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Closed-Loop Sensors With Magnetic Probe Extend High-Precision Current Measurement To Higher Current Levels

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In power electronics, the measurement of currents higher than several hundred amperes is becoming increasingly common. This trend is due largely to growth in applications in the range of hundreds of kilowatts or megawatts such as wind turbines, high-powered solar inverters and others in the field of renewable energy. In the development of these higher-power applications, there are two specific factors that fuel the need for high-current measurement.

First, there is the equipment manufacturer's goal of increasing the power output of the individual inverter modules so that the total number of inverters can be kept as low as possible while increasing the total output. Then, there is their requirement to stay within the voltage limits defined in the Low-Voltage Directive 2006/95/EC, which sets limits of 1000 V for ac and 1500 V for dc. To avoid devices being reclassified under the Medium-Voltage Directive, the output current levels of the inverter modules are increased instead.

In performing current measurement in high-power applications, both the precision and range of measurement are important. High-precision current measurement is critical for many measurement applications, such as accurate measurement of motor torque in drive systems or, in the energy sector, of current fed into the power grid (avoiding dc components.)

High-precision current measurement also enables power semiconductors to be used more effectively, given that high safety margins usually must be incorporated in the safe operating areas of tolerances to account for measurement inaccuracies. Meanwhile, wide-range current measurement is useful in designing high-efficiency control circuits and ensures safe and accurate short-circuit current measurement.

This article focuses on a class of current sensors that are well suited for use in high-power applications—closed-loop sensors with magnetic probe. The characteristics and benefits of these sensors are discussed here and their principles of operation are explained along with the key elements of sensor design that determine their performance.

With that as background, a new family of sensors from VAC, the T60404-P4640-X1xx, is introduced. Members of this sensor family extend the range of closed-loop sensors with magnetic probe to much higher current ratings (1000 A eff) and measurement ranges (±2500 A) than were previously possible. The performance of these new sensors is discussed at length and test results are presented to demonstrate their capabilities with respect to key parameters such as linearity, relative error over temperature, step response, and external field sensitivity.

Closed-Loop Sensors With Magnetic Probe

Closed-loop current sensors with magnetic or flux gate probe deliver virtually lossless measurement of practically all forms of current from dc to ac in the 100-kHz or 200-kHz range. They also offer inherent galvanic isolation between the load current and signal current circuits in compliance with relevant standards including EN61800 and UL508. Typical measurement ranges extend from a few amperes to 2500 A with a total error of less than 0.4% and linearity error of less than 0.1%. The temperature stability and long-term stability of the offset variables is in the range of a few hundred ppm—levels of precision that cannot be achieved using Hall-effect sensors or shunts with galvanic isolation.

Potential applications for current sensors span the entire range of switched-mode power electronics, from measurement of motor current in variable speed drives and dc, ac and residual current measurement in photovoltaic inverters to current measurement in welding inverters and uninterruptible power supplies.

In typical applications, the operating currents to be measured are high-amplitude dc or ac of up to a few hundred hertz. The switching current of the power semiconductors, which operate in the single-digit to mid-double-digit kilohertz range, superimposes harmonic waves into the three-digit range, with amplitude one order of magnitude lower, on these currents. Closed-loop sensors with magnetic probe are ideal for this spectrum.

Operating Principles

VAC's closed-loop current sensor with magnetic probe (Fig. 1) works by passing the conductor of the primary current to be measured through a magnetic core. The magnetic probe detects the presence of a magnetic field in the air gap of the core. The sensor's electronic system analyzes the probe signal and passes an opposing current through the compensation coil. This compensation current is proportional to the primary current but with reversed polarity, and zeroes the magnetic flux in the core, which is generated by the primary current. The magnetic probe thus serves as a zero field detector; the compensation current being an exact representation of the primary current.

