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Quasi-balanced method of measuring the dielectric loss factor

***Abstract**. Quasi-balanced methods of impedance measurements are generally intended for measuring a single component of an unknown impedance. The article presents a quasi-balanced method of measuring the dielectric loss factor (tan δ), which was implemented as a virtual instrument in LabVIEW environment.*

***Streszczenie.** Quasi-zrównoważone metody pomiaru impedancji są generalnie przeznaczone do pomiaru pojedynczego składnika o nieznanej impedancji. W artykule przedstawiono quasi-zrównoważoną metodę pomiaru współczynnika strat dielektrycznych (tan δ), która została zaimplementowana jako przyrząd wirtualny w środowisku LabVIEW. (**Quasi-zrównoważona metoda pomiaru współczynnika strat dielektrycznych**)*

Keywords: capacitance measurement, dielectric losses, impedance measurement, quasi-balanced bridges.
Słowa kluczowe: pomiary pojemności, straty dielektryczne, pomiar impedancji, mostki quasi-zrównoważone.

Introduction

Quality tests of insulating materials are extremely important to maintain continuous, trouble-free operation of electrical equipment. An important role in such tests play measurements of insulation capacitance and its dielectric loss factor tan δ, which is defined as a ratio of the active energy dissipated in a dielectric material to the total energy of the electric charge accumulated in it [1]. A rapid large change in the value of this parameter is a symptom of the degradation of the insulation materials and reflects the condition/quality of the insulation. Moreover, dielectric loss factor measurements can be used for diagnostics of other materials as well [2]. Its determination usually requires measuring impedance components. In steady state and in the low frequency range, the tested dielectric material is often modelled as a simple serial two-terminal RC circuit shown in Fig. 1.

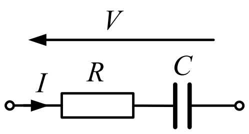


Fig.1. A simple model of the impedance of an electrical insulator

Parameters of simplified series and parallel electric dielectric models are only valid only at specific frequency. They also do not describe the phenomena of dispersion and absorption, mechanisms of dipole relaxation, and the residual inductances of the capacitor and its leads. However, in low-frequency AC circuits, they are sufficient. Although the parallel circuit physically corresponds better to the real capacitor, due to the ease of modelling the circuit, more often in practice the serial replacement circuit is used. For this model, the dielectric loss factor can be defined as:

$$\tan\delta = \omega RC \tag{1}$$

where: ω - the pulsation of the current I and voltage V.

Measurements of dielectric loss factor are realized indirectly or directly. For direct measurements balanced methods (e.g. Schering bridges) [3], unbalanced methods (e.g. resonant methods) and algorithmic methods [4] are used.

The article is extended version of [5] and is organized as follows. In section II, we briefly present an overview of quasi-balanced circuits for dielectric loss factor measurement. In section III the realization and verification of our circuit is presented. Section IV contains description of the virtual instrument for dielectric loss factor measurement developed by us. In Section V we present experimental verification of the developed quasi-balanced circuits. The final conclusions are given in section VI.

Quasi-balanced circuits for dielectric loss factor measurement

The quasi-balanced method is not widely known and relatively rarely used in measuring practice. This is probably due to the properties of the method. Known quasi-balanced circuits allow the measurement of only one impedance component or mutual relations between components, such as the dielectric loss factor. However, new quasi-balanced circuits allow to measure two components and their relationships. Typical feature of quasi-balanced circuits is the presence of a specific quasi-balanced state to which the circuit can be adjusted. This state should be different from zero fully-balanced state and despite of this there is no convergence problems which are typical for bridge methods of impedance measurements.

Currently the concept of measuring circuit very often refers to a program that performs specific actions on digital representations of real signals (usually sampled voltages) according to an algorithm implementing processing equations known from the physical implementation of measuring systems. Such systems are called virtual instruments. Quasi-balanced systems can easily be implemented in this form. In known quasi-balanced circuits [6]-[8], it is possible to measure only one of the impedance components. The second component is measured by changing the configuration of the measurement circuit. This is considered as a main disadvantage of the quasi-balanced method. However, it is possible to build quasi-balanced circuits for measuring the impedance and the electrical loss factor. Dielectric loss factor can be determined as a relation between the impedance components. Therefore, two independent quasi-balanced circuits, designed for measuring the components of the same impedance, can be combined with one another in a parallel system, which can measure two components simultaneously and independently, using two quasi-equilibrium detectors. The circuit diagram is shown in Fig. 2 [9].

