METROLOGY, QUALITY, STANDARDIZATION AND CERTIFICATION

CALIBRATION OF HIGH AND ULTRA-HIGH FREQUENCY POWER METERS IN THE RANGE OF UP TO 30 MHZ

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Abstract. High-frequency (HF) and ultra-high-frequency (UHF) power measurements are applied in various industries both in the development and design of radio-electronic equipment and in testing, commissioning, or repair. Since such measurements are one of the basic types of measurement for metrological support in the field of radio engineering and communication, it is necessary to ensure metrological traceability of the calibration of working standards and measuring instruments to standards on fundamental constants in wide frequency and dynamic ranges. The National primary standard of Ukraine for units of power of electromagnetic oscillations in coaxial paths reproduces units of power in the frequency range 0.03 … 18 GHz, and the frequency range of the nomenclature of watt-meters and power converters are much wider – from 9 kHz, and for some types of converters even from direct current. The calibration and measurement capabilities of HF and UHF power measurement of national laboratories of different countries were studied for the possibility of solving the issue of expanding the frequency range of calibration of HF and UHF power meters. The analysis of data on the calibration factor and the efficiency factor in coaxial paths with a resistance of 50 Ohm in the Database of Key Comparisons of the International Bureau of Weights and Measures was carried out. A study of possible solutions was carried out and a scheme was developed to reproduce a unit of power by units of voltage and resistance using a precision voltmeter Boonton 9242 RF for the calibration of measuring transducers Rohde&Schwarz NRP-Z55 and NRP6A in the frequency range from 0.1 … 30 MHz. A reproduction model was created based on the developed scheme, and the contributions of the reproduction model components to the calibration result and the corresponding uncertainties of the model components were estimated. The measurement uncertainty budget was drawn up based on the proposed calibration model of radio signal power measuring transducers.

Key words: Power, high frequency, power meter, working standard, measurement uncertainty.

1. Introduction

High-frequency (HF) and ultra-high-frequency (UHF) power measurements are applied in various industries both in the development and design of radio-electronic equipment and in testing, commissioning, or repair. Since such measurements are one of the basic types of measurement for metrological support in the field of radio engineering and communication, it is necessary to ensure metrological traceability of the calibration of working standards and measuring instruments to standards on fundamental constants in wide frequency and dynamic ranges [1, 2]. Fig. 1 shows a diagram of HF and HF power measurement ranges in the coaxial path.

In SE "UKRMETRTESTSTANDART" there is a need to expand the frequency range to ensure the reproduction and transmission of the unit size of HF and HF power in the coaxial path in the entire range of values, in particular up to 30 MHz. The national primary standard of Ukraine for the unit of power of electromagnetic oscillations in coaxial paths (DETU 09-06-05) reproduces units of power in the frequency range from 0.03 GHz to 18 GHz (Fig. 1, designation "1"), which makes it possible to transmit a unit of power to the output power standards – calibrator PDA-18 (power sensor R&S®NRP-Z51) and power sensor R&S®NRP-Z55 (Fig. 1, designation "2").

