Improving accuracy characteristics of the National standard unit of power flux density NE RB 26-15 through the reduction of error due to impedance mismatch in the microwave measuring tract

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This article describes the sources of systematic errors of the National standard unit of power flux density NE RB 26-15; methods of reduction the systematic error due to impedance mismatch in the microwave measuring tract; evaluation of non-excluded residues of systematic errors after the using different methods of reduction the systematic error due to impedance mismatch in the microwave measuring tract and their comparative analysis.

Introduction

The National standard unit of power flux density NE RB 26-15 is intended for reproduction, storage and transfer unit of power flux density in free space. Its work is based on a standard reference antenna method. The values of the power flux density determine using a reference measuring device that consists of a reference measuring antenna and a power meter [1]. There are lots of sources of systematic errors of method that can be investigated. Next sources of systematic error were taken into account during calculation of a total systematic error of reproduction and transfer of the unit of power flux density: accuracy power measurements at the output of the reference antenna, the error of the reference antenna effective area, the error due to impedance mismatch in the microwave measuring tract, the error due to multiple reflections between the antennas, the error due to non-uniform plane-wave field at the receiving antenna, the error of positioning of reference and investigating antennas, the error due to the instability of the electromagnetic field during measurement, the error due to multiple reflections of electromagnetic fields from the walls of an anechoic chamber [2]. The analysis showed predominance of two sources of errors: the error of the reference antenna effective area and the error due to impedance mismatch in the microwave measuring tract. There are lots of frequencies where the error due to impedance mismatch in the microwave measuring tract is dominant and it led to a significant non-excluded systematic error of the standard unit of power flux density in generally [3]. The goal of this work is to find a method of eliminating error due to impedance mismatch in the microwave measuring tract and raise the accuracy characteristics of the standard.

Assessment of error due to impedance mismatch in the microwave measuring tract and methods of its reducing

In the general case, the actual output power value in the output of the reference antenna can be determined by formula [4]:

$$P_A = P_M \frac{\left|1-\dot{\Gamma}_P\dot{\Gamma}_A\right|^2}{\left(1-\left|\dot{\Gamma}_P\right|^2\right)\cdot\left(1-\left|\dot{\Gamma}_A\right|^2\right)}, \tag{1}$$

P_M - the absorbed by the thermoelectric converter power;

P_A - the actual value of the output power of the reference antenna;

$\dot{\Gamma}_A$ и $\dot{\Gamma}_P$ - complex reflection coefficients of the reference antenna and the thermoelectric converter of power meter.

The relative systematic error due to impedance mismatch in the microwave measuring tract can be found from the formula:

$$\delta_{mis} = \frac{\left(1-\left|\dot{\Gamma}_P\right|^2\right)\cdot\left(1-\left|\dot{\Gamma}_A\right|^2\right)}{\left|1-\dot{\Gamma}_P\dot{\Gamma}_A\right|^2} - 1 = -\frac{\left|\dot{\Gamma}_P\right|^2}{\left(1-\dot{\Gamma}_P\dot{\Gamma}_A\right)^2} - \frac{\left|\dot{\Gamma}_A\right|^2}{\left(1-\dot{\Gamma}_P\dot{\Gamma}_A\right)^2} + \left(\frac{1}{\left(1-\dot{\Gamma}_P\dot{\Gamma}_A\right)^2} - 1\right) \tag{2}$$

It follows from the formula (2), that there are three components of error due to impedance mismatch δ_{mis} : δ_{mis1} , δ_{mis2} , δ_{mis3} . We ignored the errors of the second order and after mathematical transformation got next formulas:

$$\delta_{mis1} = -\frac{\left|\dot{\Gamma}_P\right|^2}{\left(1-\dot{\Gamma}_P\dot{\Gamma}_A\right)^2} = -\frac{\left|\dot{\Gamma}_P\right|^2}{1-2\cdot\left|\dot{\Gamma}_P\right|\cdot\left|\dot{\Gamma}_A\right|\cdot Cos\alpha+\left|\dot{\Gamma}_P\right|^2\cdot\left|\dot{\Gamma}_A\right|^2} \approx -\left|\dot{\Gamma}_P\right|^2; \quad (3)$$

$$\delta_{mis2} = -\frac{\left|\dot{\Gamma}_A\right|^2}{\left(1-\dot{\Gamma}_P\dot{\Gamma}_A\right)^2} = -\frac{\left|\dot{\Gamma}_A\right|^2}{1-2\cdot\left|\dot{\Gamma}_P\right|\cdot\left|\dot{\Gamma}_A\right|\cdot Cos\alpha+\left|\dot{\Gamma}_P\right|^2\cdot\left|\dot{\Gamma}_A\right|^2} \approx -\left|\dot{\Gamma}_A\right|^2 \quad (4)$$