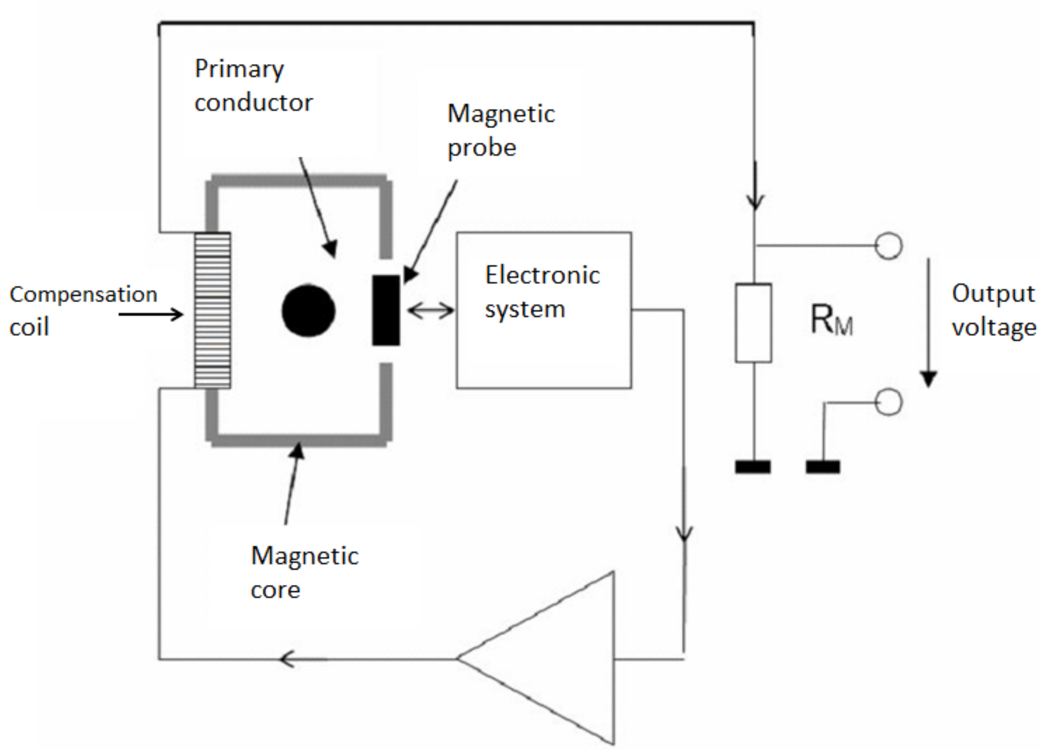

Fig 1. A closed-loop current sensor with magnetic probe works by generating a compensation current that is proportional to the current through the conductor. This technique allows for precise measurement of currents from dc up to 100 kHz or 200 kHz.

The frequency range of the control circuit is less than 10 kHz. However it is not critical for the range of the sensor as a whole, as the magnetic circuit acts as a current transformer at higher frequencies. As a result, the compensation current or the voltage passing through the resistance sensor deliver high-precision measurement of the primary current, typically in the frequency range from dc up to 100 kHz or 200 kHz.

The Magnetic Probe Principle

A special feature of the current sensors described here is the magnetic probe, a VAC design that functions on the principle of the flux gate or saturation core probe. Here, the magnetic field in the air gap of the magnetic core is not measured by a Hall element as in conventional sensors, but by a coil with an open magnetic circuit forming part of a self-oscillating loop, which is reciprocally driven to saturation (Fig. 2, left). An external field acts on the coil and shifts the magnetic symmetry of the core, thus modifying the PWM signal's duty cycle (Fig. 2, right) and generating the compensation current.

The working frequency of the probe is 400 kHz or higher and therefore far exceeds the measurable frequency range. The probe has a high inherent amplification, and thus its signal has a high amplitude. Unlike Hall element probes, it does not require amplification from the millivolt range, which avoids the disadvantages of amplifier noise and drift. In addition, the accuracy of the probe depends solely on the—physically determined—virtually perfect symmetry of the hysteresis loop, not on its gradient or on the saturation induction of the material; these being characteristics that show a temperature dependency, albeit low.

In the temperature ranges of typical applications, closed-loop sensors with magnetic probe deliver approximately twice the accuracy of closed-loop sensors with Hall element as zero field detector, and are many times more accurate than open-loop sensors.

