A Power Frequency Modular Sampling Standard for Traceable Power Measurements: Comparison and Perspectives

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A Power Frequency Modular Sampling Standard for Traceable Power Measurements: Comparison and Perspectives

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Abstract—A power frequency modular digital sampling power standard (DSPS) is developed and extensively characterized at Istituto Nazionale di Ricerca Metrologica (INRiM) for accurate electric power measurement with a relative uncertainty ($k = 1$) better than $8\,\mu\text{W/VA}$. The calibration strategy employed allows to link its key constituents to electrical quantum standards with a relative uncertainty ($k = 1$) within 3×10^{-6}. Comparison measurements against the national power standard at $53\,\text{Hz}$ agree well within the respective measurement uncertainties and did not exceed $10\,\mu\text{W/VA}$ at $240\,\text{V}$ and $5\,\text{A}$ and any power factor.

The various novelties introduced make the DSPS a versatile metrological grade measurement setup, which lends well to further improvements and accurate evaluation of electrical parameters involved in power quality measurements. The paper reports the standard, its traceability chain and calibration strategy, comparison measurements and uncertainty budget.

Index Terms—Power measurements, current shunts, measurement standards, quantum standards, comparison, signal sampling, voltage divider, measurement uncertainty

I. INTRODUCTION

THE primary alternatig (ac) power and energy standard at Istituto Nazionale di Ricerca Metrologica (INRiM) is presently based on simultaneous sampling of voltage and current waveforms using high precision synchronized digital multimeters coming from calibrated voltage and current transducers. Sampling based ac power standards have been developed by several national metrology institutes (NMIs) [1]–[5] and the most recent implementations [6]–[8] report uncertainties ranging from $1\,\mu\text{W/VA}$ to $10\,\mu\text{W/VA}$.

Over the last few years request coming to INRiM from national accredited and industrial laboratories for as low as possible uncertainties in the calibration of standard wattmeters, watthour/varhour meters, power analyzers and from instrument manufacturers involved in the development of emerging equipment for smart grid monitoring, have triggered an intense research work towards the development of a new modular digital sampling power standard (DSPS) and its comparison against the national standard of power and energy for frequencies from $47\,\text{Hz}$ to $65\,\text{Hz}$. The concept of modularity allows its use in many metrological grade experiments with the aim of probing the benefits of the sampling strategy to cope as much

as possible with the needs coming from different experimental situations in which multiparametric analysis of waveforms is not sacrified against the required precision and accuracy. The DSPS encompasses the latest efforts pursued by INRiM and partners during the participation in the EMPIR joint research project TracePQM [9]. The main goal of the project was the development of two modular macro setups, based on sampling strategy, for low frequency (LF) and wideband (WB) traceable power and power quality measurements. Herein we report the INRiM implementation of the LF modular setup presented in [10], but its content has been substantially extended. Among others it presents details about experimental setup and recent progress towards its full calibration and validation at power frequencies. The traceability chain implemented allows to link active, reactive and apparent power measurements to the dc quantum toolbox for electricity, i.e. the Josephson and quantum Hall effects, through the ac–dc transfer principle which, at the present state of development, ensures the lowest attainable level of uncertainty during the calibration of DSPS constituents at power line frequency and beyond it.

Comparing the DSPS to the most recent ac power standards, its performance and modularity as a whole resembles the standard reported in [8] and its measurement standard uncertainty $8\,\mu\text{W/VA}$ differs slightly compared to $2.5\,\mu\text{W/VA}$ achieved by introducing more complex circuit refinements as demonstrated in [5].

Its extension as three-phase power standard is straightforward at an even higher cost as well as calibration time needed for metrological characterization of all its single constituents. However, for internal calibration purpose it is more convenient and less time consuming to maintain a single-phase power standard at the lowest level of uncertainty attainable and to calibrate against it a three-phase commercial power and energy comparator of class $\pm 0.005\,\%$ to be used for calibration purpose of single and three-phase power and energy meters under sinusoidal regime. Moreover, its use as reference standard for power measurements at low frequencies, e.g. up to few kilohertz, and for power quality measurements is straightforward as long as all its components should be well characterized at all frequencies of interest. Recent research activities on this topic are in progress and the main achievement will be matter of future papers.

