Pomiary Automatyka Robotyka, ISSN 1427-9126, R. 21, Nr 1/2017, 5–12, DOI: 10.14313/PAR_223/5

Selected Current Sensing Circuits for Motor Control Applications

Wojciech Słowik, Paweł Piątek, Tomasz Dziwiński, Jerzy Baranowski
AGH University of Science and Technology, Faculty of Electrical Engineering, Automatics, Computer Science and Biomedical Engineering, al. Mickiewicza 30, 30-059 Kraków, Poland

Abstract: Precise current measurements are essential part of modern motor control algorithms. They are also required in switch mode power converters, safety circuits, current sources, supervisor systems and many other applications. In order to select the right method, it is often required from the designer to have wide knowledge of the appropriate integrated circuit, its parameters and applications. Still increasing requirements for the speed and precision of designing solutions, decreasing voltage levels, power consumption and aspects of EMC compatibility impose often contrary initial conditions.

Słowa kluczowe: current sensing, low side, high side, current sense amplifier, instrumentation amplifier, Hall effect sensor

1. Introduction

Current measurement in the case of electric motors is the most important thing essential for the implementation of motor control systems (in addition to measuring voltages). Depending on the target application and the complexity of the system we can distinguish at least several methods differing in levels of the complexity, cost and quality of the measurement. Currently, electric motors are used in many fields, ranging from simple fan drive circuits to complex systems like railways drive systems, servomotors, robotics, machines for the CNC and so on.

In the traditional control scheme for three-phase brushless motors, we can distinguish the following places for current measurement (Fig. 1): motor phase currents (yellow stars), power inverter input current (overall input current – red star), the currents in the individual branches of the inverter (green stars). Direct measurement of the phase currents is used in the most complex applications. Indirectly, the same result can be obtained by measuring the currents in the branches of the inverter between the lower keys and system ground. As will be explained later, it is convenient because the current sensor is reference to the ground of the system. Measurement of the motor currents directly on the leads require galvanic isolation. This can be done through the use of current transformer, isolated sigma-delta converters or isolated amplifiers.

There are two basic methods for current measurement: methods based on the measurement of voltage drop across the resistor (shunt resistor) and Hall effect based methods, using the measurement of the magnetic field generated around a conductor passing current.

Autor korespondujący:
Wojciech Słowik, wslowik@agh.edu.pl

Artykuł recenzowany
nadesłany 1.03.2017 r., przyjęty do druku 30.03.2017 r.

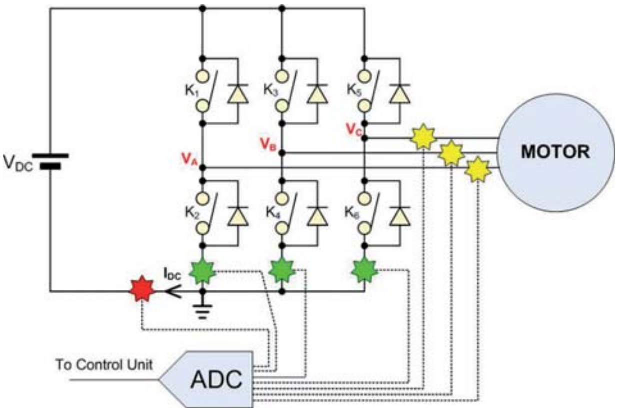

Fig. 1. Most common current sensing points in motor control applications
Rys. 1. Najczęściej stosowane miejsca pomiaru prądu w aplikacjach sterowania silnikami elektrycznymi

The first group of methods is the most common. It is characterized by relative simplicity and low cost of implementation. The method based on the measurement of the magnetic field is readily applicable for measuring currents up to hundreds amperes. For this purpose, the integrated Hall sensors are nowadays commonly used. Although the implementation cost is a little higher, this method has some strong advantages.

Methods using the voltage drop across the shunt resistor utilizes two basic ways: the resistor can be placed from the ground side (*Low Side Current Sensing*) or the shunt resistor can be placed from the supply voltage side (*High Side Current Sensing*).

2. Low Side Current Sensing

The easiest way to measure the current is to insert in the test system supply rail, a resistor of a small value as shown in Fig. 2. The current passing through the resistor produces a slight vol-

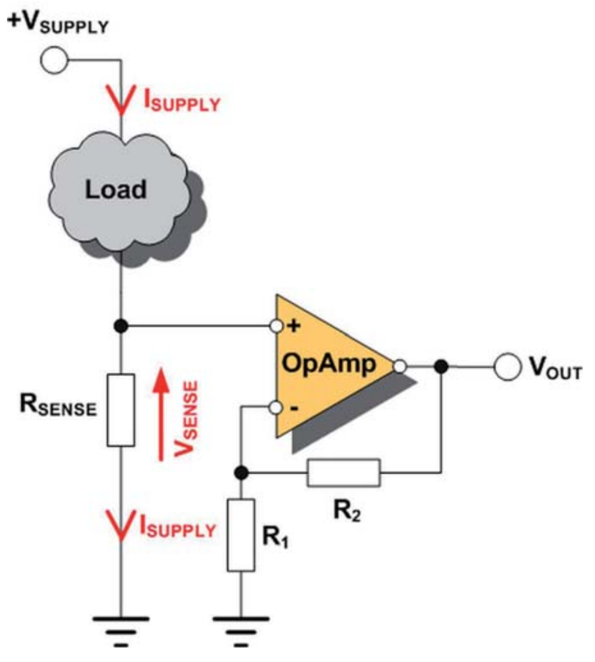

Fig. 2. Low Side Current Sensing
Rys. 2. Pomiar prądu na rezystorze od strony masy

