

Automated Calibration System with Digital Calibration Certificates Support

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Abstract – This paper presents the development of an automated system for the calibration of radio-frequency (RF) power meters, addressing the need for accurate, traceable, and efficient calibration in the RF domain. The system is based on a Rohde & Schwarz signal generator and reference power sensors, operating over a frequency range up to 43.5 GHz. A Python-based software solution enables full automation of the calibration process, including signal level auto-balancing and uncertainty estimation. Calibration results – such as calibration coefficients, linearity, and Voltage Standing Wave Ratio (VSWR) – are formatted into Digital Calibration Certificates (DCCs) using XML. DCCs offer a reliable, machine-readable solution for integration into Industry 4.0 systems, enhancing traceability and reducing human error. The proposed approach improves calibration efficiency and supports the global shift toward digital metrology. A user interface and example XML structure are also presented.

I. INTRODUCTION

Power measurement is fundamental to metrological support in the radio frequency (RF) range. Measuring parameters of the electromagnetic field, signal transmission path attenuation, and antenna characteristics is not possible without RF power measurement. These measurements are essential in areas such as radio communication, mobile communication, control signal transmission, video signal transmission, and GPS navigation. Therefore, the calibration of power meters in the radio frequency range must be performed over a wide frequency and dynamic range.

The results of such wattmeter calibration – namely, the calibration coefficient or the deviation of the measured value and the voltage standing wave ratio (VSWR) – are directly used in corresponding calculations of other measurement parameters in the RF range. These power meters can be used in automated systems, continuous monitoring systems and more. Thus, there is a growing need to create DCCs for RF power meters, which is in line with the current trend towards digitalization of metrology and provides an opportunity to automate the calculation of measurement results [1].

Automation of such measurements significantly reduces the time required for calibration, improves accuracy through statistical processing of a larger number of results, and minimizes potential human errors.

Therefore, the development of an automated system for the calibration of radio-frequency power meters is a relevant and timely task. Such a system must ensure the traceability of the power unit across the entire frequency range and dynamic range of the power meters. Calibration results – specifically, the calibration coefficient (or deviation of the measured value), linearity across the dynamic range, and the voltage standing wave ratio (VSWR, or reflection coefficient) – must be represented in a DCC.

II. BACKGROUND FOR SYSTEM

At the National Metrology Institute of the State Enterprise “Ukrmetrteststandard”, there is an extensive range of radio-frequency power meters that are used to ensure traceability of the power unit during the calibration of instruments such as spectrum analyzers, measuring receivers, field strength meters, and attenuators [2]. All

power meters are manufactured by the company Rohde & Schwarz. For the calibration of these power meters, dedicated calibrators were developed based on NRP-Z51 and NRP-Z55 power sensors, as well as 2-way resistive power splitters. This simplified procedure, unlike the classical example of calibrating a high-frequency wattmeter [3, 4], makes it possible do not take into account the reflection coefficients of the wattmeter – device under test (DUT). The errors caused by the mismatch are included in the total error [5]. Such calibrators ensure the traceability of the power unit across a frequency range up to 44 GHz. The measurement signal is generated using a Rohde & Schwarz SMF100A signal generator operating in the range of 1 GHz to 43.5 GHz. For this calibration setup, the components of the uncertainty budget have been evaluated [6].

III. AUTOMATED SYSTEM

The automation of the proposed calibration system can be implemented using a Personal Computer. The block diagram of the system is shown in Figure 1.

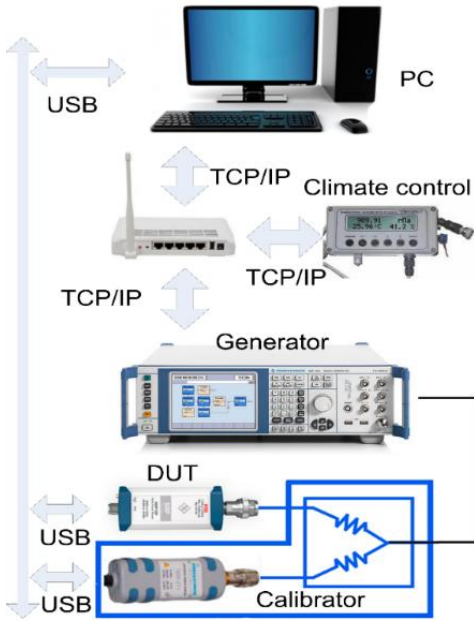


Fig. 1. Block diagram of the automated system for wattmeter calibration.

The software on Personal Computer controls the signal generator via an Ethernet interface and collects measurement data from both the Calibrator and DUT via USB connection. The system also allows for environmental condition monitoring, either directly from a sensor or via a network server over Ethernet.