II. TRACEABILITY CHAIN FOR THE ELECTRICAL SI-WATT

The traceability chain for the electrical SI-Watt realization and dissemination in ac is shown graphically in Fig. 1. Its

realization takes place on the simultaneous sampling of voltage and current waveforms using the DSPS described in section III. Here we report a short overview of the metrology-grade experiments performed at INRiM for practical realization and dissemination of dc and ac units for electrical quantities which form the basis for traceable power and power quality measurements. Further details about the DSPS calibration strategy are reported in section V.
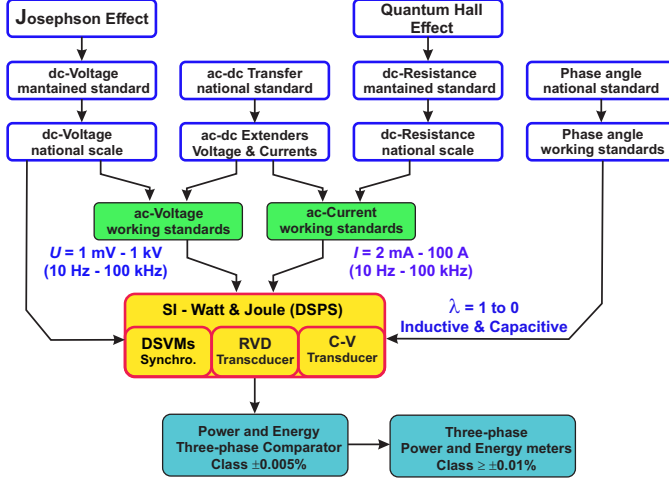

Fig. 1. Overview of the traceability chain employed for the electrical SI-Watt realization and proposal dissemination plan for the calibration of commercial single and three-phase phase power and energy meters.

A. dc-Josephson Voltage Standard (JVS)

The inverse ac Josephson effect has been used since 1983 at INRiM (formerly IEN "Galileo Ferraris") as basis for the realization of the dc volt unit starting from fundamental physical constants, i.e. Planck's constant, h, and elementary charge, e, through a single frequency measurement, f, i.e. $V = (h/2e) \cdot f$, using 1 V and 10 V Josephson array voltage standard, dc-JAVS. The dc national voltage standard is maintained at $1.018\,\mathrm{V}$ and $10\,\mathrm{V}$ level using a group of solid-state dc voltage standards calibrated periodically against a Josephson voltage standard [11]. A solid-state dc voltage standard was used for the calibration purpose of DSPS constituents. It was calibrated against the maintained dc volt unit with a relative uncertainty ($k = 1$) better than $0.3\,\mu\mathrm{V/V}$ and $1.5\,\mu\mathrm{V/V}$ at the nominal voltage of $10\,\mathrm{V}$ and $1.018\,\mathrm{V}$, respectively.

B. dc-Quantum Hall Effect (dc-QHE)

The dc-QHE has been used since 1991 at INRiM for the reproduction of the resistance unit and more recently for its practical realization [12], $R_{\mathrm{K}} = \dfrac{h}{i \cdot e^2}$. The scaling process performed for the calibration of dc-resistance standards used for the maintenance of the resistance unit and the realization of national dc-resistance scale is described in [13]. For the dc-calibration purpose of the coaxial current shunt used in this work only low-ohmic resistance standard calibrated against the dc-resistance national standard was used (see section V-B).

C. ac-dc Current and Voltage Transfer Standards

The ac-dc current and voltage transfer standards allow to link the rms-value of ac current and voltage quantities, Q_{ac}, to their dc counterparts, Q_{dc}, using thermal converters (TCs) [14] as follows:

$$Q_{\mathrm{ac}} = Q_{\mathrm{dc}}(1 \pm \delta_{\mathrm{ac-dc}}) \tag{1}$$

where δ_{ac-dc} is the ac–dc transfer difference/error of the TC. Planar thin-film multijunction thermal converters (PMJTCs) [15] are the most accurate ac–dc current and voltage transfer standards suitable to operate from $10\,\mathrm{Hz}$ to $1\,\mathrm{MHz}$.

