LEM

Life Energy Motion

Integrated current sensors

More integration for more efficiency: how to simplify current measurement in low-current applications.

Abstract

While power density of electronics is increasing, simplifying and miniaturizing the current sensing function will help the design of control and power stages for efficient and safe applications. Integrated current sensors (ICS) are made to solve the challenges of current measurement with one single device. They embed the sensing technology and the signal chain as well as the isolation and dedicated mechanisms for system protection.

Building on decades of progress in semiconductor design, manufacturing and packaging, they ensure that new gen and next gen electronics can rely on accurate information in a wide range of conditions. LEM has put together all their know-how to offer a new range of ICS.

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Fig.1: *Current sensing is needed in a wide range for applications, for system control, protection and optimized efficiency.*

Introduction

Current sensing is a crucial function in many electronic devices, ranging from power supplies and battery management systems to e-motor drives and renewable energy networks (Fig. 1).

Accurate and reliable current sensing is essential to ensure proper operation, protection and efficiency of such systems.

On the other side, one of the imposed trends in electronics design nowadays is to keep decreasing the circuit board footprint, while managing higher levels of power – voltages and currents altogether. This poses new challenges regarding PCB layout, isolation, thermal management and Electro Magnetic Interferences (EMI).

Current measurement makes no exception and must be seamlessly embedded in space-constrained applications while coping with higher power density. This article will provide an overview of how Integrated Current Sensors (ICS) can help design the current sensing function effectively in these conditions.

Designing the current sensing function meets new challenges in new applications

The main concept of current measurement is based on the transducer principle, which converts the primary current signal to be meas ured, into a proportional signal such as a voltage, as shown in figures 2 and 3:

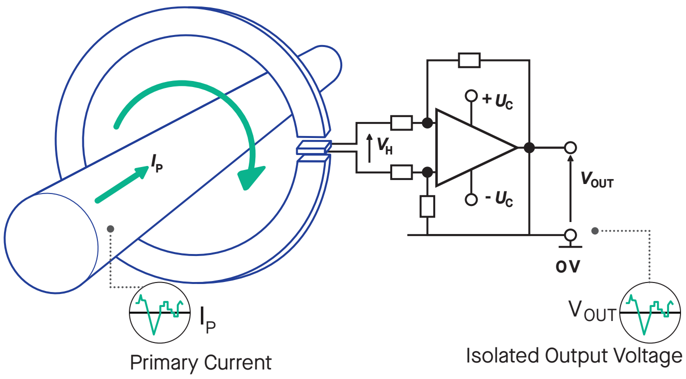


Figure 2: *A transducer converts a current signal into a proportional voltage (pictured: Hall-effect open-loop current sensor)*

While measuring the voltage drop in a resistive shunt has always been one of the ways to measure the current indirectly (figure 3), this solution is intrusive and has several limitations such as power dissipation and thermal drift. It can also cause undesired voltage ground disturbance in low-side mode, where there is a shunt placed between the load and the ground.

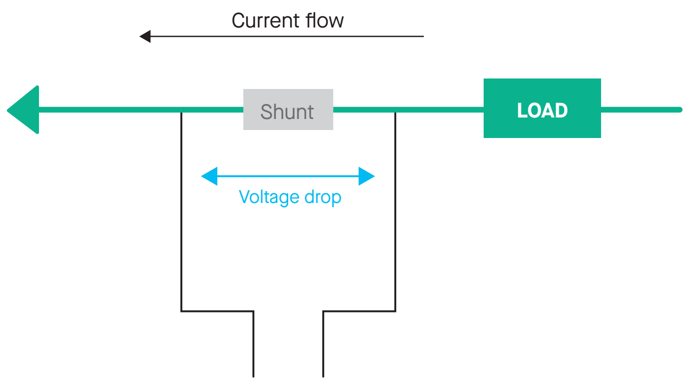


Figure 3: *As the current flows through the resistive shunt, the voltage changes proportionaly and according to V = R.I*

Flowing some current through a resistive material like a shunt produces heat as power losses. As the control and power stages become increasingly integrated, heat sources such as microcontrollers and power electronics components are closer to each other. While looking for new sources of efficiency, the current sensing function shouldn't be causing additional power loss and thermal management challenges either.

In the meantime, figure 4 shows that new industry trends, technology adoptions and technical progress have driven new usages and applications. For example, next-generation semiconductors enable high-frequency switching at higher temperatures for power conversion. This allows for smaller passive components and cooling systems, and for more compact designs.

