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# A fluxgate current sensor with an amphitheater busbar

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**Large DC and AC electric currents are often measured by open-loop sensors without a magnetic yoke. A widely-used configuration uses a differential magnetic sensor inserted into a hole in a flat busbar. The use of a differential sensor offers the advantage of partial suppression of fields coming from external currents. Hall sensors and AMR sensors are currently used in this application. In this paper, we present a current sensor of this type that uses novel integrated fluxgate sensors which offer a greater range than magnetoresistors and better stability than Hall sensors. The frequency response of this type of current sensor is limited due to the eddy currents in the solid busbar. We present a novel amphitheater geometry of the hole in the busbar of the sensor which reduces the frequency dependence from 15% error at 1 kHz to 9%.**

***Index Terms*—Current sensors, integrated fluxgate, busbar sensor, microfluxgate**

## I. Introduction

LARGE DC AND AC ELECTRIC CURRENTS are often measured by open-loop sensors without a magnetic yoke [1]. The reason is that the yoke becomes bulky for uncompensated large current sensors, and fluxgate-based compensated sensors are rather complicated and energy consuming [2, 3]. Introducing gaps into the magnetic yoke reduces the yoke size without saturation, but the gaps reduce the immunity of the core against the external fields [4].

Commercially-available yokeless current sensors such as Senis BBM [5] use Hall sensors on both sides of the bus bar. The advantage of using a differential configuration is partial suppression of the external magnetic fields, including those coming from currents in other conductors. The disadvantage is the large linearity error (typically 1.5%), poor offset stability, and high temperature coefficient of sensitivity. The available measurement ranges are typically 100 A to 3 000 A.

Another configuration, which is also used in this paper, has a differential magnetic sensor inserted into the hole in a flat busbar. Hall sensors and AMR sensors are currently used in this application. A 300 A AMR sensor with 0.5% linearity error was reported in [6].

It is well known that the precision of busbar current sensors for AC measurements is seriously limited due to the nonuniform current distribution caused by eddy currents in the solid bar. Attempts to break the eddy currents by using a busbar made of insulated conductive sheets led to gross errors caused by the unpredictable non-uniform current distribution between the individual sheets. However, the frequency dependence of busbar sensors is usually not mentioned in the literature. Other types of current sensors have a much wider bandwidth, but they are bulky and expensive devices.

In this paper we present a 1 000 A busbar current sensor using novel integrated fluxgate sensors developed by Texas Instruments (TI) [7]. We mainly discuss the linearity and frequency characteristics that have been achieved. We show that these characteristics can be improved by using more a complicated hole shape than a simple cylinder.

The DRV425 TI integrated fluxgate sensor is a feedback-compensated sensor with on-chip excitation and signal processing circuits [8,9]. The advantage of this sensor is its high excitation frequency, which gives a wide bandwidth of 47 kHz, a small sensor size of 4x4 mm, and a wide range of ±2 mT, whereas only ±100 μT range could be achieved with previous microfluxgate designs, which were restricted by the technological limitations of the CMOS design [10].

## II. A Simple Busbar Sensor with a Cylindrical Hole

The 300 x 60 x 10 mm copper busbar has a cylindrical hole 19 mm in diameter with two fluxgates in locations A and B (Fig. 1), which measure the vertical component of the magnetic field. The sensors are connected to measure the field difference, which depends on the measured current. The gradiometer configuration suppresses common-mode magnetic fields such as the Earth's field and the field from distant conductors. The field from conductors located nearby is only partially suppressed [11].

**FIG. 1 HERE**

The sensor was tested at the accredited laboratory of the Czech Metrology Institute. The sensor linearity in the current range of 1 000 A was better than 0.1% (Fig. 2). In fact, even this non-linearity was caused by metal objects in the laboratory. Due to the circular shape of the hole, the current lines in the vicinity of the sensor are also circular. The sensor constant is therefore very insensitive to the angular misalignment of the fluxgate.

**FIG. 2 HERE**

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Digital Object Identifier (inserted by IEEE).

The frequency characteristic of the integrated fluxgate was measured in 10-turn Helmholtz coils (Fig. 3). For each frequency step, the calibration field was calculated from the coil current. The calibration coil has negligible parasitic capacitance, which is demonstrated by its > 1 MHz resonance frequency.

The measured characteristics show that up to 1 kHz the frequency deviation of the bare fluxgate sensor is below 0.2%.

**FIG. 3 HERE**

The frequency characteristic of the complete busbar current sensor is shown in Fig. 4. It is clear that the 15% frequency error at 1 kHz is caused by the busbar, not by the fluxgate sensor. This error is caused by the eddy currents in the busbar, which deflect the measured current towards the surface of the busbar and especially towards its edges. Some current lines are deflected towards the inner surface of the hole, i.e. closer to the sensor, but on an average most of the current lines are deflected from the sensor. This causes a frequency-dependent drop in sensitivity.