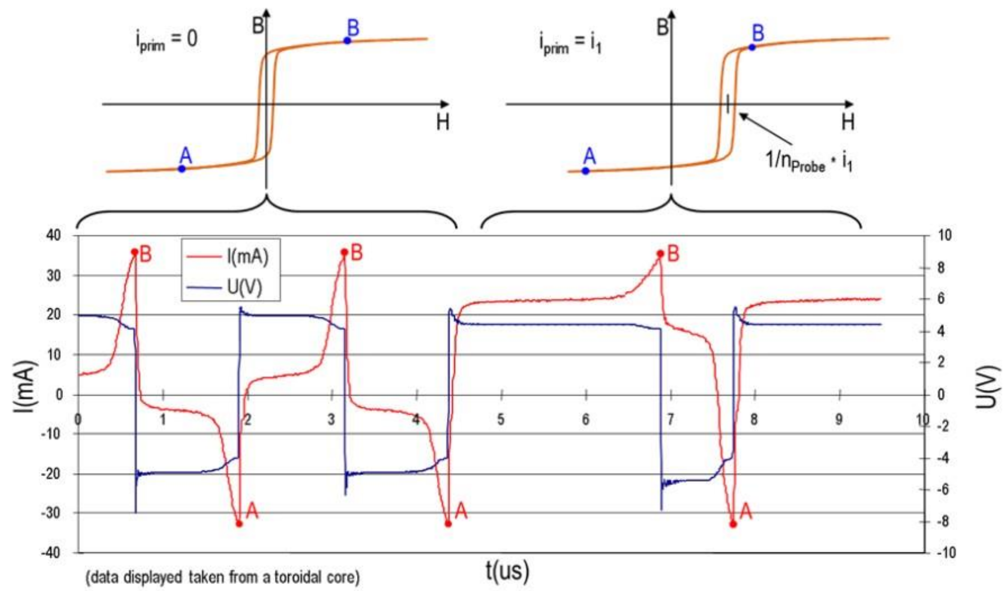

Fig. 2. Measured waveforms for a magnetic probe without (left) and with (right) an external magnetic field.

Benefits Of Modern Materials

The core of the magnetic probe consists of a strip of amorphous VITROVAC material, a mere 20-µm thick, with a Z-shaped hysteresis loop. This material offers a combination of hard saturation behavior, high permeability in a non-saturated state, and low loss, making it ideal for this application.

The primary magnetic core of the sensor is made from PERMENORM, a 50% NiFe alloy featuring low coercivity and thus high magnetic ability, enabling sensor offset and hysteresis to be minimized.

The materials expertise of a leading manufacturer of magnetic materials is the key to assuring optimum results from the finished product, the current sensor.

Control Circuit

Most of the electronic components of VACUUMSCHMELZE's closed-loop sensors with magnetic probe are integrated within an ASIC. Fig. 3 shows the control circuit of the closed-loop current sensor and its functional sections of magnetic probe, IC and compensation coil. The frequency response is as follows:

$$I_K = \frac{S * k_e + k_{HF}}{1 + k_R * S * k_e} * I_P + \frac{S * k_e + k_{HF}}{1 + k_R * S * k_e} * F_{MAG} + \frac{1}{1 + k_R * S} * F_{INT}$$

where I_K = the compensation current, S = the slope of the probe, k_e = the gain of the electronic components, k_{HF} = the "gain" of the transformer (for high frequencies), k_R = the "gain" of the compensation coil (number of turns), and I_p = the primary current.