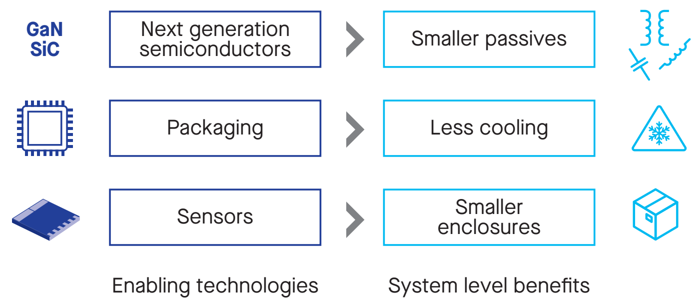


Figure 4: *Current sensing miniaturization is part of electronics integration at system level*

Similarly, current sensors must also follow the trend of electronics integration at system level by reducing their footprint and including new functionalities by design. Alternatives to passive resistive measurement exist to meet these challenges.

In figure 2, as the current flows in a conductor, it also produces a proportional magnetic field around it. Sensing this magnetic field and converting it into a proportional voltage is another indirect way to measure the current. This solution is contactless - unlike shunt measurement - and therefore provides several advantages, mainly regarding built-in isolation. Other advantages are also gained.
At lower currents, shunts have remained a viable solution, but they still have isolation challenges and request several additional electronics parts to fully complete the current sensing function as shown in figure 5.

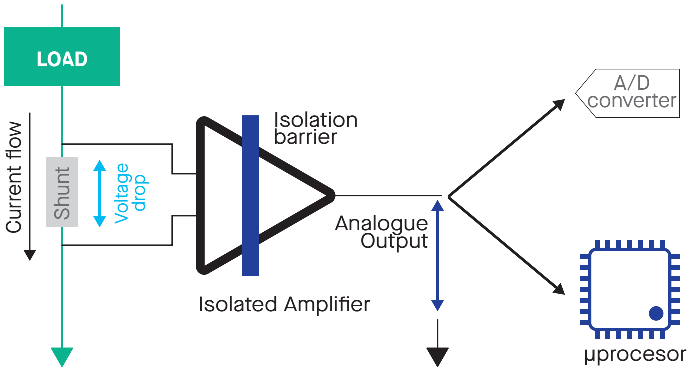


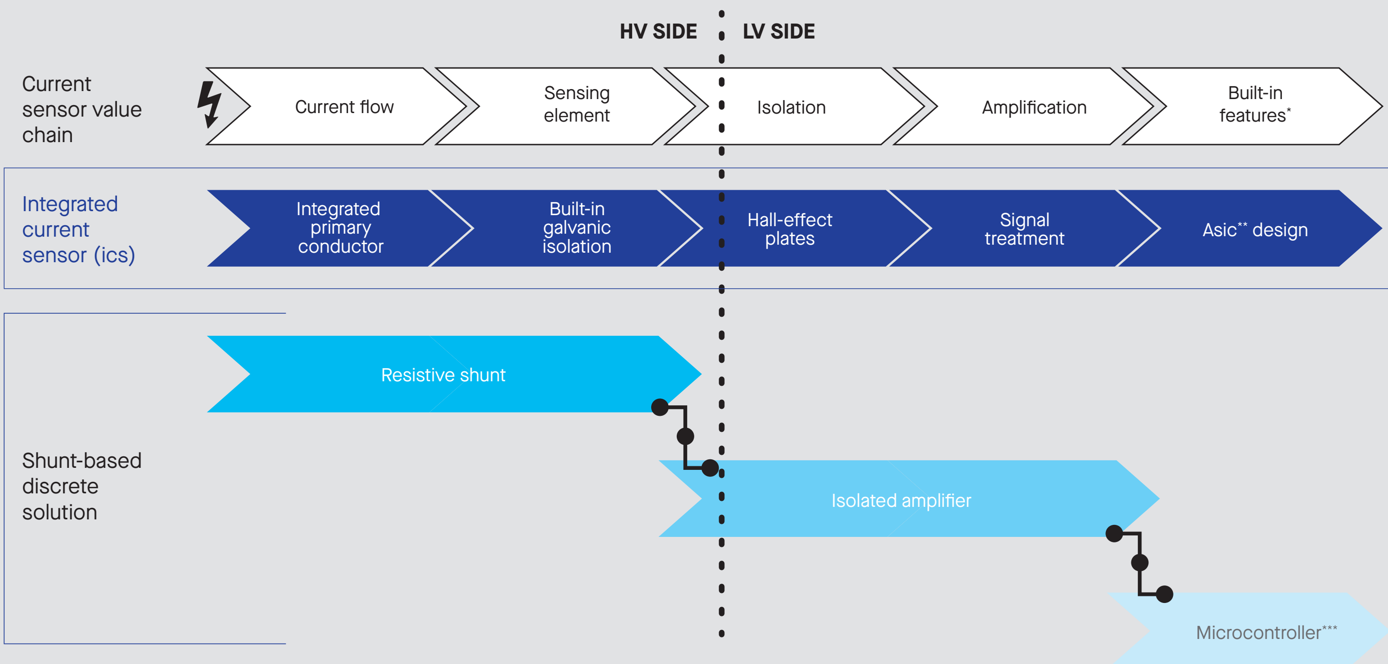
Figure 5: *A shunt needs discrete components to fully complete the function, such as an isolated amplifier for signal treatment*

