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INVITED PAPER

CURRENT SENSORS USING MAGNETIC MATERIALS

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Precise contactless DC and AC magnetic sensors are required by car industry, chemical industry, for measurement of power and many other applications. The emphasis is given on current sensors based on magnetic materials, but other methods are also mentioned for comparison. Discussed are the factors influencing precision and geometrical selectivity.

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1. Introduction

The current measurement using shunt resistor is in some cases impractical or impossible: for large currents the shunts are heavy and they cause voltage drop and dissipate heat. They are not insulated and the conductor should be disconnected for mounting. Contactless current sensors may be used for remote conductors at high potentials, underground cables etc., but they are usually more expensive. This paper is based on overview of magnetic sensors given in [1].

A wide range of AC and DC contactless current sensors is produced by LEM, F.W. Bell, VAC, Honeywell, Telcon and other manufacturers. Overview of traditional non-contact current sensors is given in [2].

Besides fulfilling the requirements common to magnetic field sensors, such as linearity, offset and sensitivity stability, and low perming, contactless current sensors should be geometrically selective – i.e. sensitive to measured currents, and resistant against interferences from other currents and external fields. The easiest way how to guarantee this, is to use a closed magnetic circuit with a measured conductor inside. This is used in current transformers, fluxgate current sensors and most of the Hall current sensors. If this is not possible (e.g. when the yoke is too large, which usually is the case when measuring large currents), gradient techniques can be used. Simple integrated current sensors use folded conductor and gradient field sensor which suppresses response from distance sources, which give low gradient. For large currents the current bar should be kept straight and circular arrays of typically four to eight sensors are being used [3]. Averaging of the sensor output increases sensitivity to the conductor between them and decreases sensitivity to the conductors outside. Instead of simple averaging of the sensor outputs, higher-order algorithms can give more effective rejection for closely located false currents [4].

2. Instrument current transformers

Current transformers have a primary winding with few turns (or a single conductor through the core opening) and a secondary winding, which should be ideally short-circuits, but in reality it has some small burden. The core is usually ring-shaped, either wound of high permeability tape (for precise, low-frequency devices) or made from ferrite (for high-frequency devices). The current transformer amplitude and phase errors depend on the core material and size, winding geometry, and amplitude and frequency of the measured current and also on the value of the burden (which is

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sometimes in the form of current-to-voltage converter).

Nanocrystalline materials are very promising for use in instrument current transformers. Relative current ratio error of the transformer with core from Nanocrystalline Vitroperm 500 F is very small and phase error is almost constant even for low values of primary current [5]. This is thanks to the material small loss angle and constant permeability over wide field amplitude range. Another advantage of this material is its larger saturation induction than commonly used Permalloy, which allows significant reduction of the core dimensions.

Electronically enhanced two-stage current transformers show accuracy improvement by two orders of magnitude: with a low burden the resulting error is below 10 ppm [6]. These devices can also indicate the remanence of the transformer core or DC component in primary current which may degrade the performance of classical current transformer; they may have lower number of turns, which avoids problems with parasitic capacitances and allows use the device at higher frequencies; and finally the volume of the core may be reduced.

3. Rogowski coil

Circular Rogowski coils (also called di/dt coils) may be used to measure AC or transient currents. The device is extremely linear, as it has air core. It is sensitive to di/dt, so that the output voltage should be integrated. Precise Rogowski coils have both magnetic and electrostatic shielding to suppress interference. Rogowski coil with digital integrator is being used for power meters: using AD 7759 signal processor with built-in sigma-delta A/D converters gives 0.1% error from the measured value in 1000:1 dynamic range [7]. Rogowski coil with integrator can also be used to measure changes in DC current: however, the limiting factor here is the offset drift of the integrator.

4. Current comparators

Current comparators are described in details in a book written by their “fathers” Miljanic and Moore [8].

AC current comparator is three-winding device on ring (torroidal) core. If the primary and secondary currents are balanced, i.e. $N_1I_1 = N_2I_2$, the core flux and also the voltage induced into the detection winding is zero. The main application of AC current comparator is calibration of instrument current transformers and other metrological tasks, such as null indicator in AC bridges. Practical devices are large and complex: they are compensated by additional windings and they have several active and passive shielding to reduce errors. AC comparators have errors below 1 ppm in amplitude and $3{\cdot}10^{-6}$ deg in phase.