The Italian national standard of alternating current and voltage is based on a reference group of PMJTCs [16], [17] with nominal current and voltage of $10\,\mathrm{mA}$ and $1.5\,\mathrm{V}$ and relative uncertainty ($k = 1$), in the audio frequency band, better than $0.5\,\mu\mathrm{A/A}$ and $0.5\,\mu\mathrm{V/V}$, respectively.

Two PMJTCs with heater resistance of $90\,\Omega$ and $180\,\Omega$ were calibrated to ensure traceability to the DSPS constituents. For higher ac currents and voltages the traceability is ensured by means of range extenders, i.e coaxial shunts and coaxial resistors connected in parallel or in series to PMJTCs for currents up to $5\,\mathrm{A}$ and voltages up to $240\,\mathrm{V}$(see section V).

D. Phase-angle Standard for Current and Voltage

The phase angle reference standard for current measurements is based on 1 A coaxial current shunt of disk design with calculable time constant. The calibration of phase angle error of current shunts is performed by direct comparison against the reference standard using a step-up/down procedure and a home-built digital phase comparator [18]. Details on phase angle error calibration of current shunt employed in the DSPS setup are given in section V-B0c.

The phase angle reference standard for voltage measurements has been built up as reported in [19]. The starting point is the evaluation of the phase difference between the channels of an asynchronous digital phase comparator at different voltage levels. Afterwards, the phase angle error of a set of compensated RVDs with nominal ratio from 1:3 to 1:51 is evaluated using the step-up procedure. Details about the calibration of the RVDs phase angle error used in the DSPS setup are reported in section V-D.

III. MODULAR DIGITAL SAMPLING POWER STANDARD

The use of sampling strategy for the primary power metrology has been thoroughly demonstrated and described in various papers [2], [20], [21].

The modular digital sampling power standard, herein reported, is the INRiM implementation of the single-phase LF modular setup developed in the framework of the TracePQM project [22] for highly accurate power measurement.

Fig. 2 shows a simplified schematic of the modular DSPS setup and its main constituents are:

- Synchronized digital sampling multimeters, $\mathrm{DSM}_{1,2}$, externally triggered using a direct digital clock synthesizer $\mathrm{DDS}_{\mathrm{Clk}}$ with time-base linked to $10\,\mathrm{MHz}$ reference clock
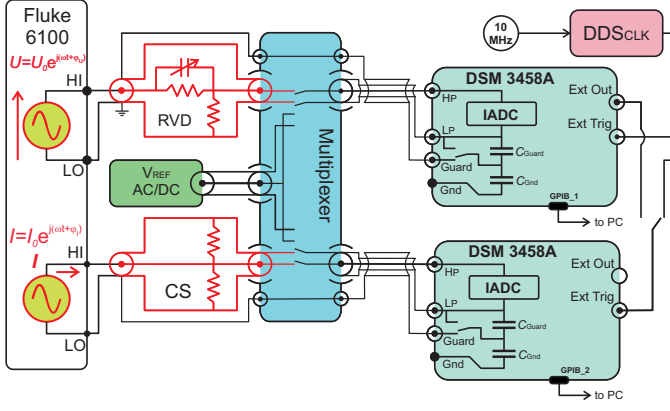
Fig. 2. Schematic of the DSPS setup.

coming from the primary atomic frequency standard. Coherent and non-coherent sampling modes can be exploited [23]. In coherent mode the DDS_{CLK} provides both the DSMs sampling clock and the reference signal of the phantom power calibrator.

Since the $DSM_{1,2}$ are floating digitizers a leakage current due to the capacitive coupling between the guard and ground of the digitizers may flow. The effect of the leakage current was determined experimentally by using a decadic IVD. The experimental results show that its effect is usually not a concern at mains frequency, i.e. lower than $0.3\,\mu V/V$, but the same cannot be said for frequencies in the kilohertz range. The approach employed to reduce and keep the effect of leakage current coming from the apparent capacitance of the $DSM_{1,2}$ under control was to use triaxial cables between transducers and digitizers configured to external guard.

