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Measurement issues of high-side AC currents

***Abstract**. This paper presents a new approach to AC constant current waveform generation. Several methods were tested during development, and their performance and differences will be described. Measuring high-side alternating current for self-regulating negative feedback circuits is a complex problem and will be described in detail.*

***Streszczenie.** W artykule przedstawiono nowe podejście do generowania przebiegów prądu stałego AC. Podczas opracowywania przetestowano kilka metod. Opisane zostaną ich działanie i różnice. Pomiar prądu przemiennego po stronie wysokiego napięcia w samoregulujących obwodach z ujemnym sprzężeniem zwrotnym jest problemem złożonym i zostanie szczegółowo opisany (**Pomiar prądów przemiennych po stronie wysokiego napięcia**).*

Keywords: Electrical Impedance Tomography, negative feedback circuits, current measure
Słowa kluczowe: elektryczna tomografia impedancyjna, układy z ujemnym sprzężeniem zwrotnym, pomiar prądu

Introduction

In industrial applications, including industrial tomography, many methods and algorithms are used for measurements and analysis [1-11]. Self-regulating negative feedback circuits are the fastest and most optimal way to perform discrete signal processing. In most cases, an additional advantage is low cost because there is no need for mixed-signal integrated circuits. Nonetheless, the signal path complexity and many caveyats at every design step are notable downsides.

The basic method of current measurement involves the computation of voltage imposed on known resistance connected in a series of measured currents. According to Ohm's law, simple calculation leads to results. Constant current can be easily and precisely measured this way [12-13].

Current measurements are among the most important measurements in impedance tomography. The approach used in this article was developed in the context of just such measurements [14-16]. Nonetheless, various problems are involved in such a scheme of measuring small currents, which will be described in the next sections.

Common mode voltage

The first obvious problem is related to the common mode voltage imposed on the measurand. The simplest mitigation method for this problem is a low-side measurement scheme [12].

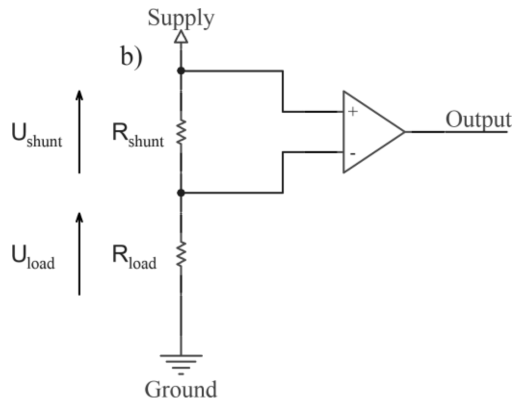

Fig.1. High and low side measurements scheme – simplified.

In the low-side current measurement shown in Fig. 1, there is no common mode voltage because the shunt and inverting input of the amplifier are directly referenced to ground. This leads to precise, simple and cost-effective methods of measurement. Such circuits have several drawbacks, such as ground disruption from a load perspective. An additional disadvantage is the necessity of a negative voltage supply if bipolar measurement is desired. Measuring small voltages referred to the ground also has caveyat of op amp's input offset voltage. Input offset voltage determines offset error related to the ground, and it can be challenging to find integrated circuits with appropriately low offset voltage to not add a large error to the output voltage. A higher-value resistor can mitigate this problem. This way, balancing such design's cost/efficiency/area is possible. A larger value resistor means higher voltage drop U_{shunt} and higher power dissipation, so using as low a value as possible is desirable. Additionally, a higher-value resistor disrupts ground voltage even more and can induce severe signal integrity problems.

