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# AC-DC Characterization of Coaxial Current Shunts and Application of the Shunt in the Digital Sampling Wattmeter

## Summary

The purpose of this paper is to give a review of ac-dc characterization of the current shunts and application of the current shunt (nominal current 1A) within the digital sampling wattmeter. It is described the ac-dc transfer difference measurement of six cage type ac shunts from 10 mA up to 10 A using step-up measurement procedure. Furthermore, the substantial part of the measurement setup is fast switching system which is also described in detail. For the purpose of measurement procedure, the application is developed in LabVIEW and whole process is fully automatized. Obtained results are analyzed and shown on graphs. This paper is extended version of two papers: [1] and [2] which are presented on 1<sup>st</sup> International Colloquium on Smart Grid Metrology. Thus, paper is extended with presented application of the shunt 1 A in the digital sampling wattmeter.

**Key words:** current shunt, step-up procedure, thermal voltage converter, automated measurement procedure, digital sampling wattmeter

## Nomenclature

$V_{AC}(rms)$	<i>root-mean square value of the sinusoidal voltage</i>
$\delta_{AC-DC}$	<i>ac-dc difference</i>
$V_{DC}$	<i>dc voltage</i>
$V_{AC}$	<i>ac voltage</i>
$E_{DC}$	<i>output EMF of the thermocouple when the dc voltage is applied</i>
$E_{AC}$	<i>output EMF of the thermocouple when the ac voltage is applied</i>
$\Delta_0$	<i>relative error between <math>E_{AC}</math> and <math>E_{DC}</math></i>
$V_{DC}^S$	<i>output voltage of the referent standard when the dc voltage is applied</i>
$V_{AC}^S$	<i>output voltage of the referent standard when the ac voltage is applied</i>
$V_{DC}^X$	<i>output voltage of the unit under test when the dc voltage is applied</i>
$V_{AC}^X$	<i>output voltage of the unit under test when the ac voltage is applied</i>
$k^x$	<i>exponent of the thermal voltage converter (TVC) response (for the referent standard)</i>
$k^S$	<i>exponent of the thermal voltage converter (TVC) response (for the unit under test)</i>

# Introduction

Resistive shunts are used as current transducers which transfer current into voltage for the purpose of current and power measurements. Such system for electric power measurement is digital sampling wattmeter. Transducers used as reference standards for these calibrations must be stable and insensitive to temperature and signal levels and have a small ac-dc transfer difference at frequencies up to 100 kHz [3]. The shunts which are used in national metrology laboratories to satisfy required parameters and also analyzed in this paper are cage type designed similar to SIQ AC shunts [4], and are fabricated using double-sided FR4 fiberglass-epoxy PCB material, equipped with N-type connectors, and constructed with three circular PCB elements, crossbars and resistors. Thermal converters are the most accurate standards for the transfer of alternating current to the equivalent dc quantities [5]. A special type of thermal converter is used in this measurement and it is planar multi junction thermal converter (PMJTC (90 Ω)). It is designed and assembled at the IPHT (*Institute of Photonic Technology*) in Jena, Germany. Switching between ac and dc source with the shortest possible interruption of the input voltage is a prerequisite to achieve constant heating conditions in the PMJTCs. Since, the switching time must be small compared to the thermal time constant of the PMJTCs [6]. Consequently, each thermal AC-DC voltage transfer measurement system requires a device which performs fast switching of the input of the thermal voltage converter (TVC) between AC and DC calibrator outputs. There are no commercially available switches on the market, which could be directly implemented in the AC-DC transfer [7].