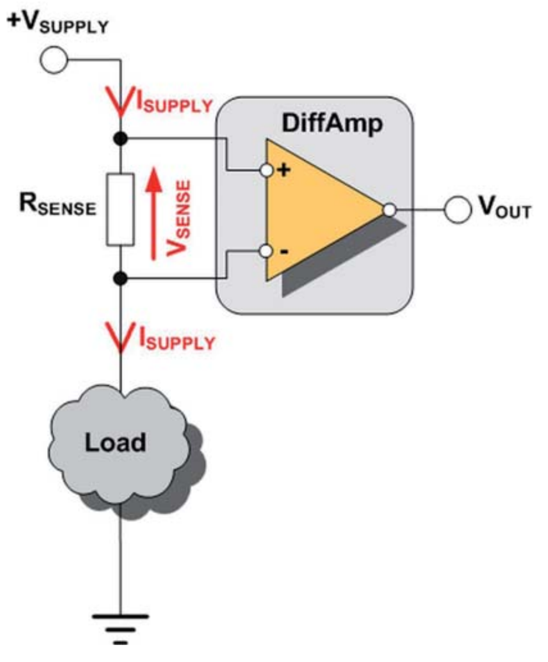

Fig. 3. High Side Current Sensing
Rys. 3. Pomiar prądu na rezystorze od strony zasilania

tage drop in accordance with Ohm's law: $U_{SENSE} = R_{SENSE} \cdot I_{LOAD}$. In most cases, voltage drop is too small to be directly used for further processing. Therefore, it is often required to use some amplification. Note, that the resistor is connected between the test system and the ground. At first glance, this solution seems to be free of defects – shunt resistor is grounded at one side, so that we can use simple operational amplifier in noninverting configuration in order to amplify small voltage drop proportional to the measured current (it should be also mention that noninverting configuration is in this case the only one solution – we assume that we have a single power supply voltage, and we want to reduce the impact of shunt input amplifier resistance on current measurement). This solution however, has some major drawbacks that cannot always be ignored. The first one results from the presence of voltage drop between the ground and tested system. Consequently, the ground of the system is at non zero potential (at floating potential if the current is variable in time). This can cause incorrect work especially of analog circuits, where the output of the amplifier is taken with respect to ground. Another important drawback is the inability to detect a short circuit in the system under test. If such a condition occurs, the short-circuit current flow from the power supply voltage through the test system to the ground. No current will pass through measuring resistor, so supervisor circuit will not even notice a serious failure in the system. Note also that in this case the common input voltage of the amplifier is close to zero. Therefore, we should pay special attention when choosing amplifier whether the selected model accepts input common mode voltage V_{CM} close to the ground (input rail to rail type of amplifier).

3. High Side Current Sensing

The second approach without the disadvantages of the previous method is to place shunt resistor at the side of power supply voltage (Fig. 3). In this case the system under test is at a constant ground potential. This does not disturb proper work of even sensitive analog circuits. Also, the possible fault short circuit to ground current will flow through the measuring resistor, which will be immediately noticed by the supervisor circuit. In this system however, there is significant drawback. While in previous method the measuring resistor was grounded at one side, here both ends of the shunt resistor are at the potential close to the supply voltage (supply voltage can be high in case of power electronic systems, motors, etc.). This creates two serious problems. Firstly, it becomes necessary to use differential amplifier. Secondly, this amplifier must accept high common mode voltage V_{CM} at their inputs. The simplest application of fully differential amplifier is shown in Fig. 3.

The standard difference configuration of the operational amplifier is shown in Fig. 4. Output voltage describes the relationship:

$$V_{OUT} = \frac{R_2}{R_1} \cdot \left(V_{IN1} - V_{IN2}\right) + V_{REF} \tag{1}$$

which is valid when the precise ratio of resistors R_2/R_1 is kept.

It should be noted that the basis of differential operation and achievement of satisfactory values of *CMRR* (*Common Mode Rejection Ratio*) is the precise selection of four resistors. In practice, the cost of the resistor with tolerance of 0.1% may be unacceptable.

Using the formula from References [1]:

$$CMRR = 20log\left[\frac{\frac{1}{2}\cdot\left(1+\frac{R_2}{R_1}\right)}{\frac{\Delta R}{R}}\right] \tag{2}$$

we can calculate the CMRR values obtained for the manually matched resistors. For example, if $R_2/R_1 = 1$, and the resistors would have a tolerance of 0.1%, the *CMRR* in the worst case would be 54 dB. If the resistors would be 1%, we would obtain 34 dB of *CMRR*, which of course is in most cases not acceptable. It should also be noted that the values of R_1 and R_2 should be much greater than the shunt resistor R_{SENSE} to avoid loading effect. This increases the problem of choosing precise resistance (resistance of the PCB tracks may also be relevant).