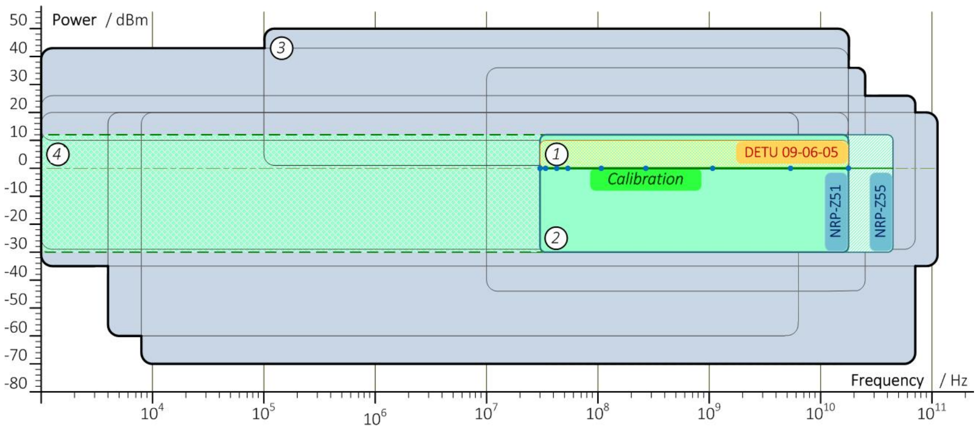


Fig.1. Diagram of HF and HF power measurement ranges in the coaxial path

When considering information about microwave watt meters and microwave power converters in the coaxial path used by metrology centers and calibration customers, as well as available on the market, it is clear that the frequency range of the wattmeter nomenclature and power converters is much wider – from 9 kHz, and for some types of converters even from direct current (Fig. 1, designation "3").

Thus, expanding the frequency range of reproducing a unit of power of electromagnetic oscillations in coaxial paths in the frequency range up to 30 MHz and ensuring the calibration of HF and UHF power sensors in this range is a rather urgent task (Fig. 1, designation "4").

2. Drawbacks

Calibration of HF and UHF power sensors at a frequency of 19 GHz is considered in recommendation EA-04/02 [4]. Features of calibration of various HF and UHF power meters in the frequency range from 30 MHz to 18 GHz are considered in many scientific works [1, 5–10]. At the same time, there are practically no works devoted to the calibration of HF and UHF power meters in the frequency range of up to 30 MHz. Only work [11] considers implementations of a direct comparison system for measuring the power of radio frequencies (from 100 kHz to 18 GHz).

3. Goal

The purpose of the study is to develop a method of calibrating HF and UHF power meters in the frequency range of up to 30 MHz.

4. Calibration and measurement capabilities of HF and UHF power measurement of national laboratories of different countries

The calibration and measurement capabilities of national laboratories of different countries were studied for the possibility of the issue of expanding the frequency range of calibration of HF and UHF power meters. Analysis of data on the calibration factor and the efficiency factor in coaxial paths with a resistance of 50 Ohm in the Key Data Database (KDB) of the International Bureau of Weights and Measures (BIPM) [12] was carried out.

Among the 26 countries represented (Fig. 2 - the dashed figure can be used if necessary), 8 national metrological institutes (China, Finland, Hong Kong, India, Japan, Mexico, Malaysia, and Russia) have radio signal power standards in the range from 10 MHz, 8 national metrological institutes (Spain, Great Britain, Korea, Poland, Saudi Arabia, Singapore, Turkey, USA, South Africa) ensure the reproduction and transmission of the size of the power unit of radio signals in the range from 100 kHz. In France and Sweden, the frequency range of power standards is provided from 10 kHz, and in Germany, Czech Republic, Netherlands, Slovenia, and Switzerland – from direct current. The national standard of Greece reproduces HF and microwave power from 50 MHz, and the national standard of Ukraine - is from 30 MHz.

HF and UHF power measurement is mostly based on the direct current substitution method with calorimeters, and splitters; direct comparison methods are also applied. Therefore, calorimeters are realized as the basis of primary HF and UHF power standards [6]. Calorimeters are distinguished by the principle of construction: with a dry load, flow [13], and microcalorimeters [6], which are used most often.

The principle of operation of the microcalorimeter consists of the substitution of direct current, and its metrological traceability is established according to the principle of equivalence of the thermal effect. Using a microcalorimeter, the efficiency coefficient of thermal power converters - bolometric and thermoelectric power sensors is determined [6, 14].

In [6], as an alternative or addition to the micro calorimetric method in the frequency range up to 30 MHz, it is described an alternating voltage standard.

Since below 10 MHz, a coaxial microcalorimeter cannot be used for the system with bolometric detection, while realizing thermoelectric converters sensitivity and, accordingly, the accuracy of power standards are reduced [6]. At the same time, it is possible to ensure high accuracy at the mentioned frequencies for voltage measurement (such measurements don't depend on the mismatch of the generator) [15].

5. The method of measuring the power at HF frequencies up to 30 MHz

In the frequency range from 100 kHz to 1 MHz, it is proposed to reproduce the Watt power unit with a precision voltmeter, which is calibrated using the National Primary Standard of the unit of electric voltage from 0.1 to 1000 V alternating current in the frequency range from 10 Hz to 1 MHz (DETU 08 -07-02). HF power is calculated by the unit of voltage Volt and resistance Ohm according to the formula:

$$P_{RF} = U_{RF}^2 / Z_{RF} , \quad (1)$$

here P_{RF} is reproduced power, U_{RF} is the voltage measured with a precision voltmeter, and Z_{RF} is the input resistance of the measuring transducer.