They need discrete elements such as (isolated) amplifiers and/or analog-digital conversion (ADC) for signal treatment of the measured voltage drop. In high-voltage applications for example, integrated local isolation is a key differentiator versus shunts, for which isolation needs to be located further away in the chain of signal processing, as shown in figure 6:

Thanks to technical progress in semiconductor manufacturing and packaging, it is now possible to integrate all the stages of a current sensor in 1 single package.

Figure 6 shows the integration of all the different stages of the current sensing functions :

- The current flows through the device
- The induced magnetic field is sensed by two Hall-effect plates
- The operation is contactless and provides inherent galvanic isolation
- The voltage signal is treated inside an Application Specific Integrated Circuit (ASIC)
- The ASIC also includes other ad-hoc features.



*Ex: Over-current detection (OCD) **Application Specific Integrated Circuit ***Extra design effort is needed to create additional functions

Fig.6: *Designing the current sensing function with an Integrated Current Sensor requires only one device vs. a shunt-based solution.*

Integrated measurement reduces the footprint of the current sensing function.

Hall-effect based sensors can now integrate the current conductor, the sensing elements, the signal treatment die, some dedicated features such as fault detections, and the isolation in one single package (figure 7). These are called Integrated Current Sensors (ICS). LEM has developed 2 families of ICS, the HMSR series and GO series.
ICS are PCB-mounted devices made to simplify the integration of current measurement in a wide range of automotive, industrial or residential applications. ICS can use Hall-effect technology for current sensing.

Hall-effect sensing is one way to achieve contactless measurement of the current-induced magnetic field. A Hall cell is a sensing element that converts a change in the magnetic field into a change of its resistance. When a constant current goes through the hall cell, it will give a voltage output change proportionate to the magnetic field.
Traditional Hall-effect current sensors are using a ferrite core around the current conductor and the sensing elements to concentrate the magnetic field, as seen previously in figure 2.

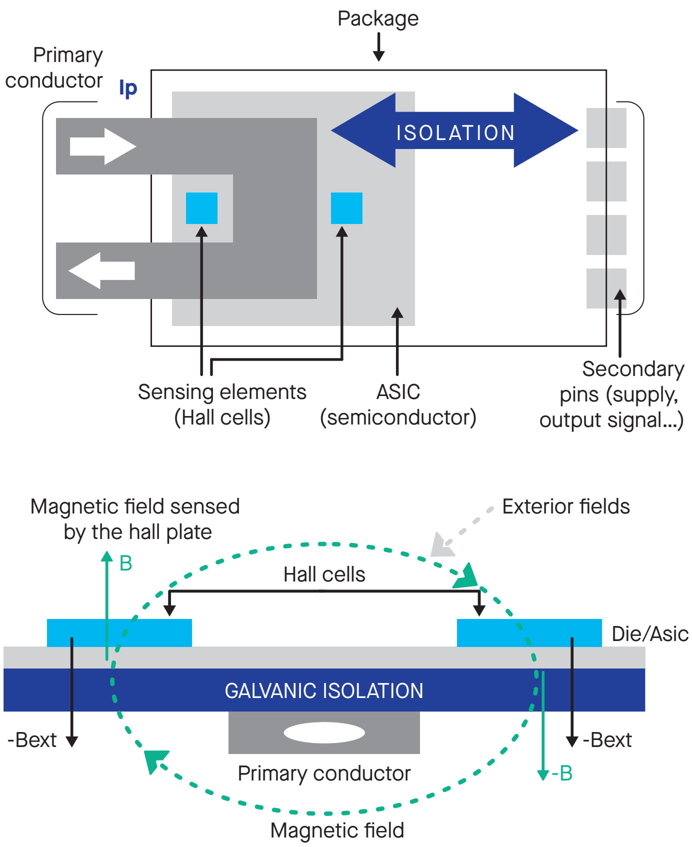


Fig.7: *Integrated current sensors (ICS) embeds the primary conductor, 2 sensing elements (Hall plates) on a die, and galvanic isolation in between. Differential measurement is equal to: (B-Bext)-(-B-Bext)=2B, as Bext is cancelled.*