- Coaxial current shunts, CSs, for direct ac current measurements. The DSPS setup enables the use of different shunts technology or transformer based current-to-voltage transducers for precise ac current measurements. For ac current measurement a Fluke shunt [24] of cage-type design with nominal current of $5\,A$ was used.
- Compensated resistive voltage dividers, RVDs, for scaling down voltages to an acceptable level for the DSMs input range. Two home-built RVDs of series-parallel structure with nominal ratio of 1:51 and 1:101 were specifically constructed for scaling down voltages from $120\,V$ to $240\,V$, giving out a nominal voltage from $1.2\,V$ to $2.4\,V$. The RVDs structure and components employed are described in [25]. The numbers and value of resistors were selected to ensure high stability, reduced power dissipation of each resistor, lower dependence upon the applied voltage and minimal losses due to parasitic and leakage capacitance.
- Direct digital synthesizer clock (DDS_{CLK}), provides the sampling clock for the DSMs. Its time base can be linked to the INRiM $10\,MHz$ signal provided by the atomic clock.
- An automatic multiplexer is inserted for $DSM_{1,2}$ calibration purpose. It was realized in a coaxial design

using high voltage vacuum relays. Its design includes two inputs with reversing capabilities for connecting dc standards and an input for ac waveforms feeding. The calibration procedure allows to align the rms value of a high precision ac calibrator * to the reference dc source using a calibrated ac-dc transfer standard. The multiplexer allows to simplify and speed up the calibration time of DMMs. A preliminary automatic calibration bench has been set up and further investigations and improvements are in progress for the calibration of DSMs at higher frequencies, which is relevant for accurate measurement of power at higher frequencies and power quality parameters. Further details about the calibration strategy are out of scope of this paper and will be discussed in a separate manuscript.
During the normal operation of the DSPS setup the voltage and current transducers are directly connected to $DSM_{1,2}$ inputs.
- TWM/TPQA open source tools for handling of the DSPS setup as well as the fast processing of voltage and current data streaming [26], [27]. The algorithm employed to compute power parameters is entitled TWM-FPNLSN (four parameter non linear sine fit) and it was developed in scope of TracePQM project [22].

The setup is completed by a set of voltage and current nodes (not shown in the schematic) used to connect in parallel and series the voltage and current transducers of the DSMS setup to power and energy standards during the comparison experiment and two optically isolated USB-GPIB-HS interfaces for bidirectional data transfer from $DSM_{1,2}$ to the PC.

IV. EXPERIMENTAL SETUP FOR DSPS VALIDATION

Fig. 3 shows the non coaxial version of the experimental setup suitable for the comparison between sampling power standards. It was employed at INRiM during the participation in the EURAMET.EM-K5.2018 key comparison [28].

A photo of the overall experimental setup is shown in Fig. 4. A phantom power calibrator with isolated voltage and current outputs sources sinusoidal test signals to $53\,Hz$, $U = 120\,V$, $U = 240\,V$, $I = 5\,A$ and different power factors/phase angles. A home-made voltage node, V_N, equipped with coaxial connectors, the British Post Office Multiple Unit Steerable Array (BPO-MUSA), feeds in parallel the testing voltage to the power meter voltage measurement inputs under comparison.

The power meter measurement current inputs under comparison are connected in series through a home made coaxial current node, C_N. Its output current ports are of gold dual binding post banana jack type and different home-made adapters, e.g. gold dual banana plug binding to N or UHF coaxial connectors, can be used for the insertion of different current-to-voltage transducers into the comparison setup. A photo of the current node with built-in current choke is shown in Fig. 5.