## AC-DC Transfer Difference

### Ac-dc transfer difference measurement system

Generally, the ac voltage is defined by the root-mean square (rms) value of the sinusoidal waveform;

$$V_{AC}(rms) = \sqrt{\frac{1}{T} \int_0^T (V(t))^2 dt} \quad (1)$$

According to the definition, it is possible to compare the ac voltage with the dc by way of the electrical power. In the thermal method, dc and ac voltage are alternately applied to the heater of a thermal converter. Then the amounts of joule heating are compared by measuring the temperature of the heater by a thermocouple. By applying ac and both polarities of dc in measurement sequence, and measuring the thermocouple output, the conventional definition of ac-dc difference is [1]:

$$\delta_{AC-DC} = \left. \frac{V_{AC} - V_{DC}}{V_{DC}} \right|_{E_{AC} = E_{DC}} \quad (2)$$

Here the quantities  $V_{AC}$  and  $V_{DC}$  represent the output EMFs of the thermocouple when the dc voltage  $V_{DC}$  and the ac voltage  $V_{AC}$  are applied to a thermal converter. If a thermal converter is ideal then [8]. The current shunt ac-dc transfer measurement system consists of following components: dc and ac voltage source, power amplifier, relay box, T-connector for serial connection of the shunts, two control digital multimeters (DMMs) and two DMMs (HP 3458A) for measuring. Detailed connections of current T-connector and coaxial cables as part of whole measuring system are shown in Fig.1 and whole measurement setup is shown in Fig.2. [1].

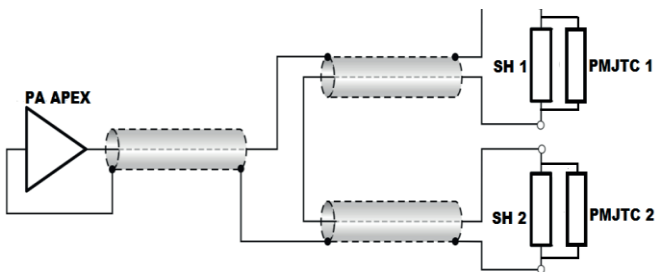


Figure 1. Connections in measuring system for AC-DC transfer difference of current shunts [1]

The software for the measurement setup was programmed in LabVIEW programming environment. Output voltages of thermal converters (PMJTCs) are simultaneously sampled using triggering function. Thus, acquired voltages are processed with developed LabVIEW application. AC-DC transfer difference of shunts (10 mA to 10 A) have been measured according to scheme depicted on Fig. 2. Calibrator Transmille 3050A is

used as a DC source. Same device is used as power source in the digital sampling wattmeter. Arbitrary/function generator Tektronix AFG 3021B is used as AC source for AC-DC transfer measurement.

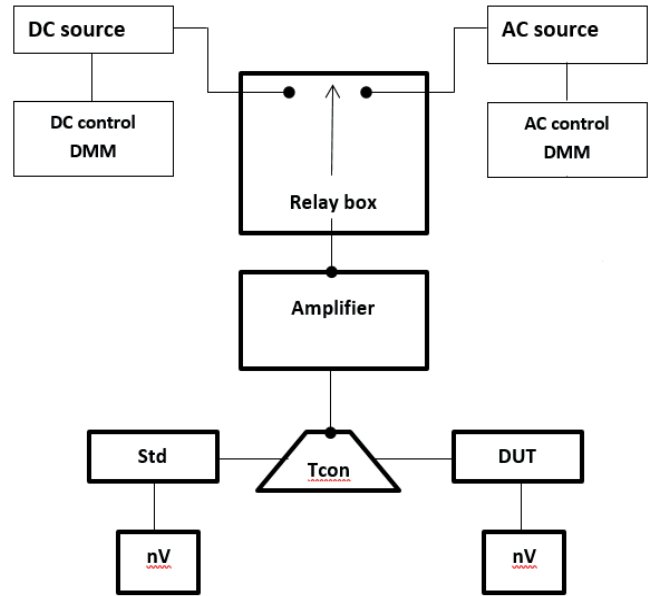


Figure 2. Connections in measuring system for AC-DC transfer difference of current shunts [1]