**FIG. 4 HERE**

## III. Amphitheater Busbar current Sensor

After a series of FEM simulations, we proposed the amphitheater shape of the busbar, as shown in Fig. 5, together with the location of the fluxgate sensors and the magnetic field lines. Fig. 6 shows the prototypes of both busbars: with a cylindrical hole, and with an amphitheather hole. The fluxgate sensors are inserted into the slot in the plastic holder, which keeps them in a desired fixed position inside the busbar hole.

**FIG. 5 HERE**

**FIG. 6 HERE**

Fig. 7 shows an FEM model of the AC current distribution in the amphitheather busbar. The increased field density at the edges is clearly visible. This was the basic intuitive idea behind using this shape: the larger number of corners and the larger surface closer to the sensor deflects the current distribution to partly compensate the sensitivity frequency dependence.

**FIG. 7 HERE**

Figure 8 shows that the linearity of the novel sensor is not compromised: the linearity error is well below 0.1% for currents up to 800 A. The sensitivity to the current depends on the vertical position of the fluxgate sensor in the hole.(Fig. 9). The maximum sensitivity point is not in the central plane, as in the case of a simple busbar sensor, but 2 mm above the central plane. At this location, the sensitivity to position error is also minimized. This is a critical property, as with changing temperature due to selfheating the geometry changes due to thermal dilatations, and the current sensor needs to be robust against these changes.

**FIG. 8 HERE**

**FIG. 9 HERE**

The frequency characteristic of the amphitheater current sensor also changes as a function of the vertical position of the fluxgate. The dependence is shown in Fig. 10. Again, the characteristic is very stable in the vicinity of the previously determined working point 2 mm above the midplane. The maximum error caused by the frequency characteristic was reduced to 9%.

We also tested the current sensor performance for different spacing of the fluxgate. When the spacing is increased, the sensitivity increases, but the full scale range decreases. This property is regularly used to set the current sensor range. We verified that changing the sensor distance has no major influence on the frequency characteristic, as is shown in Fig. 11.

**FIG. 10 HERE**
**FIG. 11 HERE**

## IV. Conclusions

Using integrated fluxgate sensors, we have designed a 1 000 A current bar sensor with 0.1% linearity. The novel shape of the hole in the current bar reduces its frequency dependence from 15% error at 1 kHz to 9%.

## Acknowledgment

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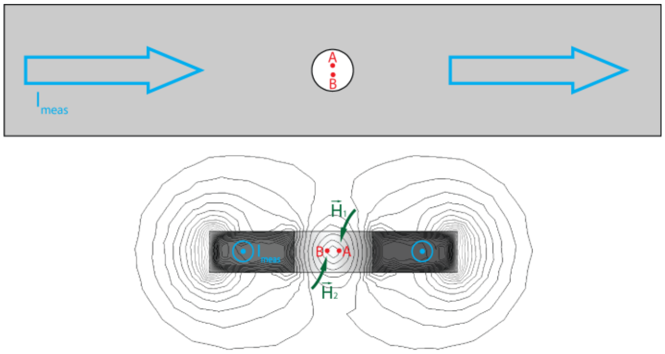


Fig. 1. Busbar current sensor with differential fluxgate sensors A and B at a distance d = 2.5 mm a) top view b) cross section

