METROLOGICAL SIMULATORS OF ELECTRICAL PASSIVE QUANTITIES WITH ALGORITHMIC STRUCTURE

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Abstract

This Review contains the systematization of the material in the domain of metrological simulators of electrical passive quantities with an algorithmic structure (MS-A, for simplicity), used as reference elements in impedance measurement. The general aspects of these devices, the MS-A classification under the relevant criteria, the formal–structural method of synthesis of the simulators with necessary characteristics, and the example of synthesis are discussed. The analysis of basic types of MS-A: I-commanded and U-commanded, in Cartesian coordinates and in polar coordinates, with asymmetric and with symmetric connection is carried out. For each type of simulator, the conversion diagram of information, the simulator structure, and the internal circuits are presented. The paper also contains the analysis of stability of presented structures, in which the conditions of guaranteed functional stability for MS-A at its connection in external circuits are determined, and experimental confirmation of the results.

1. Introduction

The use of metrological simulators of passive electrical quantities (MSs, for simplicity) as reference elements (REs) in impedance and admittance measurement opens great prospects for the improvement of technical characteristics in this branch [1-5]. The most important advantages resulting therefrom are:

- exclusion of adjustable reactive elements and reactance boxes;
- exclusion of the switchings in the measurement circuits, determined by the variation of type and character of the measured quantity;
- simplification of measuring circuit equilibration algorithm up to two operations in the case of measuring the both components of passive quantity (PQ);
- measurement of PQ with any character (active, reactive or complex) and with any substitution equivalent circuit (series, parallel) without modification of the measuring circuit structure;
- measurement of PQ with character of negative resistance;
- digital control and complete automatization of measuring process;
- possibility of RE implementation in integrated circuits;
- reduction of the price, dimension, and weight of the devices.

From the functional point of view, a metrological simulator of passive electrical quantities may be defined as an elementary resource of measurement, which assures the reproduction of a virtual PQ with the necessary character and with known metrological characteristics [6]. The researches in this domain [7] determined a class of devices that can be potentially used as MSs. According to the proposed classification [7], there are different types of MS with various characteristics and possibilities of use.

MSs with an algorithmic structure (MS-A) [7] hold a particular position in this class of devices. These devices were specially synthesized for using as REs in the devices for PQ measurement (impedance meters and admittance meters); they possess technical characteristics optimized from this point of view. The MS-A structures were synthesized through the formal–structural method (FSM) according to the requirements on the RE characteristics determined by the measuring method and circuit [8]. The most important features of them are:

- possibility to obtain PQs represented in the desired coordinate system (Cartesian or polar) and with the desired character of components (active, reactive, or complex) reproduction;
- independent control of the reproduced PQ components;
- guaranteed stability at the variation of external impedance in the measuring circuit in the range of determined values;
- possibility of reproduction of the simulated PQs (SPQs) placed in the entire complex plan: (±R, ±**j**X) for impedances or (±G, ±**j**B) for admittances;
- guaranteed and determined systematic error.

2. MS-A. General overview

Functionally, a MS-A represents a device with two poles, which assures the reproduction of SPQ represented in the necessary coordinates system and the possibility of independent control of the components (Fig. 1) [9]. The PQ reproduced by MS-A (impedance $\mathbf{Z_i}$, or admittance $\mathbf{Y_i}$) may be represented in Cartesian coordinates [10]

$$\mathbf{Z_i} = R_i + \mathbf{j}X_i,\ \mathbf{Y_i} = G_i + \mathbf{j}B_i, \tag{1}$$

alternatively, in the polar coordinates [11, 12]

$$\mathbf{Z_i} = Z_i \exp(\mathbf{j}\varphi_i),\ \mathbf{Y_i} = Y_i \exp(\mathbf{j}\psi_i), \tag{2}$$

where R_i, X_i (G_i, B_i) are the active and the reactive component of the reproduced impedance (admittance), respectively; Z_i, φ_i (Y_i,ψ_i) are the module and the phase of these quantities, respectively.

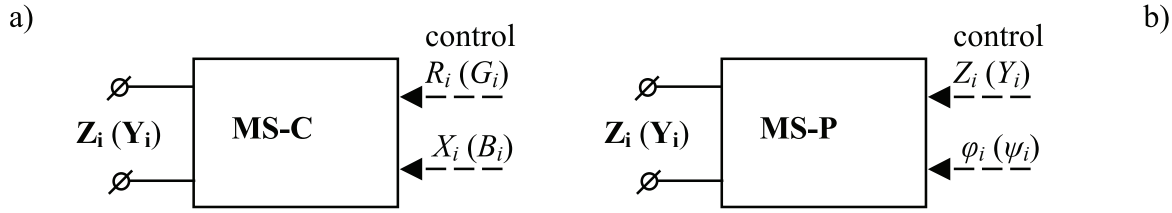


Fig. 1. Functional representation of MS-A in Cartesian coordinates (a) and in polar coordinates (b).

Therefore, the MS-A (MS-C) Cartesian coordinates must assure an independent control of the active R_i and the reactive X_i components (respectively, G_i, B_i for admittances); the polar coordinates MS-A (MS-P), an independent control of module Z_i (Y_i) and phase φ_i (ψ_i) of the PQs reproduced on the input poles.

For assurance of the MS universality in order to reproduce a PQ with any character, the domains of variation of the reproduced PQ components must be [7]

- for simulated impedances

$$\begin{gathered} R = \{-R_{\max} \div +R_{\max}\}; X = \{-X_{\max} \div +X_{\max}\} \\ Z = \{0 \div Z_{\max}\}; \varphi = \{0 \div 360^\circ\}, \end{gathered} \tag{3}$$

- for simulated admittances

$$\begin{gathered} G = \{-G_{\max} \div +G_{\max}\}; B = \{-B_{\max} \div +B_{\max}\} \\ Y = \{0 \div Y_{\max}\}; \psi = \{0 \div 360^\circ\}. \end{gathered} \tag{4}$$

In this case, the coverage of the entire complex plan is assured, and, due to this, there is a possibility to reproduce an SPQ with any character.

2.1. The MS-A classification

As is known, there are many types of MSs with various features, according to the classification proposed in [7]: classical MS [13], MS-A, MS with a ladder structure [14], MS type gyrator [15], etc.

MS-A forms a class of devices with the structure synthesized through the FSM according to the requirements determined by its concrete application in measuring circuits. The MS-A classification by relevant criteria is represented in Table 1.

Table 1. Classification of MS-A.

Character of poles	The primary input quantity	The type of coordinates for SPQ representation	
		Cartesian coordinates	**P**olar coordinates
Asymmetrical connection	**U** – comanded	**U-MS-C-As**	**U-MS-P-As**
	I – comanded	**I-MS-C-As**	**I-MS-P-As**
Symmetrical connection	**U** – comanded	**U-MS-C-S**	**U-MS-P-S**
	I – comanded	**I-MS-C-S**	**I-MS-P-S**

For designation of type of MS-A in the table, the qualifying abbreviations have been used. For example, for the simulator represented in the table as “I-MS-C-As”, the signification is:

I – current commanded (U – voltage commanded),

C – Cartesian coordinates (P – polar coordinates),

As – with asymmetrical connection (S – symmetrical connection).

These devices correspond to the general classification proposed in [7]; further, for simplicity, three criteria are considered relevant.

1. The type of primary input quantity. One of the basic properties of SPQ determines this criterion: to be commanded by current (for I-MS) or by voltage (for U-MS) [9]. As is known [9], the type of primary input quantity determines some features of MS and the type of its stability.

The principle of SPQ reproduction in I-MS [8] (Fig. 2a) is based on the process of formation of the voltage $\mathbf{U_i}$ from the input current $\mathbf{I_i}$ by means of its conversion under necessary dependence and its application in the input circuit of the SPQ. Together with the current $\mathbf{I_i}$, the voltage $\mathbf{U_i}$ results in the reproduction of the virtual impedance $\mathbf{Z_i}$

$$\mathbf{Z_i = U_i / I_i = (K_{conv} \cdot I_i)/ I_i = K_{conv}}, \quad (5)$$

where the conversion factor $\mathbf{K_{conv}}$ determines the mode of SPQ representation. For this, the structure of I-MS (Fig. 2b) contains a current-to-voltage converter I/U and a functional converter CF, which assures the desired form of $\mathbf{K_{conv}}$.

Therefore, it follows from (5) that I-MS are destined for reproduction of PQs with impedance character and possess the stability up to no-loaded regime [9].

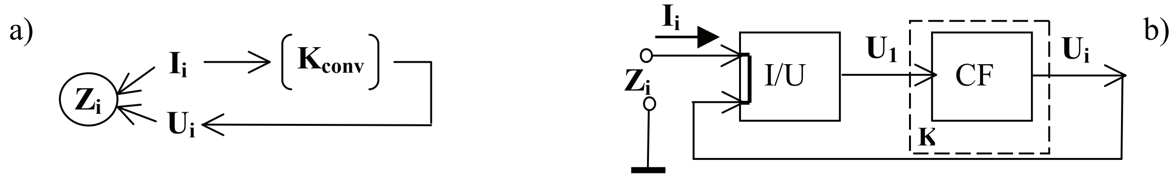


Fig. 2. The conversion algorithm of information (a) and the block-diagram of I-SPQ (b).

