The paper describes the DC characterization of AC current shunts recently developed at the Faculty of electrical engineering and computing, University of Zagreb (UNIZG-FER). The shunts of cage type design include nine shunts that range from 1 mA up to 10 A. The following DC properties were inspected: long time drift, temperature coefficients and power coefficients. The results have shown that shunts have low temperature (<7 μΩ/°C), and power coefficients (<10 μΩ/°W), and small drift which makes them suitable for precise power measurement applications. Also, relative humidity dependence of currents shunts is investigated.
the effective permittivity of the microstrip line. For a target characteristic impedance of the equivalent line, the crossbar width is calculated using the MoM routine and bisection method, based on the capacitance calculation. Finally, the inductance of crossbars is calculated from the capacitance using the lossless transmission line approach. For a target characteristic impedance of the line equal to \( Z_0 = 10 \, \Omega \) (to match the resistance of the resistors for shunts with nominal currents 1 A, 5 A, and 10 A), the width of the crossbar is calculated as 15.48 mm and its capacitance as \( C = 721.22 \, \text{pF/m} \). The numerical results have been compared with the professional software Infolytica ElecNet used as benchmark, where the capacitance of the crossbar calculated with ElecNet is 699.14 pF/m, thus giving a good agreement with the difference 3.2%. The model in ElecNet applied the accurate modelling of the electrodes using their real thickness. The difference between results can be attributed mostly to the limited accuracy of the Schneider equation in this particular application, since it assumes an infinite dielectric plane. Using a more accurate effective permittivity, calculated in ElecNet for the obtained crossbar width equal to 15.48 mm, the MoM routine yields capacitance 697.09 pF/m, which is within 0.2% as compared to FEM. The inductance is obtained from the calculated capacitance as \( L = C \cdot Z_0^2 \) and it equals 72.12 nH/m. This numerical result has been also compared with the professional software Infolytica MagNet used as benchmark, where the inductance of the crossbar calculated with MagNet is 72.25 nH/m, thus giving a good agreement with the difference 0.18%. The actual width of the crossbars was finally, due to the manufacturing reasons rounded to 15 mm.

The permittivity of the PCB material was measured over the wide frequency range using a LCR-bridge and two rectangular samples. For that purpose, two parallel-plate capacitors were cut from FR4, one of them having a 1 mm thickness and the other one having a 2 mm thickness. For the crossbars (their thickness is 1 mm), a 137 mm \( \times \) 148 mm sample was cut, and its capacitance was measured using a Rohde&Schwarz (Hameg) HMB118 LCR bridge, being 890.5 pF at 1 kHz, with the accuracy as defined by manufacturer equal to 0.11% at this frequency and impedance. Using the parallel-plate capacitor approximation, the permittivity of crossbars material is 4.96. To determine the possible error caused by the parallel-plate approximation, the calculation of the capacitance of the sample model was run in the finite-element-method (FEM) commercial package Maxwell. For the model with the permittivity equal to 4.96, the FEM-based calculated capacitance was 896.42 pF, thus giving the difference 0.67%.

For the disks (thickness is 2 mm), a 157 mm \( \times \) 168 mm sample was cut. Its measured capacitance is 565.21 pF at 1 kHz, with the accuracy as defined by manufacturer equal to 0.12% at this frequency and impedance. Using the parallel-plate approximation, its permittivity is 4.84. The FEM based calculated capacitance was 571.39 pF, thus giving the difference 1.09%.

In total, nine AC shunts have been manufactured: 1 mA, 10 mA, 30 mA, 100 mA, 300 mA, 1 A – two shunts, 5 A and 10 A. The values of shunts were chosen so it is possible to calibrate them with usual step up method starting from 10 mA Planar Multijunction Thermal converter (PMJTC) current standard obtained from Leibniz-Institute for Photonic Technology Jena (Leibniz-IPHT) up to 10 A. Resistance values of developed shunts are well suited for use with these PMJTCs which have 90-Ω heaters with a rated current of 10 mA [10]. The high precision Vishay S102C foil resistor have temperature coefficient of ±0.20 ppm/°C, and it also features low inductance, low capacitance, low power coefficient, stability and low noise [11]. The resistor is also available in wide range of nonstandard values. The shunts were designed to provide peak voltage output of approximately 1 V at nominal current, to suite most modern precision DMMS, AC measurement and AC/DC transfer standards.

Also, the dissipated power on each S102C resistor in each shunt does not exceed 30% of ambient power rating at nominal voltage output to minimise the effect of resistor self-heating due to the fact that resistors are placed close to each other. Fig. 1 shows double row of Vishay resistors in 10 A shunt during manufacturing. It is the only resistor that has two resistors per crossbar, all other shunts have one resistor per crossbar. The completed set of shunts is shown in Fig. 1b. The photo also shows two standards to easily connect shunts with PMJTC for AC/DC comparison purpose [12].