This core also brings protection from undesired external magnetic fields and noise. LEM HMSR series provides extra immunity with its integrated core.
Thanks to differential measurement, it is possible to remove the ferrite core, while keeping a good response to external fields disturbances. Differential measurement uses 2 sensing elements (the Hall cells). They both receive the magnetic field to be measured, one with a positive factor, and the other with a negative factor. They also receive any external fields with the same incidence. When making the difference between the fields seen by the 2 cells, the unwanted fields cancel each other :
(B+Bext)-(-B+Bext) = 2B, as Bext is cancelled.

Integrated Current Sensors take advantage of differential measurement by not using a ferrite core. Removing the magnetic core delivers several advantages in embedded applications:

- The cost of the device is reduced
- The power density on the sensing side is mechanically increased – up to 75A in 800V applications for LEM ICS products.
- The measure is not affected by magnetic hysteresis.
- The operating temperature is not limited to the Curie temperature above which a ferrite can experience demagnetization (105 degC), but rather by the maximum junction temperature of the device.
- Frequency and bandwidth are not limited by the inherent saturation of the magnetic element of the core.

LEM GO series takes full advantage of differential measurements to offer all the performance of a hall current sensor in a compact package – SOIC8 or 16.

Integrated isolation for integrated designs

A system is considered “high-voltage” when it goes above 60V in working conditions, as shown in figure 8:

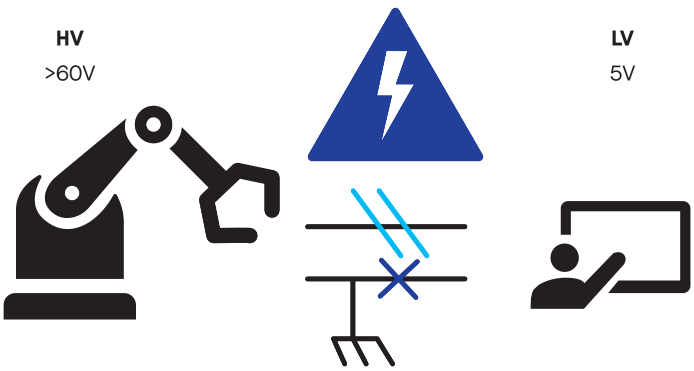


Figure 8: *The low-voltage user interface side needs reinforced isolation protection from the high-voltage side.*

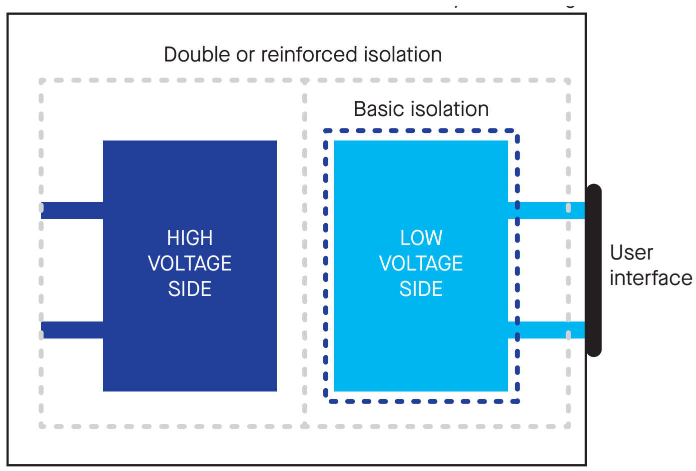


Figure 9: *Reinforced insulation offers a double protection between the primary and the secondary circuits (HV and LV sides), and towards the final user. The integrated current sensor can be responsible for the reinforced isolation on top of the basic insulation.*

In this scenario, some isolation between the low-voltage (LV) circuit - mainly made of the control functions including the micro controller, the gate drivers and the user interface - and the high-voltage (HV) circuit with the power transistors and the power supply, is mandatory according to regulation.

When designing a high-voltage system, this isolation barrier must be put wherever there is an interface of the HV and LV circuits. As transducers, integrated Hall-effect current sensors are exposed to HV signals on one side, and on the other side to the LV circuit of the system via their connection with the microcontroller.

According to the overvoltage category (OV I, II, III or IV), depending on the architecture of the system and the standard to be applied, a different level of isolation will be required: functional, basic (simple), double or reinforced. “Basic” uses one layer of isolation, while “double” adds another layer. “Reinforced” provides the equivalent performance of double isolation but in 1 package and ensures a physical separation between HV and LV (figure 9).

