Leszek WYDŹGOWSKI
NICOLAUS COPERNICUS UNIVERSITY, FACULTY OF PHYSICS, ASTRONOMY AND INFORMATICS

Inductive current sensor

Mgr Leszek WYDŹGOWSKI

Autor w 2004r. ukończył studia magisterskie na wydziale Fizyki, Astronomii i Informatyki Stosowanej Uniwersytetu Mikołaja Kopernika w Toruniu. W roku 2002 rozpoczął współpracę z firmą APATOR S.A. specjalizującą się m.in. w produkcji liczników energii elektrycznej. Celem tej współpracy jest opracowanie licznika energii elektrycznej odpornego na zakłócenia, a w szczególności na silne pola magnetyczne.
Obecnie autor kontynuuje naukę na studiach doktoranckich.

e-mail: lehu@fizyka.umk.pl

Abstract

This paper describes the design parameters and construction of current sensors based on inductive coils with no magnetic core. These sensors are contactless and can be used in remote conductors at high potentials. This sensor doesn't have iron core (unlike current transformer) so there is no non-linearity over a very wide measurement range. Unlike a shunt resistor, this sensor provides galvanic isolation and produces no heating.

Keywords: contactless AC current sensor, magnetic field sensor

Indukcyjny czujnik prądu

Streszczenie

W artykule przedstawiono konstrukcję indukcyjnego czujnika prądu, który nie generuje pola magnetycznego na zewnątrz, a jednocześnie jest odporny na zakłócające pola magnetyczne. Czujnik ten nie posiada rdzenia magnetycznego, dzięki czemu może mierzyć prąd w bardzo szerokim zakresie. Zapewnia on także galwaniczne oddzielenie obwodów wejściowych i wyjściowych.

Słowa kluczowe: bezstykowy czujnik prądu, czujnik pola magnetycznego

1. Introduction

Today, the most popular current sensor technologies are: the low resistance current shunt, the current transformer (CT), the Hall effect sensor, the magnetoresistive sensor and the Rogowski coil.

Each of these sensors has some disadvantages. Low resistance current shunt offers good accuracy, low cost of application and simple current measurement circuit, but it is a resistive element, and the heat dissipation is proportional to the square of current passing through the sensor. This self-heating problem strongly limits its applications. Moreover, there is no electrical isolation. When high precision current measurement is needed, one must consider the parasitic inductance of the shunt. The inductance is typically only a few nH, but it affects the shunt's impedance magnitude at relatively high frequency. However, its effect on phase is significant enough, even at line frequency, to cause noticeable error at low power factor [1].

Contactless current sensors must be geometrically selective – they should be sensitive to measured currents, and insensitive to interferences from other currents and external fields.

Current transformer is able to measure in a wide range of current and consumes low power, but the ferrite material used in the core can saturate at high current. Once magnetized, the core will contain hysteresis and the accuracy will be degraded unless it is demagnetized again. The CT typically has small phase shift associated with core magnetization. The amplitude and phase errors depend on the core material, size, winding geometry, amplitude and frequency of the measured current [2].

Hall effect sensors used for current measurement can work in the two main types of implementation: open- and closed-loop. These sensors have a very good frequency response and are capable of measuring large current. However, there are several drawbacks to this technology: the output from Hall effect sensor has a large temperature drift, offset voltage and it usually requires stable external current source [1].

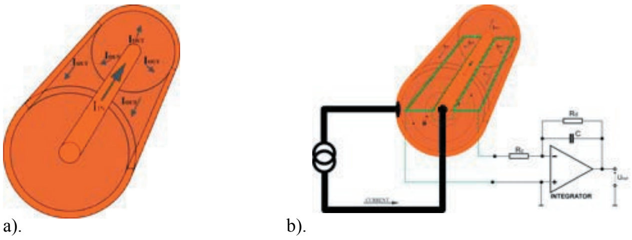
The closed-loop sensor type, by keeping the resultant field in the magnetic core near zero, makes the errors associated with offset drift, sensitivity drift and saturation of the magnetic core will effectively canceled. Closed-loop Hall effect current sensors also provide the fastest response times. However, with a secondary coil that may be needed to drive up to several milli-amps of current, power consumption is much higher in closed loop Hall effect devices than in the open loop systems. The closed loop configuration also limits the magnitude of the current that can be sensed since the device may only drive a finite amount of compensation current [3].

