MICROSYSTEM FOR ELECTRICAL CURRENT SENSING

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Key words: integrated sensors, Hall sensors, current measurement, microsystems

Abstract: In this paper a method for measuring electrical currents with a magnetic microsystem is presented. With the use of two coils, core and a magnetic microsystem closed loop system can be constructed to measure the electrical current through the primary coil. The magnetic field, generated by the primary coil current is sensed by the sensor in the air gap and amplified. This signal is used to generate a current through the secondary coil and therefore compensating the magnetic field in the air gap.

Mikrosistem za merjenje električnega toka

Ključne besede: integrirani senzorji, Hall senzorji, merjenje toka, mikrosistemi

Izvleček: Članek predstavlja metodo merjenja toka z uporabo magnetnega mikrosistema. Z uporabo dveh tuljav, jedra in magnetnega mikrosistema je možno sestaviti zaprtozančni sistem, ki meri tok skozi primarno navitje. Tok skozi primarno navitje ustvari magnetno polje v jedru, katerega zazna senzor v zračni reži. Ta signal ustvari tok skozi sekundarno navitje in s tem kompenzira magnetno polje v zračni reži.

1. Introduction

There are various methods to measure electrical current. The most common methods include the use of a shunt resistor, a transformer or a magnetic sensor. Resistive shunts operate by giving a voltage proportional to the current going through the resistor. This offers good accuracy and low offset, but does not provide electrical isolation and can have high thermal drift. Due to this nonisolated method the resistor or the electronics can be destroyed due to transients. Transformers can be used to electrically isolate the measurement system from the main system, but the main disadvantage of this method is that this only works for AC currents. To extend the operation to DC or low frequency currents, a DC magnetic field sensing element must be added to the system. This can be achieved by adding a magnetic field sensor into the transformer core, by which the DC magnetic field is measured. If the magnetic field sensor signal is combined with the AC signal the measurement range of such a microsystem is extended into the low frequency region.

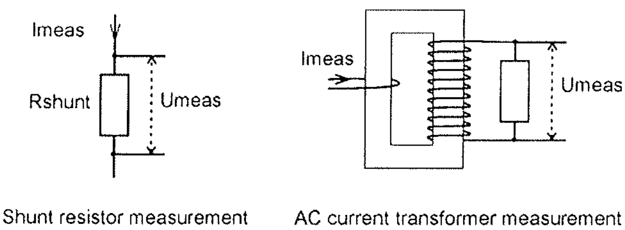

Fig. 1: Methods of current measurement - direct and galvanically separated

2. Closed loop system

The signals from the magnetic sensor and from the coil are combined in such a way, that the field in the magnetic core is always zero. This combination is a closed loop system.

In a closed loop current measuring system the sensor is placed in a compensating field which drives the field across the sensor to zero. The compensating field is generated by a secondary coil with N-turns. Therefore the current in the feedback (secondary) coil is proportional to the field from the primary current scaled by the turns ratio. Usually a shunt resistor is placed in series with the secondary coil to generate a voltage proportional to the measured current. The sensor is situated in the air gap. The magnetic sensor and the amplifying circuitry can be integrated on the same die, reducing the complexity of the wiring. The principle schematic of this closed loop system is shown on fig.2.

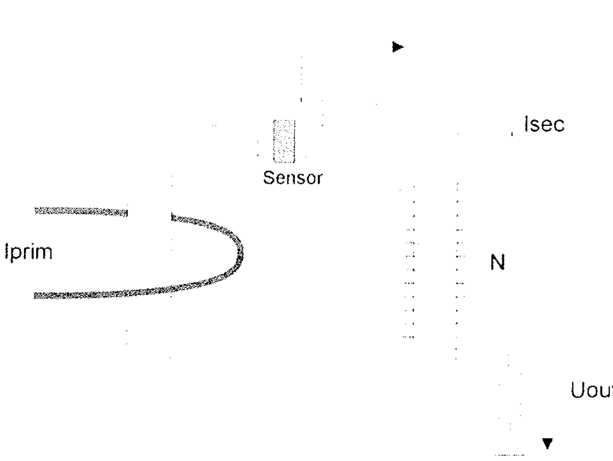

Fig. 2: Closed loop magnetic current sensing circuit

The output voltage for a single turn primary coil can be calculated from the following equation:

$$Uout = Rout \cdot I\sec = Rout \cdot Iprim \cdot \frac{1}{N}$$

The measured output voltage is dependent on the Rout shunt resistance and on the secondary coil N turn number. With these two parameters the measured secondary current can be scaled down to the values, deliverable by the integrated circuit.

The advantages for the closed loop system are:

- closed loop allows for higher accuracy
- the sensor always operates around zero magnetic field strength
- closed loop systems have higher bandwidths
- fast responses
- galvanic separation of the measuring system

3. Integrated microsystem for magnetic field sensing

To measure the magnetic field in the magnetic core gap a magnetic field sensor must be placed into the gap. Two types of sensors can be used:

- discrete sensors (for example magneto-resistive, Hall sensors)
- integrated sensors (integrated together with the processing and amplifying electronics)

The only requirement for the sensor is that it fits into the magnetic core air gap. Both types of sensors (discrete and integrated sensors) have been successfully used. The advantage of the integrated sensor system is the simpler wiring, due to the minimal on-chip wire length also the noise introduction is largely reduced. The disadvantage of the integrated version is the overall larger device, which must be fitted into the magnetic core gap.