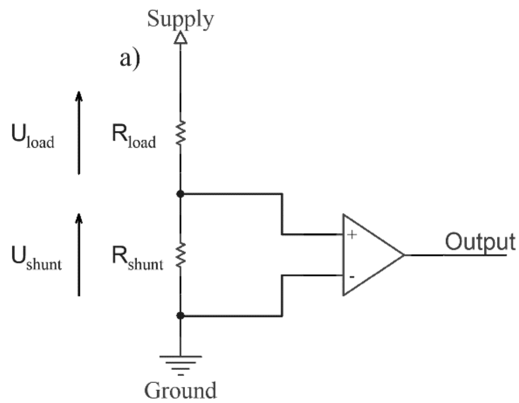

Fig.2. High and low side measurements scheme – simplified.

High-side measurement, shown in Fig. 2, is preferred because it does not break grounding paths and enables measurement at the hot wire of the electrical impedance tomography electrode. This method of measurement has substantial problems. The main one is common mode voltage. As shown in Fig. 2, the voltage at the negative terminal of the amplifier is at $V_{supply} – R_{shunt}$ and non-inverting input is connected directly to supply. It means that it is related to the ground. Constant common mode voltage is imposed on both inputs, leading to large output voltage error dependent on CMRR (Common Mode Rejection Ratio). Ideal amplifiers have infinite CMRR, but there are no ideal parts in the real world, and it is the worst problem to solve when dealing with high-side current measurement [12].

Differential amplifier

A common way to perform high-side current measurement is using the differential amplifier. A basic conceptual schematic is shown in Fig. 3.

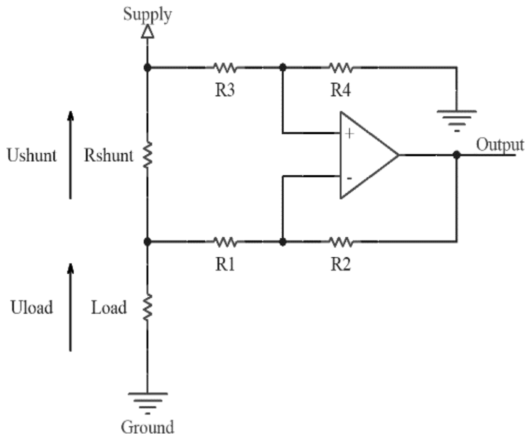

Fig. 3 Basic differential amplifier [22]

The special behaviour of differential amplifiers is based on the rejection of common voltage at inputs and amplification of the difference between inverting and non-inverting input. The transfer function of the mentioned circuit is:

$$V_{OUT} = \left(\frac{R_4}{R_3+R_4}\right) * \left(\frac{R_1+R_2}{R_1}\right) * V_2 - \left(\frac{R_2}{R_1}\right) * V_1 \quad (1)$$

If the assumption is made that R1 = R3 and R2 = R4 it is possible to simplify equation (1) to:

$$V_{OUT} = \left(\frac{R_2}{R_1}\right) * (V_2 - V_1) \quad (2)$$

Differential amplifiers composed of ideal components would have infinite CMRR. In reality, the worst concern is the tolerance of resistors R1-R4. Equation (1) shows the close connection between the values of resistors. In a real-world scenario, it is not practical to implement discrete resistors because even a slight mismatch of values will cause substantial error at output. Temperature variance would introduce additional errors, and in practical applications, discrete differential amplifiers are not used because of the substantial cost of high precision and stable resistors with a tolerance of 0,05% or better. The best solution to this problem is implementing a differential amplifier with built-in resistors. For example, INA592 [20], made by Texas Instruments, costs much less than a precision op amp with a closely matched resistor network.

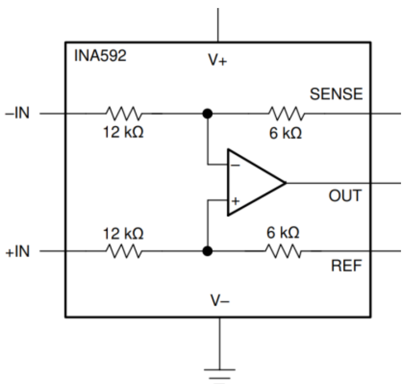

Fig. 4 Internal structure of INA592 [20]

Also, the area on board is smaller for this kind of design. Another advantage is high precision and a large Common Mode Rejection Ratio. According to the datasheet, the achievable CMRR is close to 100dB, which results in a wide range of measured currents with negligible error. High performance in this scenario comes from tightly matched, laser-trimmed resistors placed on silicon wafers. Proximity on highly heat-conductive material pushes performance even higher, providing substantial temperature matching between components. These clever techniques enable the practical usage of integrated, single-chip differential amplifiers in high-side current measurement.