Magnetoresistive sensors used for current measurement can measure DC and AC currents with the frequency of up to a few MHz. In some cases the magnetoresistive sensor needs auxiliary external magnetic fields (i.e. from permanent magnet) to get better linearity - but it is still nonlinear. The second disadvantage of these sensors is temperature drift. Magnetoresistors have other disadvantages including limited linear range, poor temperature characteristics, magnetic memory, and high costs. Also, too strong magnetic field can damage the sensor [4].

Rogowski coil is typically made as aircore coil, so in theory there is no hysteresis, saturation, or non-linearity. The voltage output of the coil only depends on the di/dt changes in the primary current. The output from Rogowski coil is proportional to the time derivative of the current and an integrator is needed to convert the di/dt signal back to the format of i(t) [5].

2. Principle of operation

Current sensor described in this article and shown in fig. 1 is made of specially shaped current conductor which contains measurement coil inside. The coil output signal is proportional to the rate of changes of the measured current. To obtain a signal proportional to the measured current, coil output signal must be integrated.



a). b).

Fig. 1. Current sensor: a - sectional view of special shaped current conductor, b - measurement circuit
Rys. 1. Czujnik prądu: a - przekrój, b - układ pomiarowy

The current generates magnetic field that can be measured using magnetosensistive device. Amper's law states that the line integral of the magnetic field intensity (**H**) around any closed path is equal to the current enclosed within that path (formula 1).

$$\oint \vec{H} \cdot d\vec{L} = I \tag{1}$$

where: **H** - magnetic field intensity,
I - current,
d**L** - infinitesimal section of the closed loop integrating path,

Faraday's law states that any change in the magnetic environment of the coil causes voltage (Electro-Motive Force - EMF) which is inducted in the coil (fig. 2). No matter how the change of magnetic field is produced, the voltage is generated (formula 2).

$$EMF = -\frac{\partial \Phi}{\partial t} \tag{2}$$

where: EMF - electromotive force,
Φ - magnetic flux,
t - time,

The flux density of a magnetic field induced by a current is directly proportional to the magnitude of the current. The changes in the magnetic flux density passing through a conductor loop generate an EMF between the two ends of the loop. The EMF is a voltage signal that is proportional to the di/dt of the current (formula 3). The voltage output from the di/dt current sensor is determined by the mutual inductance between the current carrying conductor and the di/dt sensor [1]. An integrator is needed to convert the di/dt signal back to the format of i(t) for further processing, because the output from the coil is proportional to the time derivative of the current.

$$EMF = -M \frac{\partial I}{\partial t} \tag{3}$$

where: M - mutual inductance,
I - current,
t - time,

The output voltage of the coil is directly proportional to the di/dt changes in the primary current. Printed circuit board (PCB) coil cannot measure DC current, but this type of sensor can easily measure AC current up to hundreds of Amps. This coil doesn't have iron core so there is no non-linearity over a wide measurement range.

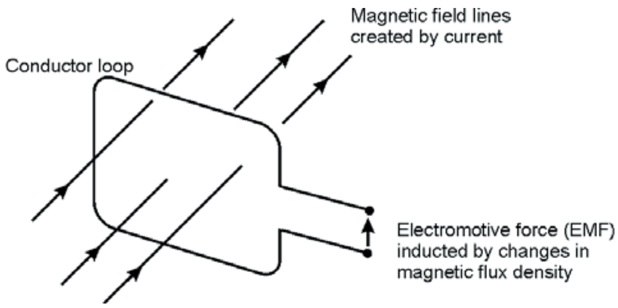
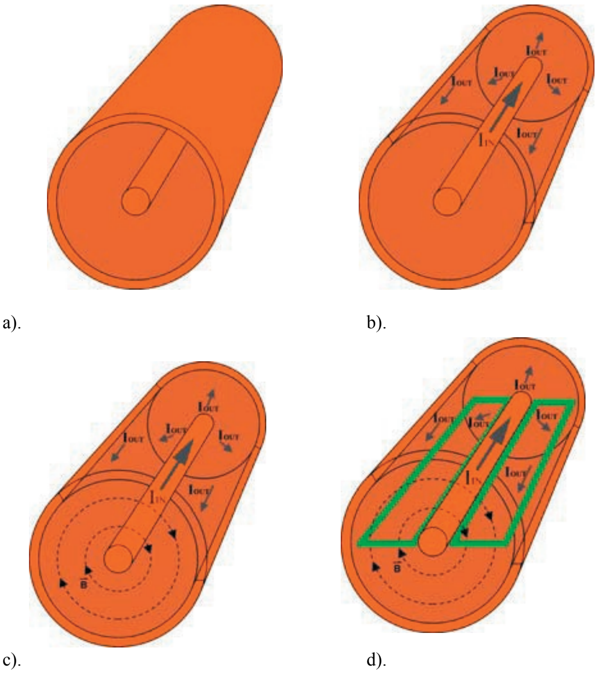