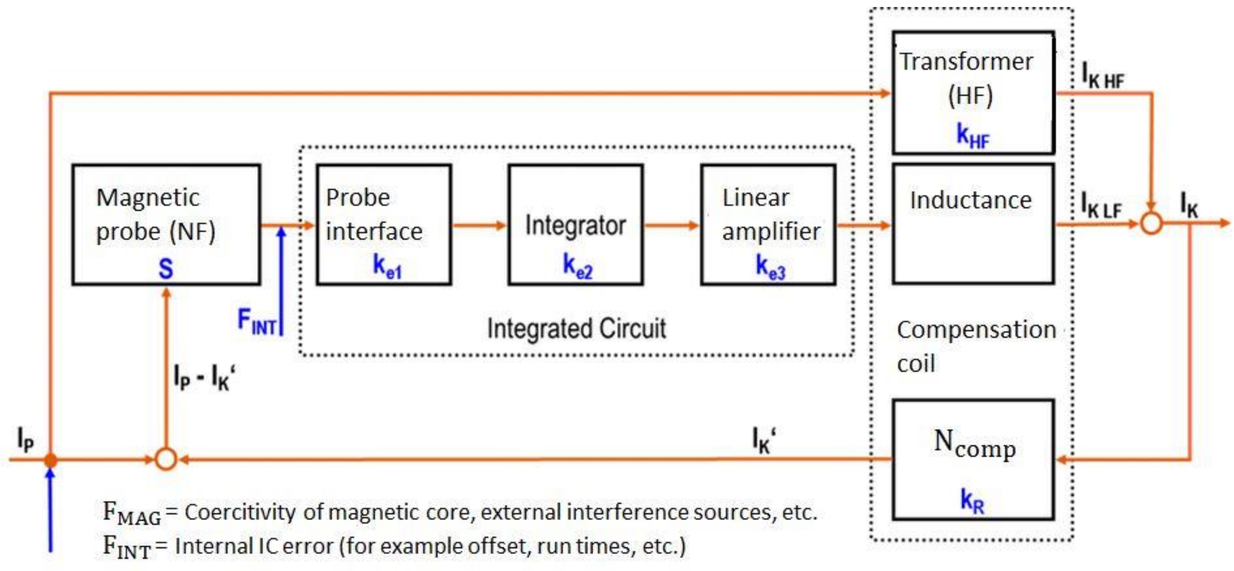

Fig. 3. Current-sensor control circuit.

In the above formula, there are three terms that are summed to obtain the overall frequency response of the sensor. The first term shows the basic frequency response for the complete control circuit. The second or middle term shows the influence of the error F_{MAG}, generated by core hysteresis and external interference. Meanwhile, the third term in the formula shows the influence of the error F_{INT}, i.e. electronic errors such as offset and delay.

Assuming the open-loop gain of the electronic components is infinite and ignoring the HF path (transformer coupling), the frequency response is simplified to:

$$I_K(k_{HF}=0) \xrightarrow[k_e \to \infty]{} \frac{1}{k_R} * I_P + \frac{1}{k_R} * F_{MAG} + \frac{1}{1+k_R * S} * F_{INT}$$

It becomes clear that the error F_{INT} is incorporated into the frequency response in inverse proportion to the probe slope. The error generated by the electronic components of the sensor is therefore minimized by the probe's high inherent amplification.

Maximum Integration Of Electronic Components

As already mentioned, the electronic components of the sensors have been virtually fully integrated in an application-specific circuit developed through a partnership between VAC and a leading manufacturer of high-end analog and digital ICs. This circuit contains the complete signal processing system for closed-loop sensors with magnetic probe, a differential amplifier for the signal across the measuring resistor, a high-precision reference voltage source, and a range of control and monitoring functions.

All the necessary function blocks for current sensors with current or voltage output are therefore already on board the IC. This high level of integration enables the dimensions of the sensors to be reduced; at the same time the number of components is minimized, thus improving the reliability of measurement results such as MTBF and FIT rate.

High-Current Sensors

Sensors for very high current ranges, e.g. I eff = 1000 A, were previously limited to open-loop sensors or closed-loop sensors using Hall-effect probes. Specialized sensors with flux gate probes were previously only used in less common fields involving very high-precision measurement, and were extremely expensive.

VAC now offers the T60404-P4640-X1xx, the first members of a new sensor family designed for rated current of 1000 A eff and measurement ranges of up to ±2500 A (Fig. 4)—the first time that VAC has applied the principle of its closed-loop sensor with magnetic probe to the field of very high current measurement.

Fig. 4. A member of VAC's new family of 1000-A rated high-current sensors.

The new sensors are available in versions for ±15-V and ±24-V supply voltage and a variety of connections. The output variable is a current in a ratio of 5000:1 to the primary current.

Maximizing Technical Advantages

With sensors based on the magnetic probe principle, high-current applications can now take advantage of their low aberration, high-temperature stability and long-term stability. PERMENORM, a highly permeable core material with low coercivity, delivers lower measurement signal offset and hysteresis than that of conventional ferrosilicon cores. A further development of the magnetic probe zero field detector design distributes magnetic flux compensation more evenly throughout the core's entire magnetic circuit, permitting a large measurement range and low external field sensitivity despite the small cross-sectional area of the core.

The measurement range (Table 1) exceeds that of other 1000-A sensors available on the market, in some areas significantly. Other sensors often fail to achieve even a peak current of 1000 A x √2 at elevated temperatures, which would be necessary to image 1000 A ac. Table 1 shows the measurement ranges of VAC high-current sensors under a range of operating temperatures. Higher currents can be imaged for a short time (e.g. 1 ms) by using the sensors' inherent transformer coupling function.

Table 1. Measurement ranges for varying conditions.

