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A FOUR TERMINAL AXIAL-BISHIELDED NETWORKS

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An impedance measurement object with an H-shaped four-terminal equivalent substitution circuit is considered. An error analysis was performed for sensors whose non-informative supply resistances are of the same order or exceed the measured impedance. A new definition of four-terminal impedance has been proposed, namely four-terminal axial be-shielded (FTABS) measuring object. Based on such new definition, the scheme of axial-bishielded bridges is proposed for precision measurement of temperature and electrolytic conductivity of liquids. Such bridges differ from the well-known coaxial bridges since the former ones have an additional circuit for equipotential protection, which is located between the flow circuits of direct and reverse currents. References 18, figures 7.
Keywords: impedance, model, four-terminal axial be-shielded object, measuring bridge.

From the works of Samuel Christie [1] and Charles Wheatstone [2], which became the prototype of the four-branch bridge [3], the Kelvin double bridge [4] or the first transformer bridges (patent Rosenthal's in 1883) to the present day, improvement of the impedance measurement accuracy has been related to bringing invariance to a large number of impact factors, increasing efficiency of the four-terminal connections, and eliminating shunting effects. The key technical solutions to achieve an error of 0.1 ppm in the measurement of AC resistance were the transformer bridges of Gibbings [5], Hill [6], Furd [7]. Amidst major requirements for such bridges, along with the high precision of branches ratio, was an effective four-terminal connection of the standard measure and the measuring object. In 1964, for precision immittance measurement Cutkosky proposed to use the definition which he formulated as ‘four-terminal-pair networks’, Fig. 1, *a* [8]. In the coaxial variation a model is presented in Fig. 1, *b* where an object is surrounded by a shield with potential equaling zero and a reverse current flowing through it.

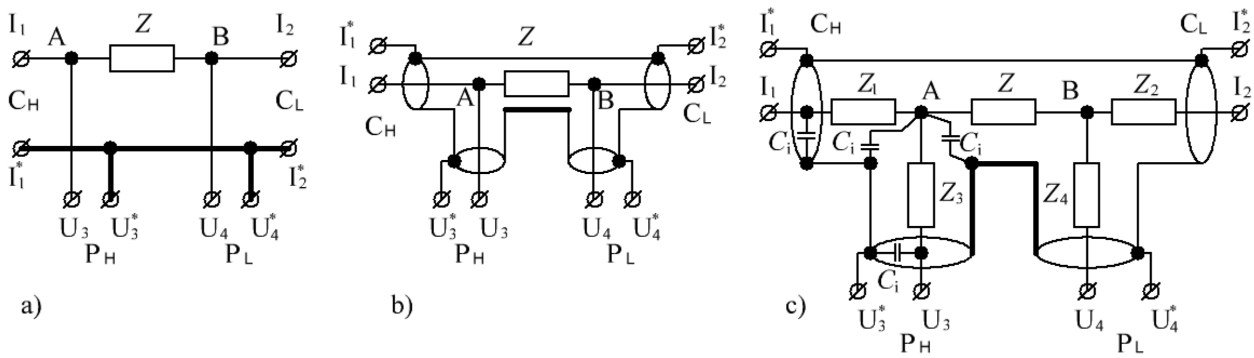

Fig. 1

Each of the four signals (two current and two potential) is fed to the object via a coaxial port. Later on, such objects and measuring networks on their basis became known as coaxial bridges [9, 10]. A model with the four-pair connection allows to pass direct and reverse currents in spatial contours with the minimum area. This enables to reduce scattering fields in the transformer measuring networks, optimize the signal-to-interference ratio (primarily magnetic), and realize, along with other techniques, high sensitivity of the coaxial bridges. The four-terminal-pair connection of a measuring object in Fig. 1 has the formula of connection 4×2, i.e. four terminals with two connectors each. The modes to be formed on each connector are given in Table 1.

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Therefore, the purpose of this article is to analyze the problems of the four-terminal-pair measuring object, to consider ways to solve these problems, to introduce a new type of object to correct the influence of transverse parasitic admittance, which was defined as four-terminal axial-bishielded (FTABS) measuring object and examples of implementation of such objects in double-shielded coaxial bridges designed for precision measurement of temperature or electrolytic conductivity.