In the laboratory of high-frequency measurements is available a precision voltmeter Boonton 9242 RF with two measuring probes RF PROBE Model 952016 and RF PROBE Model 952001B with the following metrological characteristics [16]: frequency range of measurement 952001B RF Probe – from 10 kHz to 1.2 GHz, 952016 RF Probe - from 10 Hz to 100 MHz, voltage measurement ranges from 200 μV to 300 V, measurement uncertainty for values from 3 mV to 10 V – 1 %. TEE Adapter Model 952003 and 50 Ohm Adapter Model 952002 are applied to measure voltage in coaxial paths.

To measure HF power, measuring transducers were proposed. That was, NRP-Z55 thermal transducer (frequency band up to 44 GHz; uncertainty 0.01 dB), averaged power transducer NRP6A (frequency band 8…6000 kHz; measurement uncertainty 0.022 … 0.05 dB). With the help of a vector circuit analyzer, the input wave resistances of the indicated power-measuring converters were measured. The results of the resistance measurement (Table 1) were used to calculate the HF power.

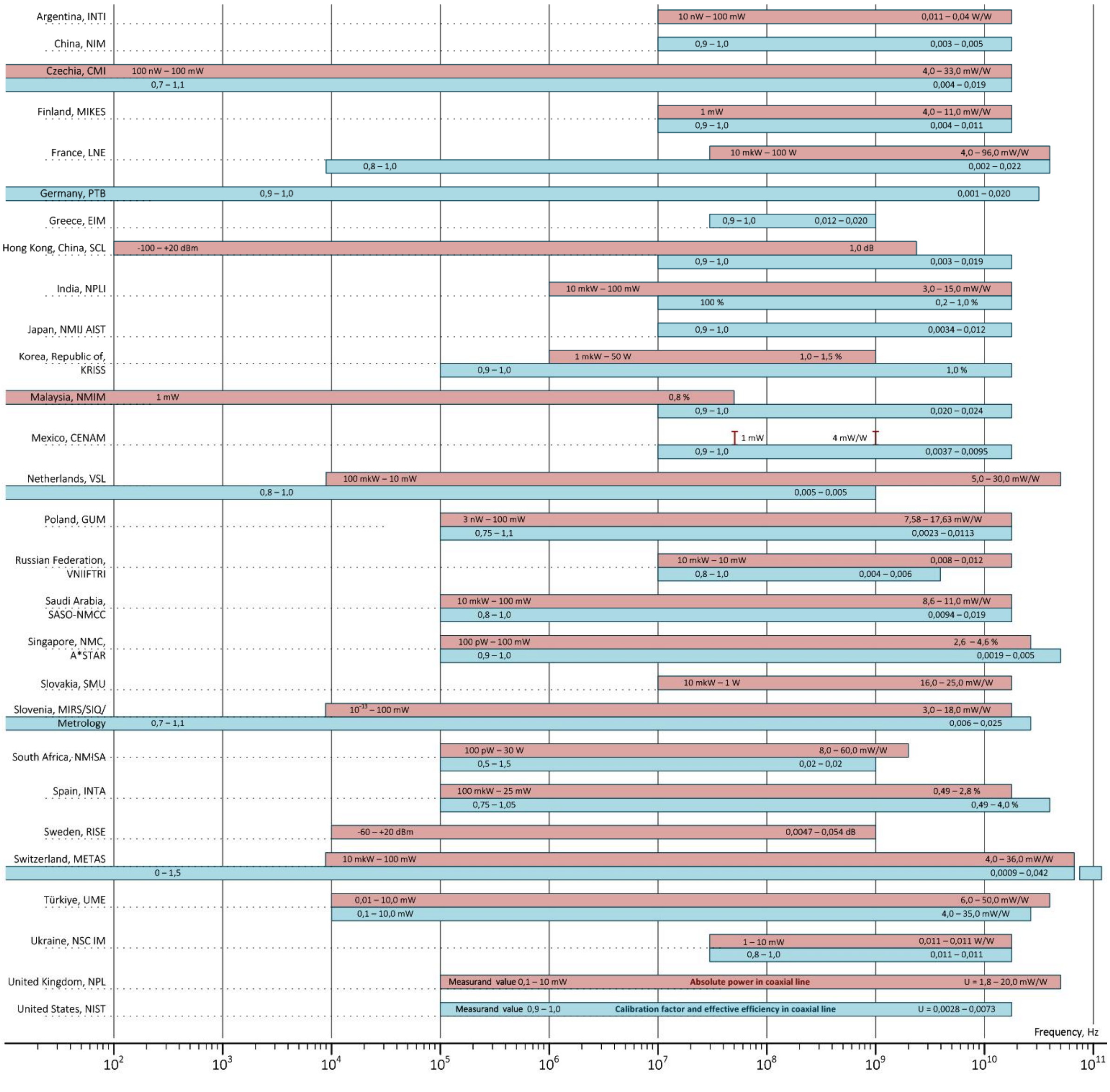


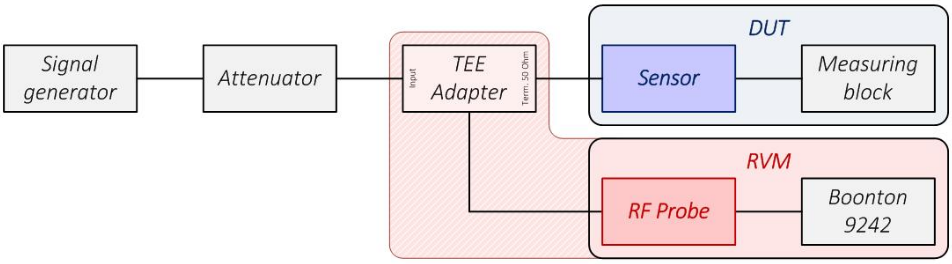