Rohde & Schwarz provides instrument drivers for their devices. Python was chosen as the programming language for software development, as it offers robust libraries for data processing and visualization [7].

It is also possible to automate the measurement of the reflection coefficient of the DUT input. To do this, it is necessary to add a directional splitter and an additional reference wattmeter. Or, such measurements can be performed separately, using a Vector Network Analyzer.

IV. SIGNAL LEVEL AUTO-BALANCING PROCEDURE

The output signal level of the generator depends on the signal frequency, the characteristics of the input connectors of the connected power meters, and the frequency-dependent transmission coefficient of the power splitter. Therefore, to ensure proper calibration conditions – specifically, a predefined signal level across the entire frequency range – it is necessary to implement an signal level auto-balancing procedure [3]. The essence of the signal level auto-balancing procedure lies in setting the required signal level on the generator, measuring the signal at the output of the power splitter using a reference wattmeter, calculating the correction factor, and adjusting the generator's output accordingly. The block diagram of this algorithm is shown in Figure 2.

The decibel-milliwatt (dBm) is a unit of power level expressed using a logarithmic decibel (dB) scale respective to one milliwatt. The developed software provides the ability to choose between dBm and watts, depending on the units in which the signal level values for the calibration points are given. The input data of the procedure are the required signal level and the calibrated deviation for the Calibrator (reference wattmeter). The values of the number of measurements and the maximum deviation from the obtained average value are set, such a check is necessary to remove gross errors. The required signal level is set on the generator. 5 power measurements in watts are performed. It is checked whether the obtained value is greater than 0. Find the average value and discard values that differ from the average by more than the maximum permissible deviation (0.001). Find the average value of the filtered results.

Calculate the adjusted signal level value using formula

$$L_{corr} = L_{watt} - (Av_{watt} - L_{cal} - L_{watt}), \quad (1)$$

where, L_{corr} is the corrected signal level value, Av_{watt} is the average of the filtered values, L_{cal} is the correction value from the calibration certificate of the standard, L_{watt} is necessary level.

For correct conversion of all values into dBm units, the conversion is carried out according to formula

$$P_{dBm} = 10 \cdot \log_{10} \left(\frac{P_w}{0.001} \right), \quad (2)$$

where, P_{dBm} is the power value in dBm, P_w is the power value in watts.

The Python code implementation for this procedure with signal level in watts is presented in Figure 3.