$$\delta_{mis3} = \left(\frac{1}{\left(1-\dot{\Gamma}_P\dot{\Gamma}_A\right)^2}-1\right) = \left(\frac{1}{1-2\cdot\left|\dot{\Gamma}_P\right|\cdot\left|\dot{\Gamma}_A\right|\cdot Cos\alpha+\left|\dot{\Gamma}_P\right|^2\cdot\left|\dot{\Gamma}_A\right|^2}-1\right) \approx 2\cdot\left|\dot{\Gamma}_P\right|\cdot\left|\dot{\Gamma}_A\right|\cdot Cos\alpha \quad (5)$$

α - the angle between the unit vector and the vector corresponding to the vector multiplication $\dot{\Gamma}_P \cdot \dot{\Gamma}_A$, degree.

Two methods can be distinguished among the existing methods to reduce of systematic error due to impedance mismatch:

1) a method based on the changing of a sign of the error;

2) a method based on the using of the correction factor.

In the first method is used precision wave-resistance gauge for the reflection coefficient phase change to π [5]. The main drawback of the method is the ability to accurately reproduce the phase shift π only at a fixed frequency and the deviation from this value in the frequency range. The second method is based on the measuring of the reflection coefficients of the reference antenna and the thermoelectric converter of power meter. Then this information is used to calculate correction factor and correct measurement results. The main advantage of the second method is its versatility in a wide frequencies range. Two approaches can be distinguished in the second method:

- measuring of the reflection coefficients by a scalar network analyzer and using correction factor based on the modules of complex reflection coefficients;
- measuring of the reflection coefficients by a vector network analyzer and using correction factor based on the modules and arguments of complex reflection coefficients.

The first approach is known and is used by laboratories, but can't completely eliminate the error. Considering the advantages and disadvantages of the above methods we proposed method with modules and arguments of the complex reflection coefficient.

The correction factor to reduce the systematic error due to the impedance mismatch in the microwave measuring tract

Iintroduce some notation to make a correction factor based on the modules and arguments of complex reflection coefficients:

$$\dot{\Gamma}_A = \Gamma_{AC} + j\Gamma_{AS}; \quad \Gamma_{AC} = \left|\dot{\Gamma}_A\right|\cos\varphi_A; \quad \Gamma_{AS} = \left|\dot{\Gamma}_A\right|\sin\varphi_A, \quad (6)$$

$$\dot{\Gamma}_P = \Gamma_{PC} + j\Gamma_{PS}; \quad \Gamma_{PC} = \left|\dot{\Gamma}_P\right|\cos\varphi_P; \quad \Gamma_{PS} = \left|\dot{\Gamma}_P\right|\sin\varphi_P, \quad (7)$$

Γ_{PC}, Γ_{AC}, Γ_{PS}, Γ_{AS} - the real and imaginary components of the complex reflection coefficient of the thermoelectric converter and the measuring antenna;

$\left|\dot{\Gamma}_P\right|$, $\left|\dot{\Gamma}_A\right|$ - the modules of complex reflection coefficient of the thermoelectric converter and the measuring antenna, relative unit;

φ_P, φ_A - the arguments of complex reflection coefficient of the thermoelectric converter and the measuring antenna, degree.

Now, after the mathematical transformations we obtain the formula for the correction factor μ considering the formula (1), (6) and (7):

$$\mu = \frac{P_A}{P_M} = \frac{\left(1-\Gamma_{AC}\Gamma_{PC}+\Gamma_{AS}\Gamma_{PS}\right)^2+\left(\Gamma_{AC}\Gamma_{PS}+\Gamma_{AS}\Gamma_{PC}\right)^2}{\left(1-\Gamma_{PC}^2-\Gamma_{PS}^2\right)\cdot\left(1-\Gamma_{AC}^2-\Gamma_{AS}^2\right)}. \quad (8)$$

After completing the measurement of complex reflection coefficients and using the expressions (6) - (8) we can find the correction factor, use it to correct power measurements of the signal at the output of the measurement antenna.