For example, the LEM GO-SMS can guarantee a basic isolation up to 2088V and a reinforced isolation of 1041V (DC or peak working voltage) according to IEC 62368-1, in a pollution-degree 2 environment.

Reinforced isolation is needed for systems with class II overvoltage to protect the final user. Therefore, the user interface needs to be physically separated from the HV network and cannot share the same voltage reference level.

An ICS integrates the isolation function inside and outside the device (figure 7). The internal isolation is called galvanic isolation. There is no physical connection between the primary conductor where the HV current flows, and the secondary circuit including the ASIC chip and the secondary pins. These 2 sides communicate only through the magnetic field produced by the flowing current. This is inherent to the current sensor design.

Creepage or arching can happen at the surface or outside the part between the primary and secondary pins and create a short circuit between HV and LV circuits. To avoid this, Creepage (any unwanted physical electric route at the surface of the part) and Clearance distances (the shortest distance in the air between HV and LV pins), as shown as dCp / dCl in figure 9, are calculated according to norms and the applications characteristics (figure 10).

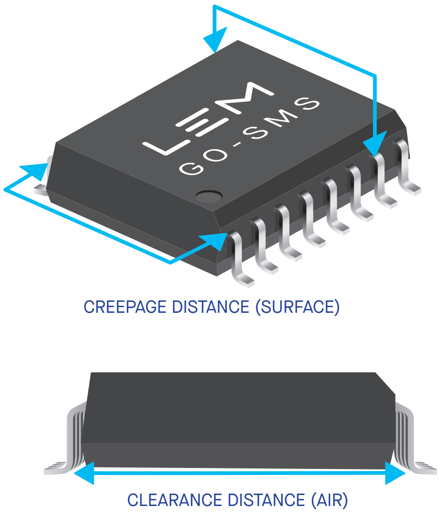


Figure 10: *Creepage and clearance distances are calculated according to basic or reinforced needs and applications specifications – 7.4 mm in the case of LEM GO series.*

Guaranteed reinforced isolation by the current sensor will ensure that the microcontroller and the user interface can stay on the same separate voltage network and reference levels with no risk (figure 11).

This is preferred for high power applications where the power stage is usually physically separated from the control stage (HV motor drive or BEV e-motor inverter for example).

Figure 12, below, shows the reinforced isolation between the microcontroller and the user interface, and the microcontroller is on the same voltage reference as the power electronics. In this case, a basic isolation is sufficient at the current sensor level. This is preferred for low power applications.

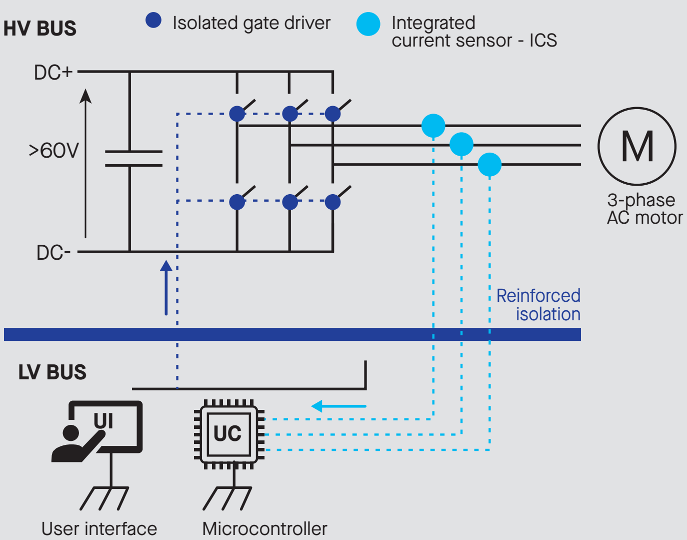


Figure 11: *Current sensing in high voltage DC/AC conversion. In high power applications, the current sensor and the gate driver are entirely responsible for the isolation of the system.*