DC current comparators are based on fluxgate effect. They are usually feedback-compensated, the core consists of two detection torroids excited in opposite directions.

The basic schematic diagram of DC current comparator is shown in Fig 1. Also DC current comparators have errors below 1 ppm..

Small-size AC/DC current comparator with amorphous cores was described in [9] and [10]. The device is excited in resonant mode by short 16 A p-p current pulses. The range is 200 A from DC up to 3 kHz. The device can work in three modes: as passive DC comparator, passive AC current transformer and active feedback-compensated AC/DC comparator. While the passive DC ratio error of the magnetic circuit was below 0.3 %, in the transformer mode the maximum amplitude error in the whole frequency range was 0.4% and the phase error was 0.5 deg. In the active comparator mode the amplitude and phase error was 0.2% and 0.2 deg, respectively.

Fluxgate DC current sensors or “DC transformers” are similar to DC comparators but of a much simpler design. The accuracy of a typical commercial 40 A module is 0.5 % , linearity 0.1 %, current temperature drift <30μA (-25^{0}C..70^{0}C). First fluxgate current sensor in PCB (printed circuit board) technology was described by Gijs et al. [11]. Their sensor had a single winding of 36 turns over toroidal core made of amorphous magnetic foil. They reached 10 mV/A sensitivity and ranges up to 5 A. Prototype of a fluxgate current sensor with electroplated core in PCB technology was described in [12]. PCB current sensors have low cross-section of ferromagnetic core and high resistance of the coils. Thus they can not be effectively tuned neither in the excitation circuit, nor at the output. External saturable inductor can be used in order to lower the excitation power [13]. The open-loop linear range is 1 A, but using a 40-turn winding also for the feedback can improve the linearity and increase the range to 10 A. Similar miniature current sensors can also be made in thin-film technology: sensor based on 2.6 mm diameter saturable ferromagnetic ring was described in [14]. Because of their low offset drift, fluxgate-based “DC current transformers” are superior to the current sensors having Hall sensor in the airgap.

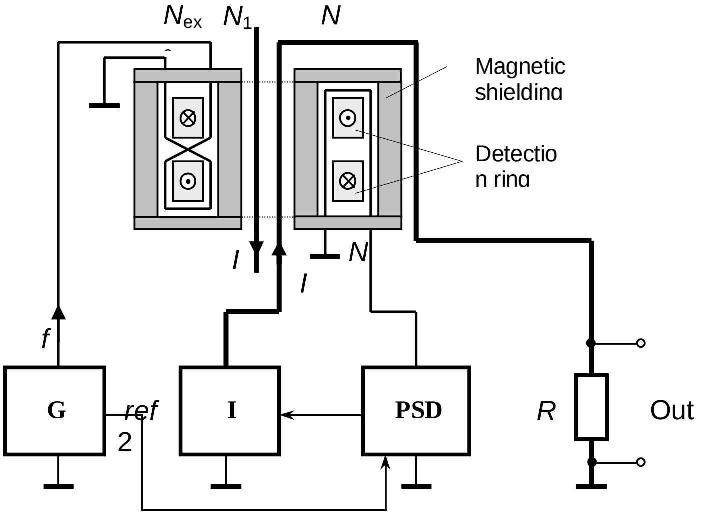

Fig. 1. DC Current comparator (from [9]).

Hall current sensors. Traditional current sensors are based on the Hall element in the airgap of a magnetic yoke. To improve the linearity, the measured current may be compensated. However, open-loop meters are preferred for battery-operated devices because of smaller size and weight and mainly lower power consumption than more precise feedback-compensated sensors. One of the best feedback-compensated small-range Hall current sensors is LTS 25-NP manufactured by LEM. The device has 25 A range and DC to 200 kHz bandwidth, error is 0.02 % and sensitivity TC is 50 ppm/K. The main problem of these sensors is their limited zero stability given by the Hall sensor offset: typical offset drift of a 50 A sensor is 600 μA in the (0^0 C...70 ^{0}C) range. This parameter is 20-times worse than that of fluxgate-type current sensor modules. Even when using magnetic yoke, Hall current sensors are sensitive to external magnetic fields and close currents due to the magnetic leakage associated with the airgap (necessary to accommodate the sensor). Another DC error is caused by the hysteresis of the magnetic core – only few Hall current meters have AC demagnetization circuit to erase perming after overrange DC current.

