A Novel Contactless Current Sensor for HEV/EV and Renewable Energy Applications

Abstract: **The novel contactless current sensors consist of an integrated CMOS Hall effect sensor covered by a thin, ferromagnetic layer structured on its surface. The Integrated Magnetic Concentrator (IMC) layer acts as a magnetic flux concentrator, providing a high magnetic gain which increases the sensor's signal-to-noise ratio. The sensor is particularly appropriate for DC and AC current measurement. Such measurements are characterized by the need for ohmic isolation, very low insertion loss, fast response, small package size and low assembly costs. Typically, current sensors are found in applications such as battery current monitoring, solar power inverters and power inverters that drive traction motors in hybrid electric and electric vehicles (HEV/EV). The presented IMC current sensors have no upper limit to the level of current measurable since their output level is only dependant on the conductor size and its distance from the sensor. This article explains how IMC current sensors are designed, how they perform, and how they are applied in these applications.**

Introducing Current Sensors

Traditionally, electrical currents are either measured by resistive shunts, current transformers or magnetic sensors. Resistive shunts are popular however magnetic sensors offer many advantages at the system level. For instance, magnetic sensors operate contactless, and do not require galvanic isolation between the current conductor and the sensor. Resistive shunts transform electrical power into heat, creating in some applications thermal management costs and troubles, magnetic sensors avoid these issues. Additionally, CMOS Hall-effect based magnetic sensors can integrate advanced features to provide high-level output signals. Sophisticated magnetic sensors contain programmable memory and even microcontroller logic to allow for a fully custom calibrated output. It is even possible to implement standard interfaces simplifying communication with other circuits.

Unlike coils in current transformers (CT), which measure the time-derivative of the magnetic flux, Hall sensors yield a signal proportional to the flux density itself. This makes practical measurement of both DC and AC current.

The widespread use of electronics in automotive applications, renewable power conversion (solar and wind power), power supplies, motor control, and overload protection demands engineers use more effective current measurement techniques. These applications benefit from robust, reliable, isolated, high speed, and low-cost current measurement techniques provided by integrated IMC sensors.

Current Sensor with Integrated Magnetic Concentrator

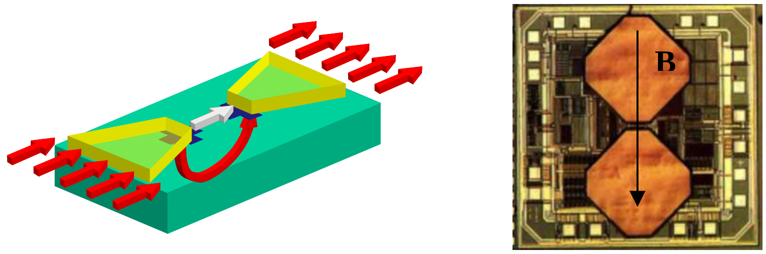
The solution for these demanding applications lies in the open-loop Hall-effect current transducer, especially the IMC–Hall sensors like the MLX91205 and MLX91206. With rapid response times of less than 10 microseconds, galvanic isolation to avoid issues related to HF common mode voltages, thermal isolation, compact size, 5V operation, robustness, machine mountable standard packaging, and economical pricing, an IMC current sensor is an appropriate candidate for these applications.

Some key features of this current sensor include sensitivity to magnetic fields parallel to the chip surface, linear output voltage proportional to the magnetic field, zero power loss in primary circuits, very high sensitivity, excellent nonlinearity, wideband (DC to 100kHz), low offset and offset drift, very low noise, and isolation from the current conductor. All this is housed in compact surface mount SOIC-8 package. In essence, it produces an analog linear, ratiometric output voltage that is proportional to the applied magnetic field parallel with the chip surface.

Practically, the current sensor integrated circuit is fabricated using a standard CMOS process. The additional ferromagnetic layer, also known as the integrated magnetic concentrator (IMC), is added in a simple post processing step. The ferromagnetic layer amplifies the magnetic field and concentrates it on the Hall elements. Consequently, the IMC-Hall effect sensor features very high magnetic sensitivity, low offset, and low noise in a compact, cost efficient package.

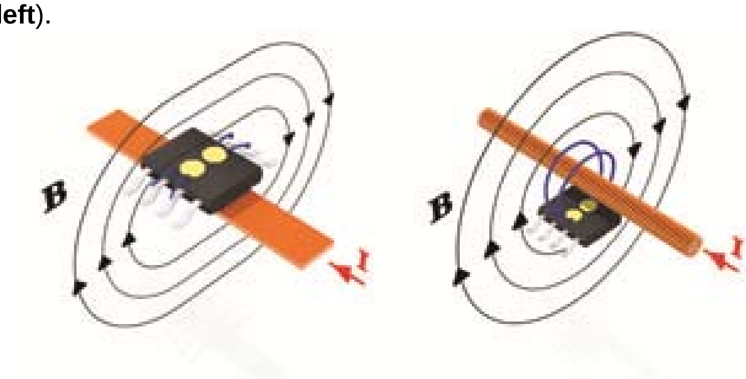
The IMC consists of a highly permeable, low-coercive-field, amorphous ferromagnetic layer directly bonded onto the Hall sensor chip's surface. An IMC, which is approximately the size of the integrated circuit, "sucks-in" the external magnetic flux lines and directly concentrates them onto the Hall elements, which are about one tenth the size of IMC.

