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INSTRUMENTAL ERRORS OF TRANSMISSION LINE PARAMETERS METER

Introduction

Each measuring instrument should have a specific set of metrological characteristics. According to these characteristics, measuring instruments are selected for use in certain technological processes. These characteristics determine the reliability of the data obtained from the measurements. Such characteristics include a list of physical quantities that can be measured, the conditions under which the measurement process can be performed, metrological (information) reliability, accuracy class or permissible errors of the measuring instrument and others.

The meter of transmission line parameters, which was considered in [1; 2], is, in essence, a meter of impedance in the ranges of very high, ultra-high and super-high frequencies. That is, its capabilities go beyond measuring only transmission line parameters. In addition, its ability to operate in a wide frequency band enables measurement of the frequency dependences of the input impedances of microwave devices.

The conditions under which such measuring instruments can be used depend on the device's design and technical implementation since the method of measurement and its implementation in the electrical circuit are not accompanied by special requirements for the device's operation. That means such a device can be manufactured with a focus on laboratory use, for use in the mobile version and the field, for use in complex electronic systems as an element of built-in control, and so on. All this follows from the above method of measurement and analysis of the meter's synthesized circuit [1; 2]. In paper [1] has not considered the measuring device's accuracy characteristics, limiting its implementation in practice. Therefore, this article focused on researching the transmission line parameters meter's instrumental errors to overcome this problem.

Analysis of Recent Research and Publications

There is a large number of scientific works devoted to the study and measurement of parameters and operation modes of transmission lines with various configurations, as well as devices built on their basis [3–6]. The main emphasis in the area of radio measurements is placed on the determination of the reflection coefficient, travelling wave ratio, the impedance of microwave network, the transmission coefficient of microwave two-port network and their dependence on frequency [7; 8]. The estimation of some parameters of transmission lines can only be done indirectly. For each specific case, it is necessary to develop an indirect measurement program, which depends on the frequency band and the design of the transmission line. Also, in the literature, a description of the procedure for assessing the main errors that arise during the measurement process was not found.

Problem Statement

The accuracy feature of any measurement has two critical components, there are method error and instrumental error [9]. Firstly, it is necessary to build a mathematical model of measuring equipment to build these dependencies on the parameters of physical or structural hardware components and values of measured quantities. If the mathematical model corresponds to a real device, then, obviously, it is possible to take into account all aspects of influences on the process of obtaining measurement data. Nevertheless, with this approach, the mathematical model is quite complicated, and its analysis encounters significant difficulties. In this regard, it is advisable to limit the construction of a mathematical model, which considers the dominant factors of accuracy characteristics that cause first-order errors. Such a model, depending on the needs that will arise during the measuring instrument's operation, can be supplemented by specific influence sources. These certain causal actions cause errors of the second and even third-order [10]. These are errors caused by changes in temperature, humidity, atmospheric pressure, mechanical vibrations, electromagnetic and acoustic fields and others.

The Purpose of the Article

The purpose of the article is to plot the dependences of the instrumental errors of the transmission line parameters meter on the parameters of the physical or structural hardware components of the meter. For this, when constructing a mathematical model, the main functional connections between the structural links of the measuring device are limited, neglecting the influence of external factors on the stability of the parameters of structural elements.

Construction of a simplified model of the transmission line parameters meter

It is necessary to limit the primary functional connections between the measuring device's structural units, neglecting the external factors' effects on the stability of the parameters of structural elements. That makes it possible to present the transmission line parameter meter in the form of a reasonably simple block diagram (Fig. 1).

The power supply includes a generator (G), the frequency of which on the processor instructions can change in the given range, and a frequency meter (FM) that constantly monitors the frequency of electromagnetic waves of the power supply transmits the results of frequency measurements to the processor.

The transducer is a sector of the transmission line loaded to the object of study (ultra-high frequency two-pole or four-pole, feeder, coaxial cable, waveguide and others). The two probes are introduced into the transmission line section, on the terminals of which voltages are generated [11]

$$\left.\begin{aligned} \dot{U}_1 &= \dot{U}_{inc} e^{i\beta_c z_0} + \dot{U}_{ref} e^{-i\beta_{tl} z_0}; \\ \dot{U}_2 &= \dot{U}_{inc} e^{i\beta_c (d+z_0)} + \dot{U}_{ref} e^{-i\beta_{tl} (d+z_0)}, \end{aligned}\right\}, \qquad (1)$$

where $\dot{U}_{inc} = l_{pr}\mathring{A}_{inc}$ is the incident voltage at the probe terminals; l_{pr} is the probe transfer coefficient from the electric field inside the section to the voltage at the terminals; $\mathring{A}_{inc}$, $\mathring{A}_{ref}$ are electric field intensities of the incident and reflected waves inside the transmission line section; $\dot{U}_{ref} = l_{pr}\mathring{A}_{ref}$ is reflected wave voltage at the probe terminals; $\beta_{tl} = 2\pi/\Lambda_{tl}$ is phase coefficient in the transmission line section; Λ_{tl} is the wavelength in the transmission line section; d is the distance between probes; z_0 is the distance from the probe to the cross-section where the object of study joins.