For U-SPQ [8] (Fig. 3), the voltage $\mathbf{U_i}$ is used as a primary input quantity. It is consecutively passed through the functional converter CF and through the voltage-to-current converter U/I. The reproduced PQ $\mathbf{Y_i}$ possesses the character of admittance and is obtained as a result of interaction of the entering voltage $\mathbf{U_i}$ and the current $\mathbf{I_i}$, produced by the converter U/I

$$\mathbf{Y_i} = \mathbf{I_i} / \mathbf{U_i} = (\mathbf{K_{conv}} \cdot \mathbf{U_i}) / \mathbf{U_i} = \mathbf{K_{conv}}, \qquad (6)$$

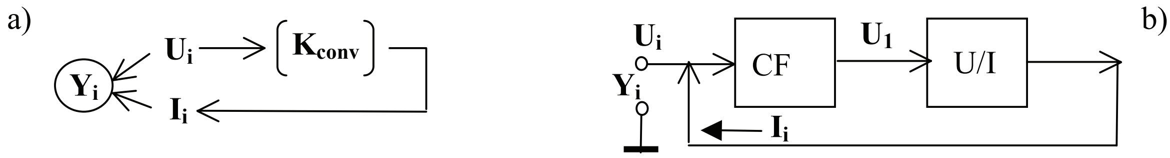


Fig. 3. The conversion algorithm of information (a) and the block-diagram of the U-SPQ (b).

As follows from (6), the U-MS are destined for reproduction of PQ with character of admittance and possess the stability up to short-circuit regime [9].

It is obvious that, under the principle of duality between the quantities with impedance and admittance character [16], the PQ reproduced by I-MS and U-MS also can be represented in the dual forms in comparison with those from (5) and (6), according to the known relation ($\mathbf{Z} = \mathbf{Y}^{-1}$). However, this affects the mutual influence of SPQ components control: functionally, in order to assure the independent control of the components, it is necessary to assure the directly proportional dependence between the SPQ components and the conversion factor $\mathbf{K_{conv}}$.

2. The type of coordinates for SPQ representation. The importance of this criterion is determined by the necessity of using MS as RE in two types of measurements of passive quantities: measurements in Cartesian coordinates and measurements in polar coordinates. So, for SPQ represented in Cartesian coordinates, the conversion factor $\mathbf{K_{conv}}$ must assure an independent control of active and reactive components, according to (1)

$$\mathbf{K_{conv.Z}} = N_R + \mathbf{j}N_X,\ \mathbf{K_{conv.Y}} = N_G + \mathbf{j}N_B; \qquad (7)$$

for SPQ represented in polar coordinates, an independent control of the module and phase of SPQ, according to (2)

$$\mathbf{K_{conv.Z}} = N_Z \exp(\mathbf{j}\varphi),\ \mathbf{K_{conv.Y}} = N_Y \exp(\mathbf{j}\psi). \qquad (8)$$

3. The type of poles for connection of SPQs in an external circuit. According to this criterion, MS can have one pole connected to ground in the internal mode (asymmetric connection, in MS-As) (Fig. 4a) or the both poles being free (symmetric connection, in MS-S) (Fig. 4b). MS-As have the simplest structures determined by using of the operational amplifiers with internal ground connection. In MS-S, the symmetric character of the PQ poles is obtained by means of precision differential amplifiers [17], which complicates the device structure. In spite of the more complicated structure, MS-S has found the practical application in some circuits and some measuring cases of PQ, where the RE with symmetric poles are necessary (for example, in the bridge circuits).

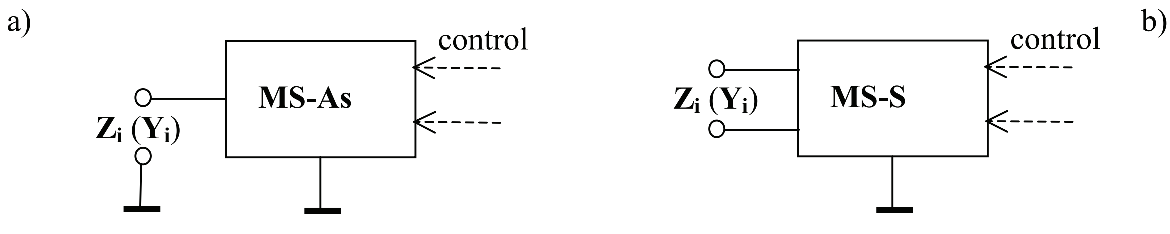


Fig. 4. The functional representation of MS-As (a) and MS-S (b).

In accordance with the mentioned above criteria, there has been defined a class that consists of eight types of MS-A (Table 1).

3. Synthesis of the MS-A structures

3.1. The formal–structural method of synthesis

For synthesis of the MS-A internal circuit, the FSM of synthesis [12] has been used. The method ensures obtaining of the internal structure of MS-A at the level of internal circuit according to its type from Table 1. The method includes the following steps:

1. *Determination of the initial requirements on MS-A.* This is made according to the use of features through designation of the type of MS from Table 1. It includes:

- determination of the primary input quantity (I-type or U-type);
- determination of coordinates type for representation of SPQ (C-type or P-type);
- existence of the ground connection of the input pole of MS-A (As-type or S-type).

2. *Elaboration of the Information's Conversion Diagram (ICD) inside the structure of MS-A.* At this step, the sequence of operations at the physical quantities in MS-A structure is represented in the form of a diagram. The used operations are the conversion of voltages and currents, which can be made with functional links, based on electronic circuits or on other devices (Table 2). The next types of information conversion operations are usually used at the synthesis of MS-A structures [18]:

- voltage into current, or current into voltage conversion,
- voltage into voltage conversion with constant or variable conversion factor,
- voltages sum or subtraction,
- introduction of the fixed or variable phase angle,
- multiplication or division of the quantities,
- functional conversion of the quantities.

3. *Elaboration of the MS-A functional structure.* The step includes the elaboration of the internal structure of MS-A at the level of functional units according to the presented in p. 2 ICD. The available functional units (Fig. 5) correspond to the information conversion operations from Table 2 and, for MS-A from Table 1; they represent the units based on operational amplifiers (OAs) [17].

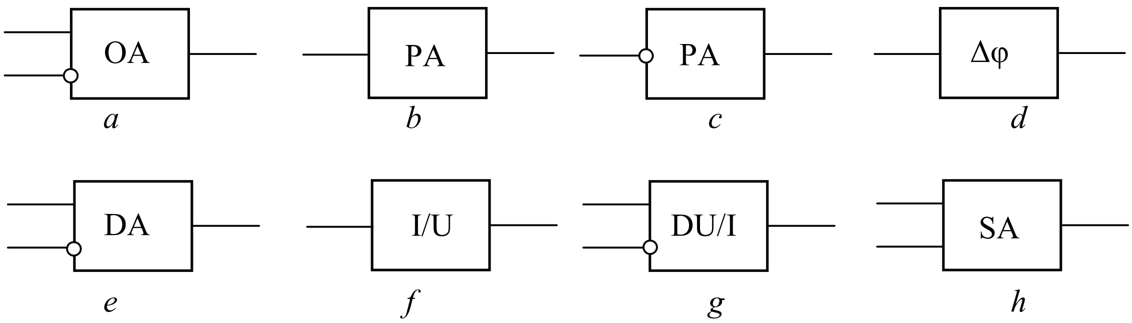


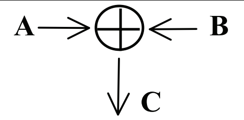
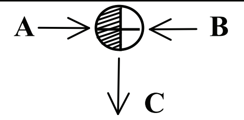
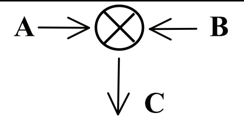
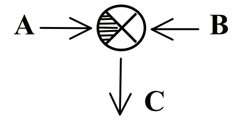
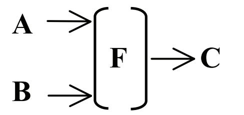
Fig. 5. The functional units used in the MS-A structures: *a* is operational amplifier; *b,* programmable non-inverting amplifier; *c,* inverting programmable amplifier; *d*, phase shifter; *e,* differential amplifier; *f,* current-to-voltage converter; *g,* differential current-to-voltage converter; *h,* summator amplifier.

The other types of functional units can be used, by necessity, for the synthesis of other types of MS-A.

4. *Elaboration of the internal circuit of MS-A*. It is the last step of the synthesis, in which the functional units from MS-A structure are substituted with circuits that implement the respec-

tive functions. The units based on OAs are used in the low frequencies MS-A for implementation of the above mentioned operations. They assure high accuracy of operations [17]. In the high-frequency circuits, where the OA accuracy decreases considerably, the functional units of MS-A can be implemented on the basis of transistors or other components.

Table 2. Typical conversion operations of the information in ICD.

Graphical representation	Essence of operation
A ⟶ **B**	Quantity **A** into quantity **B** conversion
C ↓ **A** ⟶ **B**	Functional conversion of quantity **A** into quantity **B** under the influence of quantity **C**
N_A - - -> **A**	Control of quantity A with numerical quantity N
	Sum of quantities A and B with obtaining of the result C **C = A + B**
	Subtraction of quantity B from quantity A with obtaining of the result C **C = A - B**
	Multiplication of quantities A and B with obtaining of the result C **C = A · B**
	Division of quantities A and B with obtaining of the result C **C = A / B**
	Obtaining of quantity C functionally dependent on the quantities **A**, **B** **C = F (A, B)**

3.2. Synthesis of U-MS-P-As

In order to confirm the possibility of the presented above FSM for MS-A synthesis, we shall examine as example the process of synthesis of the internal circuit of voltage-commanded (U-) MS for reproduction the SPQ with asymmetrical connection (-As) in the polar coordinates (-P) [19]. This process is executed in the following order of actions.

1. *Determination of the initial conditions*. Since the voltage $\mathbf{U_i}$ is the primary input quantity, SPQ will have the character of admittance $\mathbf{Y_i}$ [9]. The necessity of the SPQ representation in polar coordinates defines the expression for the reproduced admittance $\mathbf{Y_i}$ as type (2). So, MS must assure the independent control of the components Z_i, ψ_i and possess one pole with the internal connection to the ground.
2. *Elaboration of ICD*. Reproduction of the required type of simulated admittance $\mathbf{Y_i}$ may be obtained in the following order of operations:

- variation of the voltage $\mathbf{U_i}$ module in order to control the SPQ module Y_i (op. 2, Table 2),
- variation of the voltage $\mathbf{U_i}$ phase in order to control the phase of SPQ ψ_i (op. 2, Table 2),
- conversion of the obtained voltage into input current $\mathbf{I_i}$ (op. 2, Table 2),

- introduction of the current $\mathbf{I_i}$ into input circuit of MS, where it, together with the voltage $\mathbf{U_i}$, reproduces the simulated admittance $\mathbf{Y_i}$ (op. 7, Table 2).

