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A voltage divider with autocalibration – a version with single compensation

Abstract. *This paper presents the results of experimental and simulation studies of a divider with the autocalibration functionality, a version with single compensation when the voltage is lowered to 230 Vrms. Based on the results of simulation studies for the standard voltage of a 15 kVrms distribution line, design recommendations for a divider for this voltage were formulated.*

Streszczenie*. Przedstawiono wyniki badań eksperymentalnych oraz symulacyjnych dzielnika z funkcjonalnością autokalibracji w wersji z pojedynczą kompensacją przy obniżonym napięciu do 230Vrms. Na bazie wyników badań symulacyjnych dla standardowego napięcia linii dystrybucyjnej 15kVrms sformułowano zalecenia konstrukcyjne dzielnika dla tego napięcia. (****Dzielnik napięcia z autokalibracją – wersja z pojedynczą kompensacją).***

Keywords: voltage divider, autocalibration, compensation, harmonics.
Słowa kluczowe: dzielnik napięcia, autokalibracja, kompensacja, harmoniczne.

Introduction

Paper [1] presents 5 structures of systems that implement an innovative method of measuring high voltage. Its most important feature is the autoidentification of the voltage conditioning circuit which supports autocalibration. This is understood as determining the measurement characteristics of the divider where and when it is operating, using an unknown measured signal as the only activation of the procedure. The division ratio of such a divider should be treated as a complex number, and not a real one. This approach allows both the amplitude and phase characteristics of the voltage conditioning circuit to be determined. These characteristics may differ depending on the frequency of the signal measured.

This paper verifies one structure of the measurement systems implementing the method of autocalibrating the voltage conditioning circuit, which is significantly different from the remaining ones. The latter make use of a relationship in the form of a fraction whose denominator is the difference of two numbers of similar values. As a result, the condition number of this relationship is unfavourable, and requires very accurate methods of measuring voltages arising in the structure of the divider. The solution presented here is a proposal of the circuit and a method of proceeding which enable the direct measurement of the value in the denominator. As a result, the voltages need not be measured with such high precision.

The sections below present the results of a laboratory experiment at voltage reduced to 230 Vrms. The analysis of these results is complemented with simulation studies conducted in parallel to the experiment. Conclusions from experiments and simulations were used to formulate assumptions for simulation studies of a voltage conditioning system typically for a 15 kV distribution line. Conclusions from these studies form the basis for developing the design assumptions of a real system for medium voltage (MV).

Assumptions and expectations

Significant, beneficial features of this measurement method which should result from the proposed voltage divider circuit and the voltmeter built using it include:

- the value of the measurement system ratio is defined as a complex number dependent on the frequency of the analysed harmonic of the measured signal;
- the system can be built of components without their preselection, as its measurement characteristics will be determined during operation;
- insensitivity to the ageing of the applied components;
- insensitivity to changes of weather conditions;
- insensitivity to the impact of loading the analogue output of the divider with impedances of different values and to the parameters of the cable connecting the voltmeter;
- the autoidentification procedure allows changes of measurement system parameters to be continuously monitored, which makes it easy to assess its condition, plan its possible repairs or detect any tampering by unauthorised persons;
- there is no need to remove and transport the measurement instrument to an authorised institution for the regular verification of its measurement characteristics.

Measurement system

The measurement method applied consists in the synchronous measurement of the same voltage U changing over time using two independent dividers, referred to as "branches", presented in figure 1 (a) and (b).

The first branch is a traditional divider built of the impedances Z and R with unspecified relations between their values. The division ratio k of this divider is autocalibrated. Its output voltage is represented by V. The unspecified value of the input impedance of the A/D converter measuring this voltage is included in R as the resultant impedance of their parallel connection. The product of the voltage V multiplied by the k ratio identified during the autocalibration allows the value of the voltage U to be determined. This branch can be implemented as any transducer reducing the high voltage.

The second branch, referred to as the variable configuration branch, has its structure cyclically changed by closing and opening the switch S in subsequent steps 1 and 2. This causes an additional, indefinite impedance T to be connected in series to the divider built from the impedances P and Q with indefinite values and relationship between these values. Both the amplitude and the phase angle of the impedance P should be independently adjustable. It is assumed that the cycle time is much shorter than the time within which the k ratio changes.