### Switch used in the ac-dc transfer difference measurement system

The switch consists of three units. The control unit (NI USB-6008 and UL-N2803A Darlingtion Transistor Arrays) is outside the relay box which houses four relays and holds the input and output connectors. Input and output connectors are used to connect ac source, dc source, digital multimeter and load. So, relays are separated from electronic device because of their thermal interference. During the measurements, the relay unit is therefore free of any electrical signals on the relay driving side. This is important to obtain both a low noise level and a good thermal stability. Also, in spite the fact that relays are latch type, to be sure that each relay works on the same temperature, all relays are mounted on the copper plate with thermal paste and relays are mutually connected. Besides, these relays have been chosen as a compromise between number of mutual connections, number of connections with other components and length of operational and release time. All connections between relays in relay box, as well as out of the box, is shown in Fig.3. Further, the whole relay box and manual PCB design for relay control were assembled at our laboratory and have been used in ac-dc difference measurement application. The operating time and release time indicate the time required for each contact to close after the voltage has been applied to or removed from the coil. However, because the relay has a mechanical structure, a bounce state exists at the end of the operating and release times. Moreover, for the purpose of ac-dc transfer measurement, whole measurement process is automatized using LabVIEW and relay box performs measurement sequence: ac, dc+, ac, dc-, ac [2]. Thus, used relay box enables required conditions for ac-dc transfer measurement.

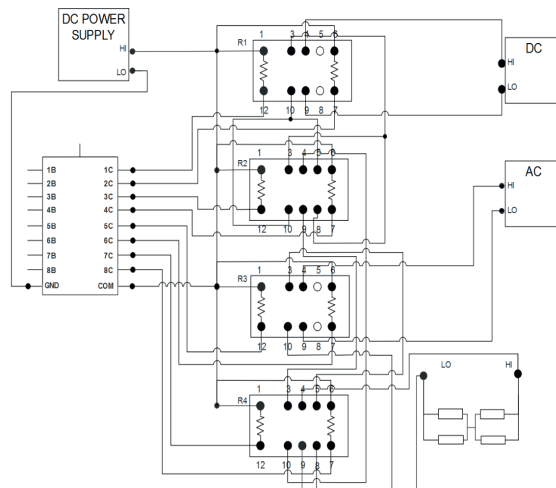


Figure 3. Mutual connections of relays in relay box and outer connections with other components [2]

### Ac-dc transfer difference measurement procedure

The software program developed in LabVIEW sets the initial voltage and frequency of ac source and voltage of dc source. After that it has been waiting for heating of current shunts and stabilization. The frequency of the output voltage waveform from arbitrary function generator is swept across a specified range (from 50 Hz to 100 kHz). "Step-up" measurement procedure which is presented in [9] has been used for AC-DC transfer difference measurement and shown in Fig. 3. Voltage signals from DC and AC source are amplified with power amplifier Apex Eval 57 R-A with gain factor of 10. Digital multimeters HP3458A are used as nanovoltmeters (100 mV input range) to measure voltage outputs from PMJTC because its voltage output has enough large value to measure without special nanovoltmeters. Voltage on the AC source is set to be constant during the AC-DC transfer measurement of a shunt and voltage on DC source has been adjusted by proportional gain of PID regulator which is also programmed in LabVIEW application. Each measurement sequence has been performed and measurement result has been taken into account only if it satisfies next condition [1]:

$$\Delta_0 = \frac{E_{AC} - E_{DC}}{E_{DC}} \leq 50 \mu V/V \quad (3)$$

where  $E_{AC}$  and  $E_{DC}$  represent the output EMFs of the thermocouple on the referent standard channel. Time delay is 60 seconds in all the steps of measurement sequence. AC-DC transfer measurement has been performed for DC and next frequency points: 50, 100, 1000, 10000, 20000, 50000 and 100000 Hz.

