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A voltage divider with autocalibration – a review of structures

Abstract. This article presents a method of autocalibrating a voltage divider and the measurement properties of systems in which it is realised in the active, passive and compensating versions. Autocalibration refers to the ability of a measurement system to determine its parameters where and when it is operating, using an unknown measured signal as the only activation of the procedure.

Streszczenie. Artykuł przestawia metodę autokalibracji dzielnika napięcia oraz właściwości metrologiczne układów ją realizujących w wersjach: aktywnej, pasywnej oraz kompensacyjnej. Przez autokalibrację określa się zdolność układu pomiarowego do wyznaczania swoich parametrów w miejscu i w trakcie pracy przy wykorzystaniu nieznanego mierzonego sygnału jako jedynego pobudzenia procedury. (Dzielnik napięcia z autokalibracją – przegląd struktur).

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

Introduction

All activities in traditional Metrology consist of using measurement standards and methods of comparing the measured value to the value of the standard. Modern Metrology aims at reconstructing the standard value of a physical variable at any time and place while relaxing the requirements concerning the impact of environmental factors on the whole procedure.

In power grids, it is necessary to use a conditioning system to reduce the range of measured voltages from up to several hundred kV to values supported by contemporary A/D converters, i.e. ±10V DC. This is usually done using voltage transformers , capacitive, resistive or inductive dividers. Their metrological parameters, and in particular the k division ratio, are sensitive to environmental factors, ageing, the load type and value. What is more important, it is generally assumed that the ratio k is a real number, while if there are numerous harmonics in the measured voltage, the ratio should be defined as a complex number which value depends on the frequency of the harmonic it refers to. Regulations applicable today refer only to measuring the True RMS of the measured voltage.

Taking a reliable measurement of high voltage waveform forms a significant metrological challenge [1], particularly as the use of increasing numbers of power electronics devices causes interference in the power grid. The results of the AMI Picnic organised at AGH [2] give a particularly glaring example of the scale of the problem. Differences between readings of different power meters exceeded 20% while they were simultaneously measuring the power in a circuit with interference. This is why it will be necessary not only to measure the effective voltage value, but also to analyse the harmonics of the measured voltage, including the relationship between their phase angles. Another challenge which modern measurement methods used in power engineering systems will face will be the need to measure time relationships between voltage signals recorded at distant switching stations. This will allow a more precise determination of the coefficients of the power grid model or tracking the routes of interference propagation and as a result locating their sources. Broadband input circuits of voltmeters and their synchronisation will enable partial discharges to be precisely located during the normal operation of a transmission line. This allows maintenance to be planned to prevent unexpected breakdowns.

Publication [3] presents the first structure of the measurement system in which the voltage transducer can autocalibrate at its operating location, during operation and using an unknown measured voltage as the only excitation

of the identified transducer. Autocalibration allows the ratio of the transducer to be determined individually for each harmonic detected in the recorded signal. In addition, the measurement method is not sensitive, within a broad range of possible changes, to the ageing of components, their susceptibility to weather conditions, the type and value of the load attached to the divider output. A high precision measurement instrument can be built of components having only roughly approximated values.

The following sections present three versions of the measurement system – and its characteristics – which autocalibrate the voltage conditioning system, thus giving measurement system the very valuable features described above. The first version includes an active semiconductor component, namely the operating amplifier. The second group of systems is built without any semiconductor components. The third group includes solutions in which compensation methods are used to measure the voltage.

Measurement method

The main purpose of the proposed method is to determine the static and dynamic properties of two analogue channels synchronously measuring the same input voltage. In the two channel structure of the analogue part of the measurement system, it is proposed to periodically change the configuration of one of the channels to autocalibrate the system, while the other channel is measuring high voltage continuously.

The channel with the fixed configuration can consist of a resistive, inductive or capacitive voltage divider or a typical voltage transformer with an unknown division ratio k. This ratio, as a complex number, is identified and, as a result, the transducer is calibrated.