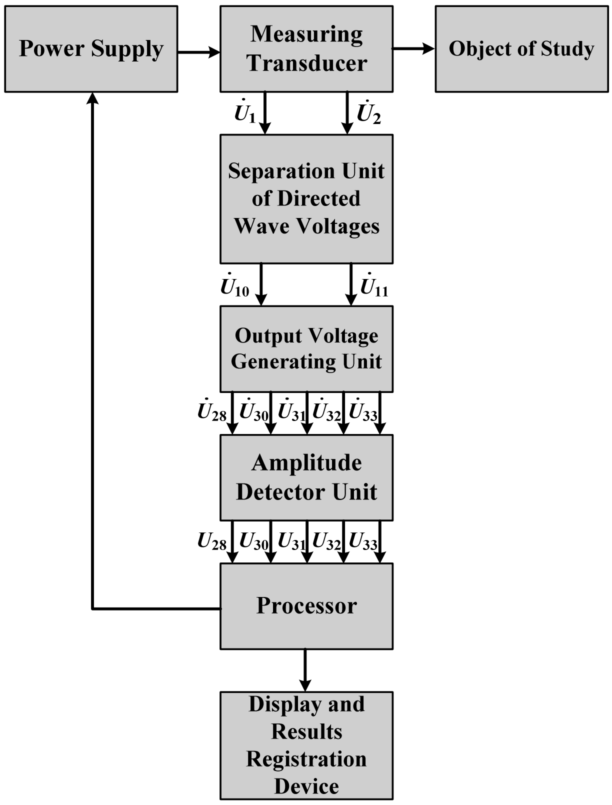

Fig. 1. Block diagram of the transmission line parameters meter

The separation unit of directed wave voltages is built on the linear elements of ultrahigh frequencies: tees T_1 and T_2, segments of transmission lines *ab*, *cd*, *fg* and adders Σ_1 and Σ_2 (Fig. 2[2]).

The voltage designations in the diagram in Fig. 1 coincide with the notation used in the meter block diagram, which is given in [1; 2].

Therefore, when constructing this unit from the elements with precisely set transmission coefficients, the operation principle of the unit is described by the following equation

$$\begin{bmatrix}\dot{U}_{10}\\ \dot{U}_{11}\end{bmatrix} = \begin{bmatrix} -e^{-i(\varphi_1+\varphi_2)} & e^{-i\varphi_2}\\ 1 & -e^{-i\varphi_1}\end{bmatrix}\times\begin{bmatrix}\dot{U}_1\\ \dot{U}_2\end{bmatrix} = e^{-i\beta_{tl}(d+z_0)}\sin\beta_{tl} d \begin{bmatrix}\dot{U}_{inc}\\ \dot{U}_{ref}\end{bmatrix}, \qquad (2)$$

where $\varphi_1 = \beta_{tl} d$ is the phase shift that the waves acquire when passing through the lines segments *ab* and *cd*; $\varphi_2 = \beta_{tl}(d + 2z_0)$ is the phase shift that the waves acquire when passing through the line segment *fq* [1].

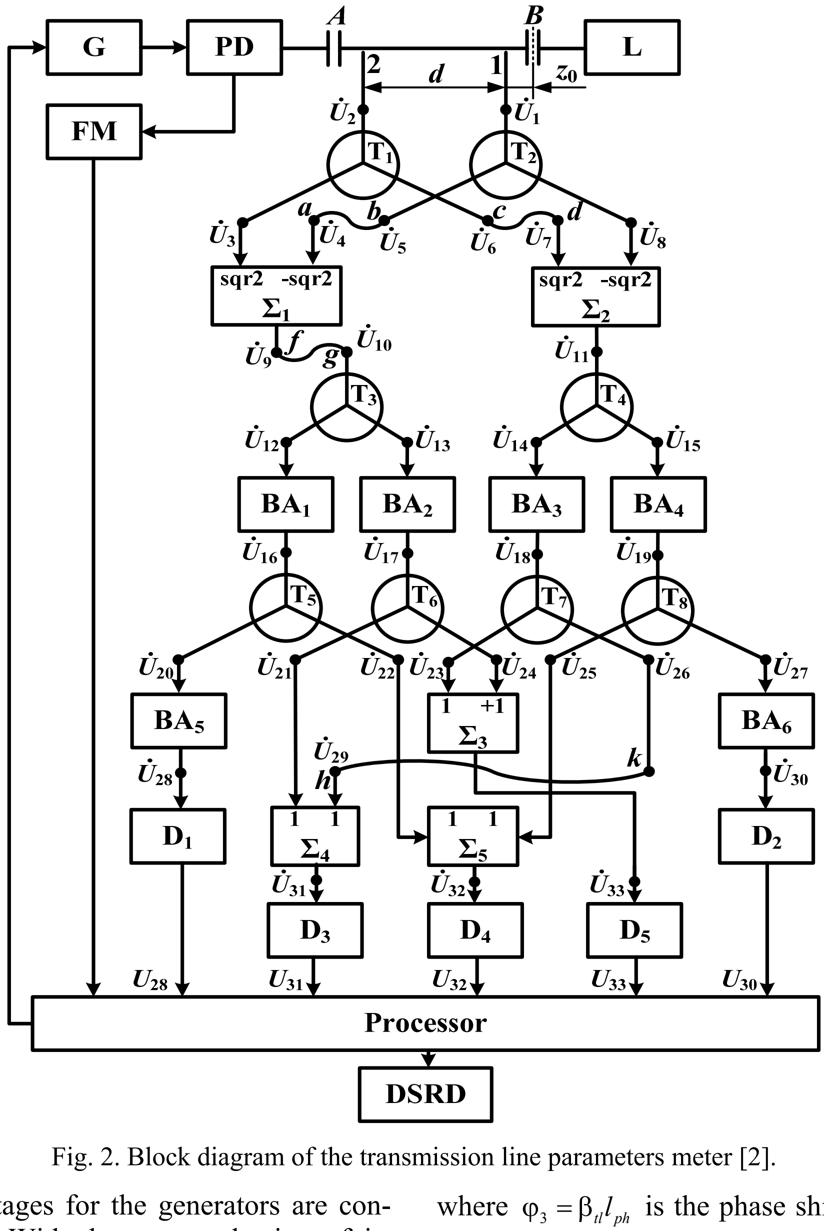

Fig. 2. Block diagram of the transmission line parameters meter [2].

The output voltages for the generators are constructed similarly. With the exact selection of its parameters, the voltages at its output are defined as

$$\begin{bmatrix}\dot{U}_{28}\\ \dot{U}_{30}\\ \dot{U}_{31}\\ \dot{U}_{32}\\ \dot{U}_{33}\end{bmatrix} = \begin{bmatrix}1 & 0\\ 0 & 1\\ 1 & e^{-i\varphi_3}\\ 1 & 1\\ 1 & -1\end{bmatrix}\times\begin{bmatrix}\dot{U}_{10}\\ \dot{U}_{11}\end{bmatrix}, \qquad (3)$$

where $\varphi_3 = \beta_{tl} l_{ph}$ is the phase shift, which is used to determine the sign of the reactive component of the load input impedance; l_{ph} is the length of the phase-correcting line.