Note that if we would like to change a gain of the amplifier it is extremely cumbersome – it requires simultaneous, precise change of two resistors. If the voltage V_{IN1} and V_{IN2} are at a high potential (exceeding the amplifier V_{CM}) we can indeed choose voltage dividers at the inputs of the amplifier (comprised of resistors R_1, R_2, for example $R_2 = 0.1 \cdot R_1$) that we will be able to measure the small differential voltage at high common voltage, but the circuit gain will also be reduced (10 times for $R_2 = 0.1 \cdot R_1$). It may turn out after while that the resulting gain that we have is not enough to detect the weak measured signal. The circuit is complicated even more if we need to measure alternating current – by supplying the amplifier by unipolar manner, we need to ensure proper shift of the output voltage to the half of the supply voltage range to avoid saturation of the amplifier. For example, if the amplifier is powered by a unipolar 5 V/GND, we should shift the output voltage to 2.5 V for zero differential input voltage, using V_{REF} input. This input, however, should be connected to a source with the possibly lowest output impedance, because each serial voltage-sources output impedance will added to the resistance R_2 and drastically deteriorating the *CMRR* factor (there is a change of the ratio of precisely matched resistances R_2/R_1). In this case, it is necessary to use additional voltage follower between the voltage source output and the V_{REF} input as it is shown in Fig. 5.

Too low achievable *CMRR* for the differential configuration depicted in Fig. 4 encourages to use instrumentation amplifier – *InAmp*. These kind of amplifiers with differential input and single ended output were designed to amplify very weak differential signals, on the background of strong interfering common mode signals. Instrumentation amplifiers are widely used in sensor signal conditioning for medical or biological applications because of their very high differential gain, high *CMRR* ratio and the presence of V_{REF} input to offset the output voltage especially when *InAmp* is unipolar powered. Simplified internal architecture is presented in Fig. 6 [7].

All components except the resistor R_G are integrated inside *InAmp* structure. The architecture of the amplifier can be divided into two blocks: amplifiers OA_1 and OA_2 which serves as amplifiers for differential signal (gain of $1 + 2R_F/R_G$) and voltage followers for common mode signal (gain $\times$ 1). The amplifier OA_3 is configured as differential amplifier (usually with a gain of $\times$1). Its main role is to remove the common component. Note that this is the same amplifier as shown in Fig. 4. However, due to the integration and laser trimmed resistors R_1, R_2 it is possible to achieve *CMRR* of 90 dB or above. Such levels would have never been achievable with manual pairing of external resistors. Due to the smart architecture, the gain is easily adjustable by external resistor R_G. Usage of instrumentation amplifier seems to be highly desirable in the application of current measurement. Note however, that the amplifier in the considered application is

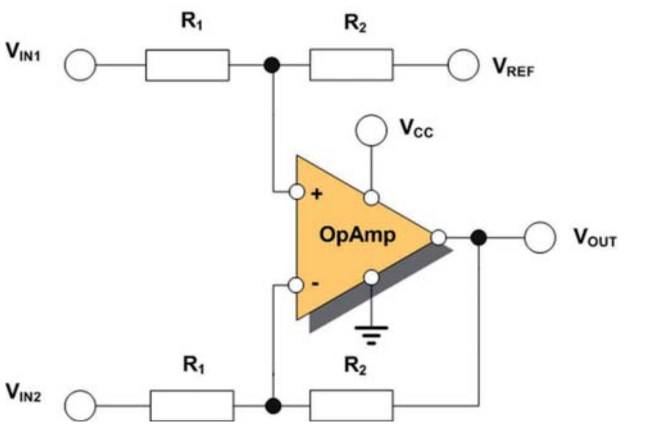

Fig. 4. Difference amplifier with external, precisely paired resistors in order to keep relation R_2/R_1 as much as possible
Rys. 4. Wzmacniacz różnicowy z zewnętrznymi, precyzyjnie dobranymi rezystorami w celu precyzyjnego utrzymania stosunku R_2/R_1

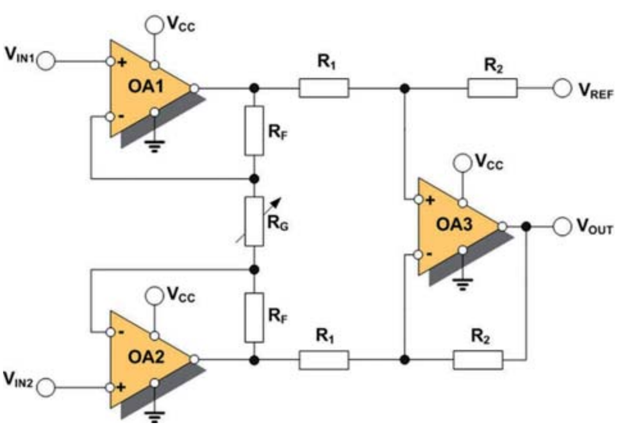

Fig. 6. Internal architecture of Instrumentation Amplifier (R_G resistor is external)
Rys. 6. Architektura wewnętrzna wzmacniacza pomiarowego (rezystor R_G zewnętrzny)

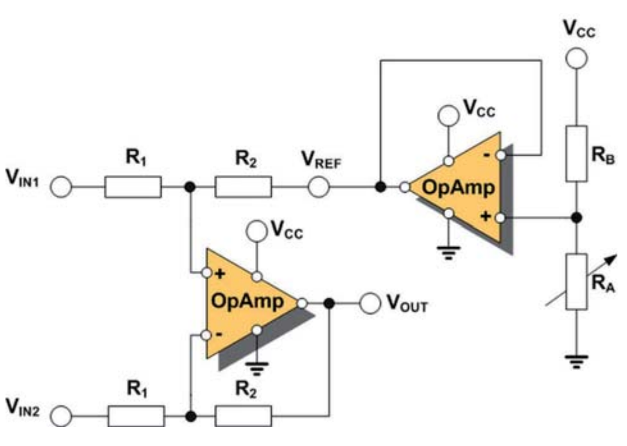

Fig. 5. Difference amplifier output voltage level shifting
Rys. 5. Przesunięcie poziomu napięcia wyjściowego wzmacniacza różnicowego