In the basic version of this method, the variable configuration channel consist of: a voltage divider, a pair of AD converters and a contact system whose switching changes the configuration of components in this divider. By measuring low voltages on the components of the divider before and after the change, and then determining the relationship between them, the value of the ratio k searched for can be determined. In every version of the system it is assumed that changes of the divider ratio k are so slow relative to the period of the configuration change cycle of the variable structure branch that they can be considered quasi-static, and therefore traceable.

It should be emphasised that the input impedance of A/D converter is included in the impedance to which these transducers are connected in parallel, and is treated as the resultant impedance of unknown value. This is the basic

assumption about the system, which is to eliminate the error of the method when measuring voltages on the impedances of the divider.

Active structure

Chronologically, the first system was the one referred to as active and presented in figure 1 (a) and (b). The divider ratio k (1) of the branch made up of impedances R and Z is the value to be autocalibrated by this and further system versions. The rule for switching contacts is "first ON then OFF", so as to prevent high voltage on components not designed to handle it. Switches have not been shown to avoid obscuring the idea of the measurement method. The Impedance Q is assumed to be resistant to at least full input voltage.

For structures presented in figure 1 (a) and (b), the equation (2) is true for voltages with the indexes, respectively, 1 and 2. It is also assumed that the measured high voltage U may differ in value for each of these structures, so they are distinguished with the same indexes. The system of equations (2) is solved by (3), which overtly determines the value of the ratio k searched for. The phasors of voltages found in (2) and (3) are determined using the DFT for sampled voltage signals. These equations are true independently for each harmonic detected in the sampled signal. As a result, one measurement cycle allows the measurement characteristics of the divider to be determined for all harmonics detected.
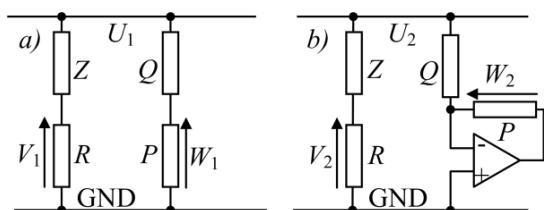

Fig. 1. Diagrams of the active divider in the (a) standard and (b) inverting amplifier configuration

$$(1) \qquad k = \frac{Z + R}{R}$$

$$(2) \quad U_1 = V_1 \frac{Z+R}{R} = W_1 \frac{P+Q}{P}, \quad U_2 = V_2 \frac{Z+R}{R} = W_2 \frac{Q}{P}$$

$$(3) \qquad \hat{k} = \frac{1}{\dfrac{V_1}{W_1} + \dfrac{V_2}{W_2}}$$

The drawback of this implementation of the measurement method is the need to supply the operating amplifier and a complicated switching algorithm. In addition, equation (3) is numerically ill-conditioned, because the denominator contains a difference between complex numbers that are close in value. Thus small errors in determining voltage indicating marks cause big changes in the value of the ratio searched for. Simulation studies and laboratory experiments have shown that if A/D converters with 24 bit resolution are used, a class 0.1 measurement instrument can be built [4].

For a real operational amplifier, the open loop gain is reduced for high frequencies. In addition, the finite input impedance of the amplifier means that not all current flowing through Q flows into P in the configuration from figure 1(b).

Passive structure – a version with an auxiliary source

The disadvantages of the active structure can be avoided if the reconfigured branch of the divider is built only of passive components. The first version referred to as "with an auxiliary source" is presented in figure 2, where (a), (b) and (c) show subsequent configurations of the variable structure branch.

The fixed configuration branch remains the same as in the active version of the system and the ratio k is the autocalibrated value.