Fig.2. CMC lines for absolute power, calibration factor, and efficiency factor in coaxial paths

Table 1. Wave impedance of converters in complex form

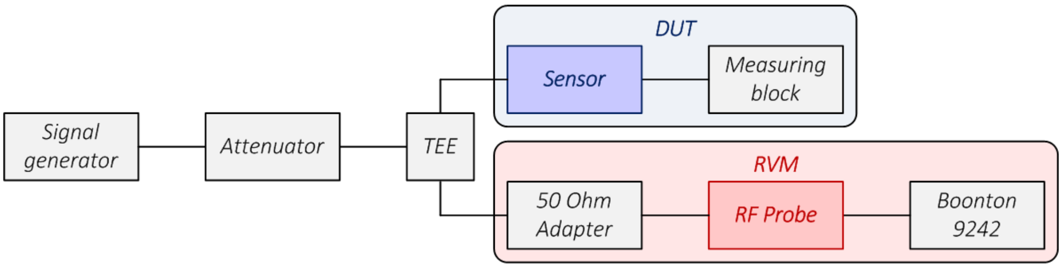
Frequency, MHz	NRP6A		NRP-Z55	
	Real, Ohm	Im, Ohm	Real, Ohm	Im, Ohm
0.1	50.835	-0.577	49.813	0.007
0.5	50.835	-0.114	49.882	-0.008
1	50.834	-0.054	49.876	-0.017
10	50.856	0.007	49.832	-0.014
30	50.885	-0.019	49.806	0.029
50	50.903	-0.053	49.811	0.079

There are two options for connecting measuring devices to reproduce a unit of power:

- serial connection of the reference voltmeter (RVM is the reference voltage meter) and the power converter (DUT is the device under testing), which are presented in Fig. 3, a. The voltage drop is measured through the TEE Adapter with the HF Probe measuring probe, the measurement result is displayed on the Boonton 9242 measuring unit. The DUT is connected to the output of the adapter;
- connection of RVM and DUT through a tee (tee connection), which are presented in Fig. 3, b. A coaxial tee is applied without attenuation between the input and outputs, and (a) 50 Ohm Adapter with a test probe is connected to one output, (b) DUT to the other.