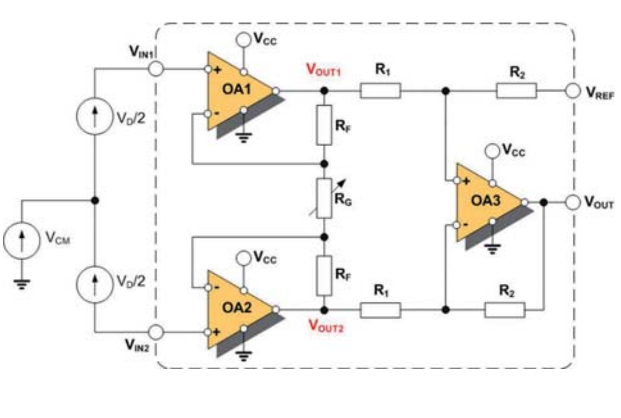

Fig. 7. Instrumentation Amplifier with external signals: common and differential
Rys. 7. Wzmacniacz pomiarowy zasilony sygnałami różnicowymi oraz sygnałem wspólnym

supplied from a single voltage source. There must be therefore ensured such conditions, that none of the internal amplifiers has never been saturated (both to GND or V_{CC}).

General analysis of the amplifier let us begin by identifying voltages V_{OUT1} and V_{OUT2} depicted in Fig. 7.

Considering only common mode component V_{CM}, amplifiers OA_1 and OA_2 work as voltage followers. Therefore $V_{OUT1} = V_{OUT2} = V_{CM}$. If the amplifier OA_3 has all the resistors of equal value, under the formula (1), $V_{OUT} = 0$, which means zero common mode signal amplification, and thus the infinite value of *CMRR*.

On the other hand, if we consider only the differential component V_D, we see that the amplifiers OA_1 and OA_2 work in inverting and non-inverting configuration depending upon which part of the differential signal we consider (superposition: $V_D/2$ and $-V_D/2$). From superposition we determine the formulas:

$$V_{OUT1} = \left(1 + \frac{R_F}{R_G}\right) \cdot V_{IN1} + \left(-\frac{R_F}{R_G}\right) \cdot V_{IN2} = \frac{V_D}{2} + \frac{R_F}{R_G} \cdot V_D \quad (3)$$

$$V_{OUT2} = \left(1 + \frac{R_F}{R_G}\right) \cdot V_{IN2} + \left(-\frac{R_F}{R_G}\right) \cdot V_{IN1} = -\frac{V_D}{2} - \frac{R_F}{R_G} \cdot V_D \quad (4)$$

Thus, the voltage

$$V_R = V_{OUT1} - V_{OUT2} = V_D \cdot (1 + 2R_F/R_G) \quad (5)$$

OA_3 amplifies voltage $V_R = V_{OUT1} - V_{OUT2}$.
Under the formula (1), output voltage of the amplifier:

$$V_{OUT} = \left(\frac{R_2}{R_1}\right) V_R + V_{REF} = \left(\frac{R_2}{R_1}\right) V_D \cdot \left(1 + \frac{2R_F}{R_G}\right) + V_{REF} \quad (6)$$

If we assume (as it is almost always), that $R_1 = R_2$, we get:

$$V_{OUT} = \left(1 + \frac{2R_F}{R_G}\right) V_D + V_{REF} \quad (7)$$

Thus it can be seen that the differential gain of V_D signal can be easily adjusted by the resistor R_G. Any voltage applied to the V_{REF} input shifts the output voltage level with the gain ×1. It should also be noted that the amplifier has a very large input impedance, depending on the construction of the input stages (about $10^9\ \Omega$).

These considerations do not however, take into account the fact that the *InAmp*, and thus – all the *OpAmps* inside are unipolar powered.

Let us analyze, the allowable range of input voltages with the assumed limitations to the supply voltage to V_{CC}.

$$V_{OUT1}, V_{OUT2} = V_{CM} \pm \left(K_D \cdot \frac{V_D}{2}\right) = V_{CM} \pm \frac{V_{OUT} - V_{REF}}{2} \quad (8)$$

where K_D is a differential gain. To prevent saturation of the amplifiers OA_1, OA_2, voltages V_{OUT1}, V_{OUT2}, V_{OUT} should meet the obvious relations:

$$0 < V_{OUT1}, V_{OUT2} < V_{CC} \quad (9)$$

$$0 < V_{OUT} < V_{CC} \quad (10)$$

i.e.:

$$0 < V_{CM} \pm \frac{V_{OUT} - V_{REF}}{2} < V_{CC} \quad (11)$$

If we assume $V_{REF} = 0$ as in the case of bipolar power, from equation (10) we get:

$$0 < V_{CM} \pm \frac{V_{OUT}}{2} < V_{CC} \quad (12)$$

If we assume $V_{REF} = V_{CC}/2$ we get:

$$0 < V_{CM} \pm \frac{V_{OUT}}{2} \pm \frac{V_{CC}}{4} < V_{CC} \quad (13)$$

By plotting inequalities (13) along with constraints (9) and (10) for $V_{CC} = 5$ V, $V_{REF} = 2.5$ V we obtain plot depicted in Fig. 8.