The impedance r connected between two branches is an indefinite input impedance of the A/D converter connected between the terminals of impedances P and R. This converter records the voltage X across the diagonal of the alternating current bridge made up of the two branches. A second A/D converter is connected in parallel to the impedance T and registers the voltage Y. The impedance of the input circuit of this converter is included in T as a connection parallel to it.

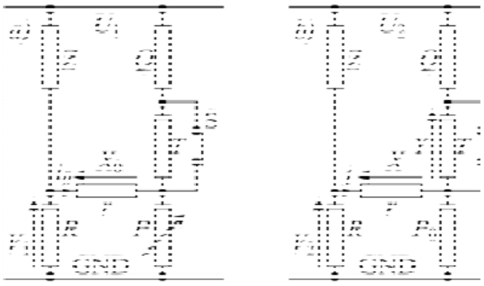

Fig. 1. Diagrams of a divider with single compensation: (a) with the S switch closed, (b) with the S switch open

In step 1, with the S switch closed, equation (1) applies after the system has been balanced like typical alternating current bridges by retuning the complex value of impedance P to P_0, with regards to both its module and phase. Then, the module of the voltage on the impedance r takes the value $|X_0|$=0V. In this way, the measurement characteristics of the branch with the constant structure are transferred to the branch whose structure will be changed. The balance conditions can be different for each considered frequency found in the measured waveform of the voltage. $T0$ represents a parallel connection of impedance T and the closed real switch *S* with a non-zero parasitic impedance.

$$k = \frac{U_1}{V_1} = \frac{Z+R}{R} = \frac{Q+T0+P}{P} \tag{1}$$

In step 2, switch S is opened, putting the bridge in an unbalanced state, in which only the voltages Y and X are registered and their phasors are determined for the established value of $P = P_0$. The equation (2) then applies and is used together with (1) to determine the ratio k, represented by $\breve{k}$ (3). It was also assumed that $T0 \approx 0\ \Omega$ because it is negligibly small compared to Q, and also that $r \to \infty\ \Omega$ across the diagonal of the bridge.

$$U_2 = (V_2 - X)\frac{P+T+Q}{P} = V_2\frac{R+Z}{R}, \quad \frac{Y}{T} = \frac{V_2 - X}{P} \tag{2}$$

$$\breve{k} = \frac{Y}{X} \tag{3}$$

The above relationships make it possible to determine the k ratio of the divider precisely, but only after the fulfilment of idealised assumptions, which are usually not true in the real implementation of the system. Errors in determining the ratio k are influenced by the bridge balancing precision in step 1, which depends on such factors as: the sensitivity threshold of the zero detector used, its input impedance r, the resolution of manipulators changing the value of P and the high substitute output impedance of the bridge according to the Thevenin model in relation to the impedance of the zero indicator. The indicator current i causes an error of the method.

Experimental studies at 230 Vrms

The first version of the system, which was to be used for an experimental verification of the measurement method, was built for low voltages, so that the system could be manually balanced in a way safe for the operator and the measurement instruments. This is why the voltage of 230 Vrms/50 Hz was used as the unknown voltage to be measured using an A/D converter with the range of ±10 V DC (e.g the C NI9239 module) and the system being tested. Impedances Q and Z were implemented as capacitors 4.7 nF/700 Vrms. Each of the P and R impedances were provided as a parallel connection of 100 nF and 47 nF capacitors. In addition, the R impedance was shunted with a resistor with the nominal value of 230kΩ. A resistor with the nominal value of 22.6 kΩ was used as impedance T. It was estimated that the effective value of the current flowing through each branch of the divider amounts to approx. 0.3 mA. Only the information about the nominal values of components is necessary to ensure the correct operation of the measurement system. Their values were selected so that when the standard voltage waveform is recorded, the signal fed to the input of the A/D converters would cover 80% of their measurement range. It was also assumed that the amplitude of the voltage recorded on impedance T should be similar to the amplitude of the voltage on impedance P. The C NI-9225 module was used for the reference measurement of the U voltage. The sampling frequency of all measurement modules was set at 50 kS/s. Impedance P was retuned using a resistance decade and a capacitance decade connected in parallel to P. The application identifying the value of k was written using LabVIEW.