Isolation amplifier

Another method of mitigation CMRR in said application is using the amplifier with galvanic isolation.

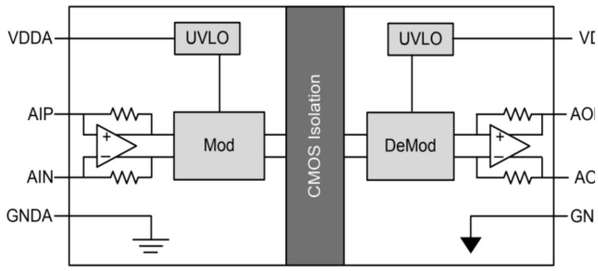

Fig. 5 Internal structure of SI8920 [19]

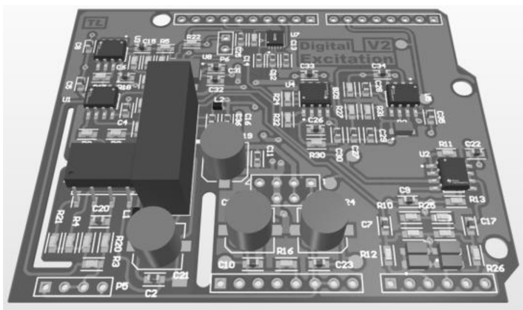

Fig. 6 Visualisation of prototype board with isolation amplifier

A device such as SI 8920 [19] mitigates the high common mode voltage issue by separating both sides. The secondary input side can reference another supply up to 600V while maintaining safe, separated, low-voltage output. Generally, it is a viable option in the measurement system and was tested with a practical circuit in the electrical impedance tomography scanner [17-18].

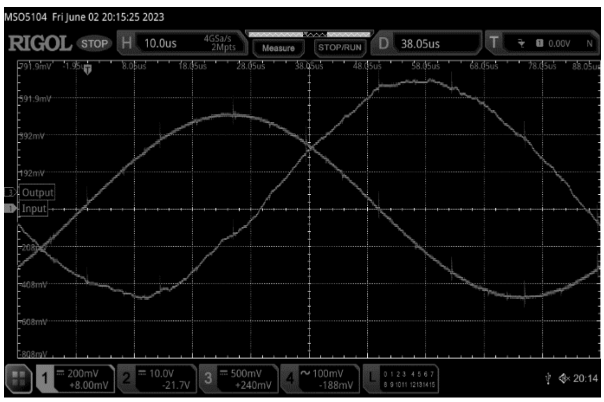

Fig. 7 Visible modulation glitches at internal sampling frequency

Nonetheless, modulation and demodulation used at the galvanic barrier introduce some noise to the output voltage. Additionally, noise propagates to the primary side if the secondary side does not have a stable supply. Another problem is when the secondary side is powered via a switch mode power supply. The capacitance between primary and secondary causes noise coupling between both sides.

In the end, substantial effort must be made to make it viable in precision measurement circuits such as electrical impedance tomography. If excitation voltage had to be separated or its peak-to-peak value was very high, op amp with galvanic isolation would probably be the best option.

The designed board was two layers PCB with isolation slots and a switch mode power supply for the secondary side of the amplifier. The prototype board proved that it is possible to use this kind of amplifier in precision measurement stages. The only downside is constant delay between both primary and secondary sides, making phase measurement harder.

Current transformer

The different method incorporates a transformer as a method of current measurement. This approach also mitigates CMRR by galvanic isolation in a similar matter as an optoisolated amplifier.

