SUMMARY

The paper presents a resistive voltage divider (RVD), developed for power measurements at much higher frequencies than the traditional 50 Hz. The design of the RVD and the methods of its evaluation are described. The RVD is intended to be used in a digital sampling wattmeter application based on National Instruments PXI-4461 Dynamic Signal Analyzer. The design of the divider includes individual copper guards for each resistor, driven by the auxiliary chain of resistors. To reduce the leakage currents, the PTFE terminals are applied between pins of the resistors and the printed circuit board.

KEYWORDS

resistive voltage dividers; power measurement; PXI-4461; guarding
design principles

Fig. 1 presents the equivalent circuit diagram of the guarded resistive divider. The parasitic capacitances are marked in dashed lines, \( C \) is the input capacitance of the instrument measuring the output voltage (including cable capacitance), \( R_{\text{in}} \) are resistances of the auxiliary chain of resistors.

\[ V_{\text{in}} / V_{\text{out}} = nR / R_0 + 1 \]

The ratio of the divider is defined as:

The leakage current through the main printed circuit board (PCB) could increase the phase and ratio errors of RTD. In order to reduce this effect, the resistors consisting the divider are soldered on the polytetrafluoroethylene (PTFE) insulated terminals, as depicted in the Fig. 2, similarly to the design described in [8].

The divider is consisted of \( n=25 \) resistors with the nominal value equal to \( R=4.4 \) k\( \Omega \) and one resistors with the nominal value \( R=2 \) k\( \Omega \), which gives according to (1) the nominal ratio of the divider \( 560 \) \( \Omega \)/10 V. All resistors are Vishay S series bulk metal foil (BMF), high precision resistors, model number S102C, with the ambient power rating 0.6 W at 70°C. The typical temperature coefficient of resistance (TCR), declared by Vishay is \( \pm 2 \) ppm/°C, for all resistors in the divider. The balanced TCRs in all resistors of the divider minimize the change of the ratio of the divider for different input voltages, and enables measuring of the ratio and phase angle responses of the divider at the voltage lower than nominal.

Fig. 3 presents the complete circuit diagram of the divider with the auxiliary chain of resistors and guards. Resistors \( R_1 - R_{25} \) are resistors consisting the divider, with the values \( R_1 = R_{25}=4.7 \) k\( \Omega \), \( R_{26}=R_{27}=2.2 \) k\( \Omega \). The resistors \( R_{26} - R_{38} \) in the auxiliary chain are standard metalfilm resistors, chosen from a lot of 88 resistors. The resistances of all resistors in the set were measured prior the assembling using the 4-wire technique and a 61/2 digit multimeter Keysight 34465A, and 24 resistors with mutually closest values were chosen for the assembling. To reduce the loop area and the parasitic inductance, and in the same time to ensure the more compact physical dimensions of the divider, the resistors in the divider in the final layout of the PCB are arranged in two parallel rows (Fig. 4), connected together with a short piece of the coaxial cable Amphenol 223/U with the sleeve cable at the corresponding resistor guard potential. Fig. 4 depicts the PCB with the resistors and guards during the assembling.
The measurement set-up was consisted of National Instruments PXI system, equipped with the acquisition cards (DAQ) NI PXI 4461. Time clock synchronization was accomplished using the internal PCI bus that divides 33 MHz clock. The additional synchronization of the start of the measurement process was achieved using a PXI trigger bus. The communication between LabView application and the PXI system is accomplished using the Ethernet protocol and the institutional local area network (LAN), thus enabling distant start and control of the measurements. All the parameters are transferred to the PXI client that adjusts the magnitude and frequency, performs the measurements and sends the measurement results to the personal computer.

The PXI system generates the stimulus signal, which is fed to the power amplifier based on Apex MP111 power operational amplifier and EK57 evaluation kit. The signal from the power amplifier is brought to the input of the divider. The input and output voltages of the RVD are brought to a NI PXI 4461 card.

