7th International Scientific Conference
Technics and Informatics in Education
Faculty of Technical Sciences, Čačak, Serbia, 25-27th May 2018
Session 3: Engineering Education and Practice
UDC: 004.9: 621.317

Educational Laboratory Setup for Electric Current Measurement using Hall Effect Current Sensors

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Abstract: *The aim of this paper is to present an educational laboratory setup for current measurement using current sensor Ametes-Senis CS10A-02, data acquisition card NI USB 6009 and personal computer with LabVIEW software. This current sensor module contains a single Hall effect sensor CSA-1V and accompanied electronic parts. The paper contains a brief description of the working principles of Hall effect sensors and the current sensor, presents its structure and technical details of interest. It also gives a description of a laboratory setup for measurements with current sensor, as well as a description of the used LabVIEW application. The paper presents the results of measurements and a proper discussion.*

Keywords: *Hall sensor; Current sensor; Open loop sensor; Closed loop sensor; CS10A-02*

1. INTRODUCTION

Nowadays, measurement, control and monitoring of electric current is needed in various applications. For that purpose, different types of sensors are used, such as: sense resistors (shunts), current transformers, Rogowski coils, magnetoresistive and Hall effect current sensors. Recently, noninvasive methods like Hall effect current sensing has become more interesting subject for research in the field of electrotechnics. Hall effect current sensor became more profitable after development of integrated circuit technology and smaller, more reliable and cheaper amplifiers needed for its operation. Advantages of Hall effect current sensors are high isolation and small insertion loss of energy. Also, some of Hall effect current sensors offer current measurement without any insertion in the electric circuit which current is being measured.

Hall effect current sensors come in a variety of configurations and offer a wide range of applications. Because of their advantages, such as small size and small insertion losses, Hall effect current sensor finds their use in systems like Battery Management Systems (BMS) and power supplies [1]. In solar and wind power plants they are used in feedback loop both for MPPT and synchronization with electrical grid [2]. Because of their ability to measure currents without galvanic connection and ability to measure both DC and AC currents, principle of Hall effect current sensors are used in electrical tools like clamp meters [3]. Because of their wide bandwidth and accuracy, they are used in electric drives (in a closed loop feedback) for control and protection [4, 5].

Hall effect sensors have a simple construction and therefor are relatively cheap. Also, other sensors based on Hall sensor are simple and cheap, which makes it suitable for student work in the laboratory.

This paper presents a student project done within two subjects "Virtual instrumentation" and "Electrical measurements of non-electrical quantities". It will be used as new laboratory exercise for future generations of students.

The paper presents a theoretical approach to the subject of Hall effect current sensors (Sections 2 and 3). A description of laboratory setup for current measurement using a Hall effect current sensor, as well as a realised control panel of PC based virtual instrument and measurement results are given in Section 4. LabVIEW software has been used for development of the virtual instrument. Alongside current measurement with Hall effect current sensor, current has been measured with one commonly used method for measuring current – shunt resistor. Also, current has been measured using a digital multimeter. A comparison of the results of these three measurements is presented in the paper.

2. Hall effect current sensors

Hall effect sensors are special electromagnetic sensors named after scientist Edwin Herbert Hall who discovered Hall effect in the year 1879 [6]. Hall effect is phenomenon of occurrence of voltage U_H (Hall voltage) on the opposite sides of strip

(Hall element) with constant current I and in the presence of external magnetic field H normal to its surface. Generated Hall voltage is linearly proportional to the magnetic flux density:

$$U_H = R_H \frac{I}{d} B + U_{off} = kI + U_{off} \quad (1)$$

where R_H is Hall coefficient, d is thickness of Hall element, B is magnetic flux density of external magnetic field, U_{off} is offset voltage and k is sensitivity of Hall element. Fig. 1 illustrates phenomenon of Hall effect.