Table 1

Tape of connections:	Modes on port connectors			
	I_1 and I_1^* (C_H)	I_2 and I_2^* (C_L)	U_3 and U_3^* (P_H)	U_4 and U_4^* (P_L)
Four-terminal-pair connections [8]	$I_1 = I_1^*$ $U_1^* = 0$	$I_2 = I_2^*$ $U_2^* = 0$	$I_3 = I_3^* = 0$ $U_3 = U$, $U_3^* = 0$	$I_4 = I_4^* = 0$ $U_4 = U_4^* = 0$
	$I_1 = I_2$, $U_1 = U_3$		$U_2 = U_4$	
Four-terminal bi-shielded connections (FTABS)	$U_1^{**} = U_1$	$U_2^{**} = U_2$	$U_3^{**} = U_3$	$U_4^{**} = U_4 \neq 0$
	$U_1 \neq U_3$		$U_2 \neq U_4$	

The problem and its analysis. The Cutkosky impedance definition is based on several conditions. The voltage difference at U_H and U^*_H connectors should be equal to the voltage of the power source, and the voltage difference at U_L and U^*_L connectors should be zero. This means that potentials of I_H, U_H connectors and point A coincide, and potentials of the connectors I_L, U_L and point B coincide accordingly. But in this case, a model of the four-terminal object neglects impedances in the current circuits Z_1, Z_2 and voltage circuits Z_3, Z_4 (Fig. 1, *c*). However, there are a number of measurement objects where impedances cannot be ignored. For EG, at cryogenic temperatures, the active resistance 100Ω of Standard Platinum Resistance Thermometer (SPRT) decreases by three orders of magnitude to 0.1Ω, whereas the input impedances Z_1–Z_4 remain significant at 0.6Ω level. Additionally, in four-electrode AC conductivity cells with the calculated constant (absolute 4T cell [11]), impedances Z_1, Z and Z_3 of liquid columns are almost identical in module and reach 10 kΩ. Moreover, informative parameter Z has a parallel capacitive equivalent circuit [12], while the non-informative parameters Z_1, Z_3 have a serial capacitive equivalent circuit, the phase angle tangent of which for some solutions approaches 1. For above mentioned objects, the working current and parasitic capacitances C_i breach the Cutkosky conditions $U_1 \neq U_3$ and $U_2 \neq U_4$. This is a major problem that leads to error. We'll look at it in more detail below.

Typically, measuring devices and sensors are connected with an communication line (cable). Fig. 2 shows a scheme for measuring informative parameter Z_X which is represented by an H-shaped four-terminal measuring object [13].

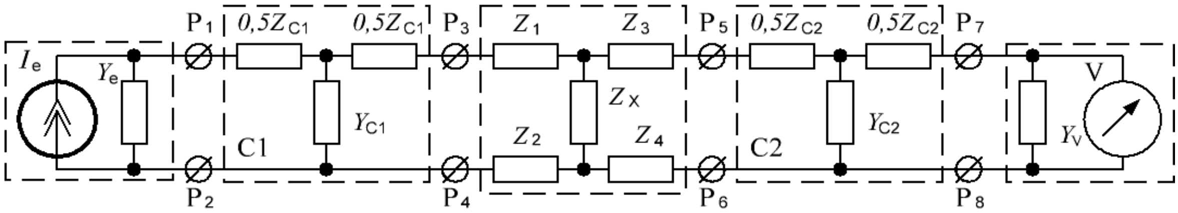


Fig. 2

The scheme contains the following elements of the device: a power source with output conductance Y_e and a voltmeter with input conductance Y_V, connected respectively by cable $C1$ with connectors P_1-P_4, and cable $C2$ with connectors P_5-P_8 to the measuring object.

A systematic error caused by non-informative parameters will occur during the measurement process. For its calculation in [13] the following formula is applied:

$$\delta_Z = -\left[\left(Y_e + Y_{C1}\right)z_1 + \left(Y_V + Y_{C2}\right)z_2\right], \qquad (1)$$

where:

$$z_1 = Z_{C1} + Z_1 + Z_2 + Z_X \frac{1 + \left(Y_V + Y_{C2}\right)\left(Z_{C2} + Z_3 + Z_4\right)}{1 + \left(Y_V + Y_{C2}\right)\left(Z_X + Z_{C2} + Z_3 + Z_4\right)};$$

$$z_2 = Z_{C2} + Z_3 + Z_4 + Z_X \frac{1 + \left(Y_e + Y_{C1}\right)\left(Z_{C1} + Z_1 + Z_2\right)}{1 + \left(Y_e + Y_{C1}\right)\left(Z_X + Z_{C1} + Z_1 + Z_2\right)}.$$