This kind of plot gives us very important information about relation of the common input voltage as a function of the output

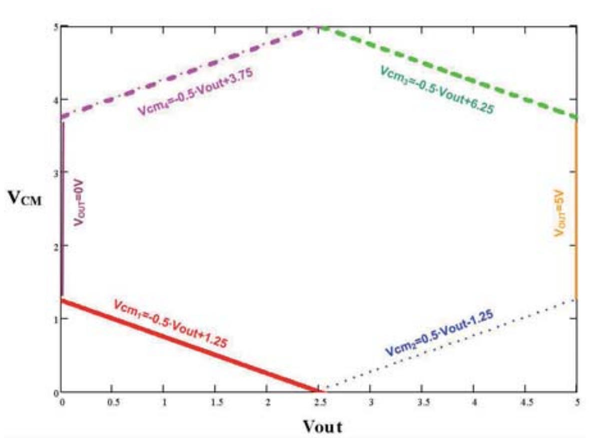

Fig. 8. "Diamond plot" showing relations between V_{CM} and V_{OUT} for single 5 V powered instrumentation amplifier with V_{REF} = 2.5 V
Rys. 8. Wykres typu „Diamond plot" ukazujący relacje pomiędzy V_{CM} oraz V_{OUT} dla zasilania wzmacniacza 5 V oraz V_{REF} = 2,5 V

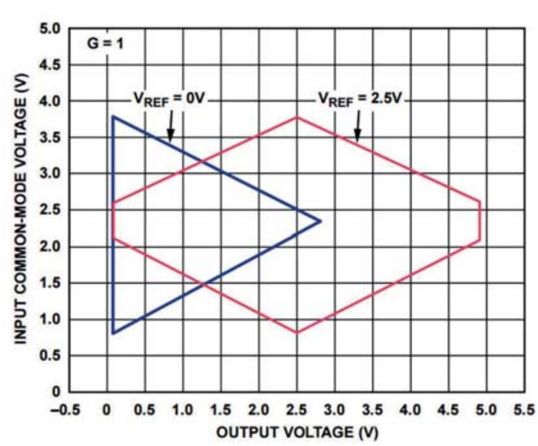

Fig. 9. Example instrumentation amplifier "diamond plot" – AD8422 from Analog Devices [2]
Rys. 9. Przykładowa charakterystyka „Diamond plot" wzmacniacza AD8422 firmy Analog Devices [2]

voltage $V_{CM} = f(V_{OUT})$. The graph is commonly called "*diamond plot*", so named because of its shape. Presented in Fig. 9 is an example graph of commercially available amplifier AD8422 from Analog Devices.

From the plot we can read the following information: for $V_{REF} = 2.5$ V, if the common input voltage will stay within the range of approximately 2.1–2.6 V, then we will have a full range of output voltage available. For $V_{REF} = 0$ V, the widest range of output voltage is available only for $V_{CM} \approx 2.4$ V.

In other common voltage ranges, output voltage range is limited because of the saturation of the internal stages.

There are also used monolithic instrumentation amplifiers designed for bi-directional common mode voltage range. An example might be LT1168C type of precision instrumentation amplifier from Linear Technology [6]. It can be bipolar powered from ±2.3 V up to ±18 V and its input common-mode voltage range is form $-V_S+1.9$ V to $+V_S - 1.4$V. This type of amplifier has very good parameters like very small voltage unbalance (80 µV), low temperature drift of the offset voltage (0.4 µV/°C) and very high input resistance – larger than 200 GΩ.

4. Current Sense Amplifiers

As is apparent from the foregoing, each of the previous methods have certain advantages and disadvantages. In order to facilitate the measurement of current systems and minimize the number of necessary elements to achieve the goal, many leading IC manufacturers have introduced amplifiers called CSA (*Current Sense Amplifier*). They are ready to use ICs (*Integrated Circuits*) designed strictly for current measurement using a high side shunt resistor. An exemplary IC from STMicroelectronics TST101 is shown in Fig. 10.

Note that the system may have a higher common mode voltage at the inputs V_P, V_N than its supply voltage. The principle of operation is as follows: measured current causes a voltage drop across the shunt resistor. This voltage is being applied to the internal operational amplifier, which feedback controls the internal transistor so as to both inputs of the amplifier were balanced. If this condition occurs the voltage across the resistor R_{G1} will be equal to the voltage across the resistor R_{SENSE} (assuming zero current consumption of the amplifier input and thus zero voltage drop across the resistor R_{G2}). Deriving elementary calculations we are able to determine the value of the output voltage corresponding to the measured current:

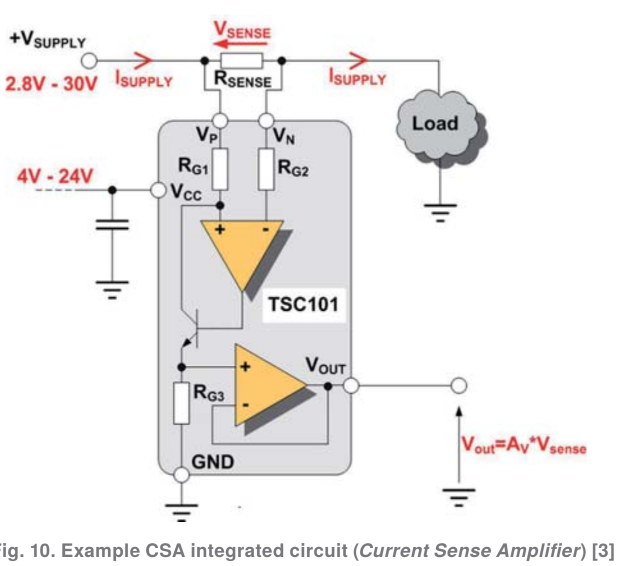

Fig. 10. Example CSA integrated circuit (*Current Sense Amplifier*) [3]
Rys. 10. Przykładowy układ CSA (*Current Sense Amplifier*) [3]

$$V_{SENSE} = R_{SENSE} \cdot I_{SUPPLY} \tag{14}$$

$$V_{SENSE} = R_{G1} \cdot I_1 \tag{15}$$

$$V_{OUT} = R_{G3} \cdot I_1 = R_{G3} \cdot \frac{V_{SENSE}}{R_{G1}} = \frac{R_{G3}}{R_{G1}} \cdot R_{SENSE} \cdot I_{SUPPLY} \tag{16}$$