At the first activation of the system, it was found that the bridge is very easy to balance, but is difficult to keep in this state for the time necessary to manually open the switch S and determine the ratio k. During the balancing, the voltage phasor X_0 fluctuated in a way similar to a phasor illustrating voltages in the power grid. This suggested the hypothesis that the reason for the X_0 voltage fluctuation in a state close to the bridge balance is the unstable frequency of the power grid and its simultaneous lack of synchronisation with the measurement system clock. This is why it was decided to generate the voltage U using the C NI-9269 analogue output module and a voltage amplifier (APEX PA94) in a way synchronous to the measurement system clock. This did not remove the beating in of the test signal with the power grid. To minimise these undesirable effects, the entire stand was put in a Faraday cage. This reduced the intensity of the unfavourable phenomena, but did not eliminate them completely. To completely eliminate the beating in, the voltage amplifier with its power supply unit were removed from the Faraday cage. Only the input and output cables of the amplifier were routed through openings in the cage wall. A fibre optic connection was used for communication between the measurement modules and the laptop with the application controlling the test stand. Measurement modules were supplied with power from a 12 V battery. These modifications allowed the bridge to be kept in balance for a time sufficiently long to manually switch the bridge configuration without haste and establish the value of k. The connection of the GND potential of the bridge with the PE of the power grid and the cage also significantly reduces system instability.

Laboratory experiment results

The balanced state was achieved for adjustment subassemblies with the values of 79480 Ω and 144 pF. These values are not necessary to determine the k ratio, but they determine the value change ranges of these subassemblies and their resolution, which are needed to balance the bridge. It was also noticed that the real part of the X_0 voltage phasor can be adjusted by changing the value of the capacitance decade, while the imaginary part by changing the resistance decade in a way in which the two are almost independent. In practice, this enables the bridge to be balanced in two moves. This is a very important characteristic which simplifies the automatic balancing in future tests.

When the bridge was balanced, the searched-for ratio was determined at the value of k_1 = 33.9262 - j3.885 for the frequency of 50 Hz as the ratio of the phasors of the measured voltages U_1 and V_1. After the switch S was opened, this ratio, calculated as U_2/V_2, took the value of k_2 = 33.8477 - j3.885. This proves a significant impact of the method error caused by the flow of the current i through the A/D converter measuring the voltage X. The value of the ratio $\breve{k}$ = 33.805 - j5.396 was obtained as a result of the autoidentification. The autoidentification procedure established the real part of the divider with an error of 0.3% of its value, which is a perfectly acceptable figure. However, the imaginary part of the ratio was identified with a significant error. A hypothesis was made that the reason for this failure is the insufficient input resistance r of the A/D converter.

Simulation studies of the 230 Vrms version

The purpose of simulation studies of the autocalibration method is to verify the hypothesis about the reason for the large errors in identifying the imaginary part of the k ratio and to determine the sensitivity of the autoidentification result to the parameters deviation of the divider components.

Simulation studies were carried out for the nominal values of the impedance $Q = Z$. The impedance value R = 2.3936e+003 - j2.0286e+004 Ω was determined from (1) using an experimentally and overtly established value of the ratio k_1. The value of the impedance $P_0 = R$ for the configuration with the closed S switch was determined from the balance conditions of an alternating current bridge.

For a divider with the open S key, the value of the divider ratio was established for various values of the r. Study results are presented in table 1. Studies were also carried out for divider impedances in divider branches reduced 10 times. The results obtained confirm that the proposed hypothesis is correct. The increased operating current of divider branches will also reduce the sensitivity of the measurement system to the impact of external disturbances.

Tab. 1. Influence of the voltmeter input resistance r across the diagonal on the precision of identifying the divider ratio k

r [MΩ]		$\breve{k}$
Q(4.7 nF), T = 22.6 kΩ	1	33.9262 - j5.2395
	10	33.9262 - j4.0205
	100	33.9262 - j3.8985
Q(47 nF), T = 2.26 kΩ	1	33.9262 - j4.0205

In the real system, the resistance of the S switch will never be zero. The results of simulation studies for $T0$ = 0.2 Ω and r = 10 MΩ are presented in table 2. The non-zero value $T0$ only impacts the quality of identifying the real part of the k ratio, and that to a small degree. Using a switch with the resistance of about 100 Ω in its closed position, e.g. a semiconductor one, does not significantly reduce the quality of identifying k.