The transfer coefficients of the amplitude detector unit for all five channels are equal to the same value t_D. We can assume that this transfer coefficient t_D is equal to one.

Then for the voltages at the outputs of the detector unit, it is possible to write that $U_{28} = \left|\dot{U}_{28}\right|$, $U_{30} = \left|\dot{U}_{30}\right|$, $U_{31} = \left|\dot{U}_{10} + \dot{U}_{11} e^{-i\varphi_3}\right|$, $U_{32} = \left|\dot{U}_{10} + \dot{U}_{11}\right|$, $U_{33} = \left|\dot{U}_{10} - \dot{U}_{11}\right|$.

The parameters of the transmission line are calculated by the processor using the following functional equations [1]:

– modulus of the reflection coefficient

$$\Gamma_l = \dot{U}_{30} / \dot{U}_{28}, \qquad (4)$$

– where the index «*n*» becomes «0» for the shorted line and «∞» for the open transmission line;

– the phase of the reflection coefficient

$$\varphi_l = \arccos \frac{U_{32}^2 - U_{33}^2}{4U_{28}U_{30}}; \qquad (5)$$

– the active component of the load impedance of the measuring section

$$R_l = W_{m.s} \frac{U_{28}^2 - U_{30}^2}{U_{33}^2}; \qquad (6)$$

– reactive component of the load impedance

$$X_l = W_{m.s} \frac{2U_{28}U_{30}\sin\varphi_l}{U_{33}^2}; \qquad (7)$$

– the characteristic impedance of the transmission line (object of study)

$$Z_{tl} = \sqrt{(R_0 + iX_0)(R_\infty + iX_\infty)}; \qquad (8)$$

– immittances of transmission line under ultimate loads

$$Y_{ll} = \sqrt{\frac{X_0 X_\infty}{R_0^2 (X_\infty - X_0)^2 + X_0^2 (X_\infty + X_0)^2}}; \qquad (9)$$

– attenuation coefficient

$$\alpha = \frac{1}{2l} \mathrm{Arsh}(2R_0 Y_{ll}), \qquad (10)$$

where l is the length of the investigated transmission line,

– wave phase coefficient in the line

$$\beta = \frac{1}{2l}\left[\arcsin(2X_0 Y_{ll}) + 2\pi q\right], \qquad (11)$$

where q is an integer, which is calculated according to the method considered in [1].

These relations are the basis of the creation of a metrological model of the device. Analysis of functional relations between voltages in such a model allows determining the transmission line parameters meter's methodological and instrumental errors.

Dependences of instrumental errors of the meter

Real relations between voltages, real matrices of transmissions in equations (2) and (3) can be established using the transmission coefficients of the physical elements on which the measuring device is built. As noted earlier, the main analogue part, namely, the separation unit of directed wave voltages and the output voltage generation unit, consist of tees, phase-correcting lines, adders and buffer amplifiers (BA). Therefore, the designation of nominal voltage transmission coefficients for these elements is introduced. Then, the transmission coefficient from the matched input arm of the tee to the output arm is $t_T = 1/\sqrt{2}$. It was assumed that each arm's transmission coefficient is set regardless of the other arm's transmission coefficient. The correlation of transmission coefficient errors for the outputs of the same tee was neglected.

The transmission coefficient of the phase-correcting line is denoted as $t_{ph}^{(p)}$, where $p = 1,2,3$ is the line number. That is $t_{ph}^{(1)} = e^{-i\beta_{tl} d}$, $t_{ph}^{(2)} = e^{-i\beta_{tl}(d+2z_0)}$ and $t_{ph}^{(3)} = e^{-i\beta_{tl} l_{ph}}$.

It has already been noted that the line segments, which are part of the measuring device, can have noticeable attenuation coefficients. However, it is better to use all the elements of ultra-high frequencies as lossless, which does not lead to difficulties in the device's physical implementation.

The active elements of the researched device are adders and buffer amplifiers. In the general case, the adder's transfer coefficient can be denoted as $t_{\Sigma_q}^{(p)}$, where $p = 1,2,...,5$ is the number of the adder and $q = 1,2$ is the number of the input arm. The transmission coefficients' nominal values are $t_{\Sigma_1}^{(1)} = \sqrt{2} = t'_\Sigma$ for the left input and $t_{\Sigma_2}^{(1)} = -\sqrt{2} = -t'_\Sigma$ the right input if $p = 1$. The transfer coefficients of the second adder ($p = 2$) have the same absolute values $t_{\Sigma_1}^{(2)} = -\sqrt{2} = -t'_\Sigma$ and $t_{\Sigma_2}^{(2)} = \sqrt{2} = t'_\Sigma$. The transfer coefficients of the third adder are defined as $t_{\Sigma_1}^{(3)} = 1 = t''_\Sigma$ and $t_{\Sigma_2}^{(3)} = -1 = -t''_\Sigma$. The other adders transfer coefficients are the same signs and module, that is $t_{\Sigma_1}^{(4)} = t_{\Sigma_2}^{(4)} = t_{\Sigma_1}^{(5)} = t_{\Sigma_2}^{(5)} = 1 = t''_\Sigma$.

Buffer amplifiers (BA_1-BA_6) provide matching arms of tees with a load and equalize amplitudes of the voltage. Their transfer coefficients have the following values $t_{BA}^{(1)} = t_{BA}^{(2)} = t_{BA}^{(3)} = t_{BA}^{(4)} = 2 = t'_{BA}$ and $t_{BA}^{(5)} = t_{BA}^{(6)} = 1 = t''_{BA}$.