The ratio R_{G3}/R_{G1} setting the gain is fixed at the production stage to the values of 20 V/V, 50 V/V, 100 V/V, depending on the version of the chip.

5. Hall Effect-Based Linear Current Sensors

As it was previously mentioned, all resistive methods insert unavoidable voltage drop. Of course it is also the essence of the methods. However, if we would like to measure high currents, the voltage drop across shunt resistor in accordance with current flowing through it may causes significant power losses according to I^2R law. Moreover, if power line voltage is very high or negative related to ground, it may turn out to be impossible to measure current without isolation. In this situation very attractive solution is to use Hall effect based magnetic field sensors. Figure 11 presents exemplary integrated circuit ACS712 from Allegro Microsystems.

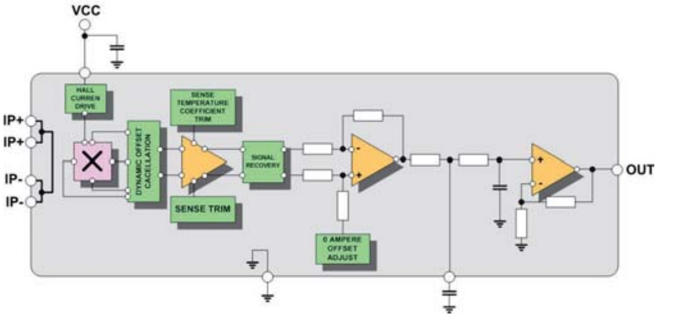

Fig. 11. Example Hall effect-based current sensor [4]
Rys. 11. Przykładowy układ czujnika Hallotronowego [4]

It is fully integrated Hall sensor together with all necessary signal conditioning circuits. Chip has built in piece of wire, which conduct measured current. Practically there is no voltage drop (exactly 1.2 mΩ internal conductor resistance) and high current side is isolated (2.1 kV_{RMS}) from rest of electronic circuits, therefore it is possible to measure current even at very high potential. Circuit is powered from 5 V and its output signal is proportional to measured current with sensitivity depending on the version of the chip.

6. Isolation Amplifiers

In situations where high voltage between grounds can occur, there is a need for galvanic isolation between circuits (what is, for example, necessary in case of biomedical systems) or simply to break ground loops, the natural choice becomes isolation amplifier [6]. Isolation between two parts of circuit can be achieved by three ways:

- optical coupling – consist of *LED* diode and photodiode, isolation performed by electromagnetic fields (light radiation),
- transformer coupling – most common isolation technique [5], isolation performed by magnetic field,

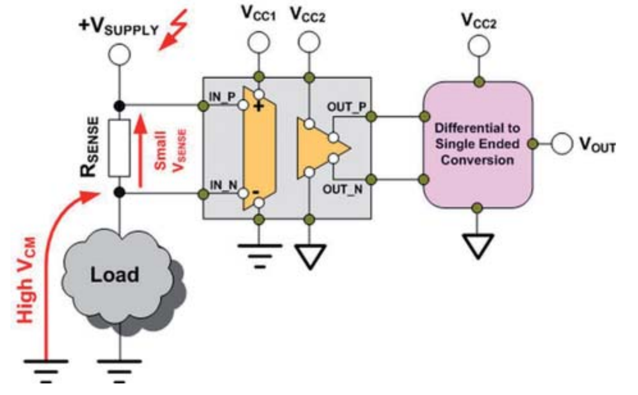

Fig. 12. Application of current sensing using isolated differential amplifier
Rys. 12. Aplikacja pomiaru prądu z użyciem różnicowego wzmacniacza izolowanego

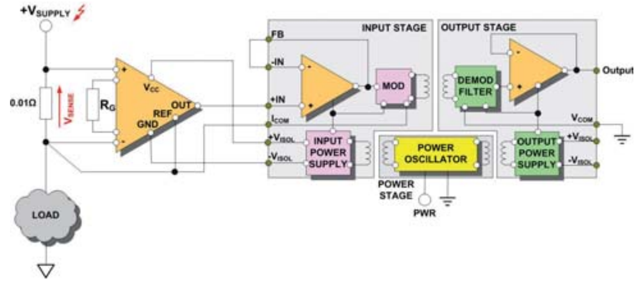

Fig. 13. Current sensing for motor control application [5]
Rys. 13. Pomiar prądu w aplikacji sterowania silnikiem

– capacitive coupling – using small high voltage capacitors, isolation performed by electric field.

In optical or capacitive coupling, both high voltage and low voltage sides need power supply. Hence, it is very important matter to use (for high voltage side) isolated power supply or take power directly from high voltage side. In the latter case, we have to note that high voltage side of power supply for amplifier (V_{CC1} at Fig. 12) is also restricted to, for example +5 V. Also inputs *IN_P* and *IN_N* voltages are restricted, for example from GND_1 +0.1 V to V_{CC1} –0.1 V. If we utilize low side current sensing there is no particular problem. Problem occurs when we want to measure small differential signal with high common mode signal as presented on Fig. 12.