Tab. 2. The influence of the resistance $T0$ of the closed S switch on the quality of k autoidentification

$T0$ [Ω]	$\breve{k}$
0	33.926200000000030 - j3.898545101539517
0.2	33.926200002000044 - j3.898545101539473
100	33.926201000000077 - j3.898545101539302

Simulation studies of the 15 kV version

The divider version designed for measuring voltages of about 230 Vrms may have little practical use, as there are easily available standard measurement modules designed for this voltage range, e.g. NI-9225. The results of experimental and simulation studies presented so far were mainly aimed at verifying whether the presented method is correct. The system may be used in practice to measure voltages on a typical 15 kVrms distribution line. An acceptable value of the current amounting to about 0.5 mA rms in the divider branch can be obtained by employing the 200 pF capacitance. The use of the C NI-9225 module to measure the output voltage of the divider on the impedance R is imposed by k = 35 + j0. R and P should then be capacitors with the capacitance of 6.8 nF, and T should be a 460 kΩ resistor.

In the 15 kV version of the divider, impedances with high module values must be used. This is why, taking into account the conclusions from studying the divider version for 230 Vrms, the influence of the non-zero resistance $T0$ can be neglected.

The results of identifying the k ratio for different r values are presented in table 3. If the r value is about 1 GΩ, the identification uncertainty of the k ratio, determined by equation (4) as TVE [2], can be expected to amount to approximately 0.1% for 50 Hz. Even changing the character of the impedance T from resistance to capacitance does not significantly change the quality of identifying the k ratio.

Tab. 3. Influence of the voltmeter input resistance r across the diagonal on the precision of identifying the k ratio of a divider designed for measuring voltages of around 15 kV for 50Hz

	r [MΩ]	$\breve{k}$
T = 460 kΩ	10	35.000000000000014 - j3.183098861837848
	1000	35.000000000000000 - j0.031830988618317
T(6.9 nF)	1000	34.999999999999780 - j0.031830988618379

$$TVE = \left| \frac{\breve{k} - k}{k} \right| \tag{4}$$

What makes the presented system unique is the ability to precisely measure harmonics present in the measured signal. For example, simulation methods were used to study the characteristics of the system for the 11th harmonic with the amplitude of 122.5 V, i.e. 1% of the amplitude of the main harmonic. When capacitors, such as mentioned for 50 Hz, playing the role of series regulators, were used, their impedances represented by Q_{11} and Z_{11} had values 11 times smaller than Q and Z. The role of the divider impedance adjacent to GND in the branch with the impedance Z_{11} was played by a resistance component R_{11} of such a value that for an arbitrarily adopted k_ref_{11} = 1 - j1 the amplitude of the voltage on it would amount to 86.6 V. Components $P_{11} = T_{11} = R_{11}$ completed the branch with Q_{11}.

Simulation studies have shown that for r = 1 GΩ $\breve{k}_{11}$ = 1.000000 - j1.002894. Just as for the main harmonic, if the r increases tenfold, it also causes a tenfold reduction of the uncertainty of identifying the imaginary part of this divider ratio k.

It is worth remembering that the measured voltage includes a dominant main harmonic of a very high amplitude. It is necessary to estimate voltages with the frequency of 50 Hz on the inputs of A/D converters for divider impedances suitable for measuring the 11th harmonic. If the component R_{11} were used directly to build the divider, then for the 50 Hz frequency, the current in this branch would increase ninefold compared to the current for the 11th harmonic. The amplitudes of voltages on components P, R, T would then reach a dangerous value exceeding 1 kV. This problem could be solved by using - as the P, R and T impedances - two-terminal networks in the form of middle-pass filters with a frequency characteristic similar to the resonance parallel to the selected harmonic frequency, e.g. the 11th. For the base frequency, the impedance module of this two-terminal network should be low enough so that the voltages that occur would be safe for A/D converters. For higher frequencies, such a two-terminal network combined with the Q or Z impedance would act as an anti-aliasing filter.