3. Determination of temperature coefficients

To begin with analysis the shunts have been photographed with thermal image camera to determine the temperature distribution and actual temperature at nominal current (Fig. 2) for two shunt types (14 crossbars and 70 crossbars). It was determined that shunts are heated up to 31 °C at nominal current, significantly from 23 °C usual laboratory temperature.

Next, to determine the actual temperature coefficients (TCR), the shunts were compared against L&N set of resistance standards (1 Ω–10 kΩ) with low TCR using two 6,5 digital multimeters in usual DVM type resistance comparison method as is discussed in literature for the similar measurements [13]. The method is capable to compare two resistors with needed precision with simultaneous triggering. Each shunt was matched with resistance standard with closest nominal resistance to tested shunt. The used DVMs have 24-bit analog to digital converters (ADS1256) and precise voltage reference type ADR421; 2.5 V that can replace usual Keysight 3458A 8,5 digitsmultimeters in DVM method for this purpose [14]. The system to measure shunt TCR consists of two temperature regulated air baths capable to set up temperature in 10–40 °C range independently, DVM resistance method, current reversal module using two SPDT OMRON G5LA-14 5 V power relays controlled by National Instruments 6008 DAQ card, Rigol DP1116A DC power supply with a switchable output up to 16 V/10 A or 32 V/5 A and computer that serves as a controller to fully automate the measurement process as shown in Fig. 3. The measurement procedure was programmed using LabVIEW programming language.

The thermal air baths are specially developed for this purpose based on Ezetil E21 Electric Cool Boxes with capacity of 20 L. These boxes have 12 V Peltier elements and their basic purpose is cooling only. As Peltier elements have ability to cool and heat, depending on polarity of DC voltage, the boxes were modified to get the ability of cooling and heating of air inside air box. Peltier elements are controlled separately from the fan that works on constant DC 12 V, and they are driven by two double H-bridges (two L298 ICs connected in parallel) which are controlled by Arduino Uno microcontroller boards. Each air bath has own microcontroller that measures temperature inside box with NTC temperature sensor and control Peltier element depending on measured temperature and desired temperature that is defined by user. Temperature of air bath is controlled in range of +10 °C and +40 °C with resolution of 0.01 °C by PID algorithm that runs on Arduino microcontroller board. This range is possible with room temperature set to 23 °C. Arduino microcontroller accepts commands over USB cable (RS232 protocol over USB) from application in LabVIEW that runs on PC. The whole TCR measurement system is shown in Fig. 4.

The fully automated procedure allows measurement to be performed when temperature stabilizes to predefined temperatures of both baths. The TCR measurements have been performed in 18 different temperatures ranging from 18 °C to 39 °C to cover temperature range of shunts. The whole procedure lasts approximately 4 hours, and each measurement was repeated at least twice to check the repeatability of measurements. To reduce the self-heating
during TCR measurements the shunt is powered to less than 10% of nominal current and the reference resistor is powered to maximum of 100 mW. The reference resistance standard is kept in separate regulated air bath at constant temperature of 23 °C ± 30 mK.

All reference standard resistors (L&N Rosa (NBS) type produced from 1963 to 1966) used for comparison have temperature coefficient $\alpha_R$ less than 10 $\mu$Ω/°C. The results of TCR measurement for shunts have shown that TCRs for all shunts are in the range from...
−1.5 μΩ/Ω/°C to 6.2 μΩ/Ω/°C. The Fig. 5 shows typical TCR measurement for 0.1 A shunt, which is similar to all other shunts. The total uncertainty contribution of TCR depends on the data fit uncertainty calculated with Gauss-Newton fitting program [15], non-homogenous air bath temperature and temperature measurement accuracy itself and it is estimated to be 0.5 μΩ/Ω/°C for all shunts. Calculated TCRs of shunts are presented in Table 1.

### 4. Determination of power coefficients

Power coefficient measurement was conducted in the same setup as described above using one reference resistance standard and one shunt, both enclosed in separate air baths and kept at constant temperature of 23 °C. The main challenge in this setup is to increase the power dissipation of shunt while keeping the power dissipation of standard resistor constant. This was solved by supplying AC current (10 kHz frequency) to the shunt using arbitrary generator (Rigol DG4062) and power amplifier (Rigol PA1011), while keeping DC current passing through standard resistor and shunt constant at 10% of nominal current of measured shunt. In this way it was possible to power shunts (I = 1 A; I = 5 A) with additional AC current to obtain several measuring points: 50%, 60%, 75%, 90% and 100% of nominal AC shunt current ratings. The reference resistors are powered to maximum of 10 mW during measurement to minimize the heating of reference resistors. In addition, the capacitor is connected on the power amplifier to avoid shunting the resistor shunt with the function generator. Further, voltmeters on reference resistor and shunt are connected through double RC filter used to cancel AC component during DC voltage measurement. The voltmeter measuring the standard resistor does not need to have RC filter as there is no AC current passing through standard resistor but it was added to equalize the input characteristics of both voltmeters [16]. The used voltmeter is cancelling only full periods on DC range, so the maximum error during voltmeter integration time T will be when integration time lasts for n + 1/2 periods of AC current with frequency f (Fig. 6).