Evaluation of non-excluded residues of systematic error due to impedance mismatch in the microwave measuring tract

In case when correction factor isn't used, evaluation of systematic error due to impedance mismatch can be made using the error limits of the formulas (3) - (5):

$$\left|\delta_{mis1}\right| = \left|\dot{\Gamma}_P\right|^2; \qquad \left|\delta_{mis2}\right| = \left|\dot{\Gamma}_A\right|^2; \qquad \left|\delta_{mis3}\right| = 2 \cdot \left|\dot{\Gamma}_P\right| \cdot \left|\dot{\Gamma}_A\right|.$$

In order to take into account $\left|\delta_{pac3}\right|$ that the possible values lie angle α can be from - π to π.

Assuming normal distribution of the components $\left|\delta_{mis1}\right|$ and $\left|\delta_{mis2}\right|$, arc sine distribution of the component $\left|\delta_{mis3}\right|$ the systematic error due to impedance mismatch in the microwave measuring tract can be found from the formula:

$$\delta_{S\,mis} = k \cdot \sqrt{\left(\frac{\left|\delta_{mis1}\right|}{\sqrt{3}}\right)^2 + \left(\frac{\left|\delta_{mis2}\right|}{\sqrt{3}}\right)^2 + \left(\frac{\left|\delta_{mis3}\right|}{\sqrt{2}}\right)^2},$$

k =2.58 – coverage coefficient corresponding to a confidence interval of approximately 99 % assuming a normal distribution.

In the case of using the scalar network analyzer and the correction factor based on the results of measurements of modules of complex reflection coefficients $\left|\dot{\Gamma}_P\right|$ and $\left|\dot{\Gamma}_A\right|$ we have in the formula only component $\left|\delta_{mis3}\right|$, but added two components owing to the non-ideal characteristic of the scalar network analyzer. Assuming normal distribution of the components $\left|\delta_{mis4}\right|$ and $\left|\delta_{mis5}\right|$ their limits can be found as partial errors of indirect measurements:

$$\left|\delta_{mis4}\right| = 2 \cdot \left|\dot{\Gamma}_P\right|^2 \cdot \delta_{|\Gamma|}, \quad \left|\delta_{mis5}\right| = 2 \cdot \left|\dot{\Gamma}_A\right|^2 \cdot \delta_{|\Gamma|},$$

$\delta_{|\Gamma|}$ - the relative error of the measurement modules of the reflection coefficients using the scalar network analyzer, relative unit.

The non-excluded residue of systematic error due to impedance mismatch in the microwave measuring tract $\delta'_{S\,mis}$ can be found from the formula:

$$\delta'_{S\,mis} = k \cdot \sqrt{\left(\frac{\left|\delta_{mis3}\right|}{\sqrt{2}}\right)^2 + \left(\frac{\left|\delta_{mis4}\right|}{\sqrt{3}}\right)^2 + \left(\frac{\left|\delta_{mis5}\right|}{\sqrt{3}}\right)^2}.$$

Finally, for the case of using the vector network analyzer and the correction factor based on the results of measurements of modules and arguments of complex reflection coefficients $\left|\dot{\Gamma}_P\right|$ and $\left|\dot{\Gamma}_A\right|$, we have available only the components $\left|\delta_{mis4}\right|$, $\left|\delta_{mis5}\right|$, $\left|\delta_{mis6}\right|$, $\left|\delta_{mis7}\right|$ and $\left|\delta_{mis8}\right|$ owing to the non-ideal characteristics of a vector network analyzer. The limits of the components $\left|\delta_{mis6}\right|$, $\left|\delta_{mis7}\right|$ and $\left|\delta_{mis8}\right|$ can be found from the next formulas:

$$\left|\delta_{mis6}\right| = 2 \cdot \left|\dot{\Gamma}_A\right| \cdot \left|\dot{\Gamma}_P\right| \cdot Cos\alpha \cdot \delta_{|\Gamma|} \approx 2 \cdot \left|\dot{\Gamma}_A\right| \cdot \left|\dot{\Gamma}_P\right| \cdot \delta_{|\Gamma|};$$

$$\left|\delta_{mis7}\right| = 2 \cdot \left|\dot{\Gamma}_P\right| \cdot \left|\dot{\Gamma}_A\right| \cdot Cos\alpha \cdot \delta_{|\Gamma|} \approx 2 \cdot \left|\dot{\Gamma}_A\right| \cdot \left|\dot{\Gamma}_P\right| \cdot \delta_{|\Gamma|};$$

$$\left|\delta_{mis8}\right| = 2 \cdot \left|\dot{\Gamma}_A\right| \cdot \left|\dot{\Gamma}_P\right| \cdot Sin\alpha \cdot \delta_{\varphi} \cdot \alpha_{RAD} \approx 3{,}14 \cdot \left|\dot{\Gamma}_P\right| \cdot \left|\dot{\Gamma}_A\right| \cdot \delta_{\varphi},$$

δ_{φ} - the relative error of the measurement arguments of the reflection coefficients using the vector network analyzer, relative unit;

α_{RAD} - the angle between the unit vector and the vector corresponding to the vector multiplication $\dot{\Gamma}_P \cdot \dot{\Gamma}_A$, radian.