The information conversion diagram (Fig. 6a) assures the execution of these operations in a desired order.

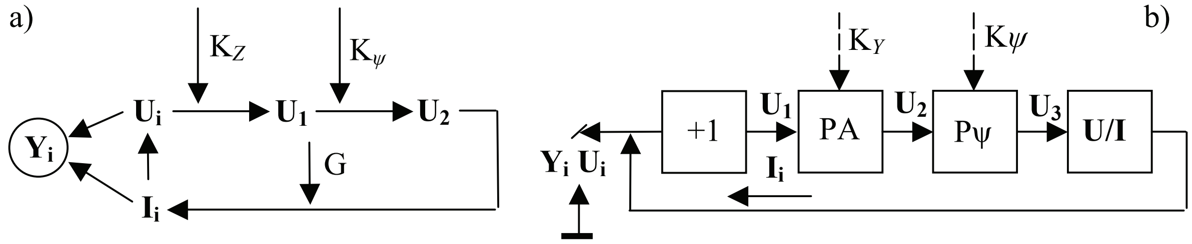


Fig. 6. ICD for the structure synthesis (a) and the internal structure (b) of U-MS-P-As.

3. *Elaboration of the MS functional structure*. The internal structure for implementation of the above determined operation from ICD contains the functional units (Fig. 6b):

- The programmable amplifier PA with the transfer factor K_{PA} for control of the module Y_i. The voltage at its output constitutes: $\mathbf{U_1} = K_{PA} \cdot \mathbf{U_i}$;
- The programmable phase shifter PΦ with transfer factor $\mathbf{K_{P\Phi}}=1 \cdot exp\ (\mathbf{j}\psi_i)$, which produces the voltage $\mathbf{U_2} = \mathbf{K_{P\Phi}} \cdot \mathbf{U_1} = K_{PA}\ exp\ (\mathbf{j}\psi_i) \cdot \mathbf{U_i}$ at its output;
- The voltage-to-current converter U/I with conversion factor G for conversion of the voltage $\mathbf{U_2}$ in the current $\mathbf{I_i}$. The current on its output: $\mathbf{I_I} = G \cdot \mathbf{U_2} = G \cdot K_{PA}\ exp\ (\mathbf{j}\psi_i) \cdot \mathbf{U_i}$.

With evidence of the unit transfer functions, the virtual admittance reproduced by MS at its poles constitutes [19]

$$\mathbf{Y_i} = \mathbf{I_i} / \mathbf{U_i} = G \cdot K_{PA}\ exp\ (\mathbf{j}\psi_i) \equiv Y_i\ exp\ (\mathbf{j}\psi_i). \quad (9)$$

As follows from (9), the reproduced admittance $\mathbf{Y_i}$ is represented in polar coordinates and assures an independent control of module Y_i through the variation in the transfer factor K_{PA} of the programmable amplifier PA and of the phase ψ_i through the variation in the phase angle ψ_i introduced by the programmable phase shifter PΦ.

4. *Elaboration of the internal circuit of U-MS-P-As*. The functional units based on OAs [17] were used for the practical implementation of the structure from Fig. 6b (Fig. 7).

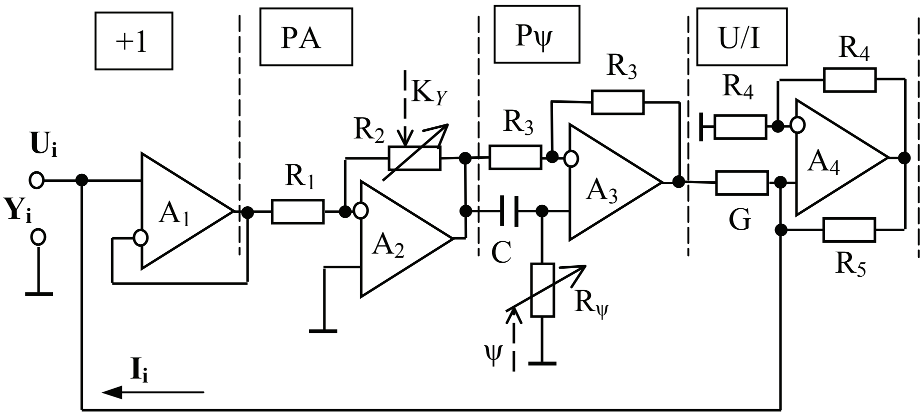


Fig. 7. The internal circuit of U-MS-P-As.

The voltage repeater A_1 was used in order to exclude the influence of the units input impedance to the reproduced admittance. The PA and PΦ units from structural scheme are implemented on the basis of OAs A_2, A_3; the current-to-voltage converter U/I, on the basis of OA A_4. With regard for the known expressions [17] for the transfer factors of the MS units, the expression for reproduced admittance $\mathbf{Y_i}$ becomes

$$\mathbf{Y_i} = 2G \cdot R_2 / R_1 \, exp\left[\mathbf{j} arctg\left(\omega R_\psi C\right)\right]. \tag{10}$$

As follows from (10), the variation of R_2 results in the control of module Z_i; the variation of R_ψ, in the control of phase ψ_i of the reproduced admittance without mutual influence. According to (10), the variation domains of module Y_i and phase ψ_i of the reproduced admittance are

$$Y_i = 0 \div 2G{\cdot}R_{2max}/R_1, \ \psi_i = 0 \div 180°. \tag{11}$$

In order to assure the range of control of admittance phase $\psi_i = 0 \div 360°$, what is essential for reproducing the admittance with any character, in the simulator contains a programmable phase shifter with the phase angle control range 0 ÷ 360° [7]. It can be formed of two consecutive links of the phase shifter used in the presented simulator [20] or of the next type, [21], for example.

3.3. Other types of MS-A with asymmetrical connection

The other types of simulators from Table 1 were synthesized in the same sequence of actions used at the U-MS-P-As synthesis. For these ones, we shall present only the synthesis results with the most important elements of this process.

The simulator I-MS-P-As [22]**.** The device presents a current-commanded MS (**I-**) for reproduction of simulated impedances in polar coordinates (-P) with asymmetrical connection (-As). I-MS-P-As can be used as a RE in the polar-coordinate impedance meters, which assure a direct measurement of the impedance module and phase [23]. The information conversion diagram (Fig. 8a), the functional structure (Fig. 8b), and the internal circuit (Fig. 8c) of this simulator were obtained similarly to the procedure used at the U-MS-P-As synthesis.

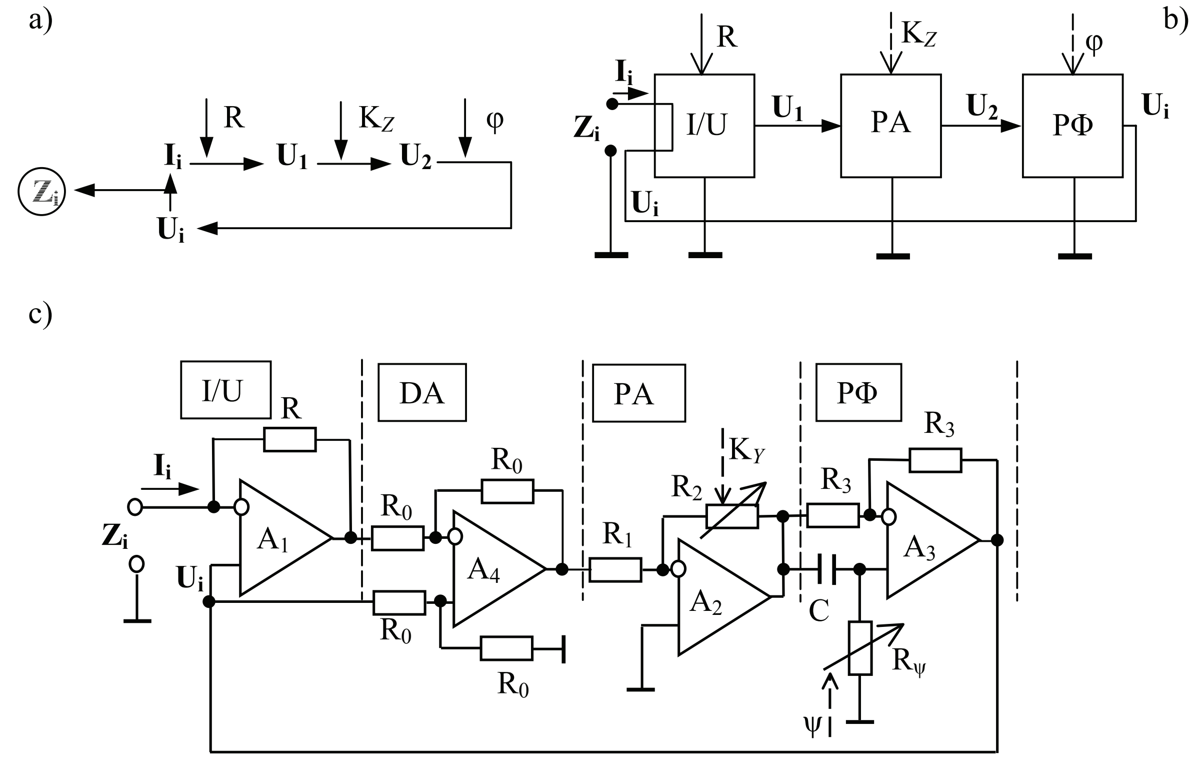


Fig. 8. ICD (a), the functional structure (b), and the internal circuit of I-MS-P-As (c).