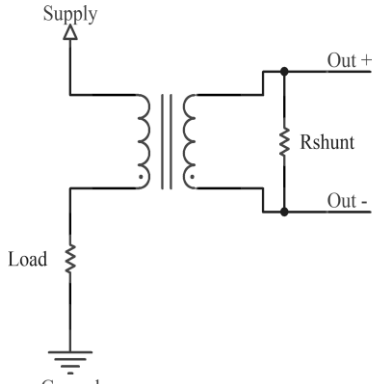

Fig. 8 Basic schematic of the current transformer

The current transformer measurement method was tested by building a prototype. Test circuit incorporated ideal diode circuit made with op-amp. The output signal of this circuit is DC proportional to peak-to-peak current value at primary winding.

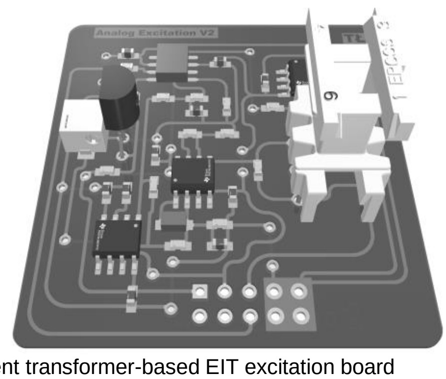

Fig. 9 Current transformer-based EIT excitation board

After that stage, the signal is inverted to mix with the requested input waveform. Input signal with mixed feedback signal is fed to output amplifier which purpose is amplification and buffering of signals. Experiments proved that the approach is valid. Nonetheless, it has some limitations which make it hard to implement in electrical tomography devices. The greatest concern is the transfer ratio in the function of frequency. According to basic laws of physics, primary impedance increases linearly with frequency. In EIT tomography, the circuit must be tuned to a certain frequency. Added primary parasitic impedance reduces output amplitude and further complicates the design of such a device. Another concern is winding to winding capacitance, which affects precision. The transformer has to be made with great care to minimise interwinding capacitance. Also, its design should be optimised with as low inductance as possible.

Rectification at secondary winding is not required but greatly simplifies the design. It is possible to use a secondary waveform as a direct feedback value. If so, care must be taken for phase shifts between waveforms. When designing this kind of circuit for a single, constant frequency, it is possible to compensate for phase lag properly.

Transimpedance amplifier

Modern electronics mostly forget about this kind of amplifier, but their special characteristics make them tempting for implementation in EIT tomography. An approach with LM13700 [21] as the main element was made.

An unusual property of a trans-impedance amplifier is its current mode of operation. Most integrated circuits operate with Voltages as input/output values. OTA is described as a Voltage Controlled Current Source (VCCS). The transfer equation of OTA is:

(3) $$I_{out} = (V_{IN+} - V_{IN-}) * g_m$$

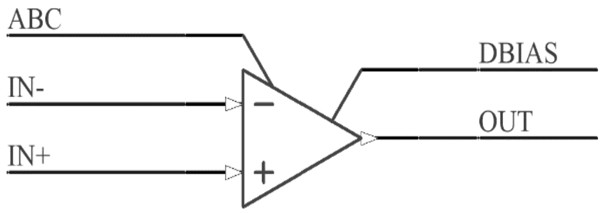

Fig. 10 Operational Transimpedance Amplifier (OTA) symbol

Where g_m is transimpedance, Transimpedance is dependent on Amplifier Bias Current (ABC). The ideal OTA transimpedance is a linear function of bias current. A prototype board with OTA was designed and tested in a scenario of EIT excitation.