The emphasis in this article is on the closed loop system with an integrated magnetic sensor, although the discrete version is very similar in operation. A N-well Hall sensor array was used as the sensing element. The Hall sensors can be easily integrated in standard CMOS processes. The array is made from 12 Hall sensors, each biased with 1 mA. On the same die also the processing electronics and the current driving amplifiers are integrated. Figure 3. shows the block diagram of the presented integrated circuit, figure 4. the layout of the integrated circuit with the integrated Hall sensor array in the middle.

The magnetic sensor signal processing is similar for the Hall sensors and for the magneto-resistive sensors. Both sensor signals need to be alternated for offset compensating reasons. The sensor signal is amplified and buffered to provide current capability.

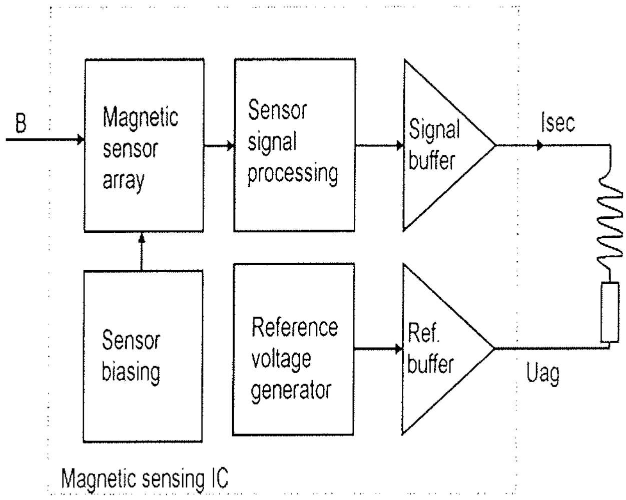

Fig. 3: Magnetic sensing integrated circuit block diagram

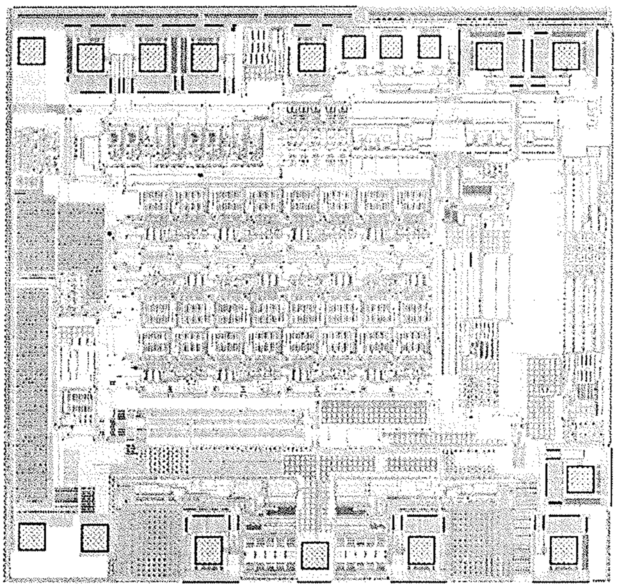

Fig. 4: Integrated microsystem for closed loop measurement

4. Simulation and measurement results

The magnetic core and the two coils have been modeled, enabling the SPICE simulation of the whole microsystem. With that the principle and the realization could be simulated. On fig 5. the step response (0 -> 25A) simulation is visible. The expected secondary coil current is 12.5mA (25A /N=2000). The simulated current is smaller due to the finite open loop gain of the amplifiers. On the secondary current the internal offset canceling circuitry settling is visible. This offset canceling is achieved by HF switching of the sensor signals.

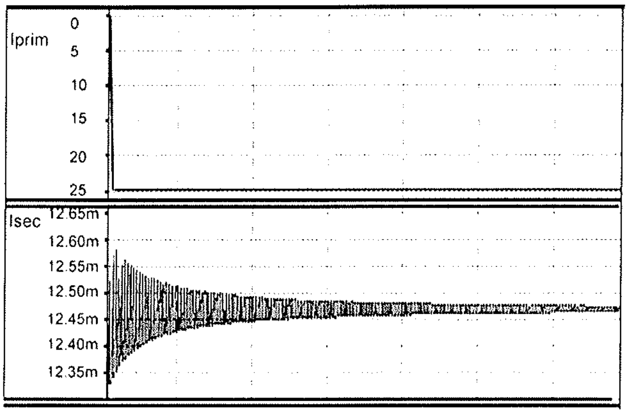

Fig. 5: Simulated 25A step response

On the following simulation the response to a 20A pulses with a frequency of 250Hz is shown. The response to these pulses is a combination of the secondary coil (HF response) and the sensor signal (LF response).