The needed software was entirely programmed in-house in the NI LabView environment. The measurement process starts with the definition of the frequency range, magnitude and the set of replicate measurement for the averaging process. The communication between LabView application and the PXI system is accomplished using the Ethernet protocol and the institutional local area network (LAN), thus enabling distant start and control of the measurements. All the parameters are transferred to the PXI client that adjusts the magnitude and frequency, performs the measurements and sends the measurement results to the personal computer.

**MEASUREMENT RESULTS**

The measurement results are consisted of two main parts: the measurement of the ratio of the divider, and the measurement of the phase shift of the RVD.

The ratio and the phase shift are measured in a wider frequency bandwidth than defined by the international standard EN 50160, which defines measurement of the harmonics and interharmonics up to the 40th harmonic of the fundamental frequency. The frequency response of the ratio and phase shift have been measured in two ranges:

(i) **Lower range**, covering two sets of first 50 harmonics of fundamental harmonics equal to 50 Hz and 60 Hz (frequencies up to 3 kHz)

(ii) **Extended range**, covering the frequencies up to 50 kHz

The ratio of the divider is in all subsequent results defined as

\[ k = \frac{V_{in}}{V_{out}} \]

where \( V_{in} \) denotes the input voltage and \( V_{out} \) denotes the output voltage. The phase angle is defined as \( \phi = \angle V_{out} - \angle V_{in} \) where \( \angle V_{out} \) denotes the phase angle of the output signal and \( \angle V_{in} \) denotes the phase angle of the input signal. Fig. 7 presents the ratio of the divider for the frequencies below 3 kHz. Fig. 8 presents the phase shift for the same frequency range. Fig. 9 and 10 present the ratio and the phase angle of the divider for the extended frequency range.

\[ \text{RVD - amplitude ratio up to 3 kHz} \]

\[ \text{RVD - phase difference up to 3 kHz} \]
The digitizer NI PXI4461 has a two-channel 24-b sigma-delta A/D converter. A very significant parameter in characterizing a digitizer is the integral nonlinearity (INL), and its INL is smaller than 1 μV/V at frequencies higher than 40 Hz. The large INL (maximum INL is more than 80 μV/V) appears at lower frequencies, accompanied with a significant hysteresis, which can be attributed to thermal effects [7]. For 1 V signal amplitude, 1 V input range and 51.2 kS/s sampling frequency and simultaneous sampling, the digitizer’s full metrological properties are as follows [8]: the temperature coefficients of the magnitude and phase are 7.4 μV/V/K and 0.000008 °/K. The standard deviation of the magnitude of the voltage ratio is 2.3 μV/V. The deviation of the magnitude of the voltage ratio from the nominal value is within 3 μV/V. The phase deviation is less than 16 μ.

At 40 Hz the ratio of the RVD is 56.116 V/V where the nominal ratio is 56 V/V. The ratio of the RVD at 100 Hz is 56.116 V/V, and at 3 kHz it equals 56.117 V/V. According to Fig. 7, for the frequency range below 3 kHz it reaches the maximum value equal to 56.118 V/V and minimum value equal to 56.110 V/V, both for the frequencies between 1 kHz and 3 kHz. Therefore, the maximum ratio error for the first 60 harmonics is below 0.011 %.

The phase angle at 40 Hz is -0.0211, and at 100 Hz it is -0.0250. Finally, the phase angle is -0.6010 at 3 kHz. From the Fig. 6 it may be concluded that the phase angle changes linearly with the slope -0.2/kHz.

**CONCLUSION**

The resistive voltage divider, intended for the use in a sampling wattmeter application is developed and manufactured.

According to these results, the errors of the divider are within satisfying limits, and it yields significantly better results than a previously developed instrument voltage transformer [1] for a laboratory sampling wattmeter based on the NI 4461 DAQ. The RVD will be used in line with a set of precise current shunts of the cage type already developed at our laboratory.

The presented design is also a good basis for the further improvements that will possibly decrease the phase angle error. It can be achieved using the active elements (e.g. operational amplifiers) and compensation of the load capacitance, which is the main factor affecting the phase angle error. Those improvements will be necessary if the improved design of the RVD will be implemented in a future power standard.

**REFERENCES**


**UNCERTAINTY ANALYSIS**

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