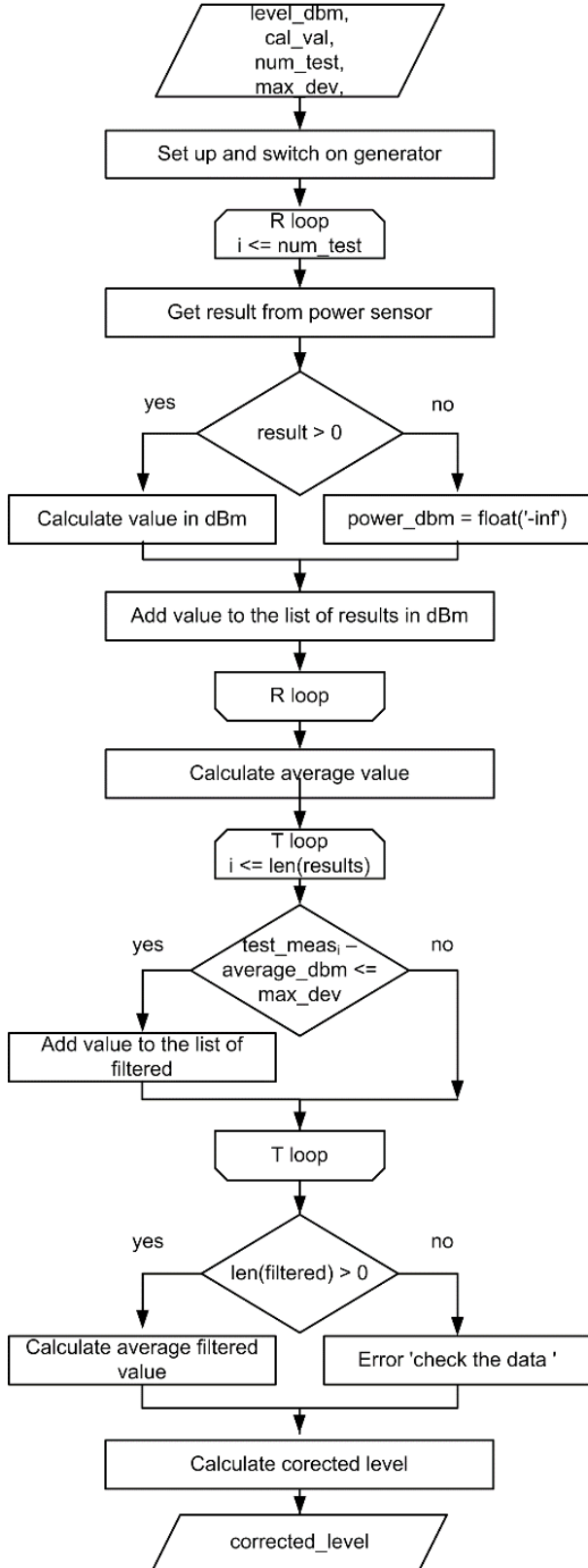


Fig. 2. Auto-balancing procedure algorithm.

```

def collect_test_measurements(self, sensor, level_watt,
                              cal_val, num_test, max_dev):
    test_measurements = []
    set_output_level(self.smf100a, level_watt)
    rf_on(self.smf100a)
    for _ in range(num_test):
        sensor.write_str('INIT:IMM')
        result = sensor.query_str('FETCH?').split(',')
        power_watt = float(result[0])
        if power_watt > 0:
            test_meas.append(power_watt)
        else:
            power_watt = float('-inf')
    average_watt = sum(test_meas) / len(test_meas)
    filtered_measurements = [x for x in test_meas
                             if abs(x - average_watt) <= max_dev]
    if filtered_measurements:
        average_filtr_watt = sum(filtered_measurements) / len(filtered_measurements)
    else:
        raise ValueError('check the data')
    corrected_level = level_watt - (average_filtr_watt - cal_val - level_watt)
    rf_off(self.smf100a)
    return corrected_level
  
```

Fig. 3. Code fragment of the generator signal level auto-balancing procedure.

Using the developed software, it is possible to calculate the type A uncertainty for the measurements made at each calibration point using formula

$$u_A = \sqrt{\frac{1}{n \cdot (n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (3)$$

where, n – number of measurements, x_i – i -th measurement result, $\bar{x}$ – average value n measurements.

The user interface of the developed software is shown in Figure 4.

The developed software provides automatic detection of wattmeters connected to the system and allows the operator to define calibration points, specifically the frequency and signal level. It also includes functionality for measuring the reflection coefficient and calculating the reflection coefficient.

V. DIGITAL CALIBRATION CERTIFICATES

DCCs are a key component of the digital transformation of metrology in the era of Industry 4.0. They provide a machine-readable format with a high level of reliability and ease of integration into automated quality management systems. Unlike traditional paper-based or PDF certificates, DCCs enable automated data processing, reducing the risk of human error and accelerating production workflows. They support digital signatures, ensuring the integrity and authenticity of the information [8, 9].

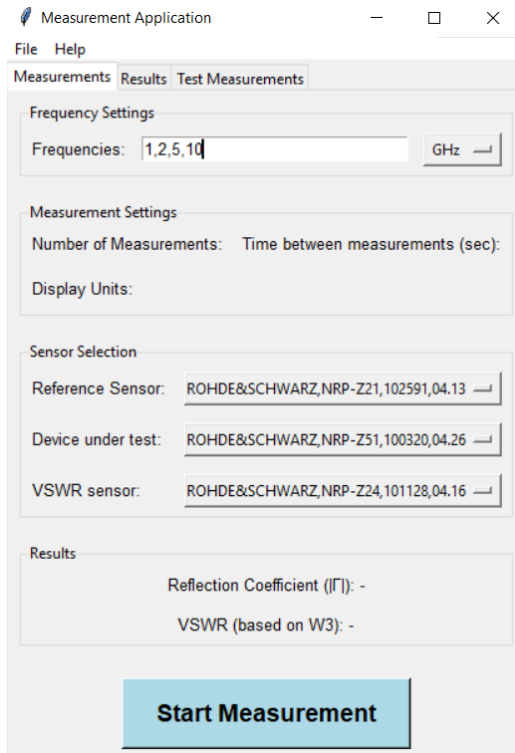


Fig. 4. User Interface.

The main formats of DCCs are based on XML data structures. The use of DCCs enhances transparency, traceability, and efficiency in industrial processes, enabling reliable exchange of calibration data at both national and international levels [10].

The GEMIMEG project website [11], dedicated to DCCs, provides examples of calibration results for temperature, and humidity measuring instruments.