When any zero method is used, the insensitivity error when establishing the balanced state should be estimated. For this purpose it was analysed how disturbances of the P impedance value from P_0 influence the quality of identifying the k ratio. Complex disturbances of ΔP determined by the relative modulus p (5) and the argument γ were added to P_0. The results of this analysis are presented in figure 2 for r = 1 GΩ. The X-axis shows the range of changes of p, while the Y-axis the range of changes of γ in radians. Contours with contour lines identify the range of changes of TVE.

The shapes of contours do not differ for r = 1 GΩ or r = 1 TΩ. A linear relationship becomes visible and shows that increasing the r by 1 order causes the TVE to decrease by 1 order as well when the range of p changes is reduced by 1 order. The influence of the changes in γ is not significant for the quality of the k ratio identification and does not depend on changes to the value of r.

(5) $$p = \left| \frac{\Delta P}{P_0} \right|$$

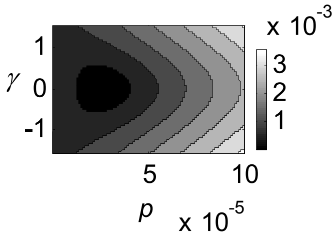

Fig.2. Dependence of TVE on p and γ when r = 1 GΩ

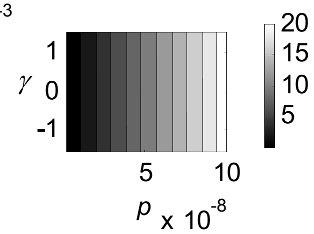

Fig.3. Dependence of the imbalance voltage module (in LSB) on p and γ for r = 1 MΩ

To estimate the error of insensitivity caused by the parameters of the balance indicator, the dependence of the bridge imbalance voltage with the S switch closed on changes of ΔP was analysed in the same way as for disturbances of the P value relative to P_0. The value of 1 LSB corresponds to the voltage of 1.19 μV for a 24 bit C module with the range ±10 VDC and r = 1 MΩ as a balance indicator. Figure 3 shows the value of the imbalance voltage module, expressed in LSB, depending on the value of the modulus disturbance (X-axis) and the argument (Y-axis) of the impedance P from P_0 for r = 1 MΩ. The value of this voltage does not significantly depend on the disturbance of the P argument. The disturbance of p with the value of 10^{-8} produces an imbalance voltage with an amplitude corresponding to 20 LSB. This magnitude can be detected by analysing the signal using a DFT. If r is increased to 1 TΩ, this causes the sensitivity of this indicator to increase only to 25 LSB with the same relative disturbance to the P modulus.

Conclusions

Experimental and simulation studies have shown that it is really possible to build a measurement instrument for voltages up to 20 kV, which also autocalibrates the voltage conditioning circuit. For the autoidentification to be highly accurate, an A/D converter with extremely high input impedance should be used to measure the imbalance voltage of the bridge when the S switch is open. This can be ensured by using a follower with very high input impedance, e.g. AD795, as the input circuit of the A/D converter. It is also recommended to use a bridge balance indicator of very high resolution. In addition, it is necessary to use a PLL to synchronise the clock of the measurement system with the fluctuating frequency of the measured voltage. At the same time, a high resistance measurement system requires very effective shielding.

An alternative solution, free of the method error but at the cost of a complicated procedure, is to use a second balancing of the system with the open S switch [1].

The results presented justify the construction and the experimental verification of a system designed for voltages of several kV. However, the technical problem of automatically balancing the system must be solved.

In laboratory applications or where the system will be used periodically, batteries can be used to supply power to the system and this provides galvanic insulation at the same time. Data can be synchronised and exchanged between circuits on different potentials using fibre optics.

However, the favourable characteristic of the new method, namely the high measurement precision of voltages amounting to several kV comes at the price of two other impediments. The value of the k ratio can be identified only for one selected harmonic, and not simultaneously for all harmonics present in the signal. The second impediment is the need to bring the system to a balance, just as it is done in balanced alternating current bridges.

No measurement method or authority calibrating measurement instruments has been found yet that would allow the measurement characteristics of the proposed measurement system to be verified within the whole scope of functions it offers. This is why it makes sense to apply for the type approval of the measurement system with autocalibration and the measurement method it executes. In parallel with further research on the presented measurement method, it is necessary to propose the establishment of a new standard that would allow the legal use of the presented measurement method in many industrial and laboratory applications.

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