Figure 1



The two parts of the IMC collect and amplify the small magnetic flux parallel to the chip surface (e.g. generated around a current-carrying conductor) and locally rotate the in-plane component into a magnetic field perpendicular to the chip's surface. Whereas a conventional Hall sensor is sensitive to a magnetic field perpendicular to its surface, the IMC-Hall sensor is sensitive to a magnetic field parallel to its surface.

The IMC-Hall sensor is packaged in a standard plastic SOIC-8 package so that it can be mounted onto a printed circuit board (PCB) using standard pick-and-place machines and soldered using conventional soldering techniques. The measured current is sent either directly through a current track of the PCB located under the sensor **(Figure 2, right)**, or the sensor is mounted at a given distance from a larger current conductor (**Figure 2, left**).



In both the configurations, the magnetic flux around the current conductor enters the sensor on the outside of one octagonal IMC element, then passes through the Hall elements under the gap, and exits the other octagon on the opposite side. Since the material used for the IMCs has a very high permeability, the concentrator collects all the flux lines in its vicinity and focuses them on the Hall elements where the flux density is increased by a factor of about six.

Applications and Results

To demonstrate its usefulness in a variety of applications, a few examples are illustrated**.** Figure 3 shows a current sensor constructed for a hybrid electric vehicle (HEV) inverter application with a current range of 200 A. The sensor was placed into an inverter driving a 3-phase traction motor of an HEV (Figure 4).

Figure 3

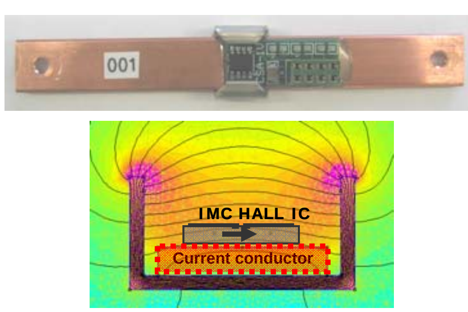
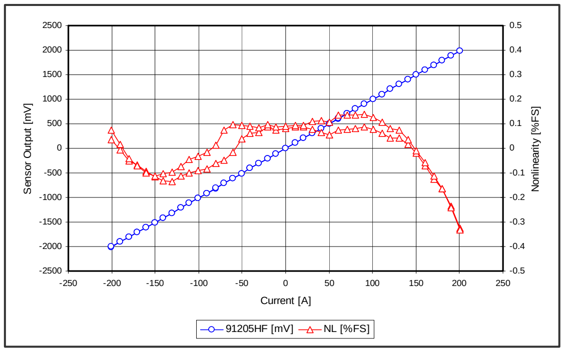


Figure 4

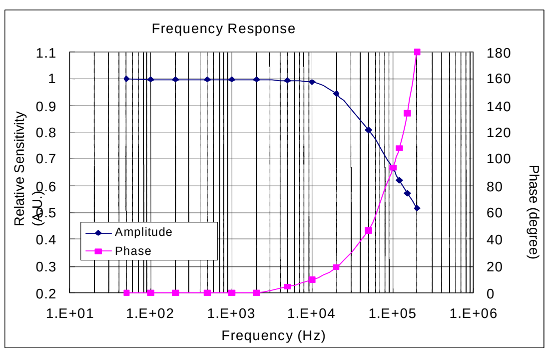
The current sensor module's sensitivity measures 10mV/A, and yields an output voltage of +/-2V for +/-200A. It also exhibits a response time of <8µseconds, and <0.3 percent linearity over the full current range.

Figure 5



The IMC Current sensor Hall-ICs typically operate in ranges from a few A to 1000A, very high bandwidths (Figure 6), ranging from D.C. to 100kHz, fast response times, and a resolution >0.1 percent of the full scale range.

Figure 6

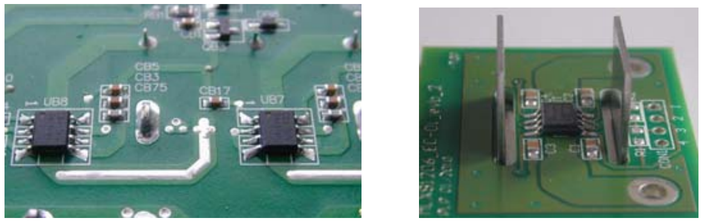


The sensor's current range is only limited by the geometry of the conductor and the shield. The current range may be increased easily by increasing either the cross-section of the bus bar, or the distance between the sensor and current conductor. In essence, it is designed to monitor currents from 5 A to 100 A on PCBs or up to 1000 A on bus bars.

