Jerzy NABIELEC, Andrzej WETULA, Dariusz BORKOWSKI

AGH University of Science and Technology, Department of Measurement and Electronics

doi:10.15199/48.2016.11.38

Voltage divider with autocalibration – laboratory studies of a passive version

***Abstract**. Voltage divider with autocalibration is a high voltage converter with unique set of properties. It features low and known uncertainty in a wide frequency band and can recalibrate almost continuously on-line during normal operation. This makes it immune to environmental conditions and component properties. The paper presents results of laboratory experiments with a passive version, especially related to testing of influence of leakage currents.*

Streszczenie.** Dzielnik wysokiego napięcia z autokalibracją jest przetwornikiem napięcia o unikalnych właściwościach. Cechuje się on niską i określoną niepewnością w szerokim paśmie częstotliwości oraz możliwością prowadzenia ciągłej rekalibracji w miejscu pracy. Dzięki temu jest niewrażliwy na warunki środowiskowe czy właściwości elementów. W artykule przedstawiono wyniki badań wersji pasywnej dzielnika, dotyczące badania prądów upływu. **(Pomiarowy dzielnik wysokiego napięcia z autokalibracją – badania laboratoryjne wersji pasywnej).

Keywords: voltage divider, autocalibration, harmonics, "blind method".
Słowa kluczowe: dzielnik, autokalibracja, harmoniczne, metoda "w ciemno".

Introduction

One of the major problems related with a use of modern power grids is increasing content of higher harmonics in both voltage and current. It is related on one hand with an increaseing share of renewable power sources, and on another with more power electronic loads being introduced. Devices commonly used to transform high voltage for measurement purposes are inductive voltage transformers and multi-stage capacitive dividers or their combinations. Inductive transformers have relatively low bandwidth; moreover, their frequency responses depend on environmental conditions [1]. Other types of transducers often present a resonant behavior, which depend on power grid parameters. These instruments also require a regular recalibration, which can only be performed off site of operation.

The solution of aforementioned problems that authors propose is the use of an adaptive high voltage divider. It was earlier presented in [2] and [3], and the method itself is patented [4]. The divider is based on a two-sensor method, also known as a "blind" method of calibration, first proposed in [5]. The main goal of its operation is to provide corrections of dynamic errors caused by the analog sensors with unknown dynamic properties. The basic version of the method was proposed for sensors of inertial character, the mathematical model of which can be described by the first order differential equation. A system realizing this method is presented in Fig. 1.

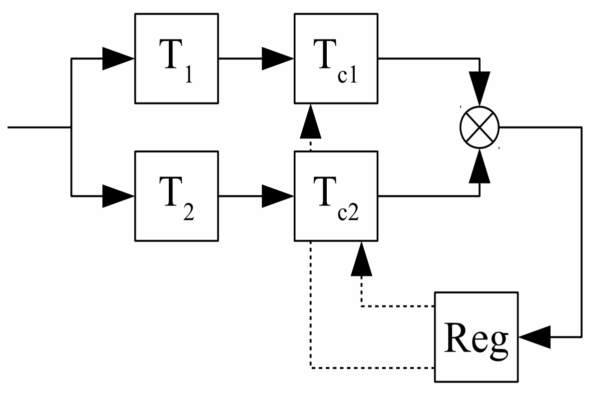

Fig.1. Two-sensor ("blind") method of auto-identification

It consists of 2 sensors characterized by time constants, T_1 and T_2, which can simultaneously measure the input signal u. Output signals p and x of these sensors are supplied to inputs of serial correctors with adjustable dynamic parameters, Tc_1 and Tc_2. Based on the difference between output signals of correctors, the value of the criterion used by the regulator *Reg* to adjust the dynamic properties of both correctors is determined in this way that the value of the employed criterion would be brought down to zero. Once this criterion is fulfilled, the output signals of both correctors reproduce the measured signal reliably. It needs to be emphasized that the task of automatic detection is realized on-site and during normal operation of the measurement system. Moreover, the unknown measurement signal is used in the process of auto-detection as the only excitation.