The Z block contains the impedance under test and the power source. The V and I signals are the voltage and current of the tested impedance Z, respectively. Block H_1 is an amplifier with a gain H_1, blocks H_2 and H_3 are current/voltage converters with an adjustable conversion factors. The „j" block stands for multiplication by the imaginary unit, which actually means a phase shifting of the signal by $\pi/2$.

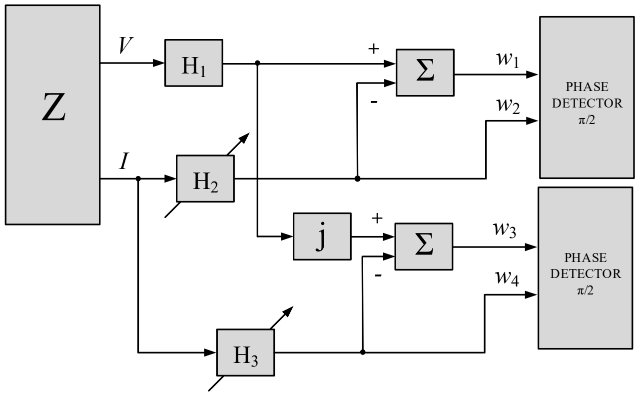


Fig.2. Schematic diagram of the parallel quasi-balanced circuit

Blocks shown on the Fig. 2 can be realized as electronic circuits, or after converting the V and I signals into digital form, as software signal processing blocks. The virtualization of the blocks is very easy as these are just additions and multiplication by factor. Furthermore, software phase detectors can also be implemented.

Quasi-equilibrium means orthogonality of w_1 and w_2, and w_3 and w_4 signals, respectively. This state is achieved independent by changing values the parameters H_2 and H_3. The measured dielectric loss factor can be determined in the quasi-balance state as:

(2) $$\tan\delta = \frac{H_2}{H_3}$$

Another possible way to measure the electrical loss factor is the use of the double quasi-balancing method. In this case, the circuit is brought successively into two quasi-equilibrium states, given as orthogonality of w_{11} and w_{12} . The principle of operation of the circuit is presented in more detail in [10]. The circuit requires two consecutive quasi-balances. In the first quasi-balancing, the regulating element is H_1 and the coefficient H_2 is constantly equal to 1/2. After bringing the circuit to the first quasi-equilibrium state, the value of the H_1 parameter does not change in the second quasi-equilibrium and the H_2 becomes the regulated element.This method allows for direct measurement of the dielectric loss factor. The circuit has the structure shown in Fig. 3 [10], where H_1 is gain of H_1 and H_2 is conversion rate of the H_2 transducers in quasi-balance state, respectively Designations of other blocks and signals are the same as in Fig. 2.

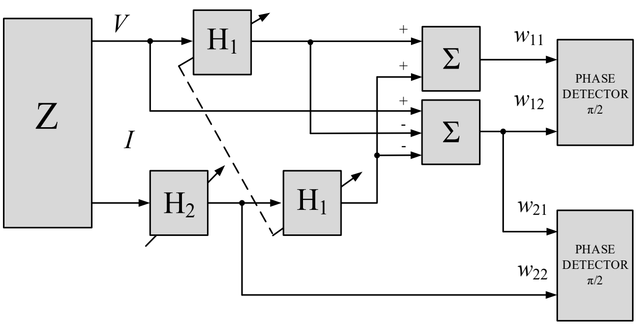


Fig.3. Schematic diagram of circuit with dual quasi-balancing

The dielectric loss factor can be calculated from:

(3) $$\tan\delta = \frac{H_1}{\sqrt{1-2H_1}}$$

where H_1 is the gain of H_1 transducer.