In the first configuration "1" of the system shown in figure 2(a), the switch S realises a voltage divider made up of the impedance Q and P. In the second configuration "2" shown in figure 2(b), the switch S implements a voltage divider made up of impedances Q and T. For configurations "1" and "2", (4) is true, with the same indexes next to voltage phasors. At the third stage of the variable configuration cycle, the serial connection of P and T is fed from an auxiliary voltage source isolated from the GND, to determine the P/T impedance ratio according to (4) for voltages with indexes "3". In this solution, the common point between these impedances is connected to the GND neutral potential to keep the parasitic impedances associated with these impedances unchanged. At the same time, the conditions for voltage measurement on these impedances are maintained in the same way as in previous configurations. The searched for value of the ratio k is given by (5). The obvious advantage of this structure is that it contains no active components. In addition, the control of the contacts, including protection ones, is easier than in the active structure. Just as in the active structure, the value of k can be determined for all detected harmonics of the recorded signal during one measurement cycle. However, this passive system is characterised by a worse condition number of equation (5), which makes the autocalibration result more sensitive to errors in measuring voltages and determining their phasors.
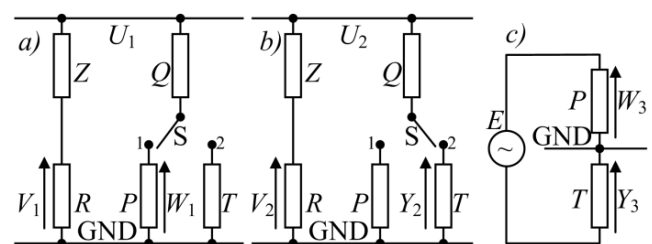

Fig. 2. Diagrams of a passive divider "with an auxiliary source", configurations: (a) "1", (b) "2", (c) the P/T relationship

$$(4) \quad U_1 = V_1 \frac{Z+R}{R} = W_1 \frac{P+Q}{P}, \quad U_2 = V_2 \frac{Z+R}{R} = Y_2 \frac{T+Q}{T}$$

$$\frac{W_3}{P} = \frac{Y_3}{T}$$

$$(5) \qquad \hat{k} = \frac{W_1}{V_1} \frac{\dfrac{Y_3}{W_3} - 1}{\dfrac{V_2 W_1 Y_3}{V_1 Y_2 W_3} - 1}$$

Passive structure – a version without an auxiliary source

The drawbacks of the previous passive structure have been eliminated in the system version presented in figure 3 (a) and (b). At the autocalibration cycle steps with the S contact open and closed, the system is described by (6), with the phasor of voltages with the indexes "1" and "2", respectively, and phasor Y, i.e. the voltage on the open contact. The value of the searched – for ratio k is determined by (7).
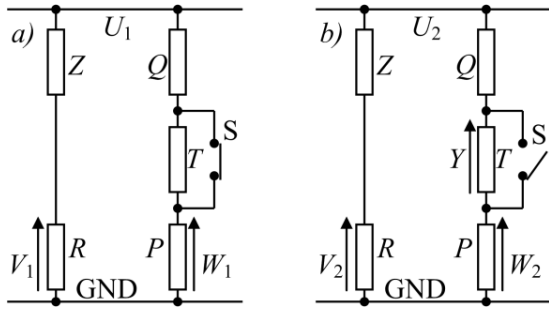
Fig. 3. Diagrams of a passive divider without an auxiliary source

$$(6) \quad U_1 = V_1 \frac{Z+R}{R} = W_1 \frac{P+Q}{P}, U_2 = V_2 \frac{Z+R}{R} = W_2 \frac{P+T+Q}{P}$$

$$\frac{W_2}{P} = \frac{Y}{T}$$

$$(7) \quad \hat{k} = \frac{W_1 Y}{W_1 V_2 - W_2 V_1}$$

Apart from the obvious advantage of a system which does not have an auxiliary voltage source, this version features the simplest possible control of a single contact. There is no need to use protection procedures, systems and contacts at the time of the configuration change. Regardless of whether the contact S remains open or closed, high voltage cannot occur on the low voltage side as a result of a switching operation error. In addition, the condition number of (7) has a value better than for (5). The first drawback of this system is that measured voltages do not adjoin the same potential. Consequently, voltmeters of a very high CMRR or with high quality galvanic insulation between measurement channels must be used. In addition, this configuration may cause some of the current flowing through Q not to flow into P when the S contact is open. This problem became very obvious during experiments with incorrectly shielded components of the divider.