In order to ensure that the task of identification and correction reaches an unambiguous solution, the following conditions must necessarily be fulfilled:

- the dynamic properties of both sensors, that is their time constants, must differ from each other and must linearly depend on each other: $T_1 = cT_2$, c=const, $c \neq 1$;
- the static properties of both measurement channels (offset, gain) must be known.

In 1999, the assumptions underlying the method were proposed to be liberalized [6]. Presented was the procedure which enabled unambiguous solution of identification task if the dynamic properties of sensors were independent of each other. Moreover, the numeric realization of correctors was also proposed. Subsequent extension of the method involved liberalization of the assumption concerning the static properties of the measurement channels. It turned out to be sufficient to determine the static properties of only one measurement channel. The static properties of the other measurement channel are determined during the process of auto-identification. The suitability of method in the case of sensors, the dynamic properties of which are described by a second-order differential equation was also demonstrated in [7]. Further extension of the two-sensor method gives the possibility to evaluate the suitability of the method to be used with sensors, whose dynamic properties are changing with the frequency comparable to the one of the measured signals. Notwithstanding, the assumption of algebraic dependence between the coefficients describing the dynamic properties of sensors must hold in such a case [8].

The adaptive voltage divider

The schematic diagram of the divider is presented in Fig. 2. It consists of two independent branches constructed using elements of (generally) unknown values and relations between them. One branch, further named a fixed branch, is a high voltage transducer of any kind, e.g. voltage transformer or resistive divider. It can be constructed specifically as an element of the adaptive divider. Alternatively an instrument already installed on site can be used. Fixed branch has an output voltage V and is described by a ratio k. Estimation of this factor is a goal of an autocalibration procedure. It shall be noted that, unlike regular voltage transducers, k is assumed to be a complex, frequency dependent number.

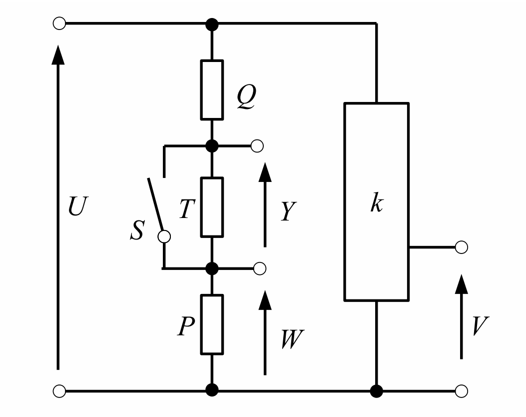

Fig.2. Schematic diagram of an adaptive high voltage divider

The other branch, called variable or commutating branch, may be implemented in various manners. Most of them is presented in [8]. In this paper the simplest solution is presented. It features a variable branch built from three impedances denoted Q, T and P. Element Q is a high-voltage one and its voltage is not measured. Complex voltages (voltage phasors) on T and P are denoted as Y and W. These voltages are low enough to acquire safely. The key element of the variable branch is a switch S that allows eliminating impedance T from a circuit by shorting it. The switch is controlled by a microprocessor unit that implements autocalibration algorithm.

Autocalibration procedure consists of two steps. In the first step switch S is closed and the following equation is true:

$$V_1 k = W_1 \frac{P+Q}{P} \tag{1}$$

Index at voltages denotes a number of step of the auto-calibration procedure for which a given voltage was calculated. In the second step, S is open and the following equations are held:

$$V_2 k = W_2 \frac{P+Q+T}{P} \tag{2}$$

$$\frac{W_2}{P} = \frac{Y_2}{T} \tag{3}$$

Based on equations (1) – (3), ratio k can be estimated as:

$$k = \frac{W_1 Y_2}{V_2 W_1 - W_2 V_1} \tag{4}$$

Periodic repetition of autocalibration procedure allows for estimation of k along with its changes caused by varying environmental conditions or element aging. Hence, the divider is adaptive. Ratio k can be also estimated as frequency dependent $k(f)$ due to a fact that a Fourier transform based algorithm is used for calculating complex voltages from waveforms. This way, a complex (amplitude and phase) frequency response of the fixed branch can be estimated for all frequency components of interest (i.e. ones of sufficient amplitudes present in a measured voltage U) during an autocalibration cycle.