Type	Supply voltage V_C	Ambient temperature T_U	Measurement range I_{peak} at R_M = 10 Ω
T60404-P4640-X100	± 15 V	25°C	1580 A
		55°C	1450 A
		85°C	1340 A
T60404-P4640-X150	± 24 V	25°C	2500 A
		55°C	2330 A
		85°C	2150 A

Fig. 5 shows the virtually perfect linearity of the sensor over a measurement range at room temperature (measurement of 10 test specimens, plotted overlapping).

Fig. 5. Linearity of VAC's TP60404-P4640-X150 current sensors over the current measurement range.

Fig. 6 shows the relative error in relation to the current measured (10 test specimens) at room temperature. Even at 100 A, relative error is still within the defined limit of ±0.4% for the rated current of 1000 A.

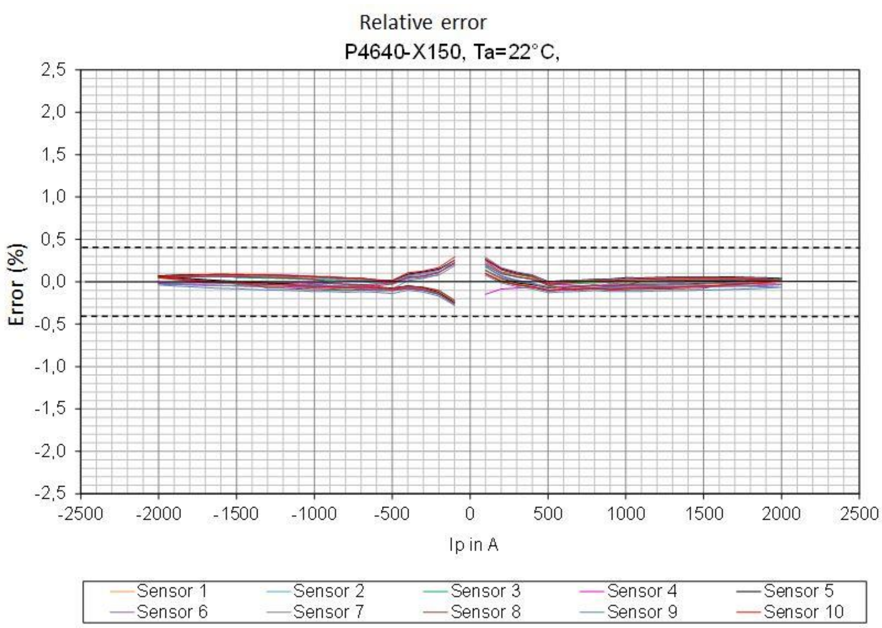

Fig. 6. Relative error of the TP60404-P4640-X150 at room temperature.

Fig. 7 shows relative error at the most critical temperature (lower temperature limit, -40 °C) for nine test specimens. Accuracy compared to room temperature scarcely varies.

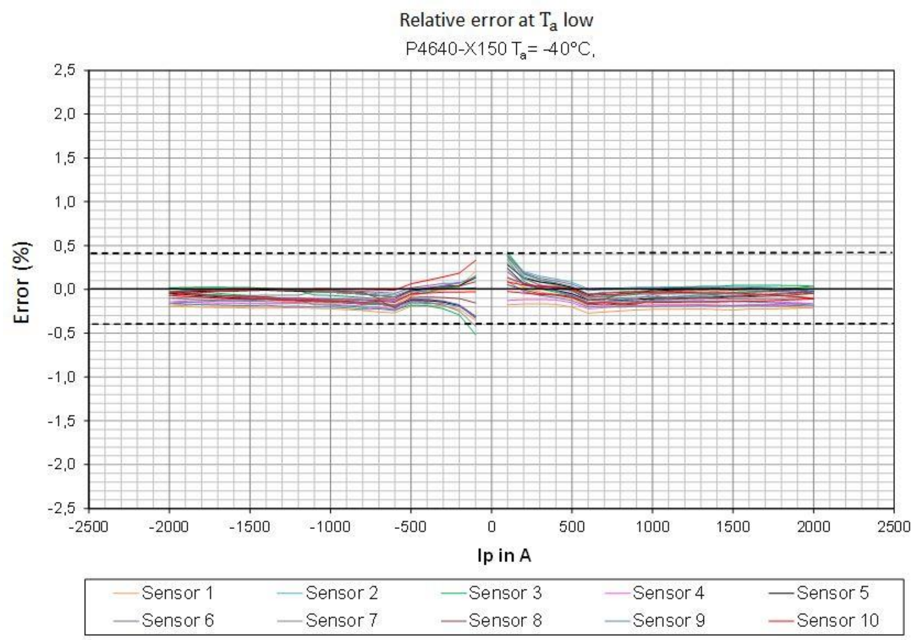

Fig. 7. Relative error of the TP60404-P4640-X150 at low temperature.