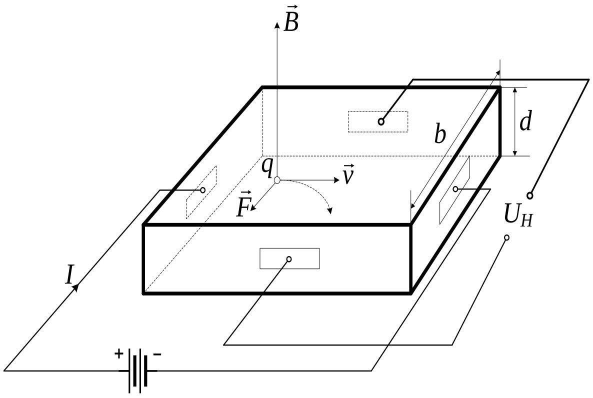

Figure 1. *Hall element*

Semiconductor material like indium arsenide (InAs), indium arsenide phosphate (InAsP), gallium arsenide (GaAs) and indium antimonide (InSb) have high value of the Hall coefficient [7]. A typical value of Hall voltage is in order of mV. Therefore, amplifiers are used to increase this voltage up to order of V [8].

Hall element is the basic part of modern Hall sensor with integrated circuit (IC), which is widely used for measurement of magnetic field, electric current, position, speed sensing, detection of presence and other [8, 9]. It can be manufactured as analog or as digital device.

There are two basic types of Hall effect current sensors – Open loop and Closed loop sensors.

2.1. Open loop Hall effect current sensor

Current measurement using device with only Hall sensor and amplifier is possible in case of PCB (Printed Circuit Board) where the distance between a conductor and Hall element is small and where conductor is rigidly fixed in space [10]. The magnetic field decreases fast with distance. Thus, accuracy of current measurement is highly dependent on position of conductor.

For accurate current measurements in other applications, it is necessary to amplify magnetic flux from conductor using high permeability toroid magnetic core [8, 11]. This type of Hall device is called the Open loop Hall effect current sensor, Fig. 2. Hall element is placed in the air gap of such magnetic core. Magnetic core is also called Flux Concentrator because it concentrates and amplifies magnetic flux in the air gap where the Hall element is placed.

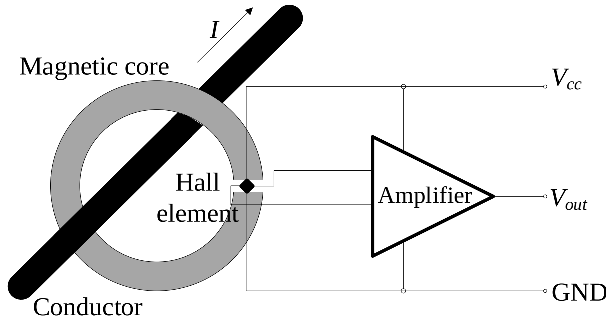

Figure 2. *Open loop Hall effect current sensor*

Magnetic flux density B in the air gap created by the conductor is given in (2) [8]:

$$B = \frac{\mu_0 \mu_r}{l + \mu_r l_0} I \,, \quad (2)$$

where I is the electric current, μ_0 is the permeability of vacuum, μ_r is the relative permeability of magnetic core, l is the length of magnetic core, l_0 is the length of air gap. It can be seen from (2) that the magnetic flux density depends on conductor current, lengths of air gap and magnetic core and the permeability of magnetic core.

For a wide linear range of current measurement, the magnetic core must have high value of saturation magnetic flux density. For smaller offset of measured current core material should have a small coercive magnetic field. Materials that fulfil these requirements are ferrites [11], which are also cheap and widely applicable.

Advantage of Open loop Hall effect current sensor is its small package (small size and weight) [12]. Also, it is cheap. It provides current measurement with high isolation and low insertion losses. There are some disadvantages of open loop current sensor [12]. Open loop Hall effect current sensor has a lower frequency bandwidth (DC-25 kHz) caused by the appearance of eddy currents in magnetic core at measurement of high frequency currents. Because the magnetic core can go out of its linear range (saturation), linear range of Hall effect sensor in open loop is reduced. Also, accuracy is reduced because the magnetic core cannot eliminate temperature drift, presence of noise and current offset that originates from Hall element and additional electronics. With appropriate electronics many of these disadvantages can be reduced, which increases its accuracy over a wide range of measured currents and frequencies.