In this case the non-excluded residue of systematic error due to impedance mismatch in the microwave measuring tract $\delta''_{S\,mis}$ can be found from the formula:

$$\delta''_{S\,mis} = k \cdot \sqrt{\left(\frac{|\delta_{mis4}|}{\sqrt{3}}\right)^2 + \left(\frac{|\delta_{mis5}|}{\sqrt{3}}\right)^2 + \left(\frac{|\delta_{mis6}|}{\sqrt{2}}\right)^2 + \left(\frac{|\delta_{mis7}|}{\sqrt{2}}\right)^2 + \left(\frac{|\delta_{mis8}|}{\sqrt{2}}\right)^2} \,.$$

Analysis has showed that the error due to impedance mismatch reduces in 1.5 - 2.5 times using the correction factor based on the scalar reflection coefficients, and in 9-10 times using the complex reflection coefficients. Residual systematic errors due to impedance mismatch in the microwave tract is 4-6 times lower after using the correction factor based on the vector reflection coefficients than after using the scalar coefficient. Implementation the vector measurements are more effective when the value of the reflection coefficients of the reference antenna and thermoelectric converter of power meter are bigger (see figure 1).

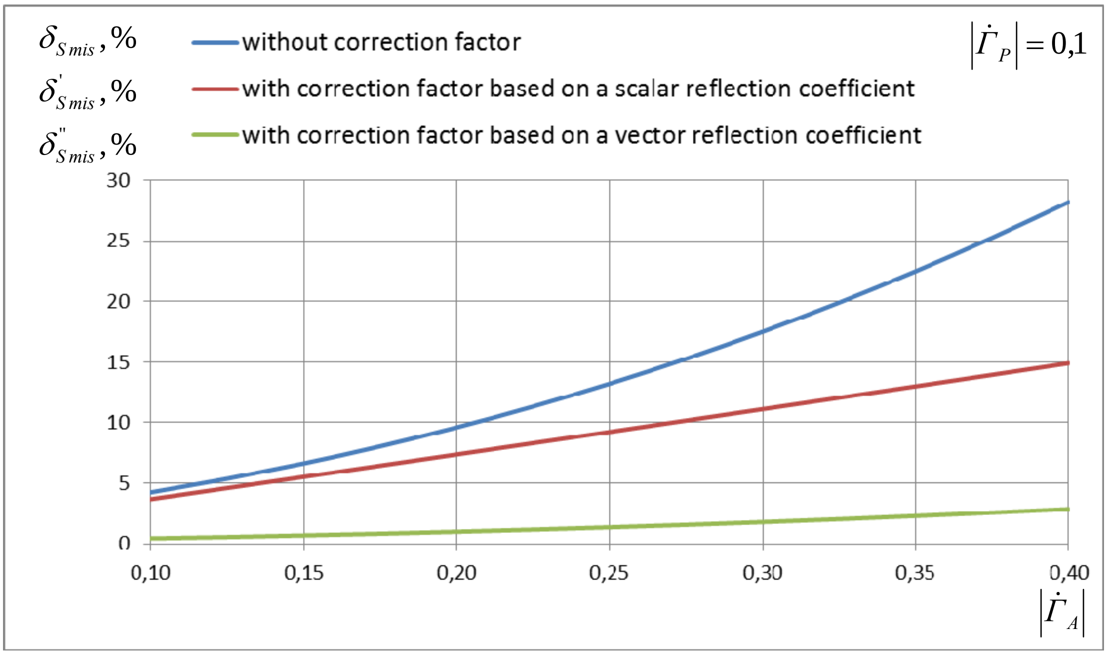

Figure 1 - The levels of the relative error due to impedance mismatch in the microwave measuring tract for different values of modules of the reflection coefficients

Conclusion

The proposed method of reduction the systematic error due to impedance mismatch is the most effective among the described methods to reduce systematic error due mismatch. It almost eliminates error so it can be recommended for high-precision measurements. Using the correction factor based on the complex reflection coefficients we has reduced the error due to impedance mismatch in the microwave tract of our standard unit of power flux density in 8-9 times. The total error of standard unit of power flux density has been reduced in 1.5 - 2.0 times in the frequency range from 0.3 to 6.0 and from 37.5 GHz to 39.65 GHz.

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