In [13] all non-informative parameters (Fig. 2) denoted by symbols Z_i are called longitudinal impedance, and Y_i-denoted parameters are named transverse admittance, respectively. As a rule, only short-length cable [9, 10, 13] parameters are used in the analysis. In [9], linear parameters of a standard (50 Ω) coaxial cable, based on one-meter-length, are given: $Z_{C1} = Z_{C2} = 10^{-2} + j\omega 2{,}5 \times 10^{-7}$ and $Y_{C1} = Y_{C2} = j\omega 10^{-10}$. It stands to reason that at typical operating frequencies ranging from 100 to 1000 Hz inductance in the impedances Z_{C1} and Z_{C2} can be neglected for thermometry and conductivity measuring instruments. It should be noted that, for EG, SPRTs are calibrated at reference points which are located over a large area, sometimes in different rooms. Whereby a thermometry bridge (F900), depending on its configuration, has a weight of 27-31 kg, is grounded and, as a rule, is installed as stationary one. Therefore, the length of the measuring cables for the thermometry bridges can reach 10-30 m in the laboratories of the national metrological institutes. Thus, the longitudinal impedances of the measuring objects can be an order of magnitude larger than the informative parameter. Under interconnection line we mean not only the measuring cable connecting a device and a sensor (we denote these parameters as r_{CAB} and C_{CAB}), but also the part of the cable inside the device (parameters r_{INDEV} and C_{INDEV}), as well as the cable inside the sensor, which links sensor connectors and electrodes of the sensing element (parameters r_{INSEN} and C_{INSEN}).

For some of the most commonly used types of precision thermometry and conductivity sensors (high-temperature SPRTs of BTC type and ПТС10 type; low-temperature SPRTs of platinum resistance thermometer ТСПН-4В type, Russian designation; or absolute 4T conductivity cell), the values of longitudinal and transverse parameters are presented in Table 2.

Table 2

	Parameters of interconnection line						Object parameters		
Sensor type	r_{INDEV}, MΩ	C_{INDEV}, pF	r_{CAB}, MΩ	C_{CAB}, pF	r_{INSEN}, MΩ	C_{INSEN}, pF	$\|Z_1\|$,$\|Z_2\|$,	$\|Z_3\|$,$\|Z_4\|$	$\|Z_X\|$
BTC	1-3	10-30	10-300	100-3000	10-15	100-150	0.2-0.6 MΩ	0.2-0.6 MΩ	0.6-2 Ω
ПТС10	1-3	10-30	10-300	100-3000	10-15	100-150	2-6 MΩ	2-6 MΩ	10-25, Ω
ТСПН-4В	1-3	10-30	10-300	100-3000	10-15	100-150	0.3-1 Ω	0.3-1 Ω	0.1-100 Ω
4T cell	1-3	10-30	10-15	100-150	1-3	10-30	5 Ω - 10kΩ	3 Ω - 3kΩ	5 Ω - 10kΩ

In the formula for an error (1) there are three components: additive, multiplicative, and linear error. We make a simplified estimation of the additive component of an error in the assumption that the parameters of a source and a voltmeter are compensated, i.e. $Y_e << Y_{C1}$ and $Y_V << Y_{C2}$. At the highest range, upon equal distance between the potential and current electrodes, impedance modules of the conductivity sensor are equal $Z_X \approx Z_1 \approx Z_2 = 5$ kΩ. Hence, an additive component of the error (1) will be $\delta Z_a \approx Y_{C1}(Z_1 + Z_2)$. Then at an operating frequency of 1 kHz the error can reach 0.6%. Thereby, linear and multiplicative errors will be of the same order of magnitude. There are two methods to handle this problem. The first method is based on the compensation of the voltage drop on the longitudinal parameters to reduce the influence of the impedances Z_1, Z_2. The second one is based on equipotential protection in coaxial measuring networks to reduce the impact of the Y_{C1} and Y_{C2} transverse admittances. There are ways to solve the second problem. This is the use of three axial measuring cables with the formation of a protective potential. But in [10] only the idea is formulated. Even the principle of action is absent. There is also an original solution based on a symmetrical passive transmission structure obtained with a center-tapped four-coaxial cable [14, 15]. It requires four axial cables in current or potential circuits. But the effect is achieved only for a cable of a specific length. Further, since, for example, for $Z_1 = Z$ (Fig. 1, *c*), the potentials of terminals I_1 (port C_H) and U_3 (port P_H) will differ twice, this method will not work. This article discusses the second method in more detail.

Ways to solve the problem. The essence of new approach lies in combining methods of magnetic and electrostatic protection of the measuring networks. Schematically this idea is shown in Fig. 3, *a*. Well-known coaxial measuring networks [9, 10], where operating current I_X flows through an object with impedance Z_i and returns to the power source through a shield with impedance Z_{i2}, forming in the space contour L with a minimum area. It is suggested that such networks will be supplemented by an additional contour which performs the function of equipotential protection of the direct working current circuit. It should be located between the direct and reverse working current circuits. The new object, Fig. 3, *a* (as opposed to two-terminals pair 2P or four-terminals coaxial 4C [16]) can be defined as two port triple-coaxial impedance (code 2 TC). The following relation is a condition for the absence of leakage currents (I_{leakage} = 0, Fig. 3, *a*):

$$I_{i1}Z_{i1} = I_X Z_i . \quad (2)$$

If we apply the above approach to all elements of the four-terminal object ($Z_1 – Z_4$, Z_X, Fig. 2), then we obtain the multi-terminal model of the measurement object. The model presented in Fig. 3, *b*, allows organizing universal protection against magnetic and electrostatic external or internal interference.