Practical example of Open loop Hall effect current sensor is an Allegro ACS750 sensor presented in Fig. 3 [13].

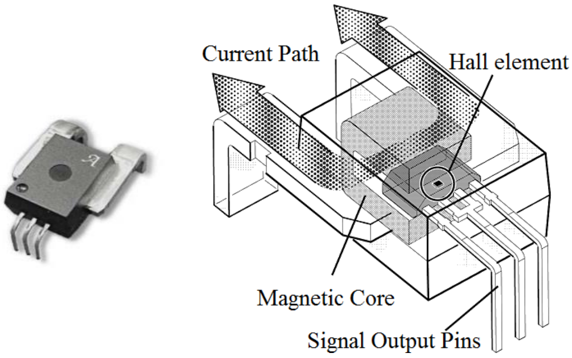

Figure 3. *Allegro ACS750 sensor (left) and its components (right)*

2.2. Closed loop Hall effect current sensor

Most problems of Open loop Hall effect current sensor appear because of saturation of magnetic core. Solution to this problem is to add a secondary coil on the magnetic core which current creates opposite magnetic field to the magnetic field of the conductor and therefor cancel it, Fig. 4 [8, 11]. Thus, the magnetic flux in magnetic core is brought to zero. Current from the Hall element is amplified and passed through a secondary winding (used as negative feedback). This secondary current is used to produce the voltage on sense resistor Rs. This voltage is used as linear output voltage of the sensor.

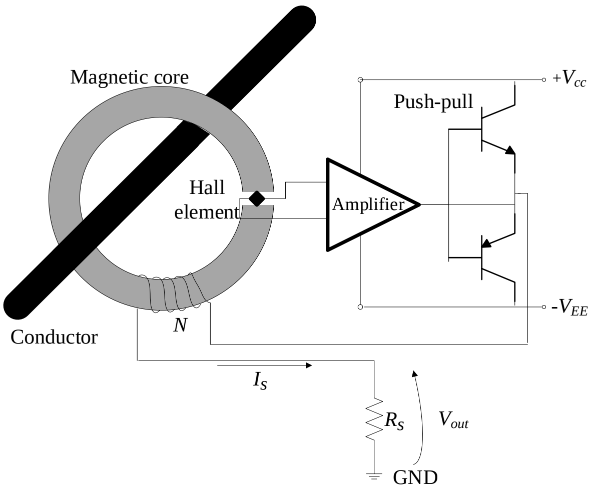

Figure 4. *Closed loop Hall effect current sensor*

Closed loop Hall effect current sensor offers high accuracy and linearity (better than 1 %) [12]. Also, it has good response times of 3 μs, which allows measurement of impulse currents and currents of high dynamic systems (i.e. electric drives). It has low insertion losses, wide bandwidth (DC-200 kHz), low temperature drift and noise. It has low power loss in measurement of small currents [12, 14]. But, in measurement of higher current power dissipation is higher because of power loss on sense resistor. Also, sensor with higher rated current need more powerful amplifiers (more powerful electronics) and a higher number of turns on magnetic core, which causes higher prices and increases size. Also, like Open loop, Closed loop Hall effect current sensors have zero current offset (because of coercivity of magnetic core).

3. Current Sensor Ametes-Senis CS10A-02

Current sensor Ametes-Senis CS10A-02 is Hall effect-based sensor for measurement of currents up to 10 A with high galvanic isolation (4 kV) [15]. It has a linear analog output. It requires a single DC power supply of 5 V, suitable to be provided by data acquisition card. It has low consumption of power and small insertion losses. It is of a small size and can be easily mounted on the PCB (Printed Circuit Board). It can be used for measurement of DC, AC and impulse currents. The sensor can withstand up to 1 T, so high currents cannot damage the sensor. The sensor is saturated around 8.3 mT, which gives great linearity from 0 mT to 5 mT.