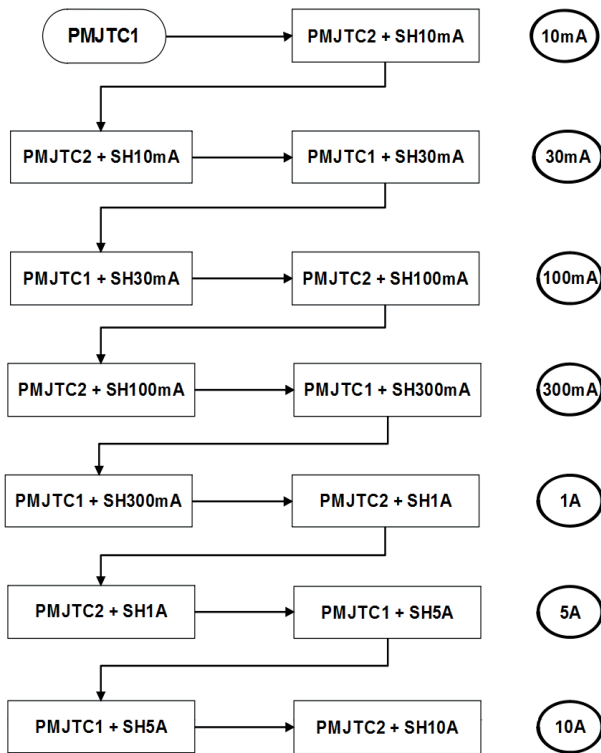


Figure 4. Step up procedure [1]

When two shunts (with PMJTCs in parallel with each of the shunt) "s" and "x" have been compared, difference between two ac-dc transfers can be obtained from next two expressions [1]:

$$\delta = \delta_X - \delta_S \quad (4)$$

i.e.,

$$\delta = \frac{V_{DC}^x - V_{AC}^x}{k^x V_{DC}^x} - \frac{V_{DC}^s - V_{AC}^s}{k^s V_{DC}^s} \quad (5)$$

, where  $V_{DC}^S$  i  $V_{AC}^S$  are output voltages of the referent standard (shunt and PMJTC in parallel combination) when dc and ac is applied.  $V_{DC}^X$  i  $V_{AC}^X$  are output voltages of the unknown combination (shunt and PMJTC in parallel combination).

$k^x$  i  $k^S$  are the exponents of the thermal voltage converter (TVC) response, with typically  $k = 2$  for PMJTCs [10].

Considering preformed measurement procedure and related measurement sequence, following expressions are applied [1]:

$$V_{DC}^S = \frac{V_{DC+}^S + V_{DC-}^S}{2}, V_{AC}^S = \frac{V_{AC1}^S + V_{AC2}^S}{2}, \quad (6)$$

$$V_{DC}^X = \frac{V_{DC+}^X + V_{DC-}^X}{2}, V_{AC}^X = \frac{V_{AC1}^X + V_{AC2}^X}{2}$$

Since the ac-dc difference of the reference standard is known, then the ac-dc difference of the unknown can be obtained from the next expression [10]:

$$\delta_X = \delta_S + \frac{V_{DC}^x - V_{AC}^x}{k^x V_{DC}^x} - \frac{V_{DC}^s - V_{AC}^s}{k^s V_{DC}^s} \quad (7)$$

Thus, when condition (3) is fulfilled, ten measurement results has been taken and their mean is calculated [1]:

$$\delta_X = \frac{\sum_{i=1}^{10} \delta_i^x}{10} \quad (8)$$

## Results and Discussion

### Ac-dc transfer difference results

Graph shown in Fig. 5. represents values of ac-dc differences for all shunts, values are overlapped and visible as one line. So, all shunts have almost the same trend to the frequency of 20 kHz.

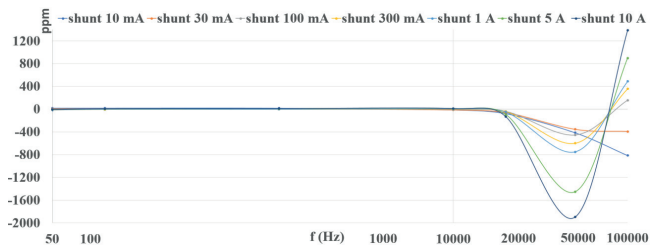


Figure 5. AC-DC transfer difference for shunts with nominal current from 10 mA to 10A for whole frequency range (Linear approximation) [1]

Further, the graph in Fig.6. shows ac-dc difference of shunt (nominal current 1A) that is used as component in digital sampling wattmeter.