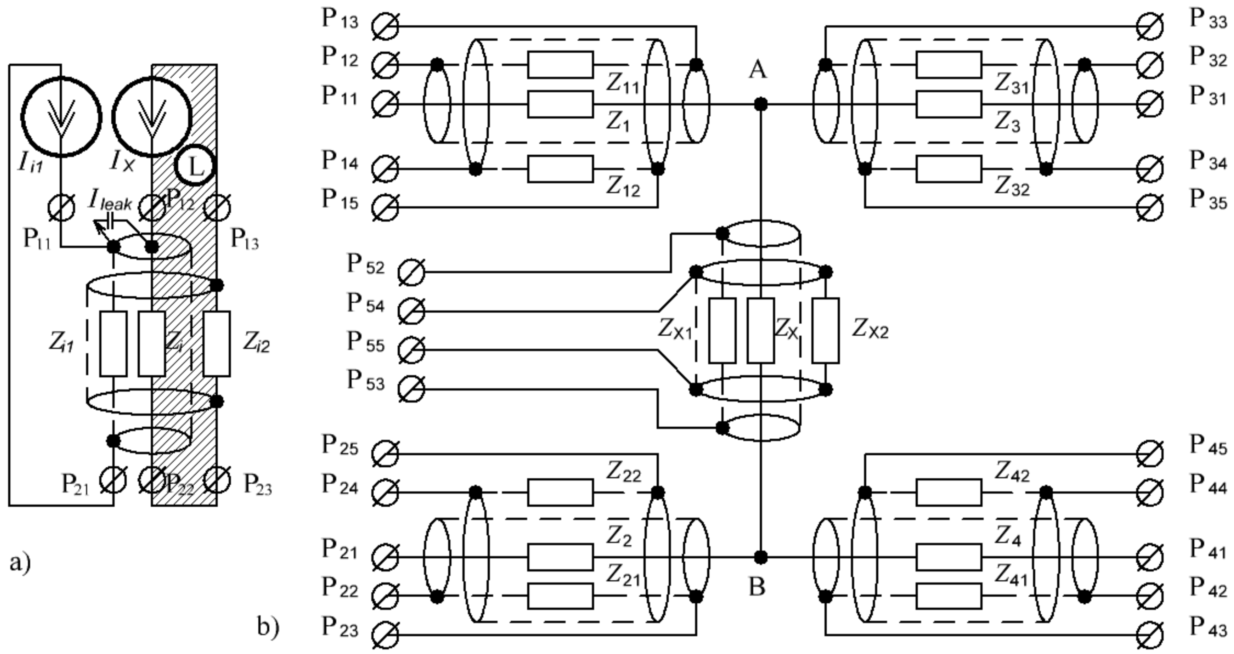


Fig. 3

The scheme shown in Fig. 3, *b* contains five ports (terminals) *P*1 – *P*5 with connectors P_{ij} to form the respective modes. The first four ports have the same set of five connectors each. A pair of P_{i2} and P_{i3} connectors for the inner shield, a pair of P_{i4} and P_{i5} connectors for the outer shield, and P_{i1} connectors for a classic four-terminal connection. Fifth port terminals have the same functions, but do not have terminal P_{51}, because by definition four clamping objects, the corresponding terminals of ports *P*1, *P*3 and *P*5 are connected at point *A*, and the terminals of ports *P*2, *P*4 and *P*5 with are connected at point *B*. The scheme in Fig. 3, *b*, upon forming appropriate modes, is suitable for the implementation of wires bifilarity with direct and reverse currents and for equipotential protection of sensor sections, connectors and measuring networks.

If you combine P_{15} and P_{54} connectors, as well as P_{53} and P_{25} connectors, you are able to form a circuit for reversing current through the connectors P_{14} and P_{24}. If you exclude circuits for equipotential protection, but combine pair wise connectors P_{15} and P_{54}, P_{53} and P_{25}, P_{35} and P_{45} both electrically and constructively, then in combination with the connectors P_{i1} one can obtain a four-terminal pair definition of the object, Fig. 1. In general representation of the scheme in Fig. 3, *b*, 21 variants of independent connector combinations for P_{ij} connectors can be identified to form protection circuits. The variations with the most practical significance are given in Table 3.