Using the notation entered of the transfer coefficients and the block diagram of the device, the equations (2) and (3) are written in the form

$$\begin{bmatrix} \dot{U}_{10} \\ \dot{U}_{11} \end{bmatrix} = T_1 \begin{bmatrix} -t_{ph}^{(1)} t_{ph}^{(2)} & t_{ph}^{(2)} \\ 1 & -t_{ph}^{(1)} \end{bmatrix} \times \begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \end{bmatrix}; \qquad (12)$$

$$\begin{bmatrix} \dot{U}_{28} \\ \dot{U}_{30} \\ \dot{U}_{31} \\ \dot{U}_{32} \\ \dot{U}_{33} \end{bmatrix} = T_2 \begin{bmatrix} t''_{BA} & 0 \\ 0 & t''_{BA} \\ t''_{\Sigma} & t_{ph}^{(3)} t''_{\Sigma} \\ t''_{\Sigma} & t''_{\Sigma} \\ t''_{\Sigma} & -t''_{\Sigma} \end{bmatrix} \times \begin{bmatrix} \dot{U}_{10} \\ \dot{U}_{11} \end{bmatrix}, \qquad (13)$$

where $T_1 = t_T t'_{\Sigma}$ і $T_2 = t_T t'_{BA} t_T$. The nominal values of the rendered multipliers of transfer matrices are equal $T_1 = 1$ and $T_2 = 1$.

The voltages used in the processor to calculate the transmission line parameters are formed by the passage of signals with voltages (13) through five independent channels of the amplitude detector unit with transmission coefficients t_D. At the outputs of the amplitude detectors, taking into account the matrix equation (13), we obtain

$$\left.\begin{aligned} U_{28} &= t_D t''_{BA} T_2 U_{10}; \\ U_{30} &= t_D t''_{BA} T_2 U_{11}; \\ U_{31} &= t_D t''_{\Sigma} T_2 \sqrt{U_{10}^2 + U_{11}^2 + 2U_{10}U_{11}\cos(\varphi_l - \varphi_{ph})}; \\ U_{32} &= t_D t''_{\Sigma} T_2 \sqrt{U_{10}^2 + U_{11}^2 + 2U_{10}U_{11}\cos\varphi_l}; \\ U_{33} &= t_D t''_{\Sigma} T_2 \sqrt{U_{10}^2 + U_{11}^2 - 2U_{10}U_{11}\cos\varphi_l}, \end{aligned}\right\} \qquad (14)$$

where $U_{10} = |\dot{U}_{10}|$ and $U_{11} = |\dot{U}_{11}|$ are amplitude values of voltages.

Equations (1), (12), (13) and (14) fully describe the analogue part of the transmission line parameter meter. Since the accuracy of calculating the parameters at the exact value of the input voltages ($U_{28}, U_{30}, \ldots, U_{33}$) can be made relatively high, it is evident that the device's analogue units determine the errors in measuring the parameters. This fact makes it possible to ignore the errors in the calculation process of the processor's parameter values.

The basic principles by which the method of measuring the parameters of the transmission line parameters are built do not hide any approximations, simplifications or neglect of the values, the impact of which could be attributed to the effects of the second order. This means that in the operation principle of the device, there are no methodical errors. When constructing the device with an accurate selection of the transmission line parameters transmission coefficients, individual components are estimated without errors. It should be noted that the transmission coefficients of structural elements are not idealized.

The meter is based on real dissipative multipoles (measuring sections of the transmission line, tees, phase-correcting lines). Therefore, the main metrological characteristics of the device are instrumental error and voltage measurement error.

From equations (3) and (13), the errors of the output voltages, where it is necessary to take into account the measurement error, are determined by the accuracy of voltage measurements $\dot{U}_{10}$ and $\dot{U}_{11}$. These are instrumental errors to determine them it was assumed that the transmission coefficients of tees, adders, buffer amplifiers and detectors in the operating frequency range are real values. That is, the transfer coefficients do not affect the phase relations between voltages. Phase correction lines only affect phase shifts of voltages and do not change their amplitudes. With this idealization of the scheme, relatively simple expressions for the calculation of instrumental errors can be obtained.

It is necessary to substitute in equations (12) the values of voltages $\dot{U}_1$ and $\dot{U}_2$ from (1) and to represent the transfer coefficients of phase-correcting lines in the form to estimate the phase shift error

$$\left.\begin{aligned} t_{ph}^{(1)} &= \exp[-i\beta_{tl}(d + \Delta d)]; \\ t_{ph}^{(2)} &= \exp[-i\beta_{tl}(d + 2z_0 + \Delta d + 2\Delta z_0)], \end{aligned}\right\}$$

where Δd і Δz_0 are errors in the lengths of phase-correcting lines. These errors in the manufacture of line segments using printing technology can be reduced to very small values. The resulting voltages are presented as the sum of the actual values and errors.

1. In the channel of the incident wave

$$\dot{U}_{10} = \dot{U}_{10}^0 + \Delta\dot{U}_{inc10} + \Delta\dot{U}_{ref10}, \qquad (15)$$

where $$\dot{U}_{10}^0 = i2\dot{U}_{inc} e^{-i\beta_{tl}(d+z_0)} \sin\beta_{tl} d \qquad (16)$$

is the voltage component of $\dot{U}_{10}$ without instrumental error (exact value);

$$\Delta\dot{U}_{inc10} = i\dot{U}_{10}^0 \beta_{tl}(3\Delta d/2 + 2\Delta z_0) \qquad (17)$$

is the error due to the deviation of the phase shift of the incident wave in the phase-correcting segments of the line from the exact value;

$$\Delta\dot{U}_{ref10} = i\dot{U}_{ref}\beta_{tl}\Delta d e^{i[\varphi_l - \beta_{tl}(2d + z_0)]} \qquad (18)$$

is the voltage component of $\dot{U}_{10}$ specified for the inaccuracy of the compensation of the reflected waves at the adder's output in the separation channel of the incident wave. It was accepted that $\dot{U}_{inc} = U_{inc} e^{i\omega t}$ and $\dot{U}_{ref} = U_{ref} e^{i\omega t}$.