At this stage, we are using the DCC v3.2.1 scheme version, as it is supported by the working version of GEMIMEG-Tool v1. Using the GEMIMEG-Tool provides the ability to translate DCC created during the development phase in XML format into human readable format. As a general example, the PTB Temperature example (simplified) Good Practice DCC with D-SI version 2.2.1 was used.

It was also necessary to resolve the issue of the units of measurement used. The dBm is not included in the International System of Units (SI) and is therefore not recommended for use in documents or systems that follow SI standards. The corresponding SI unit is the watt. However, the decibel (dB), without the 'm' suffix, is allowed for expressing relative quantities, though it is not approved for direct use alongside SI units [12, 13]. At the same time, the use of such units is an established practice and is convenient for calibrating RF power meters [14]. An example of calibration results from the certificate issued by the accredited in DKD Rohde & Schwarz Laboratory is shown in Figure 5.

Freq. /GHz	Power level Dev. /dB	Unc. /dB	Output Real /lin.	Reflection of Po Imag /lin.	Unc. /lin.
0.001	-0.001	0.0078	0.000	0.000	0.005
0.01	0.000	0.017	-0.001	0.000	0.005
0.03	0.001	0.017	-0.001	0.001	0.005
0.05	0.000	0.017	-0.002	0.001	0.005
0.1	0.000	0.017	-0.001	0.001	0.005

Fig. 5. Example of calibration results.

Therefore, we propose the following XML-based structure for representing the calibration results of power meters within a DCC, using `<si:hybrid>` data elements for watts and dBm. Also, since it is necessary to present the calibration results for a frequency range, the `<si:realListXMLList>` data structure is used. The fragment of the DCC structure without reflection results is shown in Figure 6.

```
<dcc:quantity refType="basic_measuredValue">
  <dcc:name>
    <dcc:content lang="ua">Середнє вимірне
    значення
    </dcc:content>
    <dcc:content lang="en">Measured value
    </dcc:content>
  </dcc:name>
  <si:hybrid>
    <si:realListXMLList>
      <si:valueXMLList>0.9982 0.9977 0.9972</
      si:valueXMLList>
      <si:unitXMLList>\milli\watt</si:unitXMLList>
    </si:realListXMLList>
    <si:realListXMLList>
      <si:valueXMLList>-0.008 -0.010 -0.012</
      si:valueXMLList>
      <si:unitXMLList>dBm</si:unitXMLList>
    </si:realListXMLList>
  </si:hybrid>
</dcc:quantity>
<dcc:quantity refType="basic_measurementError">
  <dcc:name>
    <dcc:content lang="ua">Відхилення</dcc:content>
    <dcc:content lang="en">Measurement error
    </dcc:content>
  </dcc:name>
  <si:realListXMLList>
    <si:valueXMLList>0.005 0.002 -0.006
    </si:valueXMLList>
    <si:unitXMLList>\decibel</si:unitXMLList>
    <si:expandedUncXMLList>
      <si:uncertaintyXMLList>0.020 0.036 0.036</
      si:uncertaintyXMLList>
      <si:coverageFactorXMLList>2 2 2</
      si:coverageFactorXMLList>
      <si:coverageProbabilityXMLList>0.95 0.95 0.95
      </si:coverageProbabilityXMLList>
      <si:distributionXMLList>normal normal normal
      </si:distributionXMLList>
    </si:expandedUncXMLList>
  </si:realListXMLList>
</dcc:quantity>
```

Fig. 6. Example of wattmeter calibration result representation in XML format.

Presenting calibration results in units such as dB makes it possible to clearly evaluate the DUT measurement results, since to take into account the obtained corrections [15], it is enough to perform simple mathematical operations of addition or subtraction according to the expression:

$$P_{correct} \text{ (dBm)} = P_{meas} \text{ (dBm)} + P_{dev} \text{ (dB)} \quad (4)$$

However, calibration of reference wattmeters involves taking into account path mismatch, reflection coefficients, and dynamic range nonlinearity. Therefore, it is necessary to further develop a DCC structure for reference wattmeters with calibration coefficients or efficiency coefficients.

VI. CONCLUSION

An automated calibration system for radio-frequency power meters has been successfully developed and implemented. The system enables precise and efficient calibration across a wide frequency and dynamic range using reference sensors and a programmable signal generator. The software, developed in Python, supports signal level auto-balancing procedure, and user-defined calibration points. One of the key innovations is the integration of DCCs, structured in XML format, which aligns with current trends in digital metrology and supports automated data exchange. This approach enhances traceability, reduces calibration time, minimizes human errors, and ensures compliance with Industry 4.0 requirements. The system is suitable for use in national metrology institutes and industrial laboratories requiring reliable RF power measurements. Tasks for further research are identified.

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