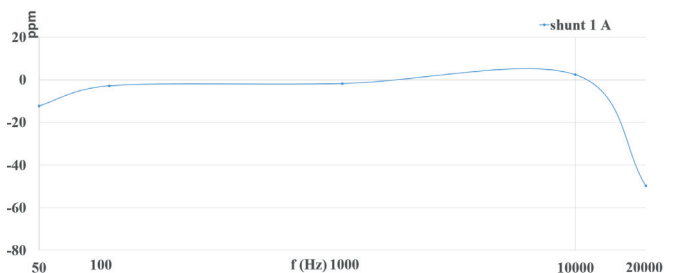


Figure 6. AC-DC transfer difference for shunt with nominal current of 1 A for frequency range from 50 Hz to 20 kHz (Linear approximation)

### Digital sampling wattmeter results

Current signal from power source is converted into voltage signal via current shunt. Used shunt has nominal current of 1 A and its ac-dc transfer characteristics is shown in Fig. 6. When nominal current of shunt is applied at the input, obtained voltage amplitude at its output is 1 V. Also, voltage signal is transformed from high level of 560 V to 10 V via resistive voltage divider developed at the Faculty of electrical engineering and computing [11]. Both signals are sampled with digital multimeters HP3458A in master-slave configuration. Output voltage of the current shunt is sampled with slave DMM over four values of frequency and results are shown in Fig. 7. Output voltage of the resistive voltage divider is sampled with the master DMM (Fig. 8.). Maximum signal frequency of calibrator Transmille 3050A when used as power source (i.e. in power mode) is 400 Hz.

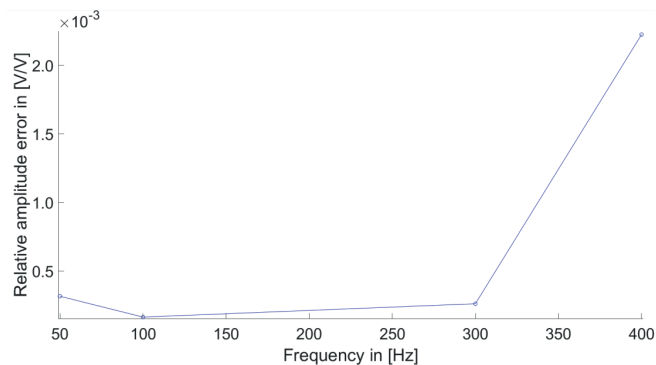


Figure 7. Relative amplitude error of voltage for current shunt with nominal current of 1 A

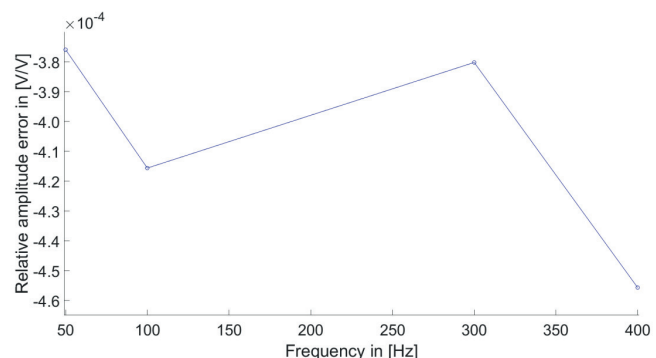


Figure 8. Relative amplitude error of voltage for resistive voltage divider

Samples are acquired in LabVIEW and processed using interpolated DFT algorithm. Interpolated DFT algorithm calculates amplitude, phase and frequency when sine wave signal is noncoherently sampled, a non-integer number of signal periods is contained in the sampled record. Also, interpolated DFT algorithm fight this inherent leakage using time-domain windowing, which effectively reduces the leakage, but at the same time increases the estimated standard deviation due to noise contained in the sampled record [12].

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## Conclusion

After analyzing obtained results, it can be concluded that relative amplitude error of current shunt is in the same order as the relative amplitude error of voltage divider. But, only difference is for frequency of 400 Hz when relative amplitude error for current shunt is larger. Obviously, relative amplitude error of voltage for the resistive divider is in the same order over whole frequency range which means that calculation of amplitude with interpolated DFT algorithm does not depend on these analyzed signal frequencies.