2. In the channel of the reflected wave

$$\dot{U}_{11} = \dot{U}_{11}^{0} + \Delta\dot{U}_{ref11} + \Delta\dot{U}_{inc11}, \qquad (19)$$

where $$\dot{U}_{11}^{0} = i2\dot{U}_{ref} e^{-i[\varphi_l - \beta_{tl}(d+z_0)]} \sin\beta_{tl} d \qquad (20)$$

is the exact value of the incident wave voltage;

$$\Delta\dot{U}_{ref11} = i2\dot{U}_{ref} e^{-i[\varphi_l - \beta_{tl}(d+z_0)]} \beta_{tl} \frac{\Delta d}{2} e^{-i\beta_{tl} d} \qquad (21)$$

is an error in the phase shift of the reflected wave;

$$\Delta\dot{U}_{inc11} = i\dot{U}_{inc} \beta_{tl} \Delta d e^{i\beta_{tl} z_0} \qquad (22)$$

is an uncompensated proportion of the incident wave in the voltage wave $\dot{U}_{11}$.

As can be seen from expressions (16) and (20), the voltage ratio $\dot{U}_{11}^{0}$ to $\dot{U}_{10}^{0}$ determine the modulus and phase of the reflection coefficient without errors. The additional phase shift, which the incident wave receives propagating in the device, is determined by formulas (17) and (18). Since the reflected wave voltage module (18) is several times smaller than the voltage module (17), it is possible to ignore the component (18) and write the following

$$\dot{U}_{10} \cong \dot{U}_{10}^{0} + \Delta\dot{U}_{inc10} = i2\dot{U}_{inc} e^{-i[\beta_{tl}(d+z_0) - \Delta\varphi_l']} \sin\beta_{tl} d, \qquad (23)$$

where $\varphi_l' = \beta_{tl}(3\Delta d/2 + 2z_0)$.

Both components (21) and (22) need to be accounted for in the reflected wave voltage (19) as they have proportional values. Using relations (21) and (22), the voltage $\dot{U}_{11}$ (19) is represented as

$$\dot{U}_{11} = \dot{U}_{11}^{0} p e^{i\Delta\varphi_l''}, \qquad (24)$$

where $\Delta\varphi_l'' = \mathrm{arctg}\left[\frac{n\sin(\beta_{tl} d + \chi)}{1 + n\cos(\beta_{tl} d + \chi)}\right]$;

$$p = \sqrt{1 + n^2 + 2n\cos(\beta_{tl} d + \chi)}; \; n = \frac{m\beta_{tl}\Delta d}{2\Gamma\sin\beta_{tl} d};$$

$$m = \sqrt{1 + \Gamma^2 + 2\Gamma\cos(\varphi_l - 2\beta_{tl} z_0)};$$

$$\chi = \mathrm{arctg}\left[-\frac{\sin(\varphi_l - 2\beta_{tl} z_0)}{\Gamma + \cos(\varphi_l - 2\beta_{tl} z_0)}\right]; \; \Gamma = U_{ref}/U_{inc}$$

is the modulus of the reflection coefficient.

According to the expressions (23) and (24), it follows that the instrumental error of the reflection coefficient phase is equal to $\Delta\varphi_{l1} = \Delta\varphi_l' + \Delta\varphi_l''$.

When measuring the parameters of the transmission lines, the modulus of the reflection coefficient is close to one, because the object of study at low losses in short-circuit and idling has a significant reactive component of the input impedance, which is much larger than the active component.

Formulas (16), (20), (23) and (24) determine the operating frequency band, in which the errors will be included in the permissible values. These formulas include the function $\sin\beta_{tl} d$ that significantly affects the sensitivity to changes in phase-correcting lines' geometric parameters. Suppose the requirements for measurement accuracy are provided when reduced $\sin\beta_{tl} d$ to 0.5. In that case, the operating frequency band from $(\beta_{tl} d)_{\min} = 30°$ to $(\beta_{tl} d)_{\max} = 150°$ the operating frequency band will reach an overlap five times.

The resulting voltage expressions $\dot{U}_{10}$ and $\dot{U}_{11}$, and the phase shift of these voltages form a basis for the accuracy analysis of measurement calculations. Since the initial data on the research object's parameters are determined by the voltages, which are given in the left part of the matrix equation (13), it is advisable to estimate the errors of these voltages. These errors will have two components: instrumental error and voltage measurement error. Hence

$$\left.\begin{aligned} \Delta U_{28} &= \Delta T_3 U_{10} + \Delta U_{10} + \Delta U_{10}^{m} = \\ &= (\Delta T_1 + \Delta T_3) U_{10} + \Delta U_{10}^{m}; \\ \Delta U_{30} &= \Delta T_3 U_{11} + \Delta U_{11} + \Delta U_{11}^{m} = \\ &= (\Delta T_1 + p - 1 + \Delta T_3) U_{11} + \Delta U_{11}^{m}, \end{aligned}\right\} \qquad (25)$$

where $\Delta T_3 = T_3(\delta t_D + 2\delta t_{BA} + 2\delta t_T + \delta t_\Sigma)$ is the sum of the relative instrumental errors of the transfer coefficients of detectors, buffer amplifiers, tees and adders; ΔU_{10}^{m} and ΔU_{11}^{m} are absolute errors of voltage measurement U_{28} and U_{30}, whose exact values are equal to $U_{28} = U_{10}$ and $U_{30} = U_{11}$.

