New Developments in Hall-Effect Current Sensing

The demand for low-cost, accurate and small current sensors has grown rapidly during the last decade in industrial, automotive, commercial and communication systems. Various technologies can be used to convert an electric current into a proportional voltage, but the advantage of a Hall-effect magnetic detector is the inherent voltage isolation from the current path and the integration of the Hall element and interface electronics on a single silicon chip. This article describes recent developments in integrated Hall-effect based current sensors, including new packaging concepts which integrate the primary current path within the device, leading to major improvements on sensor parameters. **Andreas P. Friedrich, Allegro MicroSystems Europe, Annecy, France**

New design concepts and the systematic use of advanced BiCMOS technology have resulted in significant improvements in sensor performance. They have also opened the door to a new product approach by integrating additional functions like power protection in the same current sensor IC.

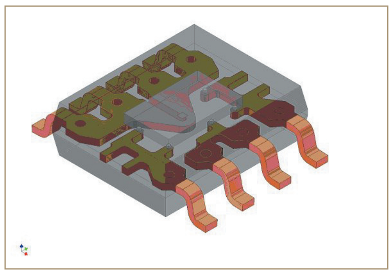


Figure 1: Internal structure of the Hall-effect current sensor, showing the primary U-shaped copper conductor and flip-chip mounted single Hall IC

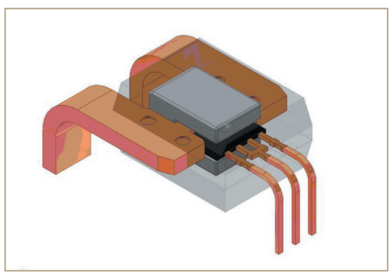


Figure 2: Internal structure of the Hall-effect sensor, showing the primary conductor, flux concentrator and linear SIP Hall IC

Packaging concept

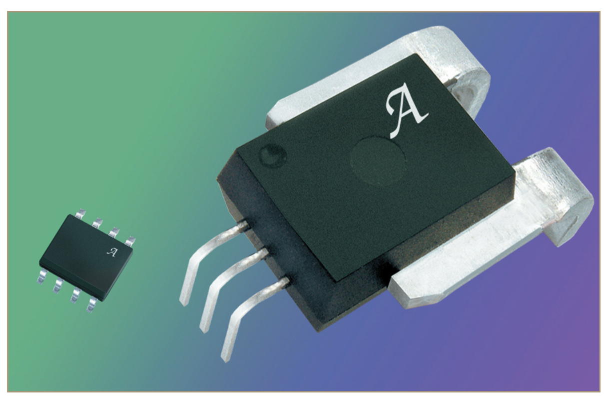
The current sensors described here are characterised by the integration of a monolithic linear Hall IC and a low-resistance primary current conduction path into a single-shot over-moulded package. Device accuracy is optimised through the close proximity and precise positioning of the Hall transducer to the copper conductor. Low power losses and high voltage isolation are intrinsic to the packaging concept. The final size, shape and additional components of the packaged current measurement systems depend on the amplitude of primary current to be measured.

For small nominal currents up to 20A, the Hall die and the primary current path are packaged in a standard-footprint SOIC8 surface-mount package. This provides a compact, low-profile solution that is compatible with high-volume automated board assembly techniques. The use of flip-chip technology leads to an optimised magnetic coupling between the active face of the Hall element and the field generated by the current to be sensed. A flux concentrator is therefore not required.

The internal resistance of the copper path used for current sensing is typically 1.5mΩ for low power loss. The power terminals are also electrically isolated from the low-voltage sensor inputs and outputs. IC and package design permits further improvement of the voltage isolation of the device, with a typical DC isolation voltage of 5kV and an RMS isolation voltage (60Hz for one minute between primary and secondary sides) of 1.6kV minimum and typically 2.5kV. Figure 1 shows the internal structure of such a current sensor rated at ±20A.