Low-cost current sensor based on highly sensitive Hall sensor with integrated flux concentrators is described in [15]. The sensor has only simple ferromagnetic circuit and it has 1% accuracy in the ± 12 A range. The device is made in PCB-based technology, which allows easy batch processing.

Yoke-less current transducer with six Hall-probes around the rectangular bus bar achieved 0.5% linearity and 0.2% temperature stability in the 100 kA range [16]. The same 100 kA return current in 50 cm distance was suppressed by the factor of 100.

Magnetoresistive current sensor shown in Fig. 2 is based on an AMR bridge, which is made insensitive to an external field, but sensitive to measured current through the primary bus bar [17]. The measured current is compensated by feedback current through compensation conductor. Typical application is galvanically isolated current sensing in PWM regulated brushless motor. These sensors are manufactured by F.W. Bell and Sensitech with ranges from 5 to 50 A. Achieved linearity is 0.1 % , temperature coefficient of sensitivity is 100 ppm/K, offset drift in the (–45 ^{0}C to +85 ^{0}C) range is 1.4% FS.

Similar sensor with GMR detector was developed by Siemens [18]. While linearization of the AMR sensors is made by using barber poles, these GMR sensors should be biased by permanent magnet, which is a source of instability. Spin-valve bridge current sensor was described in [19]. These sensors are likely to exhibit large change of characteristic when subjected to over-currents.

Magnetooptical current sensors are suitable for high-voltage high-current applications, but the reported errors are more than 1% even after temperature compensation [20], [21]. Magnetooptical current clamps were described in [22]. They do not use optical fiber, but bulk-optic glass. Achieved accuracy was 1% for 50 Hz AC current in a 1000 A range; the sensitivity was 4.45x10-5 rad /A, which is double the Verdet constant of the SF-6 glass. By using bulk flint glass optical detector in the 20 mm wide airgap of ferromagnetic yoke the noise level of 1.6 mA/√Hz @280 Hz was achieved. However such a large airgap should significantly reduce the geometrical selectivity [23].

GMI current sensor was reported in [24]**.** Amorphous $Co_{67}Fe_4Cr_7Si_8B_{14}$ strip was annealed to have 230% GMI at 20 MHz. The schematic diagram of the current sensor is shown in Fig 3. The strip was wound around the measured conductor and DC biased by external coil to achieve linear response. The first prototype has only two turns of the GMI core. The open-loop linearity was 2% in the +/- 2A range. Linearity and stability of the sensitivity can be improved by using of the feedback. The weak point of this type of sensors is poor DC offset stability: the change of the sensitivity with the temperature is 197 ppm/ºC and the GMI offset drift $\Delta Z/\Delta T$ = 25.35 mΩ/ºC. With current sensitivity of 0.24 Ω/A the offset drift recalculated to the input is 105 mA/ºC. This offset drift can be suppressed by differential configuration. When the number of turns is increased from 2 to 200, the sensitivity will be increased by the factor of 100. The impedance of such sensor would be about 2.5 kΩ. The open-loop sensitivity tempco would remain the same, but it can be easily reduced to about 50 ppm/ºC by using the feedback. The feedback would also improve the linearity.

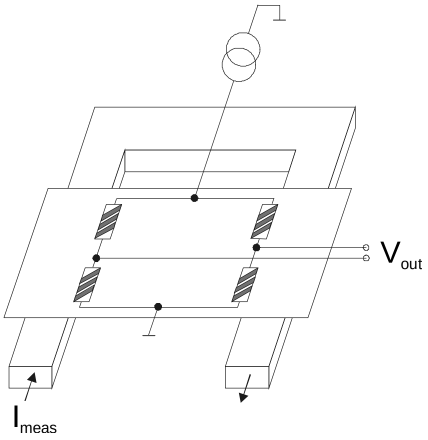

Fig. 2. Magnetoresistive current sensor – after [17].