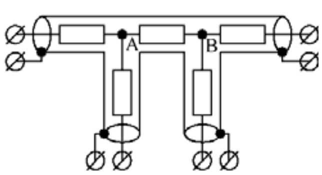
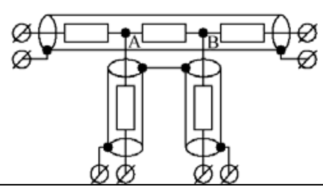
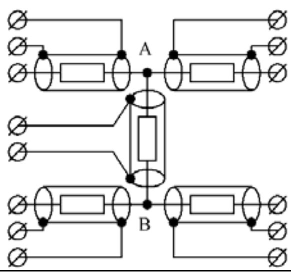
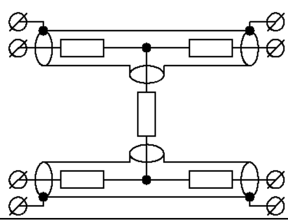
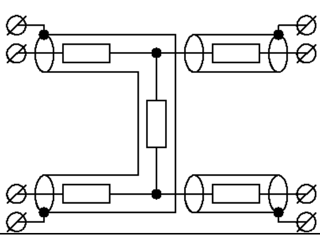
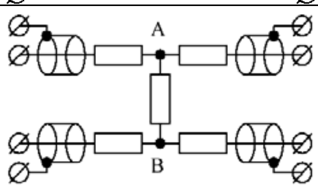
Four-terminal axial-bishielded (FTABS) measuring object. The implementation of some protection options proposed in Table 3 significantly complicates the sensor design. For existing designs (for EG, Strelkov's design of a high-temperature SPRT) it is only partially possible. This is explained by the fact that a shield can be inserted inside a thermometer's quartz tube only with the manufacturer's consent. In other cases, as a rule, additional studies of the shunting influence of the capacitances C_i (Fig. 1, *c*) are required.

The most effective and promising approach is to combine the methods of bifillation of signals and their equipotential protection, which is achieved by combining schemes *1* and *6* of Table 3. Accordingly, there is a need to identify a new type of multi-terminal object.

The new definition of a measuring object has the formula of type connectors 4×3, as shown in Fig. 4. The object differs from the well-known four-terminal-pair object by the fact that each terminal is provided with a third connector for equipotential protection. By analogy with a "bi-shielded" cable, such measuring object can be called as a four-terminal coaxial bi-shielded one. Its connection scheme and designation of the modes on the connectors are represented in Fig. 4. Table lists additional requirements for voltages and currents at the connectors which are needed to define a four-terminal coaxial bi-shielded object.

Four-terminal axial bi-shielded (FTABS) measuring object. The implementation of some protection options proposed in Table 3 significantly complicates the sensor design. For existing designs (for EG, Strelkov's design of a high-temperature SPRT) it is only partially possible. This is explained by the fact that a shield can be inserted inside a thermometer's quartz tube only with the manufacturer's consent. In other cases, as a rule, additional studies of the shunting influence of the capacitances C_i (Fig. 1, *c*) are required.

Table 3

	No	Scheme configuration	Jumper link	Scheme description and purpose
Methods of magnetic protection	1		P_{i2} and P_{i3} – none $P_{15} + P_{54} +$ $P_{55} + P_{24} +$ $P_{25} + P_{44} +$ $P_{45} + P_{34} +$ $P_{35} + P_{14} +$	Combined bifilarity of current and potential circuits. Four-terminal-pair connection. The definition given in [8] and used in [9, 10, 14-16].
	2		P_{i2} and P_{i3} – none $P_{15} + P_{54} +$ $P_{55} + P_{24}$; $P_{45} + P_{34}$	Separate bifilarity of current and potential circuits.
Methods of electrostatic protection	3		P_{i4} and P_{i5} – none	Five-port symmetrical inclusion for independent equipotential protection of each element.
	4		P_{i4} and P_{i5} – none $P_{13} + P_{33}$; $P_{23} + P_{43}$	Equipotential protection of current circuits, separately with high and low potential.
	5		P_{i4} and P_{i5} – none $P_{13} + P_{52} +$ $P_{53} + P_{22}$	Separate equipotential protection of current and potential circuits.
	6		P_{i4} and P_{i5} – none P_{52} and P_{53} – none	Equipotential protection of the communication line to a sensitive element.

The most effective and promising approach is to combine the methods of bifiling signals and their equipotential protection, which is achieved by combining schemes *1* and *6* of Table 3. Accordingly, there is a need to identify a new type of multi-terminal object.