The units known from the U-MS-P-As synthesis (a programmable amplifier PA and a programmable phase shifter PΦ) and the other units based on OAs, such as a current-to-voltage converter IU and a differential amplifier DA [8], were used in the process of the functional structure and internal circuit elaboration of I-MS-P-As. The function of DA unit is the neutralization of the common feedback loop action, which appears upon introduction of the voltage $\mathbf{U_i}$ into input circuit and leads to the expression for simulated impedance $\mathbf{Z_i}$ distortion.

The impedance $\mathbf{Z_i}$ reproduced by the simulator can be obtained by the following sequence of conversions (Fig. 8a):

- conversion of the input current $\mathbf{I_i}$ into the intermediate voltage $\mathbf{U_1}$ by means of the converter IU;
- control of its module and phase by means of the programmable amplifier PA and the programmable phase shifter PΦ, respectively;
- application of the voltage $\mathbf{U_i}$ into the input circuit of the IU converter.

The reproduced impedance $\mathbf{Z_i}$ consists of [22]

$$\mathbf{Z_i} = 2R \cdot {R_2}/{R_1}\, exp\left[\mathbf{j} arctg\left(\omega R_\varphi C\right)\right]. \tag{12}$$

Expression (12) completely confirms the correspondence of the characteristics of the synthesized I-MS-P-As to the initial requirements. The control of reproduced impedance components is assured similarly to the control in U-MS-P-As: the variation of R_2 assures the module Z_i control; the variation of R_φ, the phase φ_i control. The domains of value variation are

$$Z_i = 0 \div 2R \cdot R_{2max}/R_1,\ \varphi_i = 0 \div 180° \tag{13}$$

and can be enlarged in the same way as in U-MS-P-As.

The simulators U-MS-C-As [24] *and I-MS-C-As* [25]. They are destined for reproduction of SPQ in Cartesian coordinates with asymmetrical connection and differ from previous by the type of input quantities: in U-MS-C-As the input quantity is the voltage $\mathbf{U_i}$, and in I-MS-C-As – the current $\mathbf{I_i}$. Thus, in accordance with (1), (3), and (4), U-MS-C-As assures the reproduction of the simulated admittances, and I-MS-C-As – reproduction of the simulated impedances with independent control of the active and reactive components. The same method of information conversion (Fig. 9a) and the same circuit for creating the active and reactive components (Fig. 9b) were used in either type of these simulators. The intermediate voltage $\mathbf{U_1}$ is transmitted through two channels: the first not involving phase change for the active component; the second, with a phase angle of 90° to create the reactive component. The control of the voltage values is assured by the programmable amplifiers PA1 and PA2 for the components control in the two channels. The signal introduced later into the input circuit is obtained from the sum of the voltages $\mathbf{U_R}$, $\mathbf{U_X}$ (Fig. 9). The control of SPQ active component in the domain of positive and negative values is assured by regulation of the transfer factor K_R of amplifier PA1 in the values range ($-K_{Rmax} \div 0 \div +K_{Rmax}$) and the same control for the reactive component is achieved by regulation of the transfer factor K_X of amplifier PA2 in the values range ($-K_{Xmax} \div 0 \div +K_{Xmax}$).

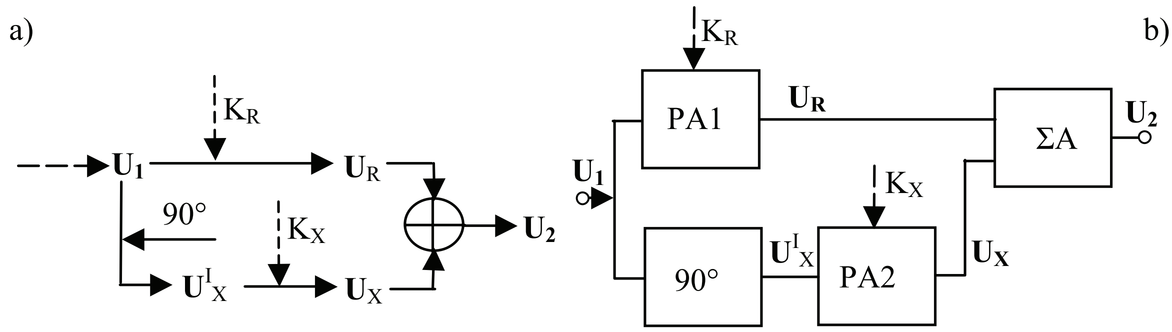


Fig. 9. ICD (a) and the circuit portion (b) for creating the SPQ components in Cartesian coordinates MS.

The ICD (Fig. 10a), the functional structure (Fig. 10b) and the internal circuit (Fig. 10c) for U-MS-C-As [24] were elaborated by the method used for the synthesis of previous simulators. The quantity reproduced by the simulator at its poles has an admittance character and represents

$$\mathbf{Y_i} = G(K_G + \mathbf{j}K_B), \quad (14)$$

where G is the conversion factor of UI converter.

The ICD (Fig. 11a), the functional structure (Fig. 11b), and the internal circuit (Fig 11c) were obtained for I-MS-C-As in a similar manner. Its reproduced quantity possesses a character of impedance and represents

$$\mathbf{Z_i} = R\,(K_R + \mathbf{j}K_X). \quad (15)$$

As follows from (14), the reproduced impedance $\mathbf{Z_i}$ is represented in Cartesian coordinates and possesses the separate control of components: the active component is controlled by variation of K_R; the reactive component, by variation of K_X.

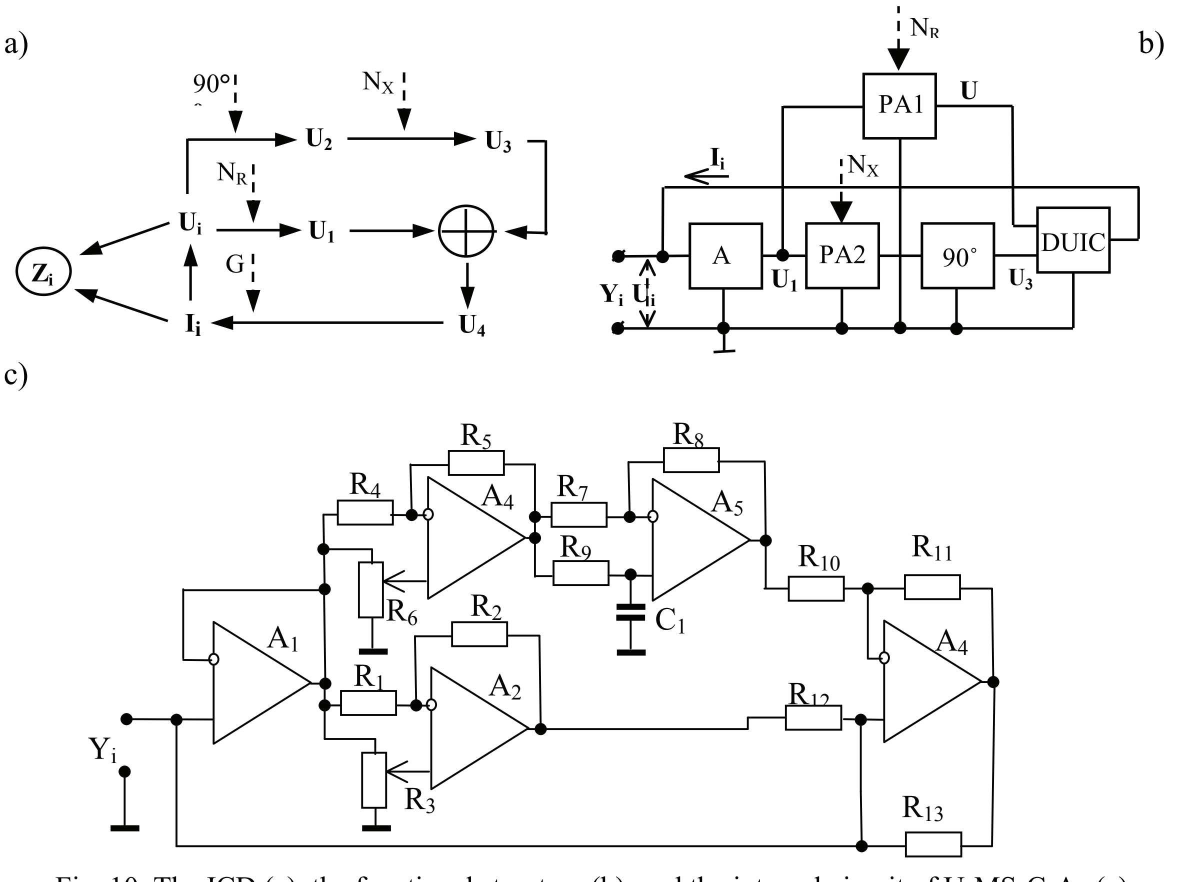


Fig. 10. The ICD (a), the functional structure (b), and the internal circuit of U-MS-C-As (c).

3.4. MS-A for reproduction of PQs with symmetrical connection

In some cases of using of MS as RE, it is necessary to reproduce SPQ with the both poles free for connection in the external circuit (Fig. 4b).

It refers, for example, to using the MS in measurement circuits with serial simulated resonance for grounded PQ measurement, in DC or AC bridges, etc. MS-A for reproduction of SPQ with symmetrical connection of the poles (MS-S) for this purpose was elaborated (Table 1).

The main aim of the elaboration of the MS-S structures was the use of OAs with traditional power supply by the grounded sources [17]. In order to obtain the symmetrical nature of SPQ poles, the circuits SM-S assure compensation of the common mode input impedance of OAs by creating the reproduced quantity depending only on the differential input quantity. The intermediary differential quantity obtained in the result of subtraction of the primary common mode input quantities is converted into Cartesian (Fig. 6) or into polar coordinates (Fig. 8) and, being introduced into the entry circuit of SM-S, assures the reproduction of the respective SPQ.