Image of Ametes-Senis CS10A-02 sensor is given in Fig. 5.

Figure 5. *Ametes-Senis CS10A-02 sensor module*

The main components of current sensor are Hall effect sensor CSA-1V and coil (bobbin) [16]. Fig. 6 shows all parts of the sensor: shield (1), duct tape (2), foil (3), coil (bobbin) (4) and Hall effect sensor CSA-1V (5).

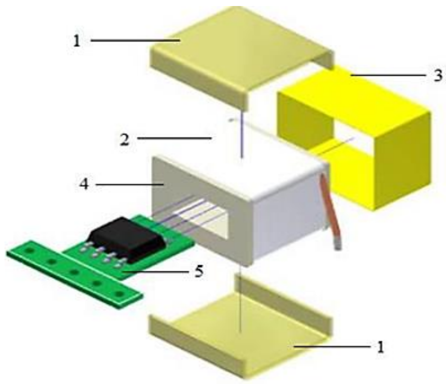

Figure 6. *Ametes-Senis CS10A-02 sensor module structure*

Outline drawings of Ametes-Senis CS10A-02 are shown in Fig. 7.

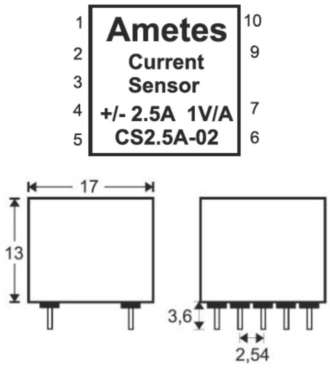

Figure 7. *Outline drawing of Ametes-Senis CS10A-02 sensor module*

Wiring schemes for Ametes-Senis CS10A-02 are shown in Fig. 8 [14]. The sensor can be used in two ways – unipolar and bipolar.

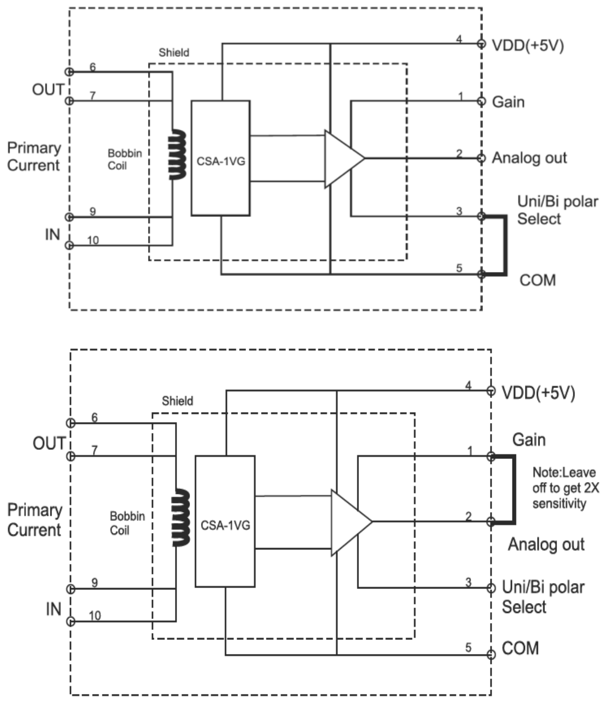

Figure 8. *Ametes-Senis CS10A-02 sensor module wiring scheme for unipolar (upper) and bipolar operation (bottom)*

For measurement of DC currents unipolar operation should be used, which gives an output from 0 to 5 V. The bipolar operation should be used for measurement of AC currents, which has a quiescent voltage of 2.5 V [14]. For negative measured current output is ranged from 0 to 2.5 V, and for positive measured current output ranges from 2.5 V to 5 V. Bipolar operation has twice smaller sensitivity than unipolar. Sensor module has a sensitivity in unipolar operation of 0.5 V/A. Bipolar operation can have a sensitivity of unipolar operation, if pins 1 and 2 stay unconnected, as shown in Fig. 8. But if mentioned pins stay unconnected measured range will be twice smaller.