In this case we have to ensure two things: proper high side power supply for amplifier and proper voltages for *IN_P* and *IN_N* with respect to power supply V_{CC1}, GND_1. In this situation it is better to choose isolated amplifier with transformer coupling. Here, isolated power supply for high side is taken from low side or common side through transformer. Figure 13 presents exemplary motor control current sensing application where small differential signal across 0.01 Ω shunt resistor is measured with present of high common mode voltage. Input instrumentation amplifier is powered from isolated "floating" power supply obtained by transformer coupling.

7. Current transformer

According to fundamental transformer formula

$$\frac{V_S}{V_P} = \frac{I_P}{I_S} = \frac{n_S}{n_P} = n \qquad (17)$$

where: n – transformer turn ratio; n_P – number of turns of primary windings; n_S – number of turns of secondary windings; V_P – primary voltage; V_S – secondary voltage; I_P – primary current; I_S – secondary current.

The secondary current is directly proportional to primary one: $I_S = I_P/n$. Therefore, we can use toroidal core with many secondary turns and one primary turn through which measured current flows (Fig. 14). Because of the fact that the primary and secondary windings are galvanically isolated they can be at a different voltage levels. Therefore, current transformer is very convenient device for measuring high and very high currents in the present of high or very high voltages. It should be noted that the secondary winding should always work in a short circuit state. Opening the secondary circuit can be dangerous because of the possibility of high voltage being induced.

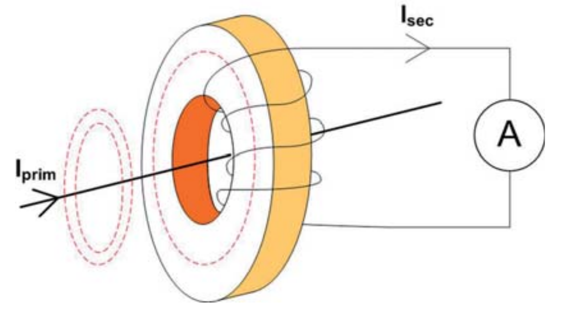

Fig. 14. Current transformer
Rys. 14. Przekładnik prądowy

The main drawback of this solution is that it can measure only AC currents.

In practical applications, at the secondary side of the transformer, it is common to use burden resistor which converts secondary current to voltage drop. Next, voltage across resistor is directly measured or amplify and directed for further processing.

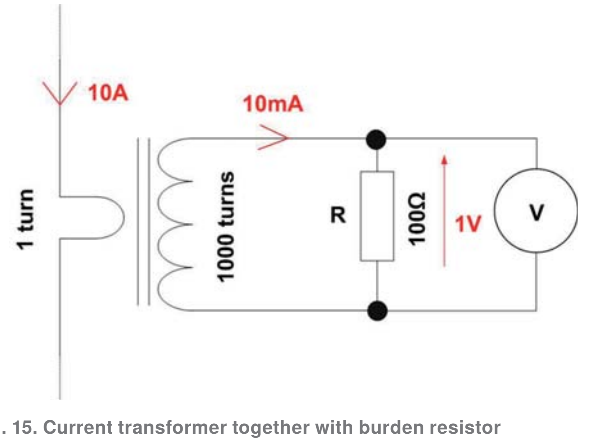

Fig. 15. Current transformer together with burden resistor
Rys. 15. Przekładnik prądowy z rezystorem obciążenia

8. Conclusions

As can be seen, there are many different topologies and methods of measuring current differing in complexity, the cost of implementation and accuracy. For applications where precision current measurement is not the primary thing, the most frequently chosen is the cheapest solution i.e. one or two shunt resistors. In the case of precision systems, it is often required to have electrical isolation and an appropriate control dynamics what is not easy due to the added phase delay introduced by the isolation and filter circuits.

However, to be able to choose (among a wide variety of application) the one, that fulfill the project expectations, the designer should know all of the available alternative methods, and fully understand how their works.

Below it is presented a summary of discussed methods.

Tab. 1. Pros and Cons of Low Side Current Sensing
Tab. 1. Zalety i wady pomiaru prądu na rezystorze od strony masy

Low Side Current Sensing	
Pros	Cons
Simplest	Distorted ground potential
Low cost	Unable to detect short circuit to ground
Easy signal amplification	Need to have rail-rail op-amp
Common mode voltage near to ground	Only for low currents due to power losses I^2R
Suitable for DC/AC measurements	No galvanic isolation between circuits

Tab. 2. Pros and Cons of High Side Current Sensing
Tab. 2. Zalety i wady pomiaru prądu na rezystorze od strony zasilania

High Side Current Sensing	
Pros	Cons
Low cost	Difficult signal amplification
Able to detect short circuit to ground	Need to have differential amplifier
Do not disturb system ground	High common mode voltage
Suitable for DC/AC measurements	Need to have rail-rail op-amp
	Only for low currents
	No galvanic isolation between circuits

Tab. 3. Pros and Cons of Current Sense Amplifiers
Tab. 3. Zalety i wady pomiaru prądu za pomocą układów CSA

Current Sense Amplifiers	
Pros	Cons
Low cost	Fixed specific gains
No external components needed	Only for low currents due to power losses I^2R
Able to detect low differential signal with high common voltage present	No galvanic isolation between circuits
Fully integrated solution – small area on PCB	
Reliability	