The circuit from Fig. 3 allows also to measure the approximate value of the capacitive component C_X of the impedance under control. The measurement is possible in the first quasi-balancing step. In the first quasi-balance state of the circuit the w_1 and w_2 signals are orthogonal. It means that the real part of their relation equals zero. Solving the equation

(4) $$\mathrm{Re}\ \frac{w_{11}}{w_{12}} = \mathrm{Re}\frac{\frac{1}{2}V+\frac{1}{2}H_2 I}{\frac{1}{2}V-\frac{1}{2}H_2 I} = \mathrm{Re}\frac{Z+H_2}{Z-H_2} = 0$$

we obtain the module of impedance under control

(5) $$|Z| = H_2$$

Some objects can be considered as low-loss. In this case we can estimate the passive component of the impedance by its module, and the capacitance can be calculated in an approximate way from the equation

(6) $$C \approx \frac{1}{\omega H_2}$$

The relative error $e(C)$ of this approximation can be written as follows:

(7) $$e(C) = \frac{\frac{1}{\omega|Z|}-\frac{1}{\omega\,\mathrm{Im}Z}}{\frac{1}{\omega\,\mathrm{Im}Z}} = \frac{1}{\sqrt{(\tan\delta)^2+1}}-1$$

The exemplary measured dependence between the relative error (7) and electrical loss factor $\tan\delta$ is shown in Fig. 4.

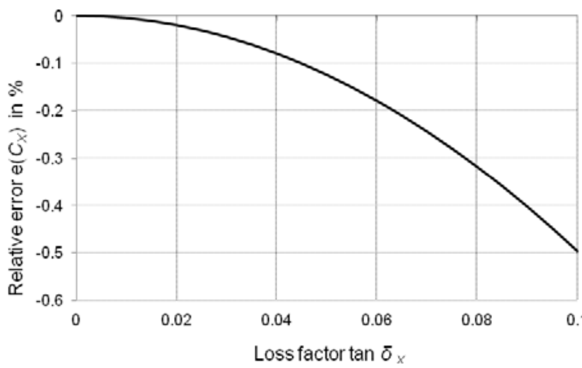


Fig.4. Relative error $e(C)$ vs. measured loss factor $\tan\delta$

It has been taken into account that the typical range of electrical loss factor of insulating materials is between 0 and 0.1. In this range the relative error $e(C)$ is less than 0.5%.

It is also possible to use a simple quasi-balanced method for measuring the dielectric loss factor, taking under consideration the dependence of the $\tan\delta$ and the phase shift Φ between the selected signals of the circuit. Fig. 5 shows schematic diagram of the circuit for measuring the reactive component of impedance and the relation between phase shift of w_1 and w_2 signals for different $\tan\delta$ values, where H_0 is value of H_2 parameter in the quasi-balance state [11].

In this circuit, after detuning from the quasi-equilibrium state by changing the value of the parameter H_2, the dielectric loss coefficient is:

(8) $$\tan\delta = \frac{\frac{H_2}{H_0}-1}{\mathrm{cotan}\ \Phi}$$

where Φ is phase shift between w_1 and w_2, and H_0 is gain of H_2 block in the state of quasi-balance. The capacitance can be calculated obtained from quasi-balance state.

Realization and verification

The circuit from Fig. 3 was verified by simulation and by measurements performed at 50 Hz [12]. One of the applications of the presented circuit may be diagnosing the condition of electrical insulation. The basic operating frequency in the power industry is 50 or 60 Hz, therefore it was chosen for the research. In industrial measurements, interferences from the power grid are practically unavoidable.

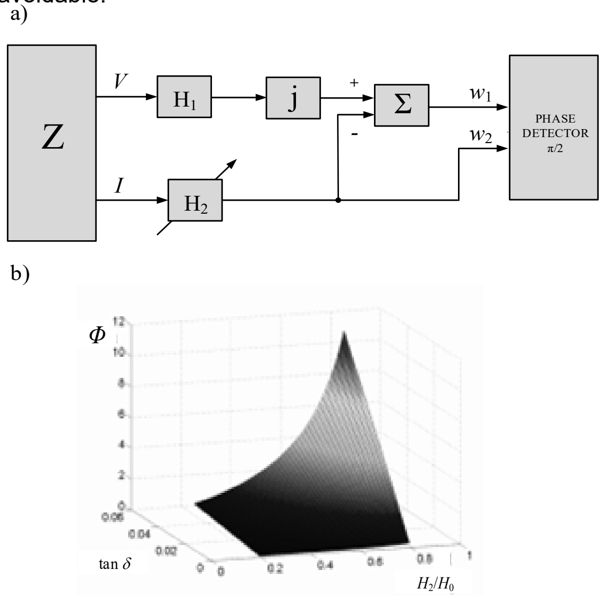


Fig.5. Quasi-balanced circuit for measuring impedance of passive components: a) schematic diagram, b) relation between phase Φ, tan δ and H_2/H_0 ratio

The circuit shown in Fig. 5 has two adjustable elements. The first is the H_1 element, the setting of which is a real number from 0 to 1. The second element is H_2, the setting of which can be any real number. The discussed circuit was synthesized in [9] according to the principle of operation of a quasi-balanced bridge.