The new definition of the measurement object requires a new type of connection. According to the formula terminal×connector, this should be the type of terminal – 4×3 connector, as shown in Fig. 4. This object differs from the well-known four-terminal-pair object by the fact that each port is provided with a third connector for equipotential protection. By analogy with a "bi-shielded" cable, such measuring object can be called as a four-terminal coaxial bi-shielded one. Its connection scheme and designation of the modes on the connectors are represented in Fig. 4. Table lists additional requirements for voltages and currents at the connectors which are needed to define a four-terminal coaxial bi-shielded object.

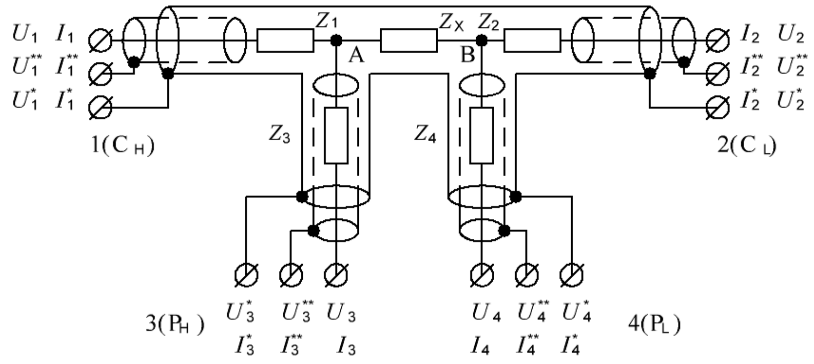


Fig. 4

Examples of coaxial bi-shielded bridges. To protect against leakage currents of the measuring circuit with inductive voltage dividers and the formation of protective potentials can be used special transformers, the secondary winding of which is made of shielded wire. This wire has a four-layer structure: flexible internal lead, insulation, screen and again insulation. In real devices, we used such a shielded cable in isolation with an outer diameter of 1.1 mm. This allows up to 30-35 turns to be performed on amorphous toroid core (dimensions 40×25×11 mm) without noticeable loss of magnetic coupling. Measuring circuits with such transformers and objects in Fig. 4 were called tri-axial [17], by analogy with a triaxial cable [10]. Further on, the authors admitted the opinion of the reviewers that the term ‘coaxial bi-shielded’ more closely corresponds to the physical essence of the proposed changes in an object. Therefore, by analogy with coaxial bridges [9], measuring networks with objects in Fig. 4 can be called as coaxial bi-shielded bridges. Here below we propose several variants of schemes for such bridges for thermometric and conductometric tasks. One of such variants is shown in Fig. 5 for temperature measurement with SPRT. The basis of the scheme is a two-stage transformer *T*2, the secondary windings of which (in the circuit of flow of working current its m_{21}, and in the circle of comparison of voltages its m_{22}) are made of shielded wire.

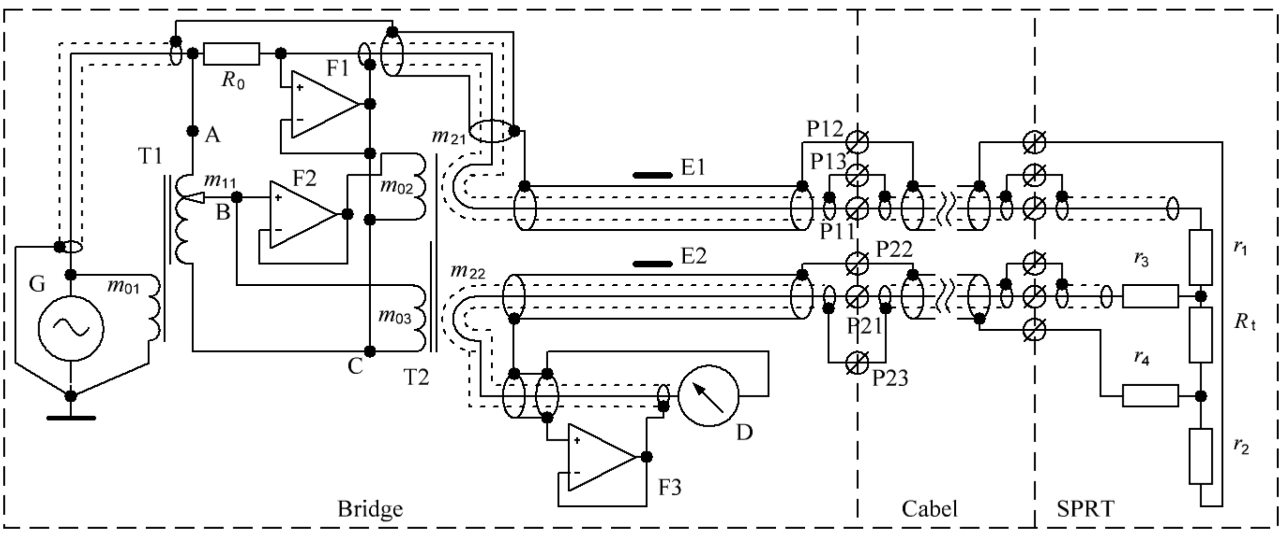
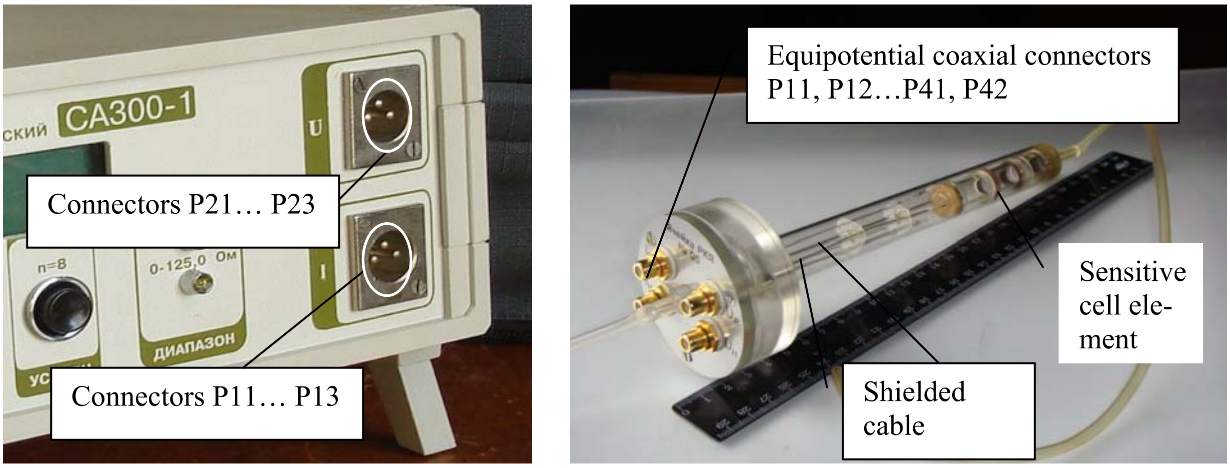