Metrological properties

The presented divider features a set of properties that allow using it as a base for a unique measurement device. The main positive properties are:

- capability to adapt to environmental conditions and aging by periodic repetition of autocalibration procedure;
- repetition period may be of an order of seconds which is way faster than environmental conditions normally change;
- possibility of estimation of frequency response. Even though it is only possible to estimate frequency response for components present in a measured signal, continuous character of frequency response allows for its interpolation between estimated points;
- neither reference voltage nor reference impedance is needed for a calibration algorithm. The divider built using a “blind” method is a division factor reference itself;
- there is no need for periodic off-site recalibration of the device as calibration is performed on-site in a continuous manner. To implement this feature in practice in power grids, legal changes would have to be introduced;
- using an already installed measurement transducer as a fixed branch opens a way for an improvement of an existing infrastructure by adding a variable branch to a substation;

The device also features some negative properties that result both from construction and algorithm properties. They are:

- poor numerical condition of equation (4), resulting from a typically small difference between denominator components. This problem can be solved to a great degree by using very high resolution A/D converters to acquire voltages V and W. Use of a 24-bit converter together with averaging over a few second period effectively lowers numerical errors to values negligible for practical purposes;
- susceptibility of the device to a non-zero resistance of closed switch S. In practice, errors caused by this resistance are low as far as the resistance itself is kept reasonably low, which means that for example semiconductor switches should not be used as S;
- susceptibility to leakage currents both between branches and from nodes of variable branch to the ground. This circuit property is proved to be the most important negative feature of the divider. The process of identification and elimination in a series of experiments is described in the following section.

Laboratory experiments

Laboratory experiments of the divider were conducted in order to verify its aforementioned properties. The paper presents a part of experiments concentrating on leakage current influence on calibration errors.

For experimental purposes, a laboratory model of the divider was built. It is constructed for medium voltage operations, specifically on the order of 8.5 kV L-N which corresponds to 15 kV grid voltage. The first model included both fixed and variable branch in the same package. Variable branch was made of:

- element Q constructed as a series of four capacitors with overall capacitance of 625 pF and rated RMS voltage of 10 kV;
- element T being a single 166 kΩ resistor;
- element P being a single 30 nF, 400 V_{RMS} capacitor.

Maximum expected voltage on T and P did not exceed 300 V_{RMS}. Typical electromechanical relay was used as switch S.

Fixed branch was implemented as a capacitive divider, with high voltage component identical as Q and low voltage component consisting of a single 47 nF/400 V_{RMS} capacitor. Nominal division factor calculated from values is 76.2. However, this value was not used as a reference as it does not take actual values of elements into an account. Instead, it only shows an order of magnitude to be expected from output voltage and estimated value of k. The actual value of k, calculated using a reference divider, is 88.78+j5.46.

As a reference instrument, a resistive voltage divider Ross VD15-8.3-A was used. It is rated at 30 kV_{max}, with division factor of 1000 and declared uncertainty of 0.1 % at DC and 0.5 % at 60 Hz. Frequency band of a reference divider (-3 dB) was 5 MHz. Reference and tested dividers were installed in a laboratory medium voltage substation at AGH laboratory. Substation busbars were powered by a 0.4 kV/15 kV voltage increasing transformer, which in turn was powered from the grid through an autotransformer in order to allow voltage regulation. Overall laboratory setup is presented in Fig. 3.