The U-MS-C-S simulator [26, 27]. This simulator (Fig. 12) assures the reproduction of the voltage-commanded SPQ represented in Cartesian coordinates with symmetrical poles. A potentiometric differential amplifier [17] based on OAs A1, A2, and A3 was used in order to create an intermediate voltage proportional to the difference of the common mode input voltages and to eliminate the influence of OA input impedance on SPQ. In order to obtain the active and reactive components and in order to assure an independent control in Cartesian coordinates, the intermediate voltage $\mathbf{U_d}$ was converted as shown in Fig. 9.

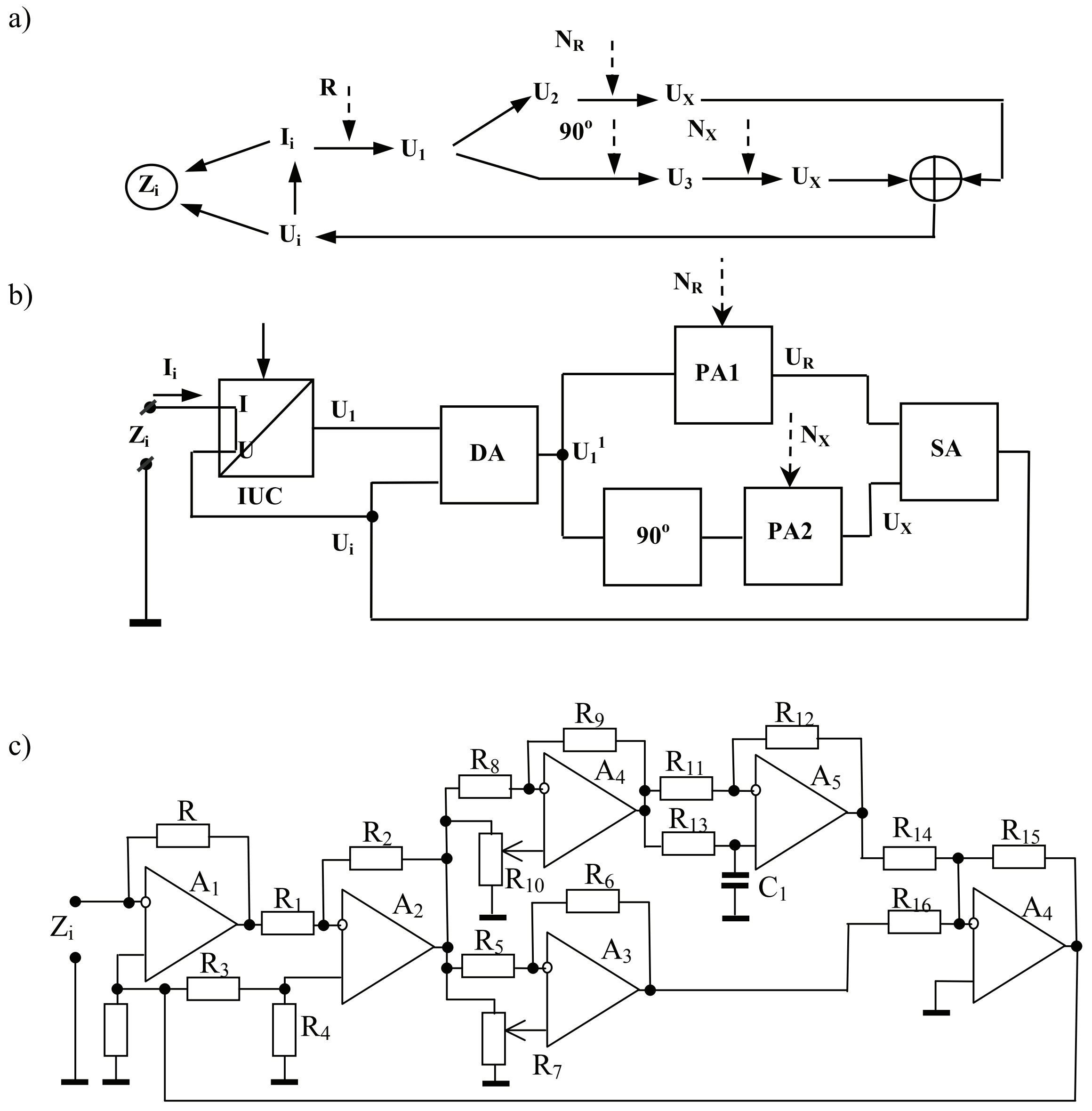


Fig. 11. The information conversion diagram (a), the functional structure (b), and the internal circuit of I-MS-C-As (c).

The currents $\mathbf{I_i}$, $-\mathbf{I_i}$ introduced in the input circuit of MS, are obtained by two voltage-to-current converters UI1, UI2 with equal and reverse transfer factors. As a result of ultrahigh input impedance of differential amplifier [17], the reproduced admittance is

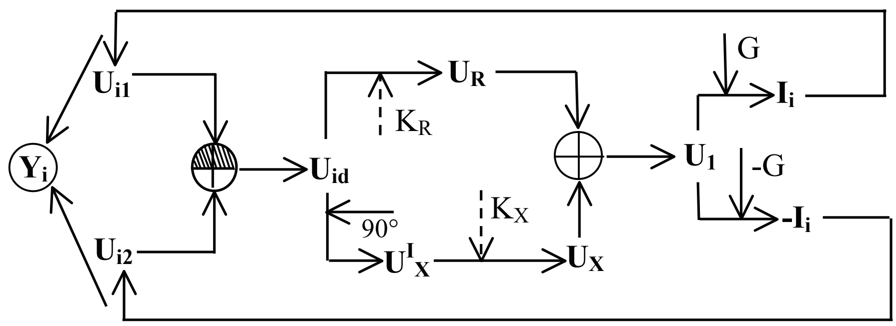
$$\mathbf{Y_i} = \mathbf{I_i} / \mathbf{U_{id}} = (R_{conv})^{-1}(K_1 + \mathbf{j}K_2). \tag{16}$$

The symmetrical character of the admittance reproduced by the simulator is assured by exclusion of the influence of the common mode input voltages on the entry current $\mathbf{I_i}$.

The U-MS-P-S simulator [28] (Fig. 13). The input circuit is similar to the one from U-MS-C-S. In order to assure an independent control of admittance components reproduced by the simulator in polar coordinates, the intermediate voltage $\mathbf{U_d}$ is consecutively passed through the programmable amplifier PA and programmable phase shifter PΦ, similarly to U-MS-P-As, and it is used for generation of the input currents $\mathbf{I_i}$, $-\mathbf{I_i}$ by the voltage-to-current converters UI1, UI2. The admittance reproduced by U-MS-P-S is [28]

$$\mathbf{Y_i} = 2G \cdot K_Z \, exp\left[\mathbf{j} arctg\left(\omega R_{\psi} C\right)\right]. \tag{17}$$

a)



b)

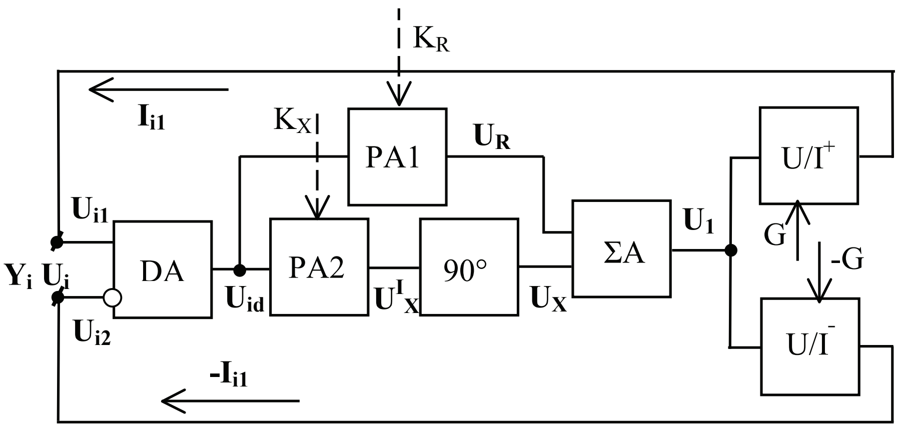


Fig. 12. The information conversion diagram (a) and the functional structure (b) for U-MS-C-S.

The current-commanded MS-S simulators. As follows from Table 1, there are two types of current-commanded impedance simulators with symmetrical poles: for reproduction of the impedances represented in Cartesian coordinates (I-MS-C-S) [29] and for reproduction of the impedances represented in polar coordinates (I-MS-P-S) [30].

Synthesis of these MS-As was carried out by the same method which was used for the synthesis of previous simulators. In order to obtain an intermediate quantity convenient for conversion in polar or Cartesian coordinates (with voltage character), a current-to-voltage converter with differential inputs DIU was used. In order to express the reproduced impedance in needed coordinates, the intermediate voltage $\mathbf{U_d}$ was converted similarly to conversion in I-MS-P-As and I-MS-C-As structures by using the circuit with transfer factor **K** expressed in Cartesian (Fig. 8) or polar coordinates (Fig. 11).

The voltage $\mathbf{U_d}^{\mathbf{1}}$ destined to be applied in the input circuit was changed into differential voltage by using an inversing amplifier A3 with unit transfer factor.

The information conversion diagrams, the functional structures and the internal circuits of I-MS-P-S and I-MS-C-S are represented in Figs. 14 and 15, respectively.