Concurrently, demand for clean energy sources is growing rapidly worldwide. As a result, production of solar and photovoltaic cells has expanded dramatically. For these applications, efficiency of each and every photovoltaic cell in the array is important to compete with the cost of fossil fuel generated electricity. Hence, the current and voltage of every panel used in this application is precisely monitored to optimize the energy transfer. By precisely measuring the current in these applications, the current sensor ensures that efficiency of the solar power converters is optimal at all times and under all conditions.

The focus here is on improving the efficiency of the photovoltaic cells, which makes a significant difference in the success of the product in the marketplace. In such solar-power converters, which require smaller currents, the sensor directly monitors the current flowing within a PCB track as shown in Figure 7.

Figure 7



Similarly, current sensors are used in motor control systems to control the torque and improve the reliability by detecting fault conditions which protect the motor. Motor current control applications include cooling fans, water pump motors and much more. Some intelligence may also be included with the current monitoring to help protect against trapping.

Likewise, current-monitoring can also be used to optimize the efficiency in power supplies. Once the power information is available inside the power supply unit, it can be used for real-time control of output voltages and currents. For instance, in systems like data storage, servers and telecommunication equipment, current sensors can be used to control the power consumption and optimize performance by adapting the load behavior to minimize power dissipation and maximize efficiency.

Such techniques are becoming attractive for DC-DC and AC-DC power converters used in data centers, where power consumption has become the most critical cost factor from the data center’s budget standpoint. As energy prices continue to climb upwards worldwide, and the pressure to cut energy wastage mounts, there is increasing pressure on these facilities to use electrical power more efficiently. Major sources of inefficiency in these applications are DC power supplies, which are typically only about 70 percent efficient. Google requires 90 percent efficiency from its’ data centers. The extra cost of this higher efficiency is easily compensated for by the reduced power consumption over the lifetime of the power supply. As a result, IMC current sensors are becoming attractive in these applications to monitor current and reduce wastage.

Another application that can benefit from the IMC-Hall current sensor is the smart grid. By monitoring the current and power usage inside homes via smart meters, home owners can significantly cut energy wastage and save money, in addition to fighting global warming by reducing power consumption. Studies show that access to a household's personal energy information is likely to save between 5–15% per month.

Google, in fact, is committed to this cause of giving people access to personal energy information so that they can make smart energy choices. For that, the search engine giant is developing a meter called the Google Power Meter, which will show consumers their electricity consumption in near real-time in a secure iGoogle Gadget. The Google Power-Meter receives information from utility smart meters and energy management devices and provides customers with access to their home electricity consumption right on their personal iGoogle homepage. Today, CTs are mostly used in this application. However, the IMC Hall current sensor is an attractive alternative because of its small SO-8 package, wide current sensing ranges, very high bandwidths, rapid response times, and resolution >0.1 percent of the full scale range.

In modern portable electronic devices, battery management is critical for achieving longer life. Hence, these devices are integrating smart fuel gauges to monitor and supervise the charging and discharging functions of batteries. Some designs rely on over current protection, especially in the case of Lithium-ion battery packs. Unlike shunts with Op amps or iron-core based current sensors, Triaxis current sensors provide many advantages. Besides offering contactless and non-intrusive current sensing with very good isolation for high and low side measurements, they also deliver good linearity, high stability versus current peaks, high immunity against fast dv/dt, as well as high bandwidth and fast response times in a miniature, low-cost package.

Meanwhile, a new member has been added to this Triaxis IMC Hall sensor family, the MLX91206, which is fully user-programmable. As a result, this sensor offers an additional benefit. It can be calibrated *in-situ* after the sensor is fixed with respect to the current conductor. This way, the user can set a pre-determined, custom calibrated current sensitivity to meet the specifications required by a particular application.

Conclusion

In summary, contactless current sensors are constructed in a manner which imparts unique and useful performance characteristics. These sensors provide a compact, robust, flexible and economical solution for applications such as battery current monitoring, renewable power conversion, motor control inverters for HEVs, load management, and over-current fault protection. They are designed to offer current monitoring from 5 to 100 A on PCBs and up to 1000 A on bus bars.

Figure Legends

Figure 1 – Left: The IMC-Hall ASIC with integrated magnetic concentrators is sensitive to a magnetic field parallel to its surface. Right: Top view photograph of the current sensor ASIC with the two integrated magnetic concentrators, each about 800µm long. The Hall elements are positioned underneath the gap in the center. The total size of the die is about 1.8mm x 1.8mm.
Figure 2 – The current sensor is packaged in a standard SOIC-8 plastic package. Current range is defined by the geometry of the current conductor.
Figure 3 – Current Sensor based on an IMC Hall-IC, a copper conductor and ferromagnetic shield. Conductor cross-section is 12mm x 2mm including a soft magnetic shield based on Si-Fe or Ni-Fe.
Figure 4 – 3-Phase Current Sensor for HEVs.
Figure 5 – Linearity vs. 200A full-scale current range.
Figure 6 – Bandwidth measurement of the MLX 91205 (-3dB at 100 kHz).
Figure 7 - Shielded and unshielded current sensor for PCB applications.