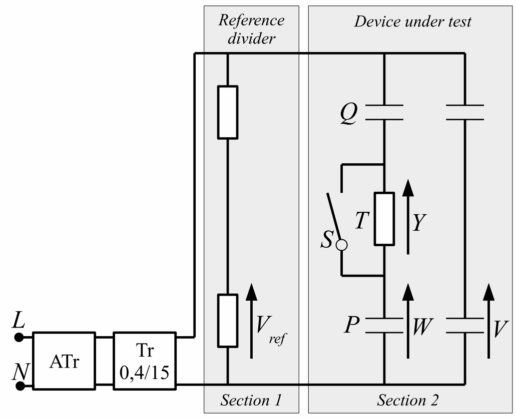

Fig.3. Laboratory setup used in experiments (tested divider represented in detail)

Autocalibration algorithm was implemented in a PC, using National Instruments cDAQ device as an interface to the divider elements. Digital output c-module was used to control S, and output voltages were sampled using 300 V_{RMS}/50 kHz c-module for Y, W and V, and 60 V_{max}/50 kHz c-module for a reference divider output voltage. Control and data acquisition program was prepared in LabVIEW. Estimation of k was performed off-line in Matlab.

As an error measure, a total vector error (TVE) was used. TVE is defined as:

$$TVE = \left| \frac{k - k_{ref}}{k_{ref}} \right| \cdot 100\% \tag{5}$$

TVE is used as a vector error in comparisons of phasor measurement algorithms [10]. Reference factor k_{ref} was calculated based on output voltage of a reference divider and V voltage. For convenience, TVE will be expressed in percents in further part of the paper.

Experiment results

The first experiments, presented in [3], have shown that the tested divider features relatively low random error of 0.5 %, but very high bias error of over 10 %. Numerical errors would have caused a high random error, so they were excluded as a reason of high bias error. Resistance of closed switch S was not an error source because a relay was chosen specifically to minimize this resistance. It was also verified in a separate experiment in which additional resistance was added in series with S. Based on simulations it was alleged that leakage currents are main reason of high bias error. Next experiments were designed to test this hypothesis and find a method of minimizing a bias error.

In order to lower leakage between branches, they were separated and put in different packages. This allowed increasing distance, lowering capacitance between branched and thus lowering leakage currents. Note that packages were made of non-conductive materials and they did not feature screening. After increasing a distance between branches, bias error was significantly reduced to around 5%. It confirmed a hypothesis that leakage currents, especially ones between two branches of the divider, are the main source of a bias error.

In order to minimize leakage currents, the variable branch was completely redesigned. It was placed in a special package featuring a few screens and shields connected to various branch nodes. In order to make branch more compact, element Q was now made of a single 1 nF/9 kV_{RMS} capacitor. Fixed branch remained unchanged and was still installed in an old package. After introducing all of the mentioned changes and some tuning of connection placing, random error did not change and bias error dropped to 1.05%.

As errors of the tested divider were now on the order of reference divider uncertainty for 50 Hz (0.5 %), an additional calibration and verification of a reference divider was needed. It was done in a laboratory of Regional Bureau of Measures in Krakow. For calibration of a reference divider, voltage source and a reference instrument were used. Voltage source generated nearly sinusoidal voltage of 900 V and frequency set to either 50, 500 or 5000 Hz. Reference instrument was a very high precision (0.001 %) RMS voltmeter based on a thermal equivalent. As such, it was not frequency-selective and only measured RMS voltage over the whole band.

Estimation of a parameters of a reference divider shown that the actual error is slightly higher for 50 Hz than a declared uncertainty; it also increased with frequency. This was most probably caused by the use of slightly longer connection cable than the one provided by a manufacturer. Increased cable capacitance caused output voltage drop, more noticeable for higher frequencies. It was also noted that used voltage source does not generate purely sinusoidal voltage, and also that some radio noise is picked due to high resistance of a tested reference divider. As the reference voltmeter was not frequency selective, it was not possible to estimate actual frequency response of a reference divider. Finally, it was decided to introduce an adjustment to measurement results for the base harmonic only. This adjustment is only a rough correction as currently there is no method of performing a proper calibration of a reference instrument and thus verification of the tested divider over the wide band. After introduction of an adjustment both random and bias errors dropped to below 0.1 % for 50 Hz RMS value. In order to verify the divider uncertainty for higher frequencies, a different verification method must be introduced.