Bandwidth of sensor amounts 5 kHz. To lower the insertion losses, sensors should have small primary resistance. The primary resistance of the used sensor amounts 0.006 Ω, and primary inductance about 0.005 mH. Current sensors are built in that way that they have maximum accuracy at the end of their measured range – in this case 10 A.

Sensitivity of the sensor depends on the size of the coil and its number of turns [16]. For used sensor, at rated current of 2.5 A and of 1 V/A, 24 turns of AWG24 wire are used. By using different wire area of cross section and the number of turns other model from same series offer different sensitivity and rated currents, which provides CS series of Ametes-Senis sensor measurement of currents from 250 mA to 10 A. The coil gives sensor high dielectric isolation, which makes this sensor good solution for high voltage power supplies with relatively low currents. Sensitivity and resistance from the foreign magnetic field can be achieved by shielding the coil. The output voltage of the sensor is scaled in such way that it obtains the maximum voltage for highest current to be measured, in order to obtain the best accuracy and resolution.

3.1. Hall effect sensor CSA-1V

Main part of previously described current sensor is Hall effect sensor CSA-1V. Its manufacturer is Swiss company Sentron. It is an IC (Integrated Circuit) sensor with analog output proportional to magnetic flux density in proximity of sensor.

The CSA-1V sensor is packaged in a SOIC-8 case and is very suitable for mounting on the PCB and miniaturization of the PCB where it is used for measurement of DC currents (Fig. 9) [17, 18].

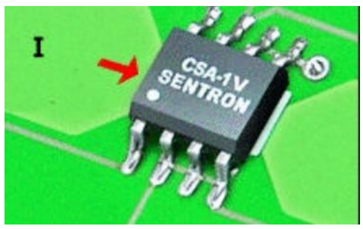

Figure 9*. CSA-1V sensor*

The CSA-1V Hall sensor uses IMC (Integrated Ferromagnetic Concentrator) [18]. Unlike toroid concentrators, IMC has a planar structure which can be laid on the surface of CMOS buffer. It enables integration of the entire sensor on one chip.

Usually, Hall element is sensitive to the magnetic field which lines are normal to its surface [19]. IMC gives sensor sensitivity to magnetic fields which lines are parallel to the surface of the chip, unlike conventional Hall sensors. Actually, IMC converts horizontal lines of magnetic field to vertical ones, normal to a surface of the Hall element placed on sensors IC. IMC enables conductor to be placed nearer to the chip which increases sensitivity around 10 times and gives 20 times higher output voltage than conventional Hall effect sensors, as shown in Fig. 10 [18].

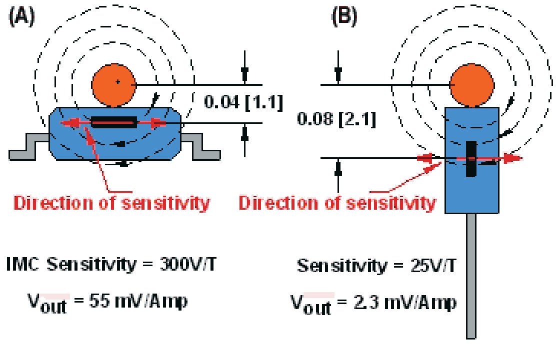

Figure 10. *IMC Hall effect sensor and conventional Hal effect sensor*

4. Realised measurements and results

This section presents a measurement of electric current, both effective value and its waveform, using Hall effect current sensor and comparison of results obtained with results obtained with shunt resistor and digital multimeter (DMM).

Measurement is realised using a virtual instrument created in LabVIEW program.

4.1. Laboratory setup

Realised laboratory setup is presented by the block diagram in Fig. 11 and by photo in Fig. 12. Analog output from the current sensor (CSA) and shunt resistor (R) is connected to the analog input of data acquisition card. Analog pins +5V and ground (GND) from data acquisition card (NI USB 6009) were used as the power supply of current sensor. AC current will be measured and sensor is configured for bipolar operation. Pins 1 and 2 (Gain and Analog Out) were left unconnected, which means that the sensitivity is increased twice (sensitivity is equal to that in unipolar operation) and measurement range is two times smaller (amounts ±5 A). Thus, a sensor is configured to a sensitivity of 0.5 V/A. Measured current is obtained from the electric network (AC) over an isolating transformer (TR).