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*A high performance Fluke 5730A calibrator has been used as reference ac standard for the calibration of low frequency digitizers.
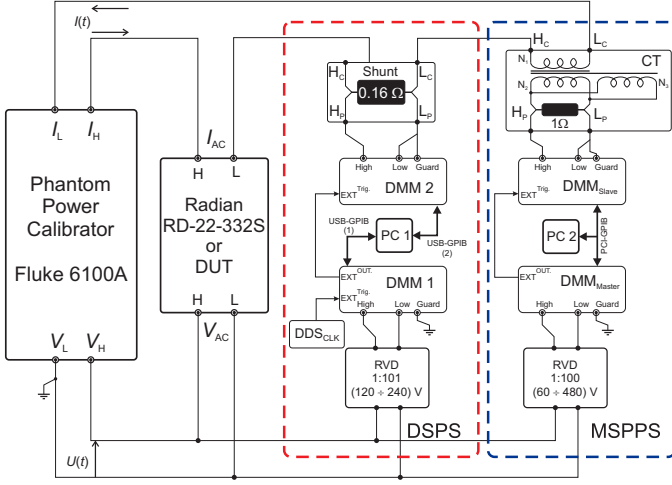
Fig. 3. Schematic of the experimental setup employed for the comparison between different power sampling standards at $600\,\mathrm{W}$ and $1200\,\mathrm{W}$ nominal apparent power. The standards under comparison are: DUT-device under test; DSPS-digital sampling power standard; MSPPS-measurement system used at INRiM as primary power standard [21].
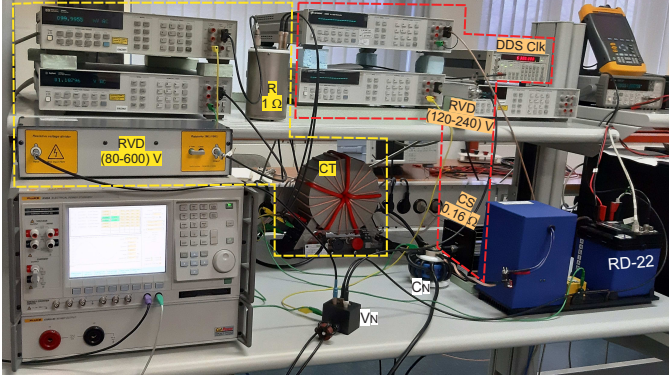

Fig. 4. Photo of the experimental setup employed at INRiM in the framework of the EURAMET.EM-K5.2018 key comparison participation. The dashed yellow box on the left refers to the MSPPS setup; the dashed red box on the right refers to the DSPS setup an in blue the travailing standard (Radian model RD-22).

V. CALIBRATION OF DSPS CONSTITUENTS

During a survey among the TracePQM project partners, it was recognized that the most efficient and direct way to ensure traceable power measurements with relative uncertainty less than $10\,\mu\mathrm{W/VA}$ is to calibrate all the DSPS constituents individually against the national electrical standards, or by direct comparison, of the whole DSPS system against a power meter standard having relative uncertainty lower than $1\,\mu\mathrm{W/VA}$ at the nominal full scale reading (for details see [22]).

The INRiM strategy for the individual calibration of DSPS constituents is as follows:

A. LF-DSMs Calibration

The calibration of LF digital sampling multimeters (DSMs) is carried out in two consecutive steps:

- applying the adjustment procedure for $\mathrm{DSM}_{1,2}$ [29], using a $10\,\mathrm{V}$ solid-state dc voltage standard and checking
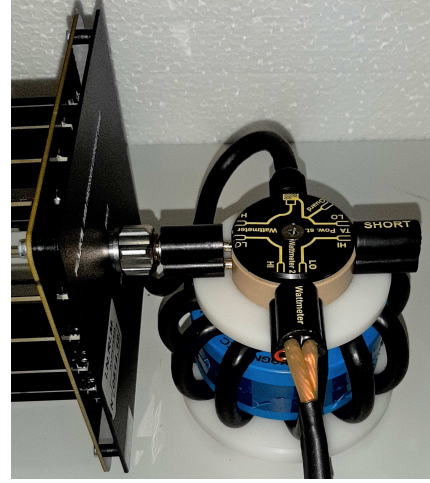

Fig. 5. Current node with built-in current choke for operation up to $20\,\mathrm{A}$ with an example of the current shunt insertion. In particular, the gold dual binding post banana jacks have center to center spacing of about $10\,\mathrm{mm}$ and are encapsulated into an epoxy compound. A short twisted pair cable with banana plug termination is used to connect the current measurement input of single and three-phase standard wattmeters and watthour/varhour meters under calibration.