Fig. 2. Principle of operation di/dt current sensor
Rys. 2. Zasada działania czujnika indukcyjnego

3. Sensor construction

The main elements of this sensor are special shape conductor carrying measured current and the coil inside the conductor (fig. 3). The coil can be made of a flat PCB. It can be constructed from a few turns of copper wire wound around nonmagnetic core. It can also be Rogowski coil.



a). b).

c). d).

Fig. 3. Current sensor construction: a). general view, b). current flow inside sensor, c). current and magneticfield, d). example coils
Rys. 3. Budowa czujnika: a). wygląd ogólny, b). przepływ prądu wewnątrz czujnika, c). pole magnetyczne wytwarzane przez przepływający prąd, d). przykładowe cewki

The special shape of this sensor causes that there is no magnetic field outside sensor generated by measured current (fig. 4). Two or more of these sensors can be used (to measure different currents) close to each other with no disturbation fields from other sensors. As there is no external field outside this sensor, magnetic shield around the sensor can be applied, and this shield does not change field inside the sensor. This shield makes the sensor very insensitive to external disturbations of magnetic fields.

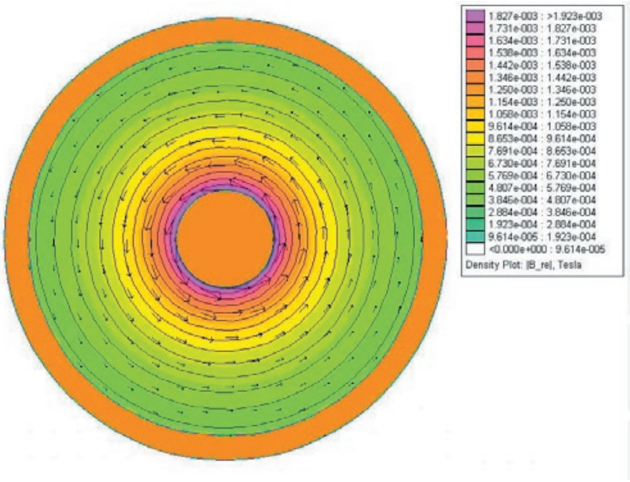


Fig. 4. Magnrtic field inside sensor (cross-section)
Rys. 4. Pole magnetyczne wewnątrz czujnika (przekrój)

The output voltage from the coil is proportional to the rate of change of the current. This voltage must be integrated, producing an output signal proportional to the measured current. The addition of an integrator to the coil completes the transducer to provide a voltage which reproduces the current waveform. Fig. 1b shows a typical active system which uses an inverting integrator. Modern system uses operational amplifiers to gain the signal from the coil, and DSP processor to integrate the signal and it makes all needed calculations (e.g. energy calculation in energy meters).

4. Using the sensor in energy meter

The sensor described in the above section was made to use it in the fiscal energy meters. Construction of this sensor makes it very useful for energy meters because it is insensitive for external magnetic fields and permanent magnet which is very often used by electrical energy thieves.

The block diagram of simple, low cost, one phase energy meter with described current sensor is shown in fig. 5. This meter contains several main components: power supply, voltage sensor, current sensor, energy calculating chip, microprocessor and display. The ADE7759 producted by Analog Devices is energy calculating DSP chip able to work with Rogowski coil current sensor without external integrator. Because the output signal from described sensor is the same as from Rogowski coil, the ADE7759 chip is used to calculate energy in this case. The microprocessor PIC16F648 (Microchip) controls the meter, contains the calibration data, reads, stores and displays calculating energy.