a



b

Fig.3. Connection diagrams of devices for reproducing the Watt power unit with a voltmeter

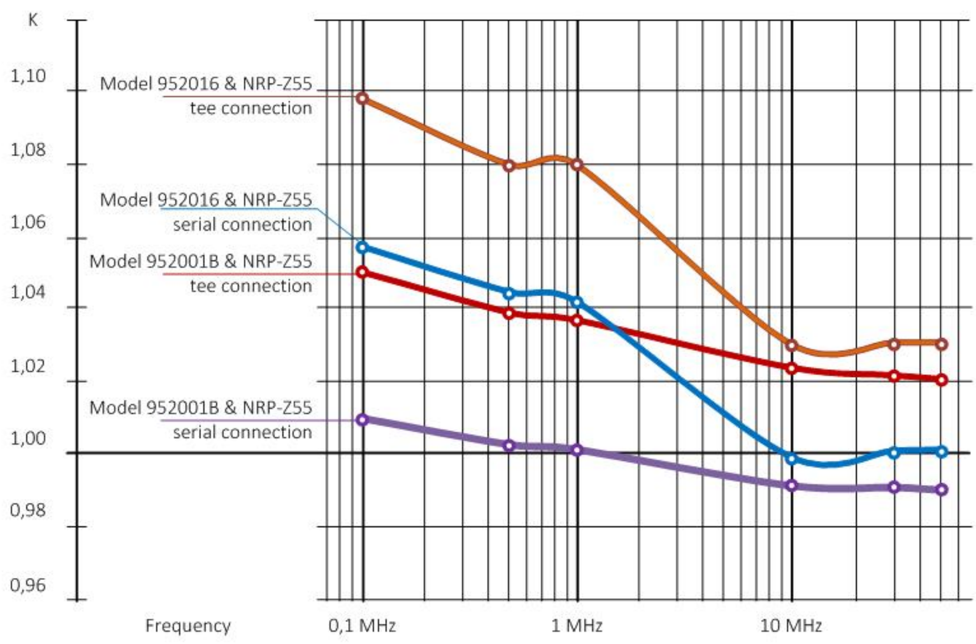


Fig.4. The results of calculating the calibration factor for the NRP-Z55 converter

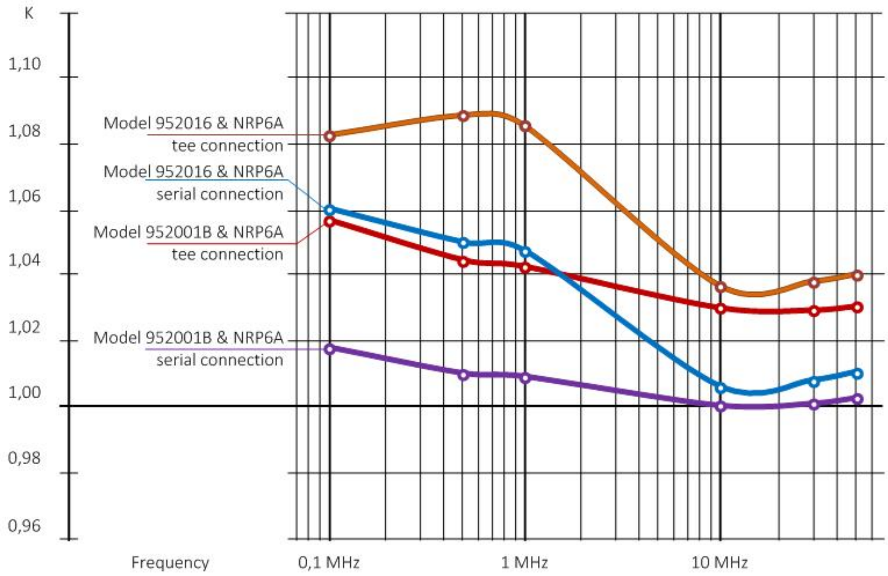


Fig.5. Results of calculation of the calibration factor for the NRP6A converter

To reduce the influence of the generator on the measuring system, a resolving attenuator with 10 dB attenuation is used. The results of calculations of the calibration coefficient for the NRP-Z55 converter and the NRP6A converter in series connection and connection through a tee with both measuring probes are shown in Fig. 4 and 5 respectively.