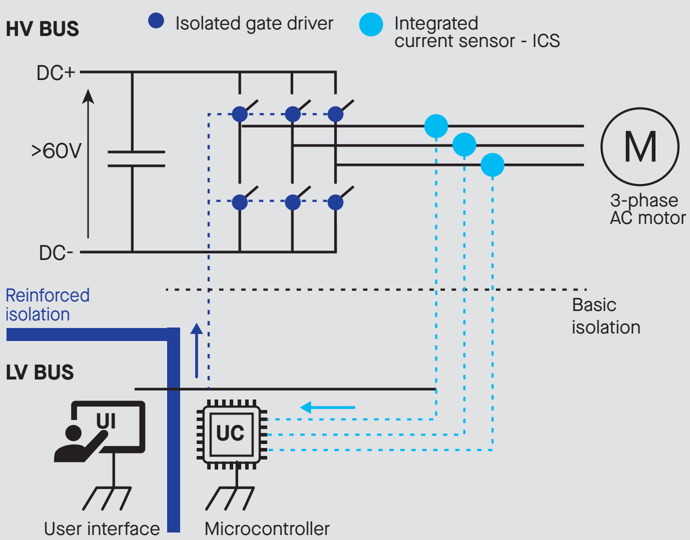


Figure 12: *Current sensing in high voltage DC/AC conversion. In low power applications, the current sensors and the gate driver ensure a basic isolation before the reinforced one.*

ICS offers unique built-in additional features

The Application-Specific Integrated Circuit (ASIC) in the ICS is made with CMOS semiconductor manufacturing process. This allows specific features to be integrated into the part, without adding any hardware, in contrast to when using shunts:

- Signal treatment: all the analog and digital elements required to sense, amplify and process the proportional voltage signal are manufactured on 1 single die with semiconductor materials. This also ensures low consumption and power dissipation.

- Over-Current Detection (OCD) (figure 13):
  - Internal OCD: when the current crosses a threshold, it internally triggers a signal output sent to a dedicated FAULT pin. This allows the microcontroller of the application to receive the alert information with minimal delay. Otherwise, the action would have to be done internally in the uC with a comparator, based on the current level sent by the sensor, which would take much longer.
  - External OCD: the threshold can be set by the customer with a voltage divider. There is a second dedicated FAULT pin.

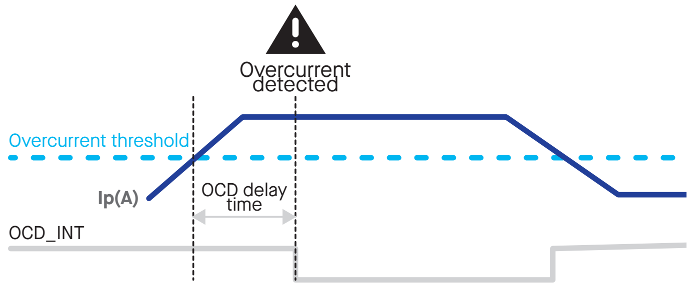


Figure 13: *OCD enables the microcontroller to react to overcurrent with minimal delay.*