Bias error summary over all conducted experiments is presented in table 1.

Table 1. Summary of bias errors over conducted experiments

Experiment configuration	Bias error TVE [%]
No screening, single package	>10%
No screening, branches in separate packages	5%
Screening and shielding, branches separated	1.05%
Corrected reference divider	0.1%

Summary

Conducted experiments confirmed that the proposed method of autocalibration allows constructing a high voltage measurement device that features low uncertainty in a wide band. They also helped to find the main negative properties, their influence on measurement errors and methods of their mitigation. Among all properties, high sensitivity to leakage currents influences an uncertainty the most. It has been proven that this influence can be mitigated by limiting leakage currents, which in turn can be done by careful screening of a variable branch.

Currently built laboratory model of the divider is about the same size and weight as an average 15 kV measurement transformer. However, it has been over-sized in order to maximize safety during experiments. Also, heavy and expensive material (PTFE) was used for insulation. Hence, further development will concentrate on lowering size and weight of the device by redesigning screens and using more production-feasible materials. Also, autocalibration algorithm will be implemented in a microprocessor system built inside the divider. This way, a prototype high precision, wideband medium voltage measurement device will be constructed, allowing to eventually prepare for production.

***Authors**: Jerzy Nabielec, Ph.D., AGH University of Science and Technology, Krakow, Department of Measurement and Electronics, al. Mickiewicza 30, 30-059 Krakow, Poland, e-mail: jena@agh.edu.pl; Andrzej Wetula, Ph.D., AGH University of Science and Technology, Krakow, Department of Measurement and Electronics, al. Mickiewicza 30, 30-059 Krakow, Poland, e-mail: wetula@agh.edu.pl; Dariusz Borkowski, Ph.D., AGH University of Science and Technology, Krakow, Department of Measurement and Electronics, al. Mickiewicza 30, 30-059 Krakow, Poland, e-mail: borkows@agh.edu.pl*

REFERENCES

[1] Klatt M., Meyer J., Elst M., Schenger P., Frequency Responses of MV voltage transformers in the range of 50 Hz to 10 kHz. *14th International Conference on Harmonics and Quality of Power, Bergamo* (2010)
[2] Nabielec J., Jamróz P., Wzorcowanie w pomiarach dynamicznych. *Pomiary Automatyka Kontrola*, vol. 59 (2013), no.6, 526-528
[3] Borkowski D., Nabielec J., Wetula A., Experimental verification of the voltage divider with auto-calibration. *XII International School on Nonsinusoidal Currents and Compensation, Łagów* (2015)
[4] Nabielec J., An adaptive voltage divider with corrected frequency characteristic for measuring high voltages. *Patent application US201214236912, US Patent Office* (2012)
[5] Pfriem H., Zur Messung veränderlicher Temperaturen von Gasen Und Flüssigkeiten. *Gen. Ingen.*, vol. 7 (1936), no. 2, 85-92
[6] Nabielec J., An Outlook on the DSP Dynamic Error Blind Correction of the Analog Part of the Measurement Channel, *Proceedings of the 16th IEEE Instrumentation and Measurement Technology Conference, Venice*, vol.2 (1999), 709-712
[7] Nabielec J., Nalepa J., The 'Blind' Method of Dynamic Error Correction for the Second Order System, *Proceedings of XVII IMEKO World Congress, Dubrovnik, Croatia* (2003), 841-846
[8] Jamróz P., Nabielec J., *Adaptive sensors for dynamic temperature measurements, Smart sensors for industrial applications, CRC Press* (2013), 227–241
[9] Nabielec J., Wetula A., A voltage divider with autocalibration – a review of structures, *VII Kongres Metrologii, Lublin/Nałęczów* (2016)
[10] IEEE Standards for Synchrophasors for Power Systems, *IEEE Std C37.118™* (2005)