The impedances reproduced by the simulators are

- for I-MS-C-S [29]

$$\mathbf{Z_i} = \mathbf{2}R_{conv}\,(\mathrm{K}_1 + \mathbf{j}\mathrm{K}_2); \tag{18}$$

- for I-MS-P-S [30]

$$\mathbf{Z_i} = 4R \cdot K_Z\, exp\left[\mathbf{j}arctg\left(\omega R_\varphi C\right)\right]. \tag{19}$$

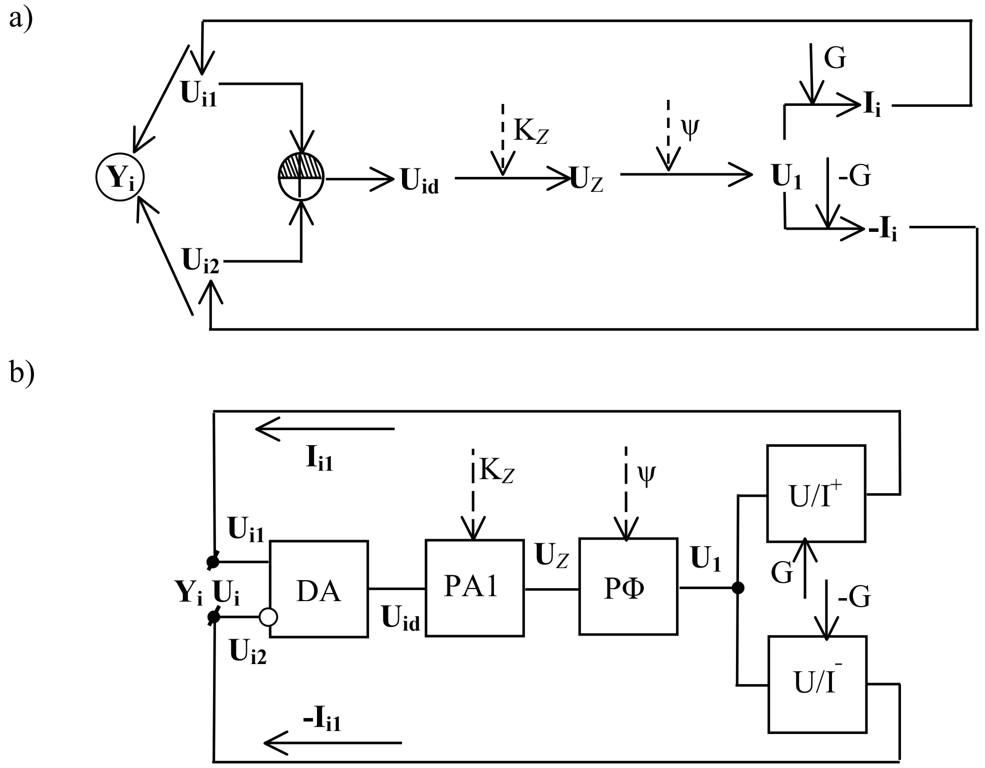


Fig. 13. The information conversion diagram (a) and the internal structure (b) for U-MS-P-S.

As follows from (18), for I-MS-C-S, $\mathbf{Z_i}$ is expressed in Cartesian coordinates and assures an independent control of the active component (by regulation of the factor K_1) and of the reactive component (by regulation of K_2). It follows from (19) that the impedance reproduced by I-MS-P-S is expressed in polar coordinates and assures an independent control of the module (by regulation of the resistor R_2) and of the phase (by regulation of R_φ).

In order to obtain the expressions for the reproduced impedances correct from algorithmic point of view, at the implementation of circuits based on OAs (Figs. 14b, 15b), the differential amplifiers which neutralize the general feedback were used [8].

4. Experimental confirmation of the results

The authenticity of results of synthesis of the simulators from Table 2 was determined by the simulation in the program PSPICE and by experimental modelling (simulation) of devices in the laboratory.

The studied simulators were connected as components of the circuit with simulated resonance (CSR) [2] together with a complex PQ with the known value. The balancing of the CRS was carried out by regulation of MPS components to achieve the state of total resonance, which corresponds to the zero value of the unbalance signal. In order to study the I-MS, the series CSR was used; to study U-MS, the parallel CSR, which is determined by the type of stability of these simulators [2].

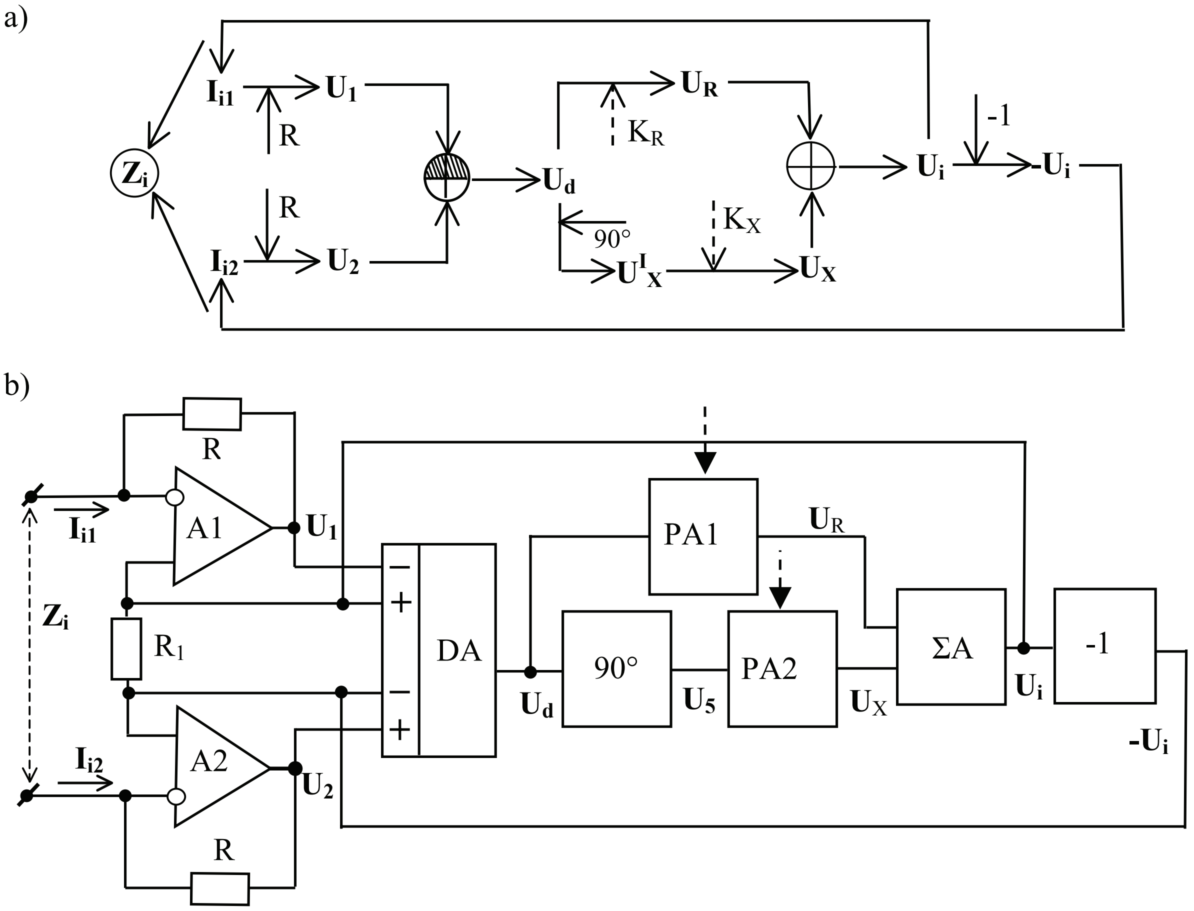


Fig. 14. The information conversion diagram (a) and the functional structure (b) for I-MS-C-S.

The studying of I-SM-C-As [31] as a component of the series CSR (Fig. 16a) is an example of modelling in the program SPICE of the simulators.

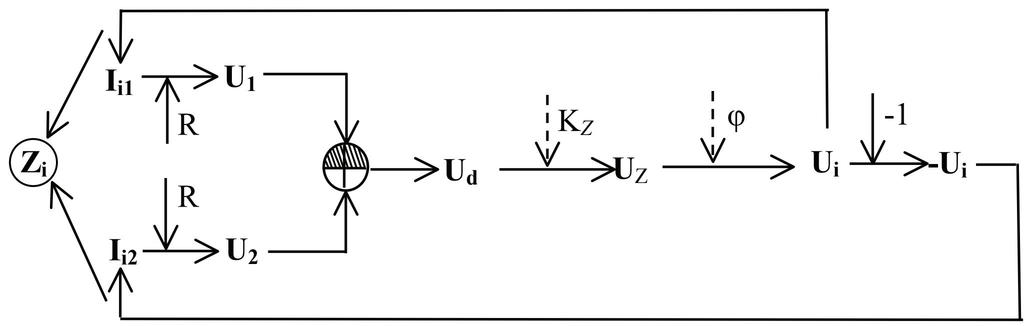
The simulation was carried out for two cases: for the measured impedance with an active character and with a complex character. The harmonic generator V1 with frequency F_S = 1 KHz and voltage U_S = 10 V for supplying CSR with measuring signal and the external resistor R_2 = 1 kΩ as a model of measured resistance were used.

The state of resonant circuit was determined by comparing the phase of the unbalance signal $\mathbf{U_{de}}$ (on p. 2 of the circuit) with the phase of the reference signal from the generator $\mathbf{U_{ref}}$ (on p. 1) and of the signal $\mathbf{U_{de}}$ amplitude by means of an XSC1 oscilloscope. In the case of modelling the complex MPS, the balancing of the CSR was made in two stages: the balancing on the active component by variation of the resistor R_9 and the balancing on the reactive component by variation the resistor R_{21} until the total resonance condition ($\mathbf{U_{de}}$ = 0) is achieved. The end of the first stage is the achievement of a phase angle of 90° between the signals $\mathbf{U_{de}}$ and $\mathbf{U_{ref}}$ (Fig. 18b); the end of the second phase is the obtaining of the state $\mathbf{U_{de}}$ = 0 (Fig. 18c).