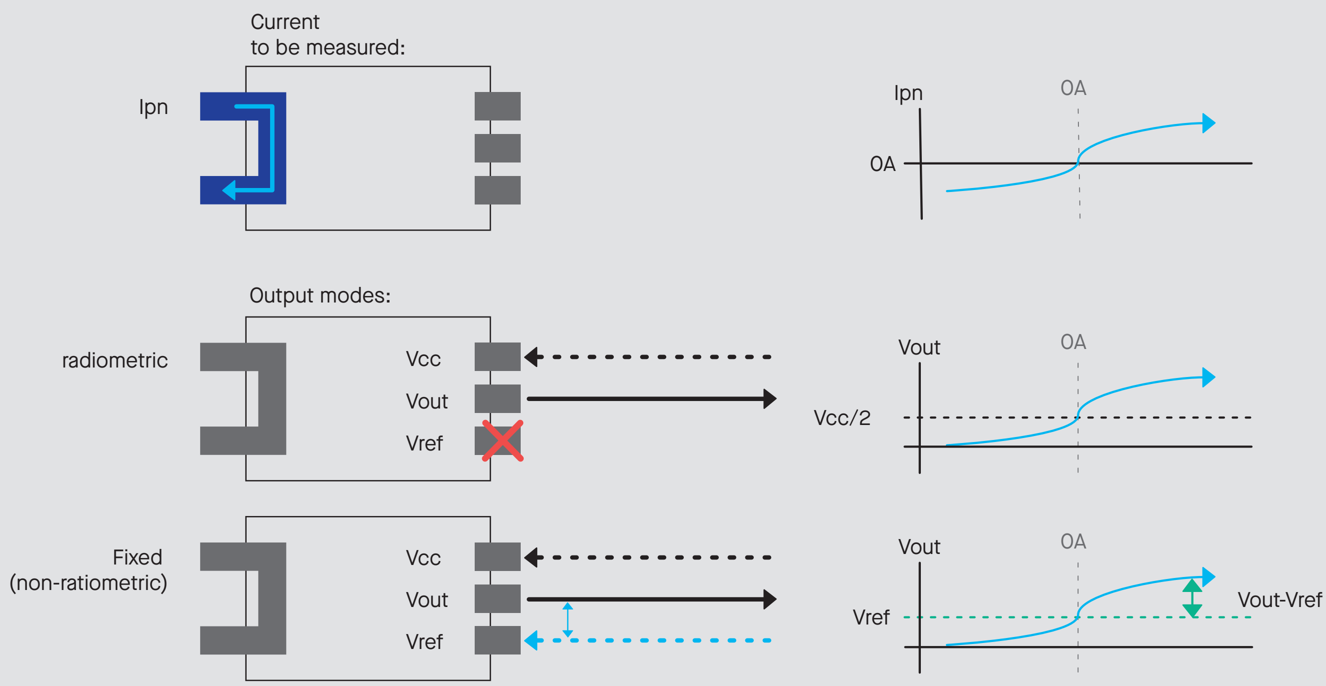


Figure 14: *Vout will always be proportional to Ipn. Ratiometric output voltage mode will be referenced to Vcc supply voltage, and Fixed mode will be based on a fixed external reference voltage Vref. In this case, the proportional signal to be read by the microcontroller is equal to Vout – Vrev.*

- LEM HMSR and GO-SMS ICS feature both internal and external OCDs for maximal system protection.

- Stress and temperature compensation: if the ASIC die is subject to mechanical stress from the package, this can create sensitivity drift. The same can occur with temperature variations over -40/125+ °C. Internal “sensors” in the die of the ASIC compensate for this drift to guarantee a linear and accurate sensitivity over a large range of conditions. In a discrete-based design, the temperature of the shunt varies widely with resistive losses. This requires an extra design step in the microcontroller to compensate for this accurately, while the ICS solution is plug-and-play.

- Different output modes: figure 14 shows the voltage output is always proportional to the measured current but there are 2 possible reference voltages :
  - In ratiometric mode, Vout is expressed as a percentage of the voltage supply Vcc. This requires a stable voltage supply.
  - In fixed mode (or non-ratiometric), Vout is compared to an external reference voltage Vref supplied on a dedicated pin by the microcontroller of the application.

The proportional signal is then Vout-Vref. When the current to be measured is 0A, Vout=Vref i.e. the reference voltage is setting the quiescent output voltage (zero current mode).

LEM HMSR and GO series are available both with Ratiometric and Fixed voltage outputs on demand, depending on the system characteristics.

Application example:
DC/AC inverters and motor drives

Motor drives and inverters are necessary to control the speed and torque of electric motors according to the required loads.

As figure 15 shows, this control requires a DC current to be converted into 3-phase AC current. In a DC storage system such as Li-ion battery, the current can be sent directly to the inverter.

If the source of energy is the AC grid, then this AC current needs to be transformed into a DC energy supply before going into the inverter. Then a Power Factor Corrector (PFC) and a rectifier are needed to get a continuous voltage. The PFC uses a current sensor as well.
In both cases, a DC link capacitor will smooth and flatten the current at the input of the system. A current sensor is needed between the DC connector and the capacitor to measure the input current.

The DC/AC power conversion happens with the microcontroller opening and closing the 6 transistors through the gate drivers, according to the required load.
After the DC/AC power conversion, the corresponding current is injected to the motor through 3 phases. At this point, 3 current sensors (1 per phase) are measuring the current output. The information is sent back to the microcontroller so the control algorithms can fine-tune the drive of the transistors to adjust the current output to the desired level. The current sensors are the cornerstones of the feedback loop.

LEM GO and HMSR ICS in this system can increase compactness (figure 17) and simplify design:

Figure 16: *Integrated current sensors are the most optimized current sensors mechanically and features-wise.*

- Low power loss ICS can be put closer to heat sources such as the microcontroller and the transistors
- Integrated isolation simplifies PCB layout.
- Built-in OCD makes sure the microcontroller can put the system in safe state with minimal delay.