Tab. 4. Hall based effect integrated sensors
Tab. 4. Zalety i wady pomiaru prądu za pomocą czujników hallotronowych

Hall based effect integrated sensors	
Pros	Cons
Fully integrated chip	Fixed specific gains
Medium cost	May be susceptible to interference from surrounding magnetic fields
Practically no inserted voltage drop in power rail	
Able to detect low differential signal with very high common voltage present	
Galvanic isolation	
No external components needed	
Also for high currents	
Temperature compensation	
May have digital interface to microprocessor systems	
Suitable for DC/AC measurements	
Reliability	

Tab. 5. Pros and Cons of Isolation Amplifiers (IsoAmp)
Tab. 5. Zalety i wady pomiaru prądu za pomocą wzmacniaczy izolowanych

Isolation Amplifiers (IsoAmp)	
Pros	Cons
Galvanic isolation between circuits	High cost
Able to detect low differential signal with very high common signal present	Only for low currents due to power losses I^2R
Breaking ground loops – accurate measurement	In practice needs additional components
	May need isolated DC/DC converter
	Difficult to implement parasitic power supply for high side in high side current scenario
	May be susceptible to interference from surrounding magnetic fields (inductance coupling), electric field (capacitive coupling)

Tab. 6. Pros and Cons of Current transformer
Tab. 6. Zalety i wady pomiaru prądu za pomocą przekładników prądowych

Current transformer	
Pros	Cons
Galvanic isolation between circuits	Only for AC measurements
Reliability	
Suitable for very high currents	

References

1. Lokere K., Hutchison T., Zimmer G., *Precision Matched Resistors Automatically Improve Differential Amplifier CMRR – Here's How*. Linear Technology Design Note 1023, http://cds.linear.com/docs/en/design-note/dn1023f.pdf
2. AD8422 – High Performance, Low Power, Rail-to-Rail Precision Instrumentation Amplifier. Analog Devices datasheet; http://www.analog.com/media/en/technical--documentation/data-sheets/AD8422.pdf
3. TSC101 – High side current sense amplifier. STMicroelectronics datasheet, http://www.st.com/content/ccc/resource/technical/document/datasheet/group2/df/85/34/d4/87/18/46/87/CD00153725/files/CD00153725.pdf/jcr:content/translations/en.CD00153725.pdf
4. ACS712 – Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kV_{RMS} Isolation and a Low-Resistance Current Conductor. Allegro Microsystems datasheet; http://www.allegromicro.com/en/Products/Current-Sensor-ICs/Zero-To-Fifty-Amp-Integrated-Conductor-Sensor-ICs/ACS712.aspx
5. Analog Isolation Amplifiers, MT-071, Analog Devices, http://www.analog.com/media/en/training-seminars/tutorials/MT-071.pdf
6. LT1168 – Low Power, Single Resistor Gain Programmable, Precision Instrumentation Amplifier. Linear Technology datasheet; http://cds.linear.com/docs/en/datasheet/1168fa.pdf
7. Horowitz P., Hill W., *The Art of Electronics*. Cambridge University Press, 1989
8. Sedra A.S., Smith K.C., *Microelectronic circuits*, Oxford University Press, 2009.

Wybrane metody pomiaru prądu w aplikacjach silników elektrycznych

Streszczenie: The control system is a cascade of three tanks of INTECO. They are used to control two of them. Two algorithms of water level control are used: two single dimensional model predictive control (MPC) algorithms, one for each tank, and a multi-dimensional MPC controlling both tanks simultaneously. A comparative analysis of developed control algorithms for variable set-point trajectory.

Keywords: pomiar prądu, wzmacniacz pomiarowy, wzmacniacz instrumentalny, czujnik Halla, silnik bezszczotkowy

Wojciech Słowik, M.Sc. Eng
wslowik@agh.edu.pl

Wojciech Słowik holds a M.Sc. Eng. in Electronics and Telecommunications from the AGH University of Science and Technology in Krakow. Currently he is Ph.D. candidate in the field of Control Engineering. Recent research topics are concerned on modelling, simulation and control of dynamic systems with emphasis on vector control of electric machines.

Tomasz Dziwiński, MSc Eng.
tdz@agh.edu.pl

Tomasz Dziwiński is currently pursuing the Ph.D. degree at the Department of Automatics and Biomedical Engineering, AGH University of Science and Technology, Krakow, Poland, in agreement with the KIC InnoEnergy International PhD School coordinated by the KTH Royal Institute of Technology, Stockholm, Sweden. He is interested in embedded control systems based on digital signal processors, microcontrollers, and FPGA, with a particular focus on power electronic systems. He is involved in the project at the European Institute of Innovation and Technology's Knowledge and Innovation Community. He is also a member of the IEEE Control System Society and the IEEE Power and Energy Society.

Paweł Piątek, Ph.D.
ppi@agh.edu.pl

Assistant Professor in the Department of Automatics and Biomedical Engineering at AGH University of Science and Technology in Krakow. The research topics are concerned on the digital control, design and development of real--time control systems and design and application of non-integer order subsystems in control systems.

Jerzy Baranowski, Ph.D.
jb@agh.edu.pl

Jerzy Baranowski has obtained M.Sc. in 2006 and Ph.D. in 2010 in Automatic Control at AGH University of Science and Technology. His research interests include fractional calculus, approximation theory, numerical methods and data analysis. From 2010 he works as an assistant professor at Department of Automatics and Biomedical Engineering at AGH.