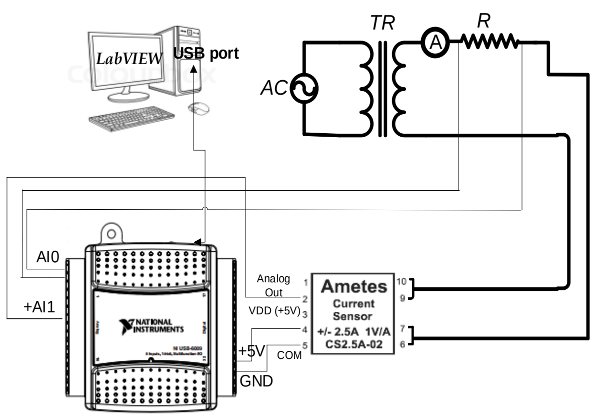

Figure 11. *Block diagram of laboratory setup*

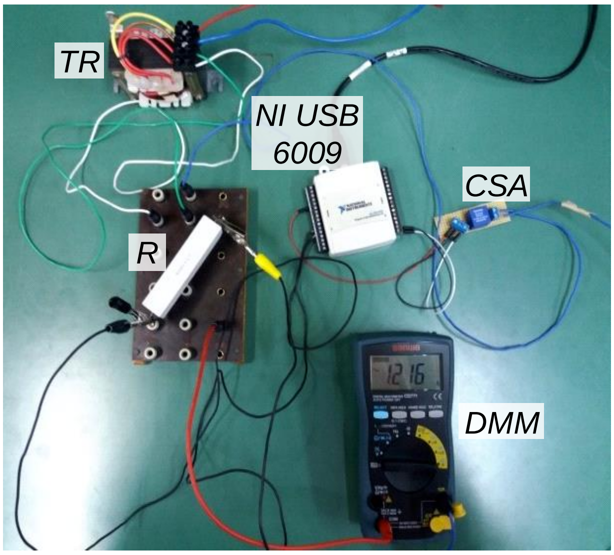

Figure 12. *Photo of realised laboratory setup*

4.2. Control Panel

Realised control panel of virtual instrument is comprised of two tabs, Fig. 13. First tab contains two graphs for representation of time-waveform of voltage from CSA (left) and for comparison of time-waveforms of currents obtained by CSA and shunt resistor. Next to the graphs there are numeric indicators that give RMS values of measured currents. Also, one numeric control exists on the left side for manual inputs of measured currents from DMM. The value of current from DMM is used as the exact value of measured current to calculate relative deviations of other two methods. By choosing the command button "SNIMI" measured values and input value from DMM are written to the table. Also, relative deviations are automatically calculated and written to the table and waveforms of one period of signal are saved to excel file. Also, in case of mistake, data from the table could be deleted by pressing button "RESET".

On the second tab there is a graph that shows all saved waveforms. The choosing of button "ISCRTAJ SIGNALE" draws saved waveforms on the graph. Command "STAMPAJ IZVESTAJ" enables printing of report in PDF format that includes a table of measured data and graph with waveforms.

The program could be stopped at any moment by pressing button "STOP" available in both tabs.

4.3. Results

The numerical results of measurement from the exercise are shown in Table 1.

Measurements of current were performed in the range from 0 A to 3.5 A (RMS values), with step of measurement of 0.35 A. Waveforms of measured signals are given in Fig. 14 where blue lined signals are waveforms from CSA and red ones are from shunt resistor.