Fig. 8 shows the step response for a primary current pulse of 1000 A. The output signal follows the input signal with no visible oscillation.

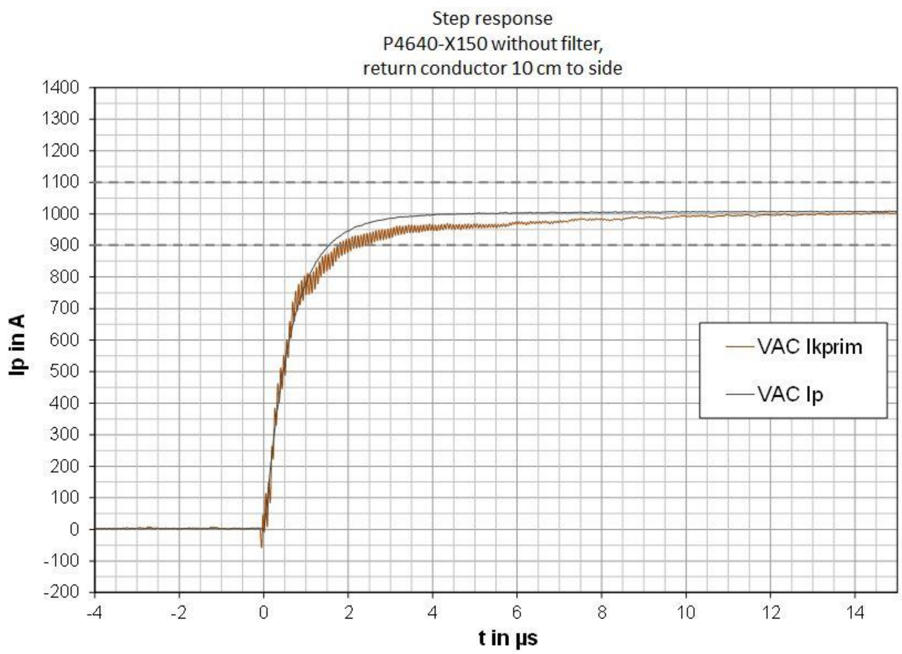

Fig. 8. Step response of the TP60404-P4640-X150.

Figs. 9 and 10 show the external field sensitivity of the sensor as the dependence between aberration and the position of the return conductor for the primary (dc) current in the immediate proximity of the sensor. This low dependence allows more freedom in the layout of the power electronics application.

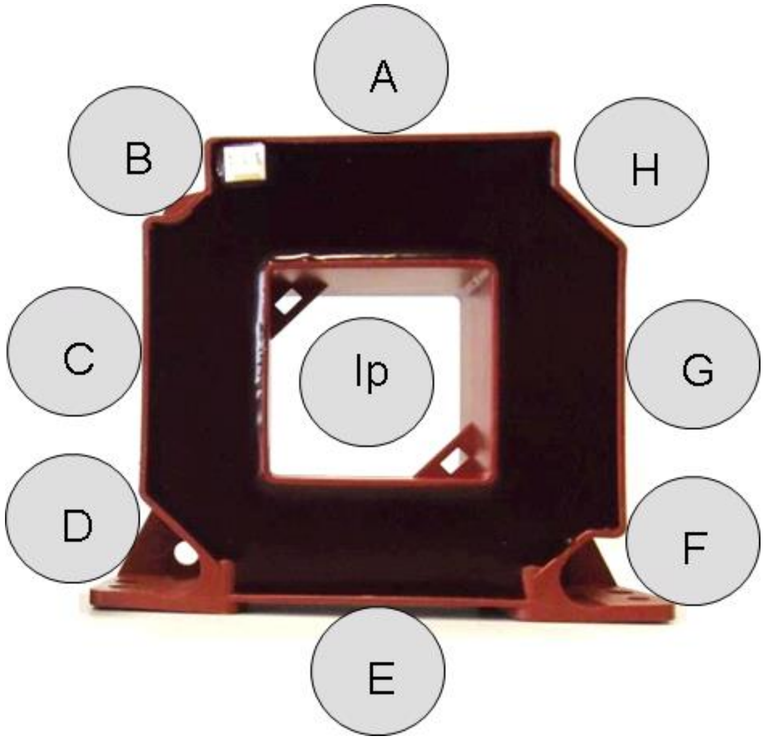

Fig. 9. Current sensor with various return conductor positions.