The balancing process of the system is carried out by two successive quasi-balancing steps. In the first one the value of the H_2 parameter is adjusted to obtain the phase shift between the signals w_{11} and w_{12} equal to π/2, while keeping the value of the parameter H_1 equal to 0.5. In the second step the parameter n is adjusted to set the phase shift between the signals w_{21} and w_{22} equal to π/2, while maintaining the unchanged value of the R_3 parameter, determined in the first step. After completing the second step, the measured loss factor can be determined from the equation (3).

Virtual instrument

The layout of Fig. 3 was built as virtual instrument using the LabVIEW environment. The Virtual Instrument (VI) consists of the following elements:

- PC computer with the National Instruments LabVIEW environment installed,
- National Instruments USB-6009 measurement data acquisition module,
- 2-channel RIGOL DG1022 signal generator enabling the selection of signal shape, amplitude, frequency and direct current (DC) offset,
- 10 kΩ standard resistor with accuracy class 0.01, used as the shunt.

The objects under test were three capacitors of nominal values 0.1 μF, 1 μF and 470 nF, respectively for which the tan δ measurements were made. The sinusoidal voltage V_X applied to the tested capacitor was generated with the RIGOL DG1022 generator. Current I_X flowing through the tested capacitor was converted to voltage V_N using a current shunt. Voltages V_X and V_N were sampled using National Instrument (NI) USB 6009 data acquisition module. Its two analog inputs were set in differential (DIFF) mode. The NI-USB 6009 data acquisition module was controlled with a PC computer running program written in NI LabVIEW environment. Acquired samples were processed according to the algorithm implemented in LabVIEW. The overall structure of the system is shown in Fig. 6.

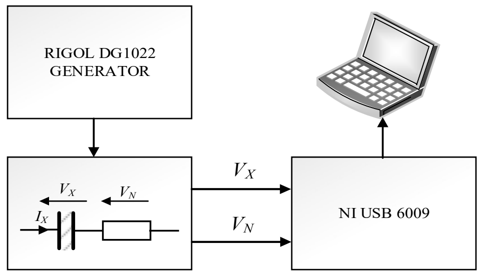


Fig.6. Simplified schematic of the virtual measuring circuit

The structure of the virtual part of the system, created on the basis of the LabVIEW environment consists of the following blocks:

- simulation block,
- block implementing quasi-balancing processes,
- block performing phase detection,
- data storing (write) block.

The simulation part allows to simulate voltage and current waveforms of an object consisting of serially connected RC elements. These signals are processed similarly to the signals of the real object. The simulation part allows to possible to examine the properties of the measuring system.

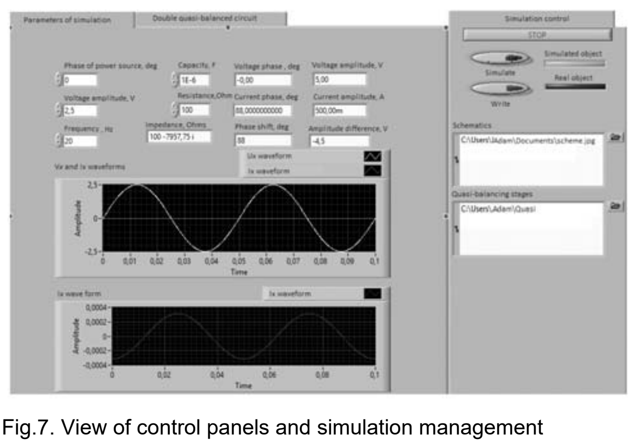


Fig.7. View of control panels and simulation management

The next part of the VI is responsible for processing measurement signals, both simulated or real, and allows adjusting the circuit to the quasi-balance state. The other part of the VI allows detection of the phase angle considered as the selected signal. These angles should be π/2, both for w_{11} and w_{12} signals in the first quasi-balancing step and for w_{21} and w_{22} signals in the second quasi-balancing step. The phase detector, used to determine the desired phase shift, performs the operation of subtracting of phase shift of both selected signals. The obtained results in numerical form are transferred to the displays of the virtual instrument. The last of the component blocks writes data to the Excel spreadsheet.