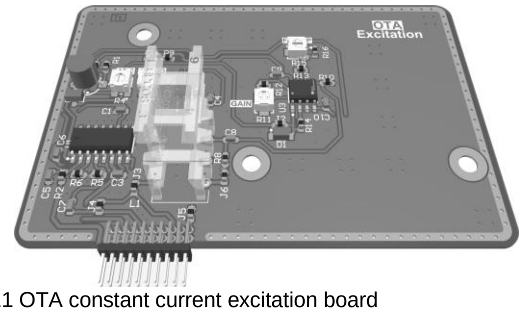

Fig. 11 OTA constant current excitation board

The Board was tested and gave promising results in the case of the EIT excitation generator. A device operated with negligible waveform distortion. Regulation times were short and were equal to a single input signal period. The only downside is this design's limited output current, which is equal to 300μA RMS. Nonetheless, the proposed circuit has good performance in the frequency domain and, with a low price, is a solid competitor to other approaches in EIT excitation.

Another advantage of OTA is its low cost. These devices are simple in their internal structure, which makes them cheap. The disadvantage of said simplicity is trans-impedance variation between parts, which causes trimming necessity. Another concern is the availability of such IC's, today's market is leading toward high integration and OTA's are mainly used as building blocks inside more complex integrated circuits. Mixers heavily depend on trans-impedance amplifiers because of their ability to easily modulate output amplitude.

Summary

During experimentation, four different constant current bipolar source circuits were tested. Each one has its advantages and disadvantages, and every designer should consider every one of them at an early stage.

The differential amplifier approach with modern parts offers good bandwidth, power consumption, board space and precision performance. One of its disadvantages is limited maximum common mode voltages on inputs and voltage drop at the shunt resistor.

The current transformer-coupled excitation circuit exhibits decent performance in the case of sensitivity and precision. Additional galvanic separation means that the secondary side can be even at very high common mode voltages until transformer isolation arcing. This approach resulted in a robust circuit with a high safety margin. Frequency dependence and interwinding capacitance make it hard to implement in variable frequency circuits such as EIT excitation. Another problem is the transformer itself. For this experiment, the transformer was made by hand. A wide variety of core coils, core shapes and core materials causes the design of the transformer to be challenging. Ultimately, good performance with the transformer can be achieved if all parameters are tailored to suit needs.

Isolation amplifier delivers high performance with galvanic isolation. The necessity of powering both sides independently is inconvenient in the case of the EIT excitation circuit. Nevertheless, the design was compact and offered short regulation times with decent precision. The proposed circuit is very capable and independent of common mode voltage. Thanks to separation, the secondary side of the amplifier can be at a potential as high as 600V. The only downside is a delay between the secondary and primary sides, which comes from the method of operation. Another concern is cost, which is higher than regular op-amps but comparable in terms of high-performance differential amplifiers.

Another proposal is a trans-impedance amplifier. In the case of current in the range of several hundred microamps, it offers high performance at a low price. Implementation of this device is slightly harder than traditional voltage mode IC's but can be rewarded by its special characteristics, enabling easy amplitude regulation via ABC input. OTA does not use a feedback loop in the proposed configuration, so the circuit is stable and reliable. Nonetheless, OTA's are more demanding in design, and it can be tricky to get repeatable characteristics without excessive distortions. Linearisation of the transfer ratio is important in this kind of circuit as external trimming is required, and internal linearising diodes are recommended.