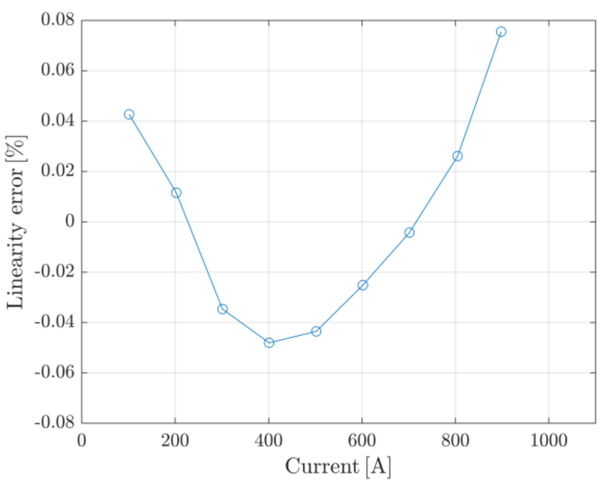


Fig. 2. Linearity error of the busbar current sensor from Fig. 1

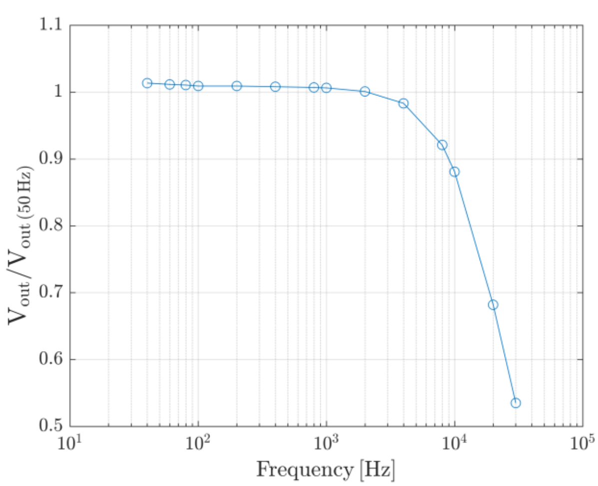


Fig. 3. Frequency characteristics of the integrated fluxgate

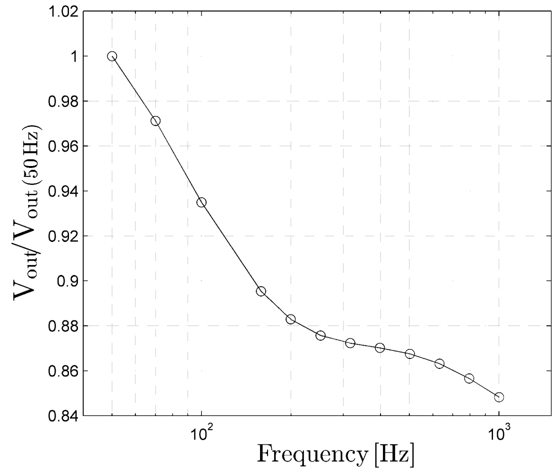


Fig. 4. Frequency characteristics of the busbar current sensor from Fig. 1. The error at 1 kHz is 14%.

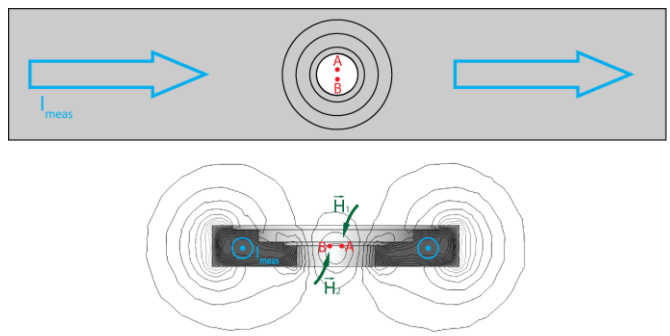


Fig. 5. Amphitheater current sensor – sensors in central vertical position

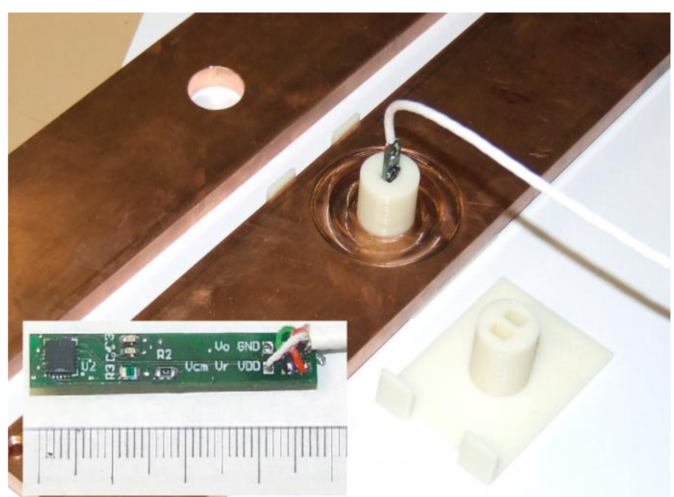


Fig. 6. Basic busbar sensor and amphitheater busbar current sensor with two sensors in the holder. The PCB with fluxgate sensor is shown in the insert. The

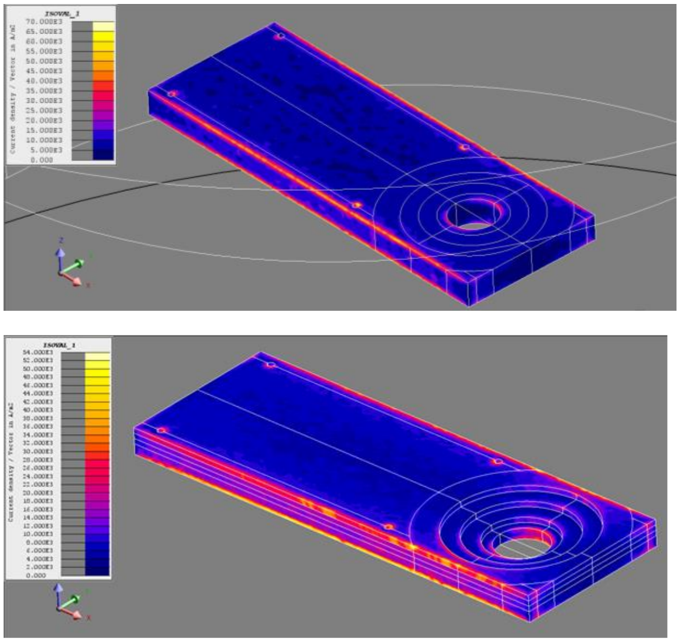

Fig. 7. FEM simulation of the AC current distribution in the busbar sensor and in the amphitheater current sensor