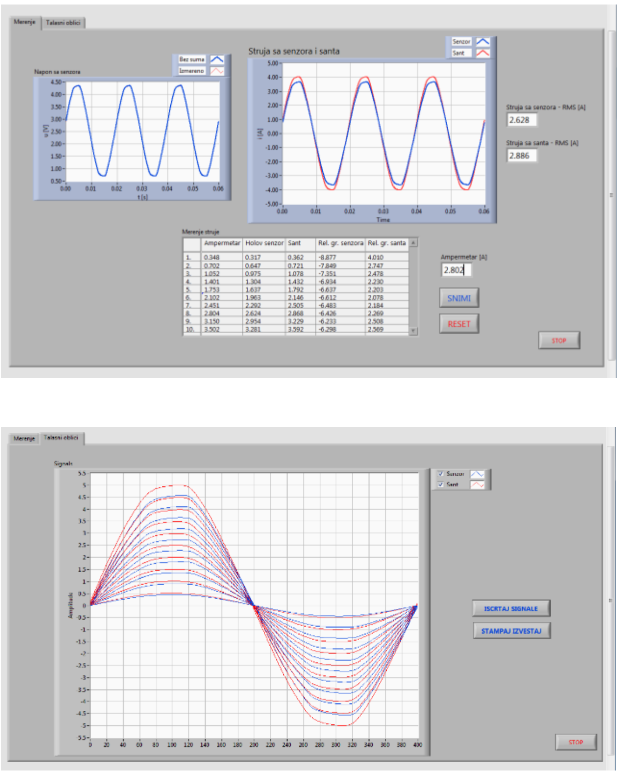

Figure 13. *Screenshots of realised Control Panel*

Table 1. *Measurement results*

No.	CSA [A]	Shunt [A]	DMM [A]	Rel. dev. CSA [%]	Rel. dev. shunt [%]
1	0.354	0.371	0.325	-8.224	4.700
2	0.703	0.726	0.647	-7.901	3.310
3	1.052	1.083	0.975	-7.284	2.906
4	1.400	1.438	1.303	-6.904	2.714
5	1.750	1.798	1.635	-6.575	2.729
6	2.100	2.161	1.969	-6.240	2.924
7	2.453	2.519	2.295	-6.443	2.673
8	2.802	2.881	2.625	-6.331	2.819
9	3.153	3.246	2.955	-6.265	2.963
10	3.501	3.609	3.283	-6.230	3.080

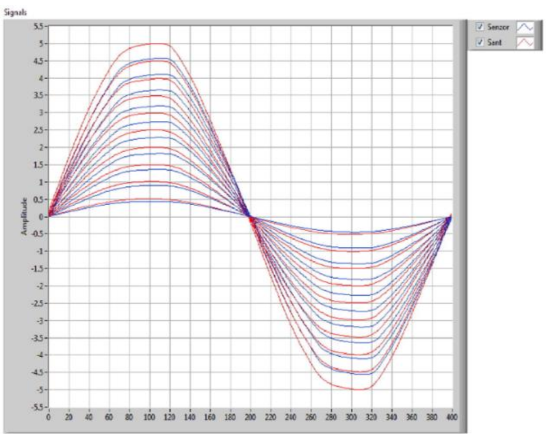

Figure 14. *Measured waveforms*

From the results presented can be seen that the CSA have a larger relative deviation (around −6%) then shunt resistor (around 3%). It can be noticed that the relative deviation decreases with the increase of measured current. It can be concluded that CSA needs additional calibration. It can be seen in Fig. 14 that time-waveforms of currents measured by CSA have the same shape as time-waveforms of currents measured with shunt resistor, with only different amplitude.

5. Conclusions

This paper presents application Hall effect current sensor CS10A-02 for measurement of electric current. It contains a theory on the working principle of Hall effect current sensor, description of necessary laboratory equipment and created virtual instrument. Also, the paper gives the results of measurement of electric current using Hall effect current sensor. The results of such measurement were compared with results obtained using other methods of current measurement – shunt resistor and a digital multimeter. Furthermore, a proper discussion of these results is given in the paper.

Realised laboratory setup opens the possibility to students to get acquainted with knowledge on Hall effect current sensors and virtual instrumentation.

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