For higher currents, the cross-section of the copper conductor has to be increased to account for the current density within the material. Because of the magnetic coupling between this thicker conductor and the linear Hall element, a flux concentrator has to be used. The copper path, linear Hall sensor and concentrator are precisely assembled before being over-moulded. Through careful design of the system, a typical primary conductor resistance as low as 100μΩ and a minimum RMS isolation voltage (60Hz for one minute between

Figure 3: ACS ±20A (LC package) and ±200A (CB package) current sensors



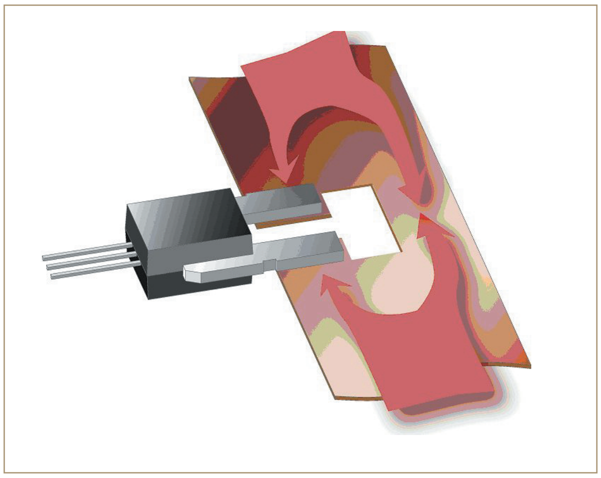


Figure 4: Current divider configuration; the current sensor can be connected directly to a bus bar

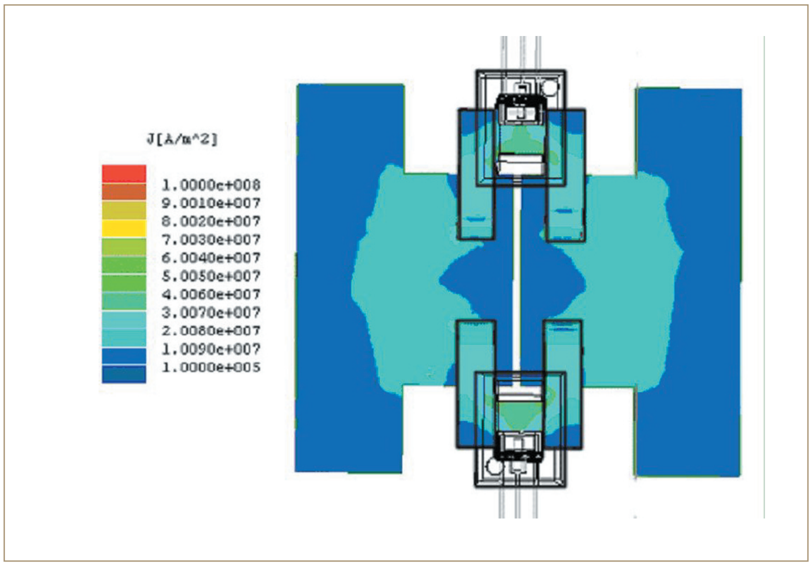


Figure 5: Equal current splitting with enhanced resolution. The outputs of the two sensors can be combined to obtain a linear output proportional to the total current to be sensed

primary and secondary sides) of 3kV was achieved. Figure 2 shows the internal structure of such a ±200A current sensor, and Figure 3 shows both package types.

If the currents to be measured are higher than 200A, the sensors can be used in a current divider configuration. This method involves splitting the path of the current being sensed. The simplest approach is to design a notched bus bar such that only a well-controlled fraction of the current flows through the sensor, the other going through a shunt path (Figure 4). The current split ratio is determined by the geometry of the bus bar. An inherent disadvantage of this approach is that it reduces the current resolution by the same proportion as the current is divided. The resolution can, however, be increased if the current is split equally and two devices are used in parallel (Figure 5). A simple circuit involving level-shifting and adding the outputs of the two sensors can be used to obtain a linear output proportional to the total primary current.