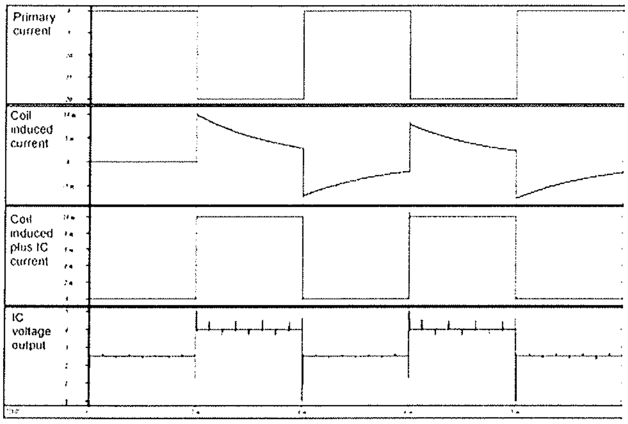

Fig. 6: Simulation of current pulses

The measured frequency response shows a flat frequency characteristics over the requested bandwidth. At lower frequencies the IC microsystem is the dominant contributor to the output signal, at higher frequencies the microsystem acts as a virtual ground and the signal comes from the current transformer. The frequency response is on fig.7. As can be seen, the frequency response shows variations below 0.6dB over the frequency range of up to 200kHz (the scale of the plot is 1dB/div). This means, that the mismatch between the secondary coil (dominant at high frequencies) and the sensor signal (dominant at low frequencies) is less than 0.6dB.

The measurement was made with a network analyzer and coils with a 5/2000 turn ratio. The primary current was measured on a 10Ω resistor, the secondary on a 100Ω. The expected result can be calculated :

$$\frac{Uout}{Uin} = \frac{I\sec \cdot Rout}{Iprim \cdot Rin} = \frac{5 \cdot 100\Omega}{2000 \cdot 10\Omega} = 0.025 \Rightarrow -32.04dB$$

The measured value is -32.27dB (at low frequencies) and shows good matching with the expected value.

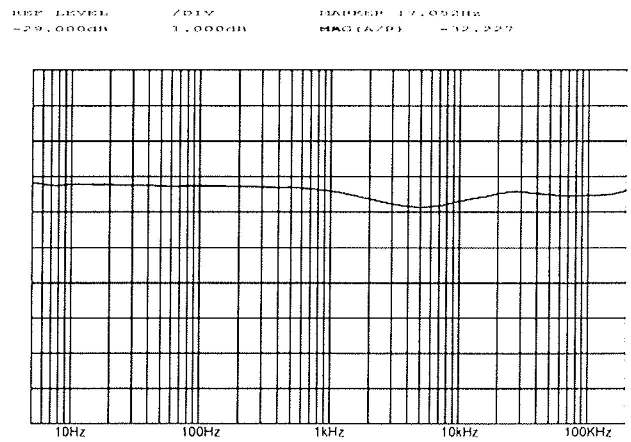

Fig. 7: Frequency dependency of the system

The positioning of the two coils largely influences the performance of the system, the best results are achieved when the primary and the secondary coil are overlapped and physically near to the sensor.

The frequency response of a non-optimal coil positioning can be seen on fig. 8, where the secondary coil was placed on the opposite side of the primary coil on the magnetic core. In this position the secondary coil induces less voltage and therefore the coil induced high frequency response is lower by almost 3dB.

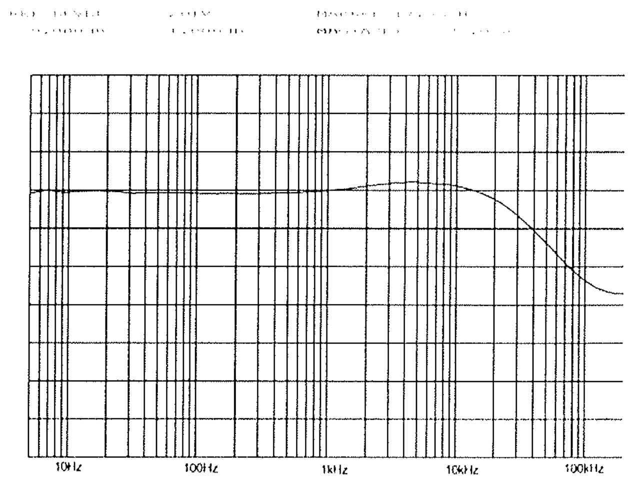

Fig. 8: Frequency dependency of the system with non-optimal coil position

5. Conclusion

It was shown, that a magnetic field sensing microsystem in a closed loop configuration for measuring currents has many distinct advantages over other methods. It combines the fast response times of the transformer method with the DC accuracy of the shunt resistor method. The Hall

Informacije MIDEM 33(2003)2, str. 118-121

magnetic sensor, processing electronics and the current amplifiers are all integrated on the same silicon die, creating an integrated microsystem. This die with the sensors is placed into the core air gap. With the use of the microsystem approach the interconnecting lines are largely shortened and therefore crosstalk and interference possibilities are reduced in comparison with the discrete sensor version. With an optimal positioning of the two coils on the magnetic core an matching error of 0.6dB between the low frequency sensor and the high frequency coil response can be achieved.

6. Literature

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Prispelo (Arrived): 06.06.2002 Sprejeto (Accepted):25.05.2003