The maximum integration error (1 V RMS superimposed on 0.1 V DC) can be calculated as:

\[ P_{\text{max}} = \frac{1}{1.11} \frac{V_{\text{max}}}{2f} \frac{1}{0.1V} \]  

With the AC frequency f = 10 kHz, and the integration time of T = 1 s, the maximum error is \( P_{\text{max}} = 450 \mu V/V \) which is significant for high precision measurements. However, with double RC filter connected to the input of voltmeter, the influence of AC current is lowered according to expression:

\[ \frac{U_{\text{out}}}{U_{\text{in}}} = \frac{1}{2\pi f RC} \]  

With the selection of \( R = 10 k\Omega \) and \( C = 1 \mu F \), the ratio \( U_{\text{out}}/U_{\text{in}} = 2.53 \times 10^{-6} \). Accordingly, the maximum integration error is then \( P_{\text{max}} = 0.00114 \mu V/V \) which is practically negligible. Thus, the shunt/standard resistor ratio will change only because of shunt resistor change due to added power dissipation in each step of the measurement process. To enable extra precision, DVMs used for this measurement are HP3458A. PCR value determined for 1 A shunt is (8.6 ± 0.5) μΩ/Ω/W. The whole PCR measurement system is shown in Fig. 7.

The calculated temperature coefficients of both reference resistors and shunts were taken into account to obtain more precise values of shunt power coefficients. The PCR measurement for shunts below 0.3 A rated current have not been measured, as the PCR for these shunts are negligible due to very low power dissipation on Vishay resistors that make the resistive elements of the shunts.

### 5. Drift measurement

Drift investigation was conducted in the same setup as for TCR and PCR using one shunt (I = 1 mA, \( R = 714.29 \Omega \)) and one reference

![Fig. 5. Measurement of 0.1 A TCR (temperature has been changed from 15 °C to 39 °C with standard deviation of each measurement).](image)

![Fig. 6. Maximum 3458A integration error on DC range.](image)

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<th>Table 1 Temperature coefficients.</th>
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resistance standard \((R = 1000 \Omega)\), both enclosed in each air bath and kept at constant temperature of 23 °C. The resistance value of the shunts was measured over a three months period in order to determine the long-term drift. The measurement procedure was repeated several times and consists of approximately three weeks of intensive measurement performed each hour to discern any day-night pattern from the drift itself. Drift is only measured for shunt resistor with nominal current 1 mA. The calculated drift value is 0.238 \(\mu\Omega/\Omega\)/year.

6. Humidity coefficient measurement

Recently it was reported in [17] that the shunts have a relative humidity (RH) dependence in the order of one \(\mu\Omega/\Omega\) per % with a time constant in the order of ten days so to investigate that claim, the humidity coefficient was measured using the similar setup for determining PCR and TCR coefficients. In this setup, standard resistor is kept in enclosed regulated chamber with temperature at 23 °C and shunt with nominal current of 1 A is kept in second thermal chamber with equal temperature of 23 °C where relative humidity has been regulated from 29% up to 85%. Fig. 8 shows that DC resistance is negligibly changed when RH is increased from 29% to 35%. Mean values are overlapped inside standard deviation limits for both RH coefficients. Measurements are carried out eighteen times where each measurement last three minutes to satisfy repeatability. Rosa type standard have resistance element sealed in a can filled with mineral oil, and thus very low humidity coefficient.

Further, to investigate behaviour in high humidity environment, RH coefficient is increased to 65% and 85%. Fig. 9 shows change of DC resistance for three different RH coefficients. Samples are approximated with regression lines and for RH coefficient values of 30 and 65 results are practically overlapped. But, significant deviation is obtained at humidity level of 85. In that case, dc resistance has changed in the order of about 1 \(\mu\Omega/\Omega\)/RH% which is shown in Fig. 9.

![Fig. 7. PCR measurement system (photo and electric diagram).](image)

![Fig. 8. Relative humidity dependence for RH 29% and 35%](image)
7. Conclusion

The DC characterization of FER AC current shunts with current range from 1 mA to 10 A are presented. The shunts have been developed for precise power measurement applications, and the results have shown that the shunts have low drift, low TCR and PCR which make them suitable for the intended purpose. It was also shown that the heating of the shunts by the measurement current is distributed very homogenous over the circle plate where the Vishay resistors are placed. According to this fact, there is direct correlation between the power coefficient and the temperature coefficient of the shunts. Considering further investigations on relative humidity dependence, improvements can be achieved using digital voltmeters with higher resolution. For this purpose, we can use HP3458A as in the PCR measurement. Besides, current shunt can be placed in humidity and temperature chamber which has finer regulation of RH coefficient.

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References