The modelling results have demonstrated full compliance of the SPQ component values calculated from expression (15) to those obtained experimentally [31]. The same result was obtained by experimental laboratory modelling of the device.

The same methods were used for experimental testing of the other simulators presented in Table 1. The experimental results obtained for SPQ values in the state of total CSR resonance fully correspond to the theoretical values determined by the method of admittances matrix [7].

a)



b)

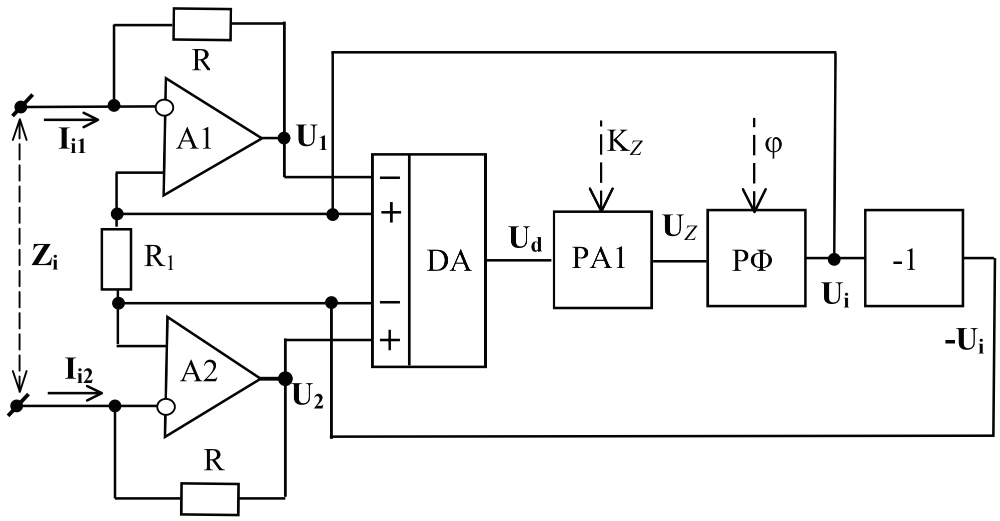


Fig. 15. The information conversion diagram (a) and the functional structure (b) for I-MS-P-S.

A result interesting in view of the possible practical application was obtained for simulators with symmetric connection poles (MS-S, Table 1). The experimental results confirmed **the floating character of the admittances reproduced by U-MS-CS and U-SM-SP**. This was demonstrated by the lack of influence on the state of resonance of any point-to-mass connection for the parallel CRS. The obtained result confirms the possibility to use these simulators as REs for reproduction of the floating measures of PQswith components commanded in Cartesian (U-MS-C-S) or polar (U-MS-P-S) coordinates.

The results of research of I-commanded (I-MS-CS, I-SM-SP) simulators reproduced by the presented circuits (Figs. 14b, 15b) showed that the MPQs reproduced by these simulators, though possessing symmetric character, are not floating. This is accounted by the usage of OAs supplied from grounded sources [17], which leads to the asymmetric nature of voltage $\mathbf{U_{id}}$ introduced in the entry circuit of MS and therefore of the reproduced impedance. To obtain the floating simulated impedances in these simulators, it is recommended to apply the methods of OA feeding from floating energy sources [17], or the internal compensation of the common mode component of entry impedance by means of the feedback loops.

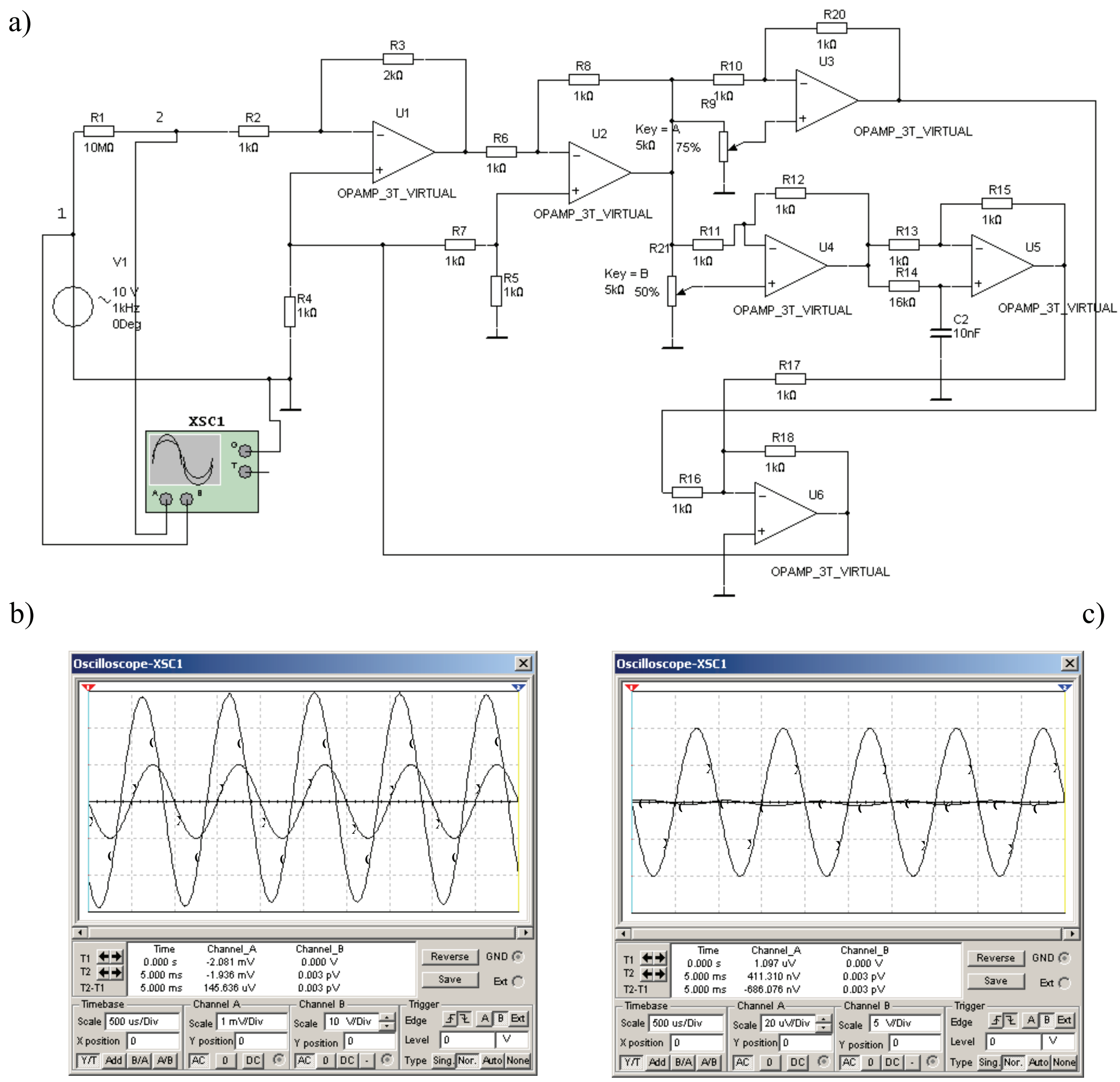


Fig. 16. The series CSR to study I-SM-C-As modelled in the program SPICE (a), the CSR balancing results at the active component (b) and at the reactive component (c) (° is the signal $\mathbf{U}_{\mathbf{de}}$, ^{x} is the signal $\mathbf{U}_{\mathbf{ref}}$).

5. Stability of MS-A

Practical application of MS-A is possible only upon fulfilment of the condition of guaranteed assurance of stability of devices at the variation of internal and external factors of the measuring circuits in the entire allowable range of values. The following factors which can potentially influence the MS-A stability were selected from the analysis of the real conditions of measuring circuits:

- the MS-A type according to Table 1,
- the character and the values of components of SPQ,
- the character and the value of equivalent external impedance (Fig. 4),
- the characteristics of OAs.

So, depending on the factor which causes the loss of device's stability, the problem of MS-A stability must be examined from three points of view:

1. Assurance of stability on direct current (DC).
2. Assurance of stability at high frequencies.
3. Assurance of the functional stability.

Stability on DC. The loss of stability on DC in the circuits based on OAs is caused by prevalence of positive feedback over negative one at direct current [17]. In order to maintain the guaranteed stability on DC, it is necessary to assure the summary negative character of DC feedback in each link (local feedback) and in the entire circuit (general loop of feedback).

Stability at the high frequencies. The absence of this type of stability is manifested by excitation of some MS links or of the entire circuit because of non-ideality of frequency characteristics of OAs [17]. In order to prevent the excitation at high frequency of the links or of the whole circuit, the optimal correction of OAs through known methods and the correct distribution of the unit frequency ranges at their cascade connection with common feedback loops are required.

The functional stability. It is determined by the summary character of the general feedback at the operation frequency on connection of the MS in an external circuit. It depends on MS type (Table 1), on the character and values of the reproduced impedance, and on the external equivalent impedance connected to MS poles [8]. The loss of this type of stability is manifested through circuit excitation at working or near-working frequency, a regime similar to the one which appears in a generator. If, in order to ensure the first two types of stability, we must observe only of the general principles of OA use [17], the assurance of the functional stability is conditioned by imposing some restrictions on the type of the used simulator, on the type of the measurement circuit, and on the values of the above impedances. Since the assurance of stability presents one of the obligatory conditions of practical use of MS [32], the determination of the functional stability conditions for every type of MS-A is absolutely indispensable.

As it is known [9], the MS stability depends firstly on the primary input quantity (**I** or **U**) (p. 2.1): I-MS maintains stability to the no-load regime; U-MS, to the short-circuit regime. However, this condition is too general and it does not adequately determine the conditions of MS usage as components of measuring circuits. In order to obtain these conditions, we shall make the analysis of MS-containing circuits based on the classical theory of stability of the circuits based on OAs with feedback loops.

