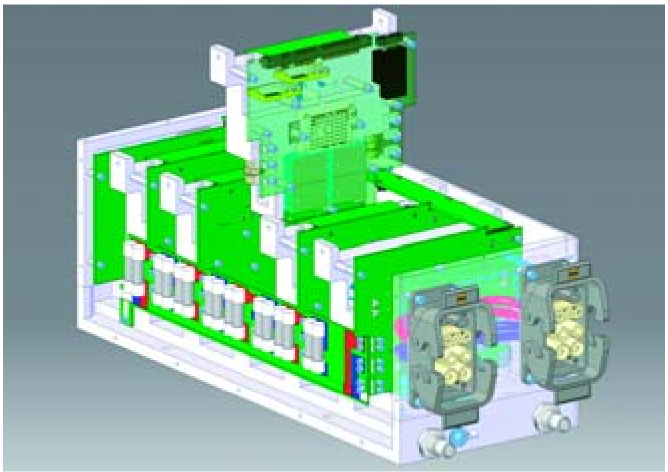

Figure 6: Complete DC/DC Converter (Source: EADS Innovation Works)

This family of high bandwidth magnetoresistive current sensors is not only interesting for aerospace applications [5], but also for electric vehicles [6]. The potential applications range from DC/DC converters to rectifiers, inverters, gate drivers, switched power supplies and power electronics for inductive, cable-less charging devices for electric vehicles. The high bandwidth not only enables higher switching frequencies and provides improved short-circuit protection, but also opens opportunities for the improved condition monitoring of power electronics equipment.

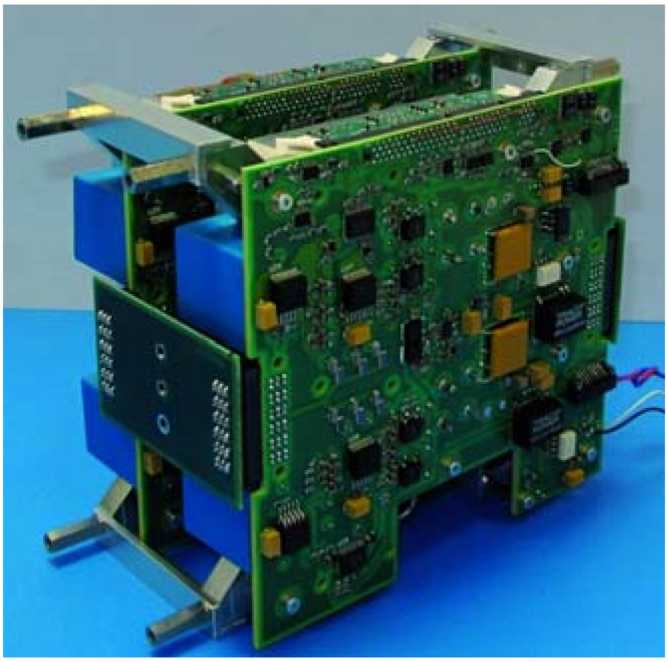

Figure 7: Technology Demonstrator (Source: EADS Innovation Works)

References

[1] Slatter, R. et al; "Highly dynamic current sensors based on Magnetoresistive (MR) technology", Proc. of PCIM Conference, Nuremberg, Germany, 17th – 19th May 2011

[2] Slatter, R.; "Highly integrated magnetoresistive sensors in aerospace applications", Proc. of Sensors 2013 Conference, Nuremberg, Germany, 14th – 16th May 2013

[3] Kaiser, A. et al. "Design of a lightweight DC/DC converter providing fault tolerance by series connection of low voltage sources", Proc. of 1st Aerospace Sensors Conference, Frankfurt / Main, 7th – 8th November 2012

[4] Kaiser, A. et al; "Design of a Lightweight DC/DC Converter Providing Fault Tolerance by Series Connection of Low Voltage Sources", Proc. of More Electric Aircraft Conference, Bordeaux, France, 20th-21st November 2012

[5] Hartmann, M.; Ultra-Compact and Ultra-Efficient Three-Phase PWM Rectifier Systems for More Electric Aircraft, PhD Dissertation, ETH Zürich, 2011

[6] Bockstette, J. et al; "Bidirectional current controller for combination of different energy systems in HEV / EV", Proc. of 5th International Conference on Power Electronics, Machines and Drives (PEMD), Bristol, UK, 27th – 29th March 2012

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