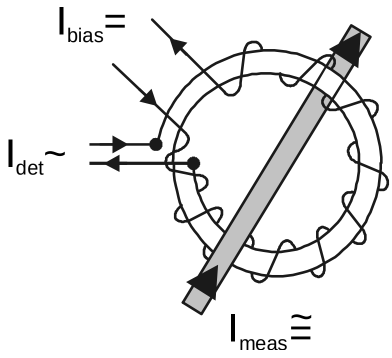

Fig. 3. GMI current sensor.

Current clamps: AC and DC. Current clamps usually consist of an openable magnetic circuit, which ensures that the reading is not dependent on the actual position of the clamped conductor and the device is insensitive to unclamped conductors.

AC current clamps are usually based on current transformers with openable core. The measured conductor forms a primary winding, secondary winding is terminated by a small resistor, or connected to current-to voltage converter. Very accurate clamp current transformers use electronic compensation of the magnetization current and achieve error of 0.05% from the measured value in 1 % FS to 100 % FS [25]. High-current AC and AC/DC openable current transformer clamps [26] and low-current multistage clamp-on current transformer with ratio errors below 50 ppm [27] were developed by So and Bennet.

Some of the available **DC current clamps** based on Hall sensor may have 10 mA resolution, but the maximum achieved accuracy is 30 mA, even if they are of the compensated type. Replacing the Hall sensor with magnetoresistor brought no significant improvement: although they are more sensitive and stable, magnetoresistors require larger airgap (about 2 mm minimum), which degrades the sensor linearity and geometrical selectivity (i.e. the reading is dependent on the position of the clamped conductor and the sensor is sensitive to close unclamped currents). Precise DC/AC current clamps based on shielded fluxgate sensor were described in [28]. The device has rectangular ferrite core consisting of two symmetrical L-shaped halves. The main advantage of fluxgate current clamps is that they need no airgap in their magnetic circuit. Permalloy shielding serves for decreasing the effect of the residual airgap at the clamp joint. Single winding serves for the excitation (by 1 kHz squarewave voltage), sensing (second harmonics in the excitation current) and feedback. The sensor linearity and hysteresis error is less than 0.3% of the 40 A full-scale. The noise is 10 μA p-p, long-term zero stability is 1 mA. The main advantage is high suppression of the external currents: 40 A current 10 mm from the sensor causes error of only 3 mA – this error linearly decreases with increasing distance.

Very simple AC/DC current clamps can be improvised from AC commercially available current clamps, which are excited by external AC generator into the fluxgate mode [29]. In order to minimize the effect of the source impedance and AC interference injected into the measured circuit, two antiserially connected clamps were used [30]. Two AC oscilloscope current probes Iwatsu CP 502 supplied by 700 Hz/290 mA p-p sinewave into serially connected secondary windings tuned by parallel capacitor gave 11.6 mV/A sensitivity in the voltage-output mode and 300 mA/A sensitivity in the current-output mode (per 1 turn of added detection winding).

5. Magnetometric measurement of hidden currents

While the field of the small distant current loop has dipole character, i.e. the field is decreasing with $1/r^3$, where r is a distance, field from the long straight conductor decreases with 1/r. Underground electric conductors can be located and their current can be remotely monitored by measuring the magnetic field in several points supposing that the back conductor is distant. In the case that the cable contains both forward and returns currents, its detection is possible, but the current value cannot be precisely measured. This technique was used for location of underwater optical cables which contain also metallic conductor delivering a DC current of about 1 A to supply the repeaters. The field distribution was measured by two three-axial fluxgate magnetometers. The cables were detected from 40 m distance and their position determined with 0.1 m accuracy from 4 m distance [31].

The magnetometer method is also used to measure the currents in constructions such as bridges and in pipelines. Changing natural magnetic fields may induce large currents in long conductors: 70 A current was observed to flow in Alaska Oil Pipeline [32].

6. Other methods

Current meters using NMR and ESR have been reported [33]. Resolution of 10^{-13} A is achievable with SQUID, but this device has very limited dynamic range. Current weights measure Lorenz force – on the same principle work some published microelectromechanical devices.

7. Conclusions

Traditional DC and AC contactless current sensors are available for ranges from mA to kA with precision from 3% (uncompensated Hall current sensors) to 0.1 % (compensated Hall devices and magnetic amplifiers). Higher precision is easily achievable with Current comparators. Very promising are current sensors based on AMR effect and di/dt sensors.

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