After studying the graphical display of the obtained results, it can be concluded that to reproduce a unit of power by units of voltage and resistance in the band 0.1… 1 MHz, it is advisable to connect the measuring transducer NRP-Z55 with the probe to the precision voltmeter 952001V HF Probe at serial connection scheme. In the range 1 …10 MHz, it is advisable to apply measuring transducers NRP6A or NRP-Z55 together with a probe for a precision voltmeter 952001V RF Probe and a serial connection scheme. And from 10 MHz to 30 MHz, it is advisable to apply the measuring converter NRP-Z55 together with the probe for the precision voltmeter 952016 RF Probe and the same scheme.

6. Evaluation of measurement uncertainty of results

Evaluation of the uncertainty of power measurements during calibration in the frequency range from 100 kHz to 30 MHz is carried out using recommendations on the measurement uncertainty [17]. The model equation for determining the calibration coefficient K_x when reproducing the power at one frequency f (hereafter) is:

$$K_x = \frac{P_x + \Delta P_x}{\dfrac{\left(U_{RF} + \Delta U_{RF} + K_U\right)^2}{Z_{RF} + \Delta Z_{RF}}} + \Delta P_{oth}, \tag{2}$$

where P_x is the measured power of the DUT, ΔP_x is the correction of the measured power for a certain scale resolution, U_{RF} is the measured voltage, ΔU_{RF} is the correction of the measured voltage for a certain scale resolution, K_U is the calibration factor of a precision voltmeter, Z_{RF} is resistance, ΔZ_{RF} is the correction of the measured resistance, ΔP_{oth} is correction caused by other factors. The standard uncertainty according to type A of the measured voltage value u_A is determined:

$$u_{A,U_{RF}} = k_n \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{N} \left(U_{RFi} - \bar{U}_{RF}\right)^2}, \tag{3}$$

here k_n is the coefficient for the number of measurements less than 10 [24], equal to:

$$k_n = \sqrt{\frac{n-1}{n-3}}. \tag{4}$$

The standard uncertainty according to type A of the measured value of the absorbed power of the DUT $u_{A,Px}$ is determined by a similar formula:

$$u_{A,P_x} = k_n \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{N} \left(P_x - \bar{P}_x\right)^2} \tag{5}$$

The standard type B uncertainty of the voltmeter calibration factor $u_{B,KU}$ is obtained from the calibration certificate.

The standard uncertainty due to the final resolution of the voltmeter and DUT readings is inherent in a uniform distribution law:

$$u_{\Delta U_{RF}} = u_{\Delta P_x} = \frac{10^{-rd}}{2\sqrt{3}}, \tag{6}$$

where rd is the serial number of the last significant digit of the measurement result. For all components of measurement uncertainty according to type B, sensitivity coefficients c_i are calculated as partial derivatives for all input values. To simplify the records, the same expressions are applied to determine the sensitivity coefficients of the quantity and its estimation. The sensitivity factor for power is:

$$c_P = \frac{Z_{RF} + \Delta Z_{RF}}{\left(U_{RF} + \Delta U_{RF} + K_U\right)^2}, \quad (7)$$

The sensitivity coefficient for voltage is:

$$c_{U_{RF}} = \frac{-2\left(P_x + \Delta P_x\right)\left(Z_{RF} + \Delta Z_{RF}\right)}{\left(U_{RF} + \Delta U_{RF} + K_U\right)^3}, \quad (8)$$

The sensitivity coefficient for resistance is equal to:

$$c_{R_{RF}} = \frac{P_x + \Delta P_x}{\left(U_{RF} + \Delta U_{RF} + K_U\right)^2}, \quad (9)$$

The resistance value of the measuring transducer is measured beforehand with the help of a vector analyzer. The standard uncertainty of the resistance value can be estimated at this stage according to the passport metrological characteristics. The total standard uncertainty of the calibration factor u_{kx} is calculated by the formula:

$$u_{k_x} = \sqrt{u_A^2 + \sum_{i=1}^{N} c_i u_i}, \quad (10)$$

where u_i is the value of the standard measurement uncertainties of type B, c_i is the corresponding sensitivity coefficients. The uncertainty budget for the reproduction of the power unit during the calibration of the power converter can be considered using the example of the calibration results of the R&S®NRP-Z55 power converter at a frequency of 1 MHz (Table 2).