The error of creating and measuring voltage U_{31} is defined as

$$\Delta U_{31} = \Delta T_4 U_{31} + K_{31}^{10}\Delta U_{10} + K_{31}^{11}\Delta U_{11} + $$
$$+ K_{31}^{\varphi}(\Delta\varphi_{l1} + \Delta\varphi_{ph}) + \Delta U_{31}^{m},$$

where $\Delta T_4 = T_4(\delta t_D + \delta t_{BA} + 2\delta t_T + \delta t_\Sigma)$ is the instrumental error of the transfer coefficient of series-connected detectors, tees, buffer amplifiers and adders; $K_{31}^{10} = (U_{10} + U_{11}\cos(\varphi_l - \varphi_{ph}))/U_{31}$ is the sensitivity [12] of voltage U_{31} to voltage deviations U_{10} from the exact (nominal) value; $K_{31}^{11} = (U_{11} + U_{10}\cos(\varphi_l - \varphi_{ph}))/U_{31}$ is the sensitivity of voltage U_{31} to voltage deviations U_{11} from the exact value; $K_{31}^{\varphi} = U_{10}U_{11}\sin(\varphi_l - \varphi_{ph})/U_{31}$ is the sensitivity of voltage U_{31} to deviations of the cosine function argument from the exact value; $\Delta\varphi_{ph} = \beta_{tl} l_{ph}(\delta l_{ph} + \delta\Lambda)$ is the instrumental error of the wave phase shift in the phase-correcting segment of the transmission line with the transfer coefficient $t_{ph}^{(3)}$; $\delta\Lambda$ is the relative deviation of the wavelength from the exact value; δl_{ph} is the relative error in the geometric length of the line; ΔU_{31}^{m} is the absolute value of measurement error of the voltage U_{31}.

Similar expressions are for the voltage U_{32}:

$$\Delta U_{32} = \Delta T_4 U_{32} + K_{32}^{10}\Delta U_{10} + K_{32}^{11}\Delta U_{11} + + K_{32}^{\varphi}\Delta\varphi_{l1} + \Delta U_{32}^{m},$$

where $K_{32}^{10} = \left(U_{10} + U_{11}\cos\varphi_l\right)/U_{32}$; $K_{32}^{11} = \left(U_{11} + U_{10}\cos\varphi_l\right)/U_{32}$; $K_{32}^{\varphi} = U_{10}U_{11}\sin\varphi_l/U_{32}$; $\Delta U_{32}^{m} = U_{32}\delta U^{m}$; δU^{m} is the relative error of voltage measurement.

The voltage error ΔU_{33} is estimated similarly to the error ΔU_{32}

$$\Delta U_{33} = \Delta T_4 U_{33} + K_{33}^{10}\Delta U_{10} + K_{33}^{11}\Delta U_{11} + + K_{33}^{\varphi}\Delta\varphi_{l1} + \Delta U_{33}^{m},$$

where $K_{33}^{10} = \left(U_{10} - U_{11}\cos\varphi_l\right)/U_{33}$; $K_{33}^{11} = \left(U_{11} - U_{10}\cos\varphi_l\right)/U_{33}$; $K_{33}^{\varphi} = U_{10}U_{11}\sin\varphi_l/U_{33}$.

The calculation error of the modulus of the reflection coefficient is obtained using formulas (4) and (25)

$$\Delta\Gamma_l = \Gamma_l\left(2\Delta T_1 + p - 1 + 2\Delta T_3 + 2\delta U^{m}\right).$$

According to formula (5), it follows that the error for determining the phase of the reflection coefficient is equal to

$$\Delta\varphi_l = \frac{1}{\sin\varphi_l}\left[\begin{matrix}\frac{1}{2U_{28}U_{30}}\left(U_{32}\Delta U_{32} + U_{33}\Delta U_{33}\right) + \\ + \cos\varphi_l\left(2\Delta T_1 + p - 1\right)\end{matrix}\right].$$

The errors obtained by this formula make no sense when $|\varphi_l| = 0,\ \pi,\ 2\pi$. In this regard, it is advisable to use expressions that calculate $\sin\varphi_l$ and $\cos\varphi_l$. From formula (5) we obtain

$$\Delta(\cos\varphi_l) = \frac{1}{2U_{28}U_{30}}\left(U_{32}\Delta U_{32} + U_{33}\Delta U_{33}\right) + + \cos\varphi_l\left(2\Delta T_1 + p - 1\right).$$

The dependence of the function $\sin\varphi_l$ on the output voltages has the form

$$\sin\varphi_l = \frac{2U_{31}^2 - \left(U_{32}^2 + U_{33}^2\right) - \left(U_{32}^2 - U_{33}^2\right)\cos\varphi_{ph}}{4U_{28}U_{30}\sin\varphi_{ph}}.$$

From this dependence we find

$$\Delta(\sin\varphi_l) = \frac{1}{2U_{28}U_{30}\sin\varphi_{ph}}[2U_{31}\Delta U_{31} + + U_{32}\left(1 + \cos\varphi_l\right)\Delta U_{32} + + U_{33}\left(1 - \cos\varphi_l\right)\Delta U_{33}] + \sin\varphi_l\left(2\Delta T_1 + p - 1\right) + + \left|\frac{\cos\varphi_l - \cos\left(\varphi_l - \varphi_{ph}\right)\cos\varphi_{ph}}{\sin^2\varphi_{ph}}\right|\Delta\varphi_{ph}. \quad (26)$$

When deriving formula (26), fractional-rational expressions were replaced according to formulas (5) and (16) by trigonometric functions and the following ratio was used

$$\cos\left(\varphi_l - \varphi_{ph}\right) = \frac{2U_{31}^2 - \left(U_{32}^2 + U_{33}^2\right)}{4U_{28}U_{30}}.$$

The calculation error of the active component of the input impedance of the research object is determined by relation (6)

$$\Delta R_l = W_{m.s}R_l\left(\delta W_{m.s} + 2\delta U_{33}\right) + + 2\frac{W_{m.s}}{U_{33}^2}\left(U_{28}\Delta U_{28} + U_{30}\Delta U_{30}\right).$$

Based on the expression (7), the absolute calculation error of the reactive component of the input impedance is found

$$\Delta X_l = W_{m.s}X_l\left(\delta W_{m.s} + 2\delta U_{33}\right) + + 2\frac{W_{m.s}}{U_{33}^2}\left[U_{30}\Delta U_{28} + U_{28}\Delta U_{30} + U_{28}U_{30}\Delta\left(\sin\varphi_l\right)\right].$$

Based on the transmission line parameters, the calculation error for the characteristic impedance formula (8) is equal to

$$\Delta Z_{tl} = Z_{tl}\left(\frac{\Delta R_0 + i\Delta X_0}{Z_0} + \frac{\Delta R_\infty + i\Delta X_\infty}{Z_\infty}\right),$$

where Z_0 is the input impedance of the investigated transmission line short circuit (the load impedance of the measuring section with a short transmission line), which is calculated by formulas (6) and (7) with the replacement of the index «*l*» by the index «0»; Z_∞ is the input impedance of the open transmission line.