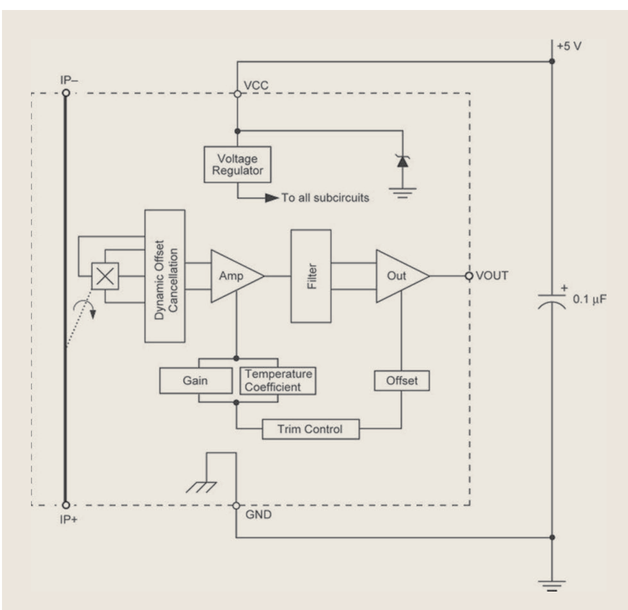


Figure 6: Block diagram of the circuit used for the integrated Hall current sensors

Sensor design

The central element of the sensor is a precise, low-offset silicon Hall-sensor integrated circuit IC (Figure 6). The magnetic flux generated by the primary current is sensed by the Hall element, with a BiCMOS chopper stabilisation circuit used to reduce signal offset and to stabilise the output of the sensor over its operating temperature range.

The on-chip circuitry produces an analogue voltage that is proportional to the input current. The output is ratiometric, which means that both the offset and sensitivity scale with V_{CC}. Device accuracy is optimised through end-of-line trimming of the offset, sensitivity and temperature response. The sensors are designed to measure both positive and negative currents, but the parameters can be trimmed for uni-directionality if required. The device is trimmed after packaging in order to reduce package stress effects on the Hall element. As can be seen in Figure 6, an external bypass capacitor is recommended to reduce noise. If the bandwidth of the application allows it, a simple RC filter can be used at the output to further improve signal/noise ratio.

Although the surface-mount current sensors are designed for ±20A, they can withstand large transient over-currents of up to 100A. The limiting factor determining the over-current capability of the devices is the junction temperature of the IC (165°C maximum), and is therefore determined by the thermal design of the PC board in the application. For the ±200A sensor, the thickness of the copper conductor allows survival of the device at up to 5X over-current conditions. Table 1 summarises the main features and benefits of the two device types.

New challenges

Current sensing solutions for advanced industrial, automotive, commercial and communication systems are facing new challenges. Although the devices described above meet a large variety of customer requirements, there is a growing demand for low-cost, high-accuracy and compact systems with added functionality.

Improved performance challenges are

Table 1: Features and benefits of the ±20A and ±200A Hall-effect current sensors

	ACS704/706: ±20 A	ACS750: ±200 A
AC and DC current measurement	Yes	Yes
Internal conductor resistance	1.5mΩ	100μΩ
Minimum isolation voltage	1600V RMS	3000V RMS
Supply voltage	4.5-5.5V	4.5-5.5V
Bandwidth	50kHz	35/50kHz
Total output error at room temperature	±1.5%	±1.0%
Operating temperature range	-40°C to +85°C	-40°C to +150°C (function of primary current)
Near-zero magnetic hysteresis	Yes	-
Package	SOIC	CB
Ratiometric output from supply voltage	Yes	Yes
Lead free	Yes (high-temperature Pb-based solder balls currently exempt from RoHS)	Yes