Fig. 5

The scheme is intended for operation in the range of non-cryogenic temperatures, where parameter r_2 indicates resistance of the wires inside the quartz tube of the standard platinum resistance thermometer (SPRT). Therefore, this resistance will be less than the resistance of the object R_t. In this case, the voltage drop across r_2 (Fig. 5) will be insignificant and, thus, there is no need to protect current and potential branches with low potential. In the scheme, the equipotential protection spreads not only throughout the device and cable, but also throughout some terminals to the sensitive element of the resistance thermometer, equalizers *E*1 and *E*2.

As a result, under these conditions, we may restrict ourselves to a type connection configuration 2×3. That is, two connectors (for current *P*11-*P*13 and potential circuit *P*21-*P*23, Fig. 5) with coaxial double shielding. In Fig. 6, *a* shows an example of a simpler, cheaper implementation of a connector that uses three terminals instead of coaxial double shielding. It is this type of connector has been used in thermometric bridge CA 300.

Upon precision conductivity measurements, the measurable temperature of the liquid is almost always stabilized with high accuracy. For this purpose, a conductivity sensor, such as a precision absolute 4T cell [11] with a calculated constant (Fig. 6, *b*), is placed in a thermostat. The metal box of a thermostat can serve as a shield from electrical and magnetic interference. However, for safety reasons, the housing must be grounded. Therefore, it can lock the capacitors' currents of the supply filter. For this reason it is impractical to use the thermostat housing as a housing for a four-pair connection.



a ***b***

Fig. 6

As such, it is possible to utilize a section of metal foil or mesh fixed just behind the quartz tube of a four-electrode cell, Fig. 6, *b*. In this case, the screen *S* (Fig. 7) will also be in the thermostat. Therefore, it is not advisable to pass reverse working current through it. But it can be used as a screen shell for protection against interference. The scheme of such equipotential protection of the precision reference cell is shown in Fig. 7. It realizes a 4×2 connection type, that is, four terminals with two coaxial connectors each. The scheme in Fig. 7 is implemented in the Ukrainian standard of the unit for electrolytic conductivity of liquids [18].