Both passive versions of the system were subjected to simulation and experimental tests. However, after comparing the first experimental results, it was decided to continue studying the system version without the auxiliary source, mainly because of the ease of controlling the S contact and not having to use an auxiliary voltage source, which was particularly important when the geometry of components and shields was changed multiple times [5]. To modify the passive version of the system without an auxiliary source, the determination of the voltage Y by measuring the voltage on the impedance P and on both P and T connected in series, with the S contact open, was considered. However, this option was rejected as it did not fulfil the basic assumption that the unknown input impedance of the voltmeter is included in the impedance of the divider component on which the voltage is measured.

A structure with single balancing

The problem of the bad condition number of the equation which forms the basis for determining the value of the ratio k along the autocalibration route became the reason to look for a different method of measuring voltage in the variable configuration branch. One of the versions of the system with single balancing is presented in figure 4 (a) and (b). The component r determines the internal impedance of the voltmeter which serves as a balance indicator. Compared to the previous systems, the structure similar to an AC bridge which is balanced for the closed contact S was proposed. This is why the value of impedance P should be independently adjustable for both its imaginary and its real part. For $P=P_0$, the equation (8) is

true when the bridge is balanced. This relationship can be true if the P_0 values of different harmonics are different. This is why the balancing procedure should be carried out individually for each harmonic.

In the configuration with the S contact open, the system constitutes an unbalanced bridge in which a voltmeter with the internal impedance r measures the imbalance voltage X. The second voltmeter measures the voltage Y on the impedance T. For this configuration of the divider equation (9) holds. Relationship (10) gives the value of the ratio k being identified.
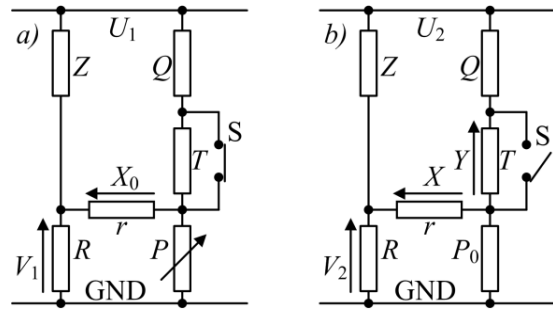

Fig. 4. Diagrams of a divider with single balancing

$$(8) \quad ZP_0 = QR \Leftrightarrow |X_0| = 0\,\mathrm{V}$$

$$(9) \quad U_2 = V_2 \frac{Z+R}{R} = (V_2 - X)\frac{P_0 + T + Q}{P_0}$$

$$(10) \quad \hat{k} = \frac{Y}{X}$$

The greatest advantage of this system is the simple relationship used to determine the searched for value of the ratio k. Another good feature is that the voltmeters used do not need a high quality source of the reference voltage. Even if both voltmeters produce the same relative gain error, the ratio of their measurement results will be completely free of this type of error.

However, a system with single balancing exhibits many drawbacks. The procedure of determining the frequency characteristics of the divider is lengthy because a single autocalibration cycle allows the divider ratio to be determined only for one, selected signal frequency. During the balancing with the S contact closed, when the alternating current bridge is still far out of balance, the current flowing through the balance indicator between the branches can change the value of the ratio k searched for. After the system has completed its start-up stage of operation and is very close to balance, at subsequent cycles, the value of the impedance P is fine-tuned only slightly and the small current flowing through the balance indicator does not significantly distort the value of the ratio k. However, in the configuration with the S contact open, the current flowing through the voltmeter measuring the imbalance voltage can significantly distort the autocalibration result, which can be seen as an error of the method [6]. Technical problems associated with the need to supply a pair of voltmeters, controlling the contact, the data transmission and synchronisation are also observed when the subassemblies have no common potential. The above shortcomings suggest that the system with single balancing should be used for sporadic measurements with a battery supply, and not for continuous operation in industrial environment.

This system has been verified experimentally for the voltage of 230 Vrms and subjected to extended simulation testing for the voltage of 15 kVrms [7].