The value of the calibration coefficient of the voltmeter at a frequency of 1 MHz was obtained later during calibration according to DETU 08-07-02. Therefore, we use passport data to estimate the uncertainty. Thus, the uncertainty of voltage measurement at 1 MHz and within 3 mV …10 V is 1.0%. The resolution of the R&S®NRP2 indicator unit when measuring absorbed power is 0.001 mW. The resolution of the Boonton 9242 RF indicator voltmeter when measuring voltage is 0.01 mV and the standard uncertainties of $u_{\Delta URF}$ and $u_{\Delta Px}$ are equal to $3 \cdot 10^{-6}$ mV and $3 \cdot 10^{-5}$ mW, respectively. The uncertainty of resistance measurement with a vector circuit analyzer is 2.0 % [25]. The standard uncertainty u_{oth}, due to the influence of other factors, such as inconsistency in the path, zero offset, noise, and repeatability of the connection, is taken as 0.02 mW.

Table 2. The budget of components of the total standard uncertainty of measurements

Quantity, x_i	Estimation of the input value x_i, dB	Standard uncertainty, $u(x_i)$, dB	Probability distribution	Sensitivity coefficient	Uncertainty contribution, $u_i(y)$
P_x	9.821 mW	0.005 mW	normal	formula (7)	$5.3 \cdot 10^{-4}$
ΔP_x	0 mW	0.00003 mW	uniform	formula (7)	$3.2 \cdot 10^{-6}$
U_{RF}	687.19 mV	0.05 mV	normal	formula (8)	$-1.7 \cdot 10^{-4}$
ΔU_{RF}	0 mV	0.000003 mV	uniform	formula (8)	$-9.1 \cdot 10^{-9}$
K_U	0	7.0	normal	formula (8)	-0.0021
Z_{RF}	49.876 Ohm	0 Ohm	normal	formula (9)	0
ΔZ_{RF}	0 Ohm	1.017 Ohm	normal	formula (9)	0.0021
ΔP_{oth}	0	0.002 mW	normal	1	0.002
K_x	1.037				0.0036

The total standard non-significance of the calibration coefficient u_{Kx} is calculated by:

$$U = 2u_{K_x}. \quad (11)$$

The expanded uncertainty is 0.0072 units, so the calibration result of the R&S®NRP-Z55 power converter at 1 MHz is recorded as (1.037 ± 0.0072) units. The obtained estimated uncertainty of reproduction of a power unit of radio signals satisfies the requirements for the accuracy of watt-meters calibration in the frequency band 0.1 … 1 MHz.

7. Conclusions

There were conducted evaluation studies of circuit solutions for voltage and power measurement, based on which a serial connection scheme was selected to reproduce a unit of power by units of voltage and resistance within the frequency range 0.1 … 30 MHz. To fulfill this, it is advisable the measuring converter NRP-Z55 together with the probe for the precision voltmeter Boonton 952001B RF Probe. In the range 1 … 10 MHz, are better the measuring transducers NRP6A or NRP-Z55 with the 952001V RF probe. The latter with the probe for the precision voltmeter 952016 RF Probe is recommended for 10 … 30 MHz. The metrological characteristics of such reproduction were evaluated. The estimated uncertainty of reproduction of a power unit for radio signals satisfies the requirements for the accuracy of watt-meters calibration within the range 0.1 … 30 MHz. The final results could be obtained following the transfer to the precision voltmeter of the voltage unit from the State primary standard of the electric voltage unit (0.1 … 1000 V of alternating current within the frequency range 10 Hz … MHz.

8. Gratitude

The authors express their gratitude to the Staff members of the Departments of the Information-Measuring Technologies of Lviv Polytechnic National University.

9. Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work.

References

[1] Velychko O., Gaman V., Kursin S., "Calibration features for power meters of high and microwave frequencies". Ukrainian Metrological Journal, 2022, No. 2, pp. 9–14. DOI: 10.24027/2306-7039.1.2022.263724.