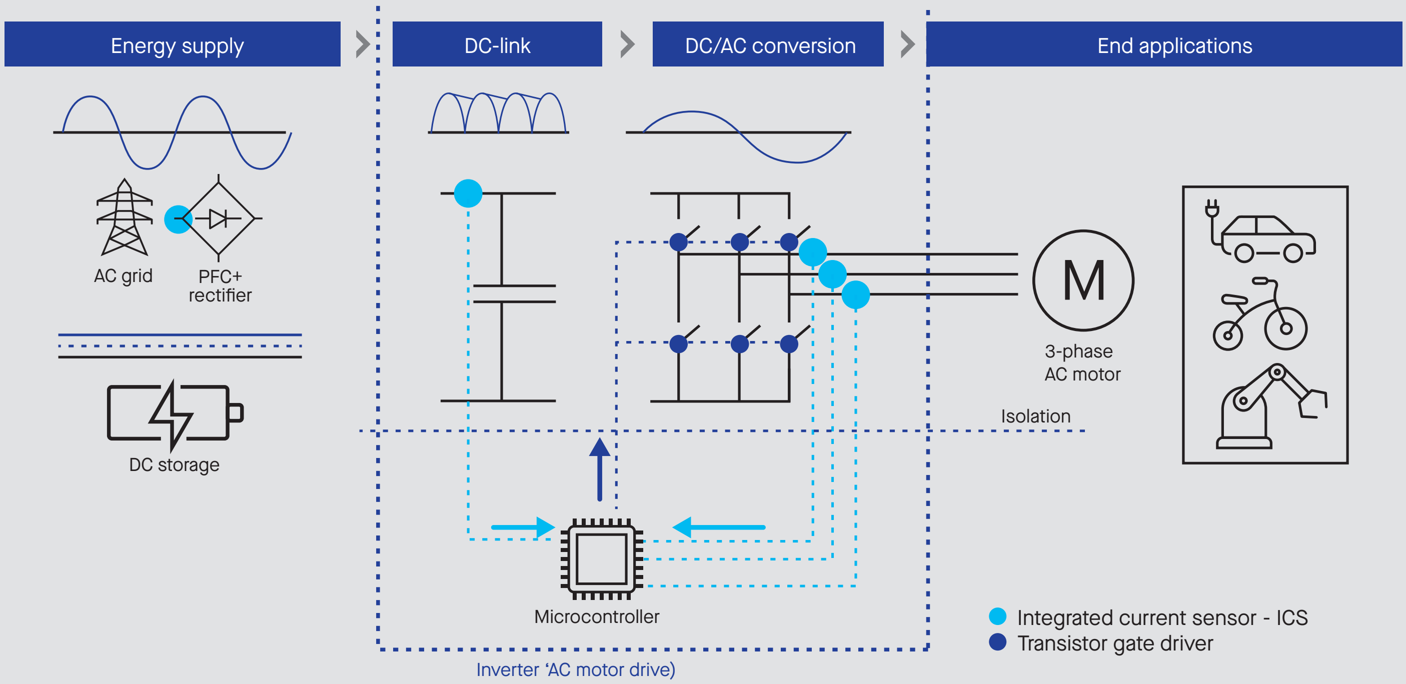


Figure 15: *ICS in DC/AC inverter for motor torque control – the current sensors feeds the control algorithm with accurate data.*

Conclusion

ICS are suitable for a wide range of applications where accurate control, efficiency and protection are needed. They allow designers to realize the current sensing function with a plug-and-play approach, with virtually all their challenges solved using only one part.

Complete mechanical integration and very low power losses makes its footprint as small as possible and do not add thermal challenges.

By design, contactless measurement with galvanic isolation and standard creepage and clearance distances make them suitable for high-voltage applications and can support the reinforced isolation design strategy.

Smaller packages with less isolation and un-populated features can bring the cost down to be cost-competitive where isolation is not needed (< 60Vdc).

This flexibility in the product definition allows LEM ICS to be suitable for various products from cost-optimized applications to high-end isolated designs.

Their performance is not compromised as all the signal treatment is done in the package with semiconductor elements. This enables the integration of adhoc, specific system protection mechanisms such as fast overcurrent detection.

Depending on the system architecture and design choices, the current-proportional voltage output can be referenced to the supply voltage Vcc or an external Vref. LEM is even expanding its range of ICS products with digital Delta-Sigma outputs on HMSR DA series.

In the end, ICS are doing more with less.

REALIZATION OF THE FUNCTION	DISCRETE	TRADITIONAL CURRENT SENSOR	INTEGRATED CURRENT SENSOR (ICS)
Sensing technology	Resistive shunt	Hall-effect with core	Differential hall-effect, with or without core
Contactless sensing	No	Yes	Yes
Power losses	High	Low	Low
Mechanical integration	No	No	Yes
PCB footprint	Small	Medium	Very small
Isolation	Separated	Integrated	Integrated
Signal treatment	Separated	Integrated	Integrated
OCD	Additional design effort	Integrated	Integrated
Stress and temperature compensation	Additional design effort	Integrated	Integrated

Figure 17: *ICS is a compact, plug-and-play solution for the current sensing function.*

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