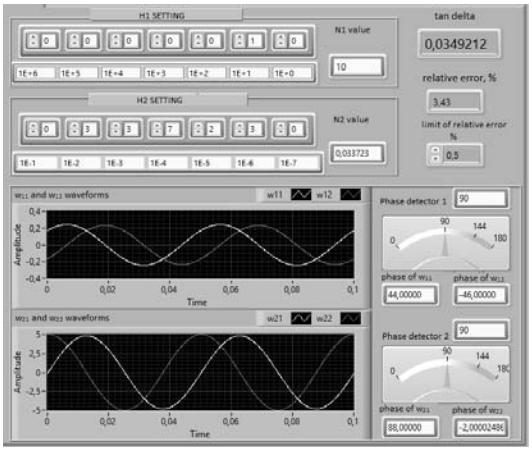


Fig.8. View of the panel implementing the quasi-balancing stages

All blocks have their interpretation in the form of a graphic control panel. This panel can be divided into 3 subgroups as follows:

- simulating panel of object parameters,
- simulation management panel,
- main panel realizing quasi-balancing process.

The main panel responsible for control of consecutive steps of quasi-balancing process is presented in Fig. 8. The panel structure enables precise control of phase shift angles of individual signal pairs. Adjustment of H_1 and H_2 values is performed smoothly using the multipliers of the basic value set by the user. According to the indications of phase detectors, the system is in a quasi-equilibrium state.

Experimental verification

The correct operation of the virtual system was verified at first, based on results of simulation tests. Then the correct operation of the system was verified by measuring real objects, namely capacitors of known capacitance. During the tests, the dielectric loss factor $\tan\delta$ of the object was determined. The view of the measuring setup is shown in Fig. 9.

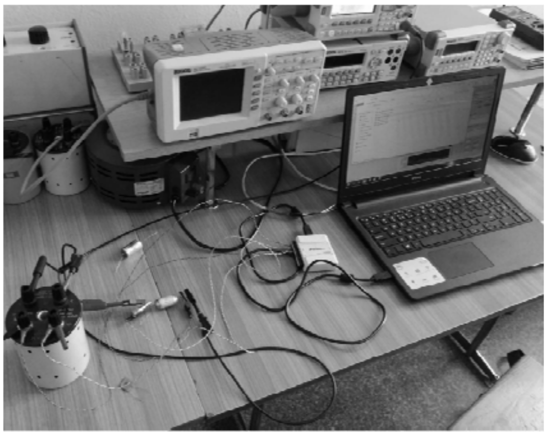
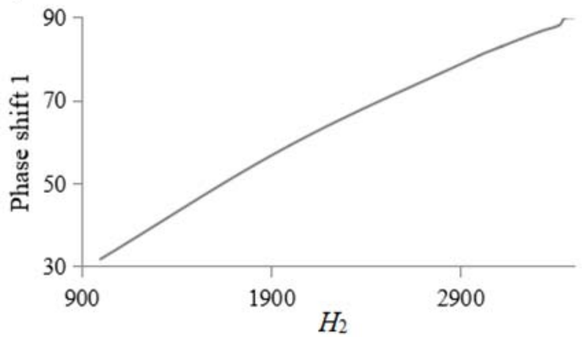


Fig. 9. View of the implemented system for measuring the dielectric loss factor $\tan\delta$

The measuring signals are the V_X voltage of the impedance under control and the V_N voltage across the terminals of the R_N reference resistor. Sinusoidal voltage of 5 V amplitude and 50 Hz frequency generated by the RIGOL DG1022 generator was applied to the tested capacitor. The process of quasi-balancing together with the determination of the dielectric loss factor $\tan\delta$ was made in a circuit composed of R_N resistance connected in series with 1 μF polyester, 0.1 μF multilayer and 470 nF polyester capacitor, respectively.