The limit loads' immittance (9) is used to determine the attenuation coefficient and the wave phase coefficient. The error in calculating the immittance of the ultimate loads is equal to

$$\Delta Y_{ll} = K_{ll}^{R}\Delta R_0 + K_{ll}^{0}\Delta X_0 + K_{ll}^{\infty}\Delta X_\infty,$$

where the sensitivity coefficients are defined as

$$K_{ll}^{R} = Y_{ll}^{3}\frac{\left(X_0 - X_\infty\right)^2 R_0}{X_0 X_\infty};$$

$$K_{ll}^{0}=\frac{Y_{ll}}{2X_0}+Y_{ll}^{3}\left[\frac{R_0^2-X_0^2}{X_0}-\frac{R_0^2+\left(X_0+X_\infty\right)^2}{X_\infty}\right];$$

$$K_{ll}^{\infty}=\frac{Y_{ll}}{2X_\infty}-\frac{Y_{ll}^{3}}{X_0}\left(R_0^2+X_0^2\right)+\frac{Y_{ll}^{3}}{X_\infty}\left(R_0^2-X_0^2\right).$$

The sensitivity coefficients of the immittance of the limit loads are [Ohm]$^{-2}$.

The measurement errors of the attenuation coefficient (10) are defined as

$$\Delta\alpha=\frac{\Delta l}{2l}\alpha+\frac{2R_0Y_{ll}}{2l\sqrt{1+\left(2R_0Y_{ll}\right)^2}}\left(\frac{\Delta R_0}{R_0}+\frac{\Delta Y_{ll}}{Y_{ll}}\right).$$

The error of the wave phase coefficient (11) has a similar structure

$$\Delta\beta=\frac{\Delta l}{2l}\beta+\frac{2X_0Y_{ll}}{2l\sqrt{1-\left(2X_0Y_{ll}\right)^2}}\left(\frac{\Delta X_0}{X_0}+\frac{\Delta Y_{ll}}{Y_{ll}}\right),$$

$$\Delta\left(\sin 2\beta l\right)=2X_0Y_{ll}\left(\frac{\Delta X_0}{X_0}+\frac{\Delta Y_{ll}}{Y_{ll}}\right). \qquad (27)$$

It should be noted that expressions (15) and (19) do not take into account the error created due to the non-identity of the parameters of the probe in the measuring section of the transmission line. As follows from relations (1), this error affects the values ΔU_{inc10}, ΔU_{ref10}, ΔU_{inc11}, and ΔU_{ref11}. They can be practically compensated using probe tuning elements.

Conclusions

The main conclusions resulting from the analysis of the instrumental errors of the transmission line parameter meter are the following:

1. The operating frequency range of the device is determined by the permissible errors, which are a function of the frequency. That applies primarily to voltages $\dot{U}_{10}$ and $\dot{U}_{11}$, which respectively characterize the incident and reflected waves. It is necessary to produce phase-correcting lines with great accuracy and achieve a constant phase velocity of propagation of electromagnetic waves in all device elements to expand the operating frequency range.

2. The measuring device can operate in a self-monitoring mode. Both open circuit and short circuit mode must be used to measure the line section. Obviously, in these modes, the amplitudes of the incident and reflected waves must be equal to each other, and the phase of the reflection coefficient will take the values of 0 and π rad.

3. The attenuation coefficient's errors at any values of the ultimate loads' immittance and the active component of the input impedance of the studied transmission line change smoothly without emissions. The error of the wave phase coefficient has an extreme value at $\sin 2\beta l=1$. In this regard, it is more appropriate to use the error of estimation of the function $\sin 2\beta l$ formula (27). Regardless of the phase $2\beta l$, the right side of the expression (27), when its value is an order of magnitude less than one, can be considered as the angle error $2\beta l$.

4. The applied technique of separating incident and reflected waves makes it possible to measure the dependencies of the transmission line parameters on the frequency over a wide range.

REFERENCES

[1] Ільницький Л. Я., Щербина О. А., Петрова Ю. В., Заліський М. Ю., Кожохіна О. В. Вимірювач параметрів лінії передачі. *Вісник інженерної академії України*. 2020. №1. С. 64–70.

[2] Shcherbyna O., Ilnitskyi L., Petrova Y., Zaliskyi M., Kozhokhina O. Parameter Meter of Transmission Line. *Signal processing Symposium (SPSympo).* Proceedings of IEEE Symposium. (September 17–19, 2019. Krakow, Poland), pp. 1–4. DOI: 10.1109/SPS.2019.8882064.

[3] St. Legez A., Cecchi V., Basu M., Miu K., Nwankpa C. Automated system for determining parameter model of transmission line in a laboratory environment. *Measurement: Journal of the International Measurement Confederation*. 2016. Vol. 92. Pp. 1–10. DOI: 10.1016/j.measurement. 2016.05.064.

[4] Yu T., Liu D., Li Z., Miao J. Design of multistage power devider based on the theory of small reflections. *Progress in electromagnetics research letters*. 2016. Vol. 60. Pp. 23–30. DOI:10.2528/PIERL16011001.

[5] Ait Ou Kharraz M., Jensen P., Audebert V., Jeandin A., Lavenu C., Picard D., Serhir M. Experimental characterization of outdoor low voltage cables for narrowband power line communication. *Power Line Communications and its Applications (ISPLC)*. Proceedings of International Symposium. (March 20-23, 2016. Bottrop, Germany), pp. 138–143. DOI: 10.1109/ISPLC. 2016. 7476267.