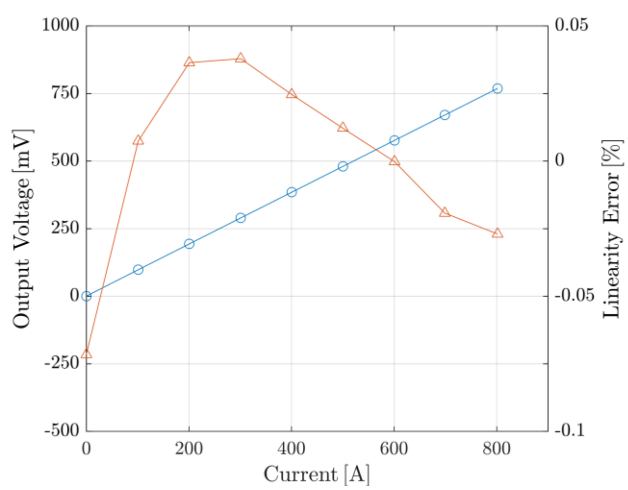


Fig. 8. Transfer function (straight line with circles) and linearity error (triangles) of the amphitheater current sensor (central sensor position).

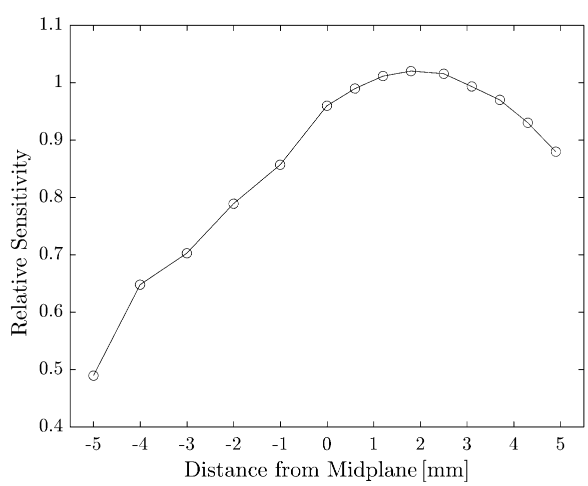


Fig. 9. Relative sensitivity as a function of the vertical sensor position for the amphitheater sensor.

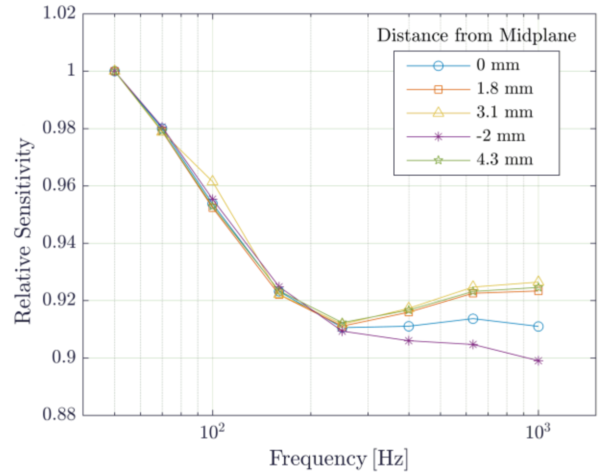


Fig. 10. Frequency characteristics of the amphitheater current sensor as a function of the sensor vertical position. The maximum error caused by the frequency characteristic was reduced to 9%

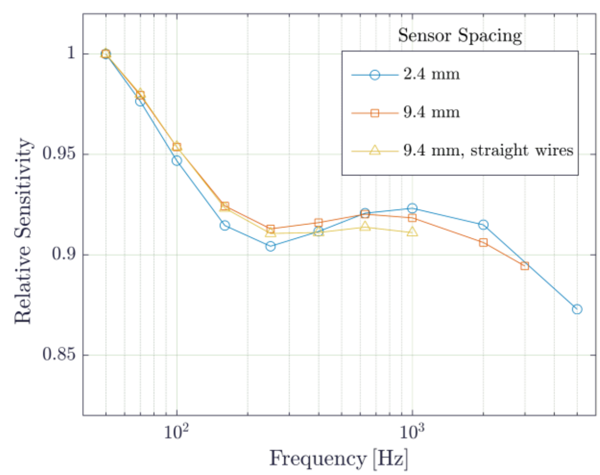


Fig. 11. Frequency characteristic of the amphitheater current sensor as a function of sensor spacing.