Table 2: Improved resolution using an external capacitor on the filter pin

Filter capacitance (nF)	Bandwidth (kHz)	Noise (A)
No capacitor	>50	0.35
4.7	20	0.22
47	2	0.07

being addressed by further enhancing the characteristics of the ±20A low-profile SOIC8 sensor, resulting in the development of a third-generation device (the ACS712) with a specific focus on noise and total output error reduction. The chip design is based on the latest Allegro low- noise 0.65μm BiCMOS process (DABIC6). A total of 23 programming bits were used to optimise the sensor parameters quiescent output voltage, sensitivity, and sensitivity temperature coefficient after packaging.

The combination of improved process performance, new design concepts and additional programming capability resulted in a two-fold reduction in noise. The total output error at 20A was improved from ±8.4% to ±4% in the industrial temperature range from -40 to 85°C. Over the extended temperature range from -40 to 125°C, the total error is ±5%. A further benefit is that the device can be programmed to act as a 5, 20 or 30A sensor.

This new device also has a filter pin that can be used to set the -3dB point with a capacitor. This reduces the number of external components required to improve sensor resolution (no resistor needed). The peak-to-peak current noise levels at 25°C for different filter capacitor values are shown in Table 2.

Added functionality can be provided – particularly for large volume applications – by integrating some additional functions on the Hall IC that would usually be realised with external components. In the example shown in Figure 7, this approach has been used to develop a new protection IC with integrated hot-swap gate driver and internal 1.5mΩ Hall-effect based current sensor.

In this device, the power-supply load is measured without the use of an external sense resistor. The part uses an integrated 1.5mΩ copper conductor and a Hall-effect current sensor to accurately measure load currents up to 30A. The device contains over-current protection circuitry that trips at a user-selectable level between 30A and 40A. If an over-current condition is detected, the fault output of the part trips and the gate of the external MOSFET is pulled to ground. The delay between the detection of an over-current condition and gate shutdown is set by an external capacitor.

Conclusion

The innovative current-sensing solutions described address the need for low-cost, high-accuracy and compact current measurement solutions in a variety of industrial, automotive and commercial applications. In particular, they offer significant benefits over traditional shunt and current-transformer techniques in applications such as battery monitoring and charging systems for UPS/inverter systems.

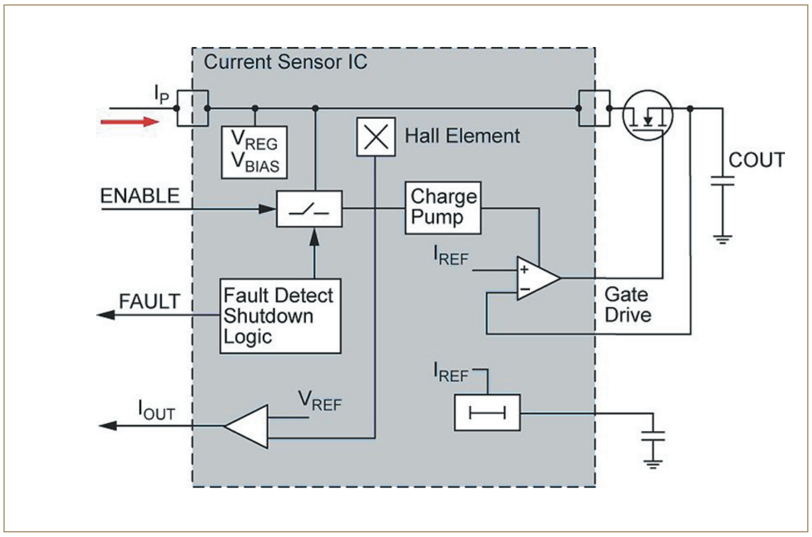


Figure 7: Block diagram of the protection IC with integrated hot-swap gate driver and internal 1.5mΩ Hall-effect based current sensor