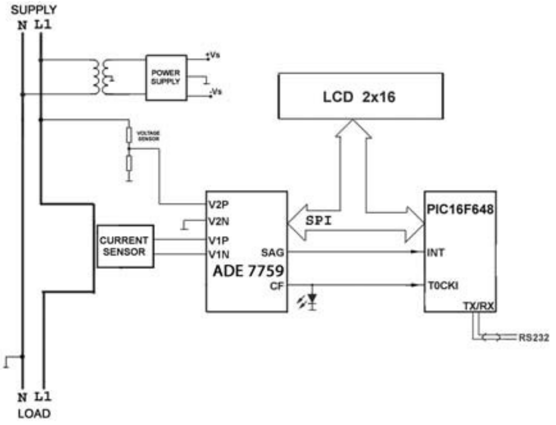


Fig. 5. Block diagram of the single phase energy meter, using tested current sensor
Rys. 5. Schemat blokowy jednofazowego licznika energii elektrycznej wykorzystującego opisywany czujnik

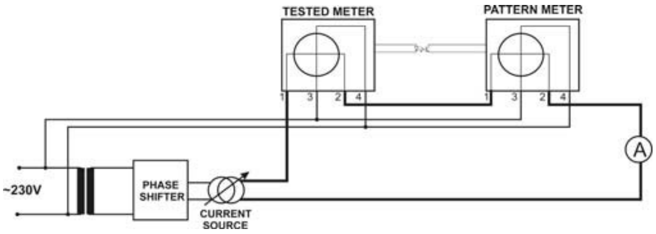


Fig. 6. Energy meter testing circuit
Rys. 6. Układ testowania licznika energii elektrycznej

The energy meter test circuit is shown in fig. 6. This circuit contains tested meter, pattern meter, regulated current source and current phase shifter. The phase shifter is essential to test the meter on the different load condition. In this circuit inductance or capicatance load can be simulated. Two main tests of energy meters was made. The first at power factor 1 (resistance load), and second at power factor 0,5 (inductance load).

The results of these tests are shown in fig. 7 and 8. The result plots show meter error depending on the magnitude of measured current with no disturbation fields, and with external disturbation. The didturbation was made by placing the disturbation wire 5mm from the current sensor. The wire was carrying the same current as it was carrying in the sensor.

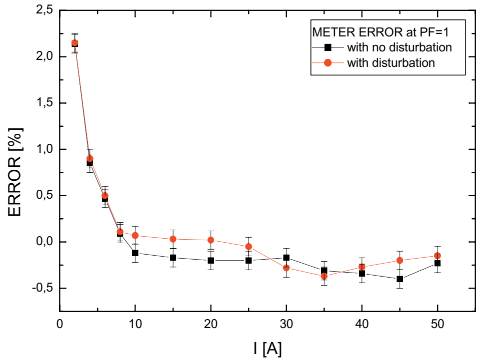


Fig. 7. Meter error, test with power factor 1
Rys. 7. Błąd licznika przy współczynniku mocy 1

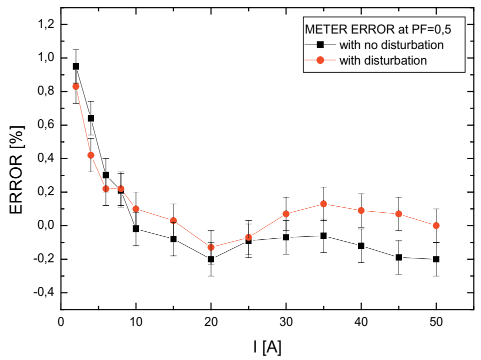


Fig. 8. Meter error, test with power factor 0,5
Rys. 8. Błąd licznika przy współczynniku mocy 0,5

5. Conclusion

Recently the old household inductive energy meters have been replaced by the new designed electronic meters. The electronic meters are more accurate and flexible. They can contain many different scales of charges. Like all energy meters, they must work with a wide range of measured current at different load. The current sensor in these meters must measure the current very accurately and must be resistant to external disturbation, and signal from the other phase in the same meter. One of the most important features of these sensors is the price. The sensor should not be too expensive. Current sensor described in this article fulfils these expectations.

6. Acknowledgements

This paper is co-financed from European Social Fund and national budget in the Marshal Office of the Kujawsko - Pomorskie Voivodeship project: Step in the future - grants for candidates for doctors degree.
This paper was written in cooperation with APATOR S.A. Company

7. References

[1]. William Koon: Current sensing for energy metering. Analog Devices Inc., 2002
[2] P. Ripka: Current sensors using magnetic materials. Journal of Optoelectronics and Advanced Materials, 2004.
[3]. Richard Dickinson and Shaun Milano: Isolated Open Loop Current Sensing Using Hall Effect Technology in an Optimized Magnetic Circuit. Allegro MicroSystems, Inc.,2002
[4]. Sławomir Tumański: Cienkowarstwowe czujniki magnetorezystancyjne. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawawa 1997
[5]. D. A. Ward, J. T. Exon: Using Rogowski coils for transient current measurements. Engineering science and education journal, 1993.

Artykuł recenzowany