The possibility of independent bringing the circuit to the quasi-balance states was verified at first. The tests were performed for the three mentioned capacitors. Sample results obtained for 1 μF capacitor are shown in Fig. 10. They show the dependence of the phase angle between the signals w_{11} and w_{12} as well as w_{21} and w_{22}, respectively, on the settings of the parameter values H_1 and H_2. Results obtained for all capacitors used in the test confirmed the independence of the adjustments of both controls responsible for balancing of the imaginary and real component. This is a significant advantage of quasi-balanced circuits over typical balanced bridges whose convergence is not always equal to 90º. The dependence of the output signals on the settings of the adjustable elements is shown in Fig. 10 a and b. These relationships are non-linear, which results from the non-linearity of the trigonometric functions on the basis of which they are determined.

a)



b)

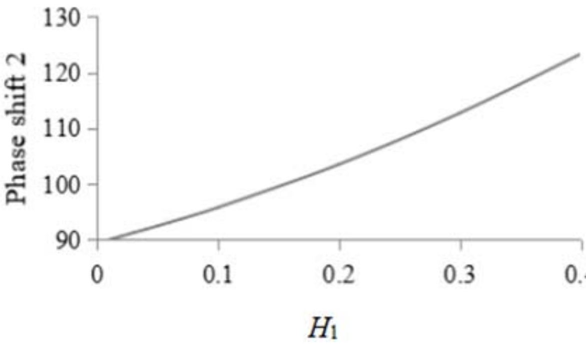
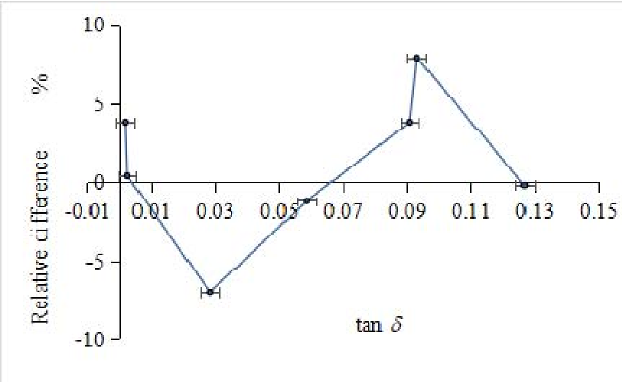


Fig.10. Dependence of the output signals (phase shifts) vs settings of the adjustable elements H_1 and H_2

Results obtained in the virtual instrument were compared with the results of capacitance and loss tangent measurements of the tested capacitors performed with commercial Motech MT4090 LCR Meter. The results are shown in Table 1. Fig. 11 shows the error dependence on $\tan\delta$ value.

Tab.1. Comparison between measurement results obtained with the quasi-balanced circuit and commercial LCR meter

l.p.	Capacitor under test	Parameter value		$\tan\delta$ VI	$\tan\delta$ MOTECH	Relative difference %
		H_2	H_1			
1	polyester 1μF	0,01	3523	0,0101	0,0101	0
2	multilayer 0,1μF	0,094	32743	0,1043	0,1042	0,1
3	polyester 470 nF	0,0199	7321	0,0204	0,0204	0



ts obtained with circuit shown in Fig. 3 and results of tan δ measurements made with a commercial LCR meter. Bars represent standard uncertainty of the measurement (k = 1)

Conclusions

The quasi-balanced measurement system present other approach to dielectric loss measurements. The presented work describes the use of quasi-balanced method for measuring tan δ of capacitors. A virtual quasi-balanced system has been built that enables the measurement of both impedance components using two fully independent control elements enabling the system to be brought to a quasi-balance state. This state is defined as a pre-adopted value of the phase shift angle between the selected signals of the circuit. In the presented solution it is angle $\pi/2$.

The system was built as a virtual instrument. This way of implementing the system allowed for simulation tests and checking of real objects. Simulations show that the virtual implementation of the quasi-balanced system with double quasi-balancing can be used to measure the dielectric loss factor.

The main difficulty in verifying the system operation was the lack of a good quality standards of tan δ. Typically, such standards are built as a series connection of a resistor with a low-loss capacitor. For the tests of the system, objects consisting of a capacitor of known capacity and a reference resistor were used.

They have so far allowed for a measurement of only a single component of the impedance under test. The new non-bridged quasi-balanced circuits allow for the measurement of the two components of the impedance or one component and the loss factor. The quasi-balanced circuits expand the range of measurement methods and may be useful in the study of insulation quality, especially at very low frequencies.

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