In order to estimate the conditions of the functional stability, we shall take advantage of the Nyquist criterion in application to the OA-containing circuits [17]. As is known, the circuits with feedbacks save the stability if the critical point (-1, +j0) is located to left of the hodograph of the transfer characteristics on the feedback loop, when the frequency changes from f = 0 up to f →∞ (Fig. 17).

Thus, in order to estimate the stability conditions for the circuits in accordance to the Nyquist criterion, it is necessary to determine its loop gain factor **βA** and to examine it in the neighbourhood of the critical point (-1, + j0) in coordinates Re (**βA**), Im (**βA**). The condition of functional stability for the MS circuit looks like [17]

$$\boldsymbol{Re}\,[H_{io}] > -1, \qquad (20)$$

where H_{io} – loop gain factor of the MS circuit.

The model of I-MSI [8] to determine the condition of stability is represented in Fig. 18a. Through the equivalent differential amplifier with the gain factor **K,** the portion of the circuit of I-MS limited by the dotted line (Fig. 2b) is designated.

The model for U-MS (Fig. 18b) contains the amplification link **K** and the current-to-voltage converter based on OA A1 connected into the feedback loop. $\mathbf{Z_e}$ stands for the equivalent external impedance connected to poles of MS.

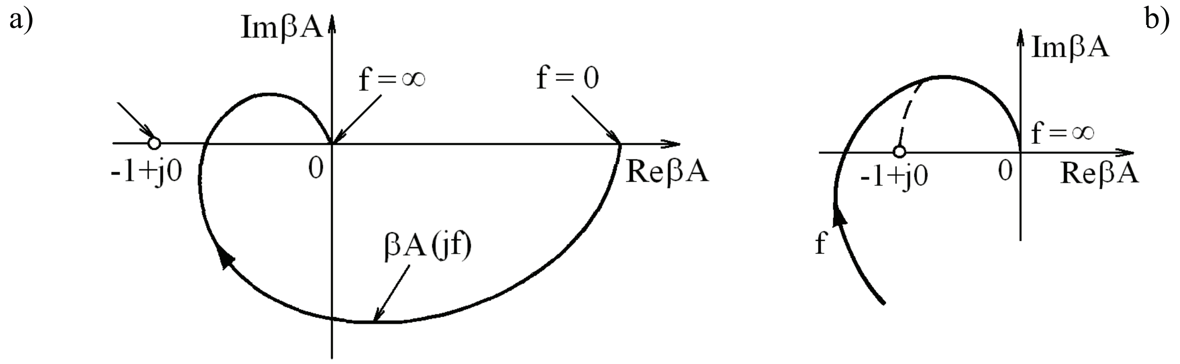


Fig. 17. Hodograph of the loop gain factor for stable (a) and unstable (b) circuits.

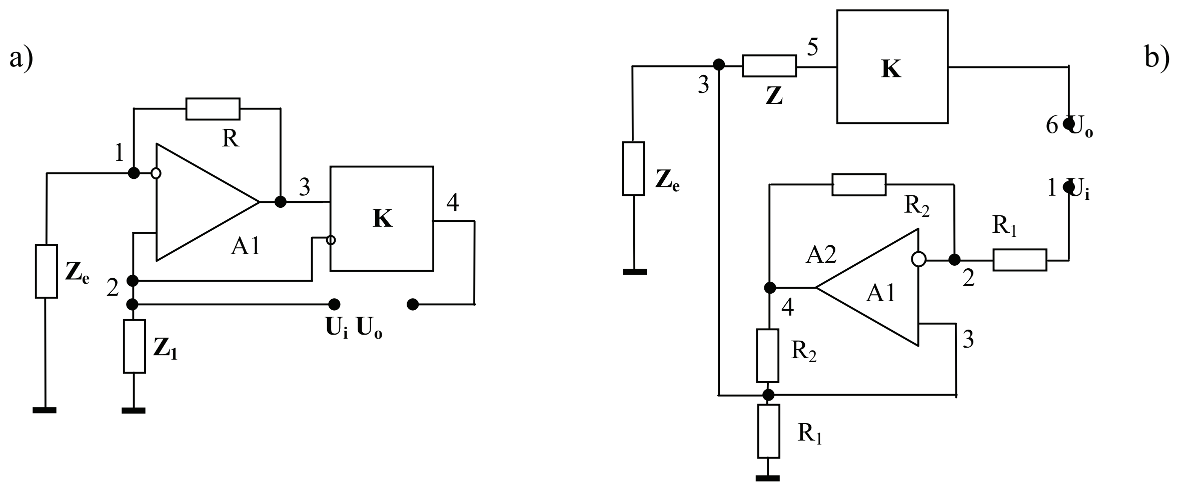


Fig. 18. The models of I – MS (a) and U-MS (b) for stability analysis.

In order to determine the stability conditions, in either case, the expressions for the transfer factor in loop $\mathbf{H_{io}}$ of the circuits were obtained [33]. They are

- for I-MS (Fig. 18a)

$$\mathbf{H_{io}} = \mathbf{U_o}/\mathbf{U_i} = \mathbf{K}\,R\,/\,\mathbf{Z_e}; \quad (21)$$

- for U-MS (Fig. 18b)

$$\mathbf{H_{io}} = \mathbf{U_o}/\mathbf{U_i} = -\,\mathbf{K}\,\mathbf{Z_e}\,/\,R_1. \quad (22)$$

The transfer factors for I-MS-C and I-MS-P can be obtained by substituting the expressions for **K** in Cartesian (7) and in polar (8) coordinates in (21). In the same way, the transfer factors for U-MS-C and U-MS-P can be obtained (Table 3).

Table 3. The expressions for stability analysis of MS-As.

Type of MS	The transfer factor $\mathbf{H_{io}}$ / The stability condition	
	for MS-C: $\mathbf{K} = K_1 + \mathbf{j}K_2$	for MS-P: $\mathbf{K} = K_Z \exp(\mathbf{j}\varphi)$
I-MS: $\mathbf{H_{io}} = \mathbf{K}\cdot R\,/\,\mathbf{Z_e}$	$\mathbf{H_{io}}=R(K_1+\mathbf{j}K_2)/(R_e+\mathbf{j}X_e)$ (3.1)	$\mathbf{H_{io}}=(R/Z_e)K_Z \exp(\mathbf{j}(\varphi-\varphi_e))$ (3.3)
	$\lvert\mathbf{Z_e}\rvert^2>R_eR_{X\,max}+X_eX_{X\,max}$ (3.2)	$Z_e > R\,K_Z$ (3.4)
U-MS: $\mathbf{H_{io}} = -\,\mathbf{K}\,\mathbf{Z_e}\,/\,R_1$	$\mathbf{H_{io}}=-(K_1+\mathbf{j}K_2)(R_e+\mathbf{j}X_e)/R_1$ (3.5)	$\mathbf{H_{io}}=-K_Z \exp(\mathrm{j}(\varphi-\varphi_e))Z_e/R_1$ (3.6)
	$K_{1max}\,R_e + K_{2max}\,X_e < R_1$ (3.7)	$Z_e < R_1/K_Z$ (3.8)

The problems of the error analysis for impedance simulators on the basis of operational amplifiers were investigated in [6]. As follows from [6], the greatest influence on the error of the given value of the reproduced impedance is exerted by the factors of non-ideality of the operational amplifier and, in particular, by the limited value of gain factor and its frequency dependence.

For minimization of this component of the error, the operating frequency of measuring signal must not strongly exceed the frequency of pole of the OA characteristic [17]. The acceptable error $\delta \leq 0.1\%$ was obtained at the operating frequency F = 100 Hz.

6. Conclusions

1. The MS-A forms a class of devices that can be used as REs to measure the impedance using the method of simultaneous comparison. Compared to the classical RE, they have such advantages as the possibility of reproduction of reference quantities with any character, the possibility of expression of the reproduced quantities in the Cartesian or polar coordinates, and the possibility of independent control of the reproduced quantity components.
2. The MS-A in Cartesian coordinates ensure reproduction of SPQs **located throughout the entire complex plane** ±R, ±**j**X (±G, ±**j**B for admittances) **with possibility of independent control of active and reactive components and with smooth variation of the character**. The MS-A in polar coordinates ensures reproduction of the same type PQs in coordinates system Z, φ (Y, ψ for admittances) with independent control of the module and phase values in bands $Z, Y = (0 \div \max)$, $\varphi, \psi = (0 \div 360°)$.
3. The MS-A classification by relevant criteria established a class of eight devices, which are distinguished by the possibilities of application in various devices for the impedance measurement. Each type of MS-A possesses relevant criteria, such as the primary input quantity (voltage or current), type of the coordinates for the reproduced quantity expression (Cartesian or polar), and type of the connection poles for external circuit (asymmetric or symmetric poles).
4. For synthesis of the MS-A internal structure, the formal–structural method was used. The method ensures the synthesis of the simulator's internal structure in accordance to the requirements determined by the conditions of use. The structures for all eight types of MS-A were synthesized using this method. The results of experimental study of these devices fully confirm their characteristics obtained in theoretical mode.
5. The practical application of MS-A is conditioned by the stability of devices. Three aspects of the stability were determined: the high frequency stability, the direct current stability, and the functional stability. The first two types of stability are ensured through compliance with standard principles for the use of OAs. The functional stability is dependent on the type of MS-A, on the character and value of the reproduced quantity, and on the character and value of the external equivalent impedance connected to the poles of MS.
6. The analysis of functional stability through the Nyquist criterion has determined the restrictions in use for each type of MS-A. Thus, the current-commanded simulators exhibit stability up to the no-load regime and are recommended for use in series circuits with simulated resonance; the voltage-commanded simulators possess stability up to the short-circuit regime and are recommended for use in parallel circuits with simulated resonance. The analysis has determined the feasible conditions of absolute stability for each type of MS-A.

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