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REFERENCES

[1] Kłosowski G, Rymarczyk T, Niderla K, Kulisz M, Skowron Ł, Soleimani M., Using an LSTM network to monitor industrial reactors using electrical capacitance and impedance tomography – a hybrid approach. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 25 (2023), No. 1, 11.
[2] Gnaś, D., Adamkiewicz, P., Indoor localization system using UWB, Informatyka, Automatyka, Pomiary W Gospodarce I Ochronie Środowiska, 12 (2022), No. 1, 15-19.
[3] Koulountzios P., Aghajanian S., Rymarczyk T., Koiranen T., Soleimani M., An Ultrasound Tomography Method for Monitoring CO2 Capture Process Involving Stirring and CaCO3 Precipitation, Sensors, 21 (2021), No. 21, 6995.
[4] Kłosowski G., Rymarczyk T., Kania K., Świć A., Cieplak T., Maintenance of industrial reactors supported by deep learning driven ultrasound tomography, Eksploatacja i Niezawodnosc – Maintenance and Reliability; 22 (2020), No 1, 138–147.
[5] Styła, M., Adamkiewicz, P., Optimisation of commercial building management processes using user behaviour analysis systems supported by computational intelligence and RTI, Informatyka, Automatyka, Pomiary W Gospodarce I Ochronie Środowiska, 12 (2022), No 1, 28-35.
[6] Kropidłowska P., Irzmańska E. Korzeniewska E., Tomczyk M., Jurczyk-Kowalska M., Evaluation of laser texturing in fabricating cut-resistant surfaces for protective gloves, Textile Research Journal, 93 (2023), No. 9-10), 1917–1927.
[7] Koulountzios P., Rymarczyk T., Soleimani M., A triple-modality ultrasound computed tomography based on full-waveform data for industrial processes, IEEE Sensors Journal, 21 (2021), No. 18, 20896-20909.
[8] Rymarczyk T., Kłosowski G., Hoła A., Hoła J., Sikora J., Tchórzewski P., Skowron Ł., Historical Buildings Dampness Analysis Using Electrical Tomography and Machine Learning Algorithms, Energies, 14 (2021), No. 5, 1307.
[9] Kłosowski G., Rymarczyk T., Niderla K., Rzemieniak M., Dmowski A., Maj M., Comparison of Machine Learning Methods for Image Reconstruction Using the LSTM Classifier in Industrial Electrical Tomography, Energies 2021, 14 (2021), No. 21, 7269.
[10] Pawłowski S., Plewako J., Korzeniewska E., Field Modeling of the Influence of Defects Caused by Bending of Conductive Textronic Layers on Their Electrical Conductivity, Sensors, 23 (2023), No. 3, 1487.
[11] Rymarczyk T., Kłosowski G., Hoła A., Sikora J., Tchórzewski P., Skowron Ł., Optimising the Use of Machine Learning Algorithms in Electrical Tomography of Building Walls: Pixel Oriented Ensemble Approach, Measurement, 188 (2022), 110581.
[12] Centurelli, F.; Della Sala, R.; Monsurrò, P.; Scotti, G.; Trifiletti, A. A Novel OTA Architecture Exploiting Current Gain Stages to Boost Bandwidth and Slew-Rate. Electronics 2021, 10, 1638. https://doi.org/10.3390/electronics10141638
[13] Bill Schweber That Simple Current-Sense Resistor Isn't Simple at All, https://embeddedcomputing.com/technology/analog-and-power/analog-semicundoctors-sensors/that-simple-current-sense-resistor-isn-t-simple-at-all January 22, 2019
[14] Filipowicz S.F., Rymarczyk T.: Tomografia Impedancyjna, pomiary, konstrukcje i metody tworzenia obrazu. BelStudio, Warsaw, 2003.
[15] Holder D.S.: Electrical Impedance Tomography: Methods, History and Applications Series in Medical Physics and Biomedical Engineering, London, 2005.
[16] J. Dušek, D. Hladký, J. Mikulka, "Electrical Impedance Tomography Methods and Algorithms Processed with a GPU", In PIERS Proceedings, 2017, 1710-1714.
[17] Z. Shuai, X. Guizhi, W. Huanli, G. Duyan, and Y. Weili, "Multi-frequency eit hardware system based on DSP," in 2006 International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, 2006, 6677–6680.
[18] A.S. Ross, G. Saulnier, J. Newell, D. Isaacson Current source design for electrical impedance tomography Physiol. Meas., 24 (2003), No. 2, 509
[19] https://www.mouser.pl/pdfDocs/si88x2x-3.pdf
[20] https://www.ti.com/lit/ds/symlink/ina592.pdf?ts=1692953023630
[21] https://www.ti.com/lit/ds/symlink/lm13700.pdf