A structure with double balancing

Eliminating the method error characteristic for the system with single balancing led to proposing a system with double balancing, presented in figure 5 (a) and (b). The operating principle of this system with the contact S closed and the relationship describing this condition (11) is the same as for the previous version. The shorted impedance T slightly raises the high impedance of the balance indicator. In the configuration with the S contact closed, described by (12), the method of measuring the voltage on the diagonal of the bridge was modified. The voltage divider made up of the impedance T split into two parts at the point marked in figure 5(b) with the slider arrow is re-tuned. In the practical implementation, the retuning of the divider made up of the impedance T must be independent of the module and phase shift angle. Voltage Y is divided to obtain X so that the voltage module X_2 on the bridge diagonal becomes zero. Then, the voltage X on the lower part of the impedance T is the same as the voltage between the common node of impedances Z and R and the node with impedances T and P. The relationship (13) used in the autocalibration process is almost the same as (10). The design of the system is made slightly easier, because the same A/D transducer does not have to serve as a zero indicator and the voltmeter. The role of the zero indicator can be played by a device of very high sensitivity, while its metrological characteristics do not require special attention. At the same time, voltages X and Y can be measured by a different voltmeter whose ranges have been selected more suitably for the measurement signal.

It is expected that the double use of the zero method will allow achieving very high autocalibration accuracies of the ratio k as a complex number, much better than that allowed by the measurement methods used currently.

The laboratory test of the double balancing version have been postponed until several technical issues are solved, particularly concerning changing the impedance value of the adjustment components used in the version suitable for the voltage of 15 kVrms. For such voltages, manual manipulation like that in the single balance system for 230 Vrms is not allowed.
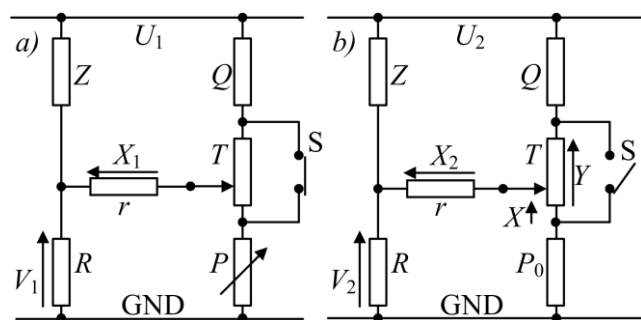

Fig. 5. Diagrams of a divider with double balancing

$$(11) \qquad ZP_0 = QR \Leftrightarrow |X_1| = 0\text{V}$$

$$(12) \quad U_2 = V_2 \frac{Z+R}{R} = (V_2 - X)\frac{P_0 + T + Q}{P_0} \Leftrightarrow |X_2| = 0\text{V}$$

$$(13) \qquad \hat{k} = \frac{Y}{X}$$

Conclusions

The presented measurement method and systems realising it have unique characteristics. All plans concerning these characteristics, mentioned as expectations in the Introduction, have been carried out. However, there is an additional unique feature that has not been presented yet, but should be emphasised. An example can be given of using an autocalibrating divider to locate partial discharges in power grids. The divider system can be designed so that the module of the ratio k of the system is very high for the main harmonic, but low for high frequencies. Then, high frequency signals will be attenuated less than low frequency ones. This feature makes it possible to boost the searched for signals of very low energy but of high frequency, which are superposed on signals of high energy but low frequency. This feature can be implemented in the system by modifying the frequency characteristic of impedance components of the divider and their interrelations. There is no need to ensure the high stability of this characteristic, as all its fluctuations will be detected in the autocalibration procedure. This will make it possible to locate partial discharges in power lines during their normal operation.

If the method presented is used to measure the highest voltages, it is necessary to use a cascade structure of the system. Preliminary tests of a system for 110 kV have been completed successfully.

A very important issue is the experimental verification of the measurement properties of the proposed method. TVE (Total Vector Error), used to establish the quality of phasor determination [8], has been selected as the assessment criterion. What remains unsolved is the problem of obtaining the reference value of a high voltage changing over time.

The presented method enables high accuracy measurements of variables changing over time, which have not been measurable before. It allows new standards and regulations to be introduced that will govern the formal aspects of measurements in power engineering. This subject will soon become very significant when Smart Grids start developing very rapidly, as the control of such grids will be based not only on the effective value but also on phase dependencies between the curves of instant values of voltages at distant nodes of the power grid.

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