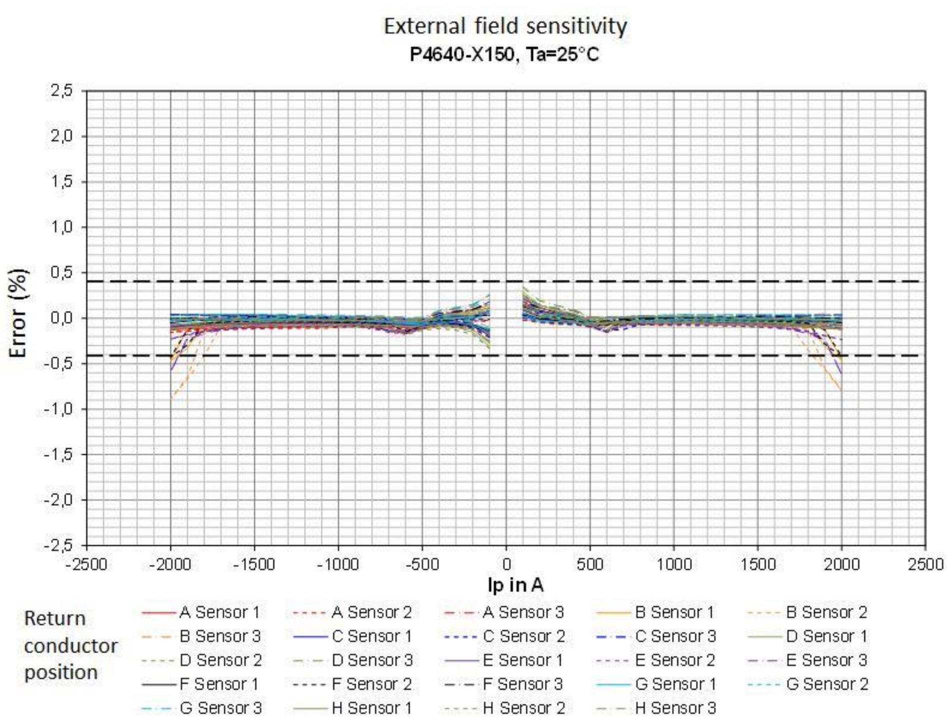

Fig. 10. Relative error of the TP60404-P4640-X150 as a function of the position of the return conductor.

A factor that should not be ignored in closed-loop sensors is that of internal losses, which are primarily generated in the power transistors that drive the compensation current and which play a significant role in sensor self-heating effects. The sensor shown here operates with pulse width modulation, significantly reducing losses in the typical transistor operating range compared with products with linear amplifiers. At full rated current, sensor self-heating is a mere 10 K.

The small cross-sectional area of the core, which was previously mentioned, and the design of the core as a compound square core allow the sensor window to be larger than that of alternative designs with external dimensions of only 40.5 x 40.5 mm (with two opposing corners angled.) This larger window allows larger primary conductors to be passed through, such as aluminium bars replacing copper, stacked bars, angled bars and cables with cable terminals.

Overall, the specifications of the new VAC sensors enable them to outperform other products on the market, in some cases significantly. These specifications can be used for the development of new applications and bring advantages for the devices as a whole. At the same time, the external dimensions (W x D x H = 90 x 34 x 95 mm without base), mounting options and electrical connections are fully compatible with common design types on the market. The sensor can therefore replace existing sensors of the same design type provided that users verify the suitability of the sensor for their specific application.

The intelligent design of the sensor, with prefabricated subassemblies and simple, low-cost assembly, also results in an attractively priced product.

About The Author

Klaus Reichert has more than 30 years of experience in electronic circuit design and the application of magnetic and electronic components. Since 1990 he has been working for VACUUMSCHMELZE GmbH & Co KG, where he is currently senior manager for Industrial Applications. Reichert received his diploma in electrical engineering from the University of Applied Sciences in Frankfurt, Germany.

For further reading on current sensors, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category and select "Test & Measurement" in the Design Area category.