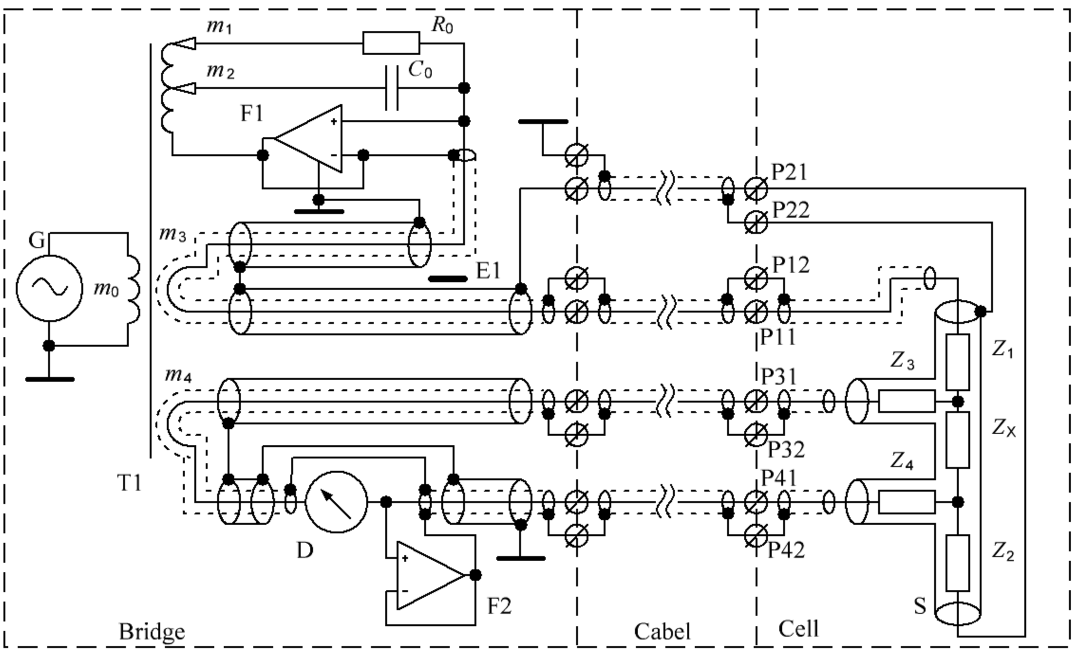


Fig. 7

It differs significantly from the well-known four-pair connection (Fig. 1) in that each of the shields has its own potential close to (ideally equal to) the potential of the central wire. Such connection enables full equipotential protection, including protection inside the sensor and the sensitive element itself, Fig. 6, *b*. That is, inside the device you can implement a coaxial bi-shielded connection but use a 4×2 cable configuration, or four terminals with two connectors. This will minimize the area of current and potential circuits, and therefore reduce the level of interference (including in-phase one) caused by the magnetic connections inside the device.

Thus, the use of the new definition of a coaxial bi-shielded measuring object and the formation of the necessary modes (Table 1) in the measuring networks of bridges allow to ensure the invariance of the measurement result to non-informative transverse admittance (Fig. 2) regardless of their magnitude with an error (1.0 – 0.1) ppm. This corresponds to the LBS of precision thermometry or conductivity bridges.

Conclusion. The scheme of known coaxial bridges (in the sense of Kibble's [9]) consists of two separate contours (frame), as if strung on top of each other. The first contour of the main is a classic four-armed bridge (in the sense of Hague's [3]). The second contour is a system of wires through which the reverse currents of the bridge branches flow, which are maximally aligned with the first circuit. The new bridges we have considered differ in that a third contour is placed between the first and second contours of the coaxial bridge. This contour performs the functions of equipotential bonding signals in the middle of the measuring circuit as well as the cable and the measuring object.

The new definition of the object of measurement - four-terminal axial be-shielded (FTABS) object allows combining as effectively as possible the bifilization of signals and their equipotential protection for four-terminal impedances having the lead (snood) resistance are commensurate with the information resistance. For such objects, the proposed approach reduces the influence of transverse admittance to the level of sensitivity of instruments, allows the use of measuring cables of any length and has the same small measurement error as in the case of four-terminal pair networks.

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ЧОТИРИТЕРМІНАЛЬНІ АКСІАЛЬНІ ПОДВІЙНО-ЕКРАНОВАНІ ВИМІРЮВАЛЬНІ КОЛА

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Розглянуто імпедансний об'єкт вимірювання з Н-подібною чотиризатискною еквівалентною схемою заміщення. Проведено аналіз похибки для давачів, неінформативні опори підводу яких одного порядку або перевищують вимірюваний імпеданс. Запропоновано нове визначення чотиризатискного імпедансу, а саме чотиритермінальний аксіальний подвійно-екранований (FTABS) *об'єкт вимірювання. На основі нового визначення запропоновано схеми аксіальних подвійно-екранованих мостів для прецизійного вимірювання температури та електролітичної провідності рідин. Такі мости відрізняються від відомих коаксіальних мостів наявністю додаткового контура для еквіпотенційного захисту, що розміщується між контурами протікання прямого та зворотного струму.* Бібл. 18, рис. 7.

Ключові слова: імпеданс, модель, чотиризатискний об'єкт, вимірювальний міст.

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