[6] Santos Juan-C G., Torres-Torres R. Assessing the accuracy of the open, short and open-short deembedding methods for on-chip transmission line S-parameters measurements. *Devices, Circuits and Systems (ICCDCS).* Proceedings of International Caribbean Conference. (June 5–7, 2017. Cozumel, Mexico), pp. 57–60. **DOI:** 10.1109/ICCDCS.2017.7959720.

[7] Teppati V., Ferrero A., Sayed M. Modern RF and Microwave Measurement Techniques. Cambridge: University Press, 2013. 474 p.

[8] Кузнецов В. А. Измерения в электронике: Справочник. Москва: Энергоатомиздат,1987. 512 p.

[9] Боженко Л. І. Метрологія, стандартизація, сертифікація та акредитація: Навчальний посібник. Львів: Афіша, 2006. 324 с.

[10] Веников В. А. Теория подобия и моделирования. Москва: Высш. школа, 1976. 479 с.
[11] Ільницький Л. Я., Савченко О. Я., Сібрук Л. В. Антени та пристрої надвисоких частот: підручник для ВНЗ. Київ: Укртелеком, 2003. 496 с.
[12] Гехер К. Теория чувствительности и допусков электронных цепей. Москва: Сов. радио, 1973. 200 с.

Щербина О. А., Заліський М. Ю., Петрова Ю. В., Кожохіна О. В.
ІНСТРУМЕНТАЛЬНІ ПОХИБКИ ВИМІРЮВАЧА ПАРАМЕТРІВ ЛІНІЇ ПЕРЕДАЧІ

Стаття присвячена побудові залежностей інструментальних похибок вимірювача параметрів ліній передачі від параметрів фізичних або конструктивних апаратурних складових вимірювача. Для цього при побудові математичної моделі було вибрано тільки основні функціональні зв'язки між конструктивними ланками вимірювального приладу, нехтуючи впливами зовнішніх факторів на стабільність параметрів конструктивних елементів. Як відомо, кожний засіб вимірювальної техніки повинен мати певний набір метрологічних характеристик. Саме за цими характеристиками вибирають засоби вимірювальної техніки для використання в тих чи інших технологічних процесах і саме вони визначають достовірність даних, отриманих в результаті вимірювань. До таких характеристик відносять перелік фізичних величин, які можна вимірювати, умови, за яких можна здійснювати вимірювальний процес, метрологічну (інформаційну) надійність, клас точності або допустимі похибки самого засобу вимірювання тощо. Умови, за яких можна користуватися засобами вимірювання, залежать від конструктивної і технологічної реалізації приладу, оскільки методика вимірювань і її втілення в електричну схему не супроводжуються особливими вимогами щодо функціонування приладу. Це означає, що такий засіб може виготовлятися з орієнтацією на лабораторне використання, на використання в мобільному варіанті і в польових умовах, на використання в складних радіоелектронних системах як елемент вбудованого контролю і т. ін. Все це випливає з наведеної методики вимірювань і аналізу синтезованої схеми вимірювача. Точністні характеристики засобу вимірювальної техніки містять дві важливі складові: похибки методу і інструментальні похибки. Для побудови таких залежностей від параметрів фізичних або конструктивних апаратурних складових і значень вимірюваних величин необхідно побудувати математичну модель засобу вимірювальної техніки. Доцільно обмежитися побудовою математичної моделі, в якій враховуватимуться домінуючі фактори характеристик точності, що викликають похибки першого порядку. Така модель, в залежності від потреб, які виникатимуть в процесі експлуатації вимірювального засобу, може доповнюватися певними джерелами впливів, певними причинними діями, які викликатимуть появу похибок другого та навіть третього порядку. Це похибки, що обумовлені зміною температури, вологості, атмосферного тиску , механічних вібрацій, електромагнітних та акустичних полів і т. ін.

Ключові слова: інструментальні похибки; коефіцієнт відбиття; вхідний опір; характеристичний опір; коефіцієнт загасання; коефіцієнт фази.

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INSTRUMENTAL ERRORS OF TRANSMISSION LINE PARAMETERS METER

The article is devoted to the construction of the instrumental errors dependences of the transmission line parameters meter on the parameters of the physical or structural hardware components of the meter. For this, when constructing a mathematical model, only the main functional connections between the structural links of the measuring device were selected, neglecting the influence of external factors on the stability of the structural elements parameters. As is know, each measuring instrument must have a certain set of metrological characteristics. According to these characteristics, measuring instruments are selected for use in certain technological processes, and it is they that determine the reliability of the data obtained as a result of measurements. These characteristics include a list of physical quantities that can be measured, the conditions under which the measurement process can be carried out, metrological (informational) reliability, accuracy class or permissible errors of the measuring instrument itself. The conditions under which the measuring instruments can be used depend on the constructive and technological implementation of the device, since the measurement technique and its implementation in the electrical circuit are not accompanied by special requirements for the operation of the device. This means that such a meter can be produced with a focus on laboratory use, for use in a mobile version and in the field, for use in complex electronic systems as an element of built-in control, etc. All this follows from the given measurement technique and analysis of the synthesized meter circuit. The exact characteristics of a measuring instrument include two important components: method errors and instrumental errors. To build such dependencies on the parameters of physical or structural hardware components and the values of the measured quantities, it is necessary to build a mathematical model of the measuring equipment. It is advisable to restrict ourselves to the construction of a mathematical model, which will take into account the dominant factors of the accuracy characteristics that cause first-order errors. Such a model, depending on the needs that arise during the operation of the measuring instrument, can be supplemented by certain sources of influences, certain causal actions that will cause the appearance of errors of the second and even third order. These are errors caused by changes in temperature, humidity, atmospheric pressure, mechanical vibrations, electromagnetic and acoustic fields, etc.

Keywords: instrumental errors; reflection coefficient; input impedance; characteristic impedance; attenuation coefficient; phase coefficient.

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