[2] Velychko O. N., "Traceability of measurement results at different levels of metrological work". Measurement Techniques, vol. 52, 2009, No. 11, p. 1242–1248. DOI: 10.1007/s11018-010-9428-7.

[3] Velychko O., Gordiyenko T., "Metrological Traceability at Different Measurement Levels. Standards". Methods and Solutions of Metrology, Published by IntechOpen, London, United Kingdom, 2019; Chapter 1, pp. 1–21. doi: 10.5772/intechopen.84853.

[4] EA-04/02 M, "Evaluation of the Uncertainty of Measurement in Calibration". EA, 2021 [Electronic resource]. – Available at: https://www.accredia.it/en/documento/ea-4-02-rev-03-evaluation-of-the-uncertainty-of-measurement-in-calibration/.

[5] Zhang Z., Liao X. A Microwave Power Sensor. In: Huang QA. (eds), "Micro Electro Mechanical Systems. Micro/Nano Technologies". Springer, Singapore, 2018. DOI: 10.1007/978-981-10-5945-2_32.

[6] X. Cui, Y. S. Meng, Y. Shan, and Y. Li., "Microwave Power Measurements: Standards and Transfer Techniques. New Trends and Developments in Metrology", Luigi Cocco (Ed.), IntechOpen, 2016, pp. 3–20. DOI: 10.5772/60442.

[7] Y. Shan and X. Cui, "RF and Microwave Power Sensor Calibration by Direct Comparison Transfer. Modern Metrology Concerns", Luigi Cocco (Ed.). IntechOpen, 2012, pp. 175–200. DOI: 10.5772/34553.

[8] Y. S. Meng, Y. Shan, "Measurement and Calibration of A High-Sensitivity Microwave Power Sensor with An Attenuator". Radio engineering, vol. 23, no. 4, 2014, pp. 1055–1060 [Electronic resource]. – Available at: https://www.radioeng.cz/fulltexts/2014/14_04_1055_1060.pdf.

[9] M. Rodriguez, M. Celep, M. Hudlicka, et. al. "Calibration of power sensors for low-power measurement: Best practice guide". EMPIR 15RPT01, RFMicrowave, 2019 [Electronic resource]. – Available at: http://www.rfmw.cmi.cz/documents/deliverables/Calibration_power_sensors_low-power_measurement.pdf.

[10] Mescheriak O., Velychko O., "Calibration of analyzers of mobile communication system parameters". Measuring Equipment and Metrology, 2022. Vol. 83(3), pp. 30–34. DOI: 10.23939/istcmtm2022.03.030.

[11] Ginley R., "A Direct Comparison System for Measuring Radio Frequency Power (100 kHz to 18 GHz)". Measure 2006; 1(4) 46–49. DOI: 10.1080/19315775.2006.11721347.

[12] The BIPM key comparison database (KCDB) [Electronic resource]. – Available at: http://kcdb.bipm.org.

[13] Agilent Technologies. Fundamentals of RF and Microwave Measurements (Part 4). An Overview of Agilent Instrumentation for RF/Microwave Power Measurements. [Electronic resource]. – Available at: https://www.ab4oj.com/test/docs/5988-9216EN.pdf.

[14] L. Brunetti, L. Oberto, E. Vremera, "Thermoelectric sensors as microcalorimeter load", IEEE Trans. Instr. Meas., vol. 56, No. 6, pp. 2220–2224, Dec. 2007. DOI: 10.1109/TIM.2007.908135

[15] Guide DKD-L 02-02 Procedures for a traceable RF voltage measurement, Edition 04/2014, Revision 0, Physikalisch-Technische Bundesanstalt, Braunschweig, and Berlin. DOI: 10.7795/550.20190509.

[16] 9240 Series RF Voltmeter Data Sheet. [Electronic resource]. – Available at: https://boonton.com/Portals/0/Datasheets/BTN_9240%20Datasheet_9.22.pdf.

[17] M3003 The Expression of Uncertainty and Confidence in Measurement. Edition 4 October 2019. [Electronic resource]. – Available at: https://www.ukas.com/wp-content/uploads/schedule_uploads/759162/M3003-The-Expressionof-Uncertainty-and-Confidence-in-Measurement.pdf.