that the relative difference between the $\mathrm{DSM}_{1,2}$ readings, used in DCV mode, and dc voltage reference value is within the relative uncertainty ($k = 1$) of the reference value, i.e. within $0.2\,\mu\mathrm{V/V}$;

- calibrating the $\mathrm{DSM}_{1,2}$ gain error in ac. The magnitude of the gain error was calibrated against an ac-dc voltage transfer standard. The $\mathrm{DSM}_{1,2}$ were set up in DCV-digitizing mode. In order to achieve best performance in terms of noise reduction, higher resolution and best measurement uncertainty the $\mathrm{DSM}_{1,2}$ were configured as follows: sampling frequency $5.3\,\mathrm{kS/s}$; integration time $150\,\mu\mathrm{s}$ and equivalent acquisition time higher than $10\,\mathrm{s}$. The $\mathrm{DSM}_{1,2}$ were externally triggered, so it was possible to fix the trigger frequency exactly to match the $53\,\mathrm{Hz}$.

The phase angle difference between the DSMs was adjusted by applying the same ac signal to both DSMs. After the phase adjustment procedure a relative phase difference between the DSMs within $\pm0.1\,\mu\mathrm{rad/rad}$ was found.

The calibration uncertainty of the DSMs magnitude and phase difference errors was estimated to be within $2\,\mu\mathrm{V/V}$ and $3\,\mu\mathrm{rad/rad}$, but further improvements are still possible.

B. Coaxial Current Shunt Calibration

Coaxial current shunts (CSs) are widely employed for direct and precise ac current measurement [30] using Ohm's law, $I_{\mathrm{ac}} = (1/Z_{\mathrm{CS}}) \cdot V_{\mathrm{ac}}$, where V_{ac} is the potential drop across the voltage-port and Z_{CS} is the shunt impedance. In general, the shunt impedance in ac is complex, $Z_{\mathrm{CS}} = |Z_{\mathrm{CS}}| \cdot e^{i\varphi}$, and frequency dependent, where $|Z_{\mathrm{CS}}|$ is the shunt impedance modulus and $\varphi = \arg(Z_{\mathrm{CS}})$ the phase angle error.

The shunt impedance modulus, according to the calibration strategy, may be expressed as follows

$$|Z_{\mathrm{CS}}| = R_{\mathrm{dc}}^{\mathrm{CS}} \cdot (1 + \delta_{I_{\mathrm{ac-dc}}}^{\mathrm{CS}}) \qquad (2)$$

where $R_{\text{dc}}^{\text{CS}}$ is the shunt dc-resistance and $\delta_{I_{\text{ac-dc}}}^{\text{CS}}$ is the ac–dc current transfer difference, which depends on frequency.

For traceable power and power quality measurements the values of $R_{\text{dc}}^{\text{CS}}$, $\delta_{I_{\text{ac-dc}}}^{\text{CS}}$ and $\arg(Z_{\text{CS}})$ must be calibrated against national reference standards.

a) dc–Resistance Shunt Calibration $\left(R_{\text{dc}}^{\text{CS}}\right)$: The shunt dc-resistance calibration is crucial for absolute and reliable ac current measurement. In general, shunts employed for direct ac current measurements ranging from $10\,\text{mA}$ to $100\,\text{A}$ have low-ohmic resistance, from $100\,\Omega$ to about $7\,\text{m}\Omega$, therefore the calibration methods developed for low-ohmic resistance [31] can also be used for purpose calibration of ac shunts [32], also taking the stability, resistance temperature coefficient (TCR) and power coefficient (PCR) influence on shunt dc-resistance value into account.

The dc-resistance of the $5\,\text{A}$ shunt was calibrated at different currents from $3\,\text{A}$ to $5\,\text{A}$ against a $100\,\Omega$ Tinsley resistance reference standard, kept in a thermostated oil-bath set to about $23\,°\text{C}$, using an automated direct current comparator (DCC) resistance bridge†, combined with a high-current range extender. The calibration uncertainty ($k = 1$) of the shunt dc-resistance was within $3\,\mu\Omega/\Omega$.

b) ac–dc Current Transfer Difference $\left(\delta_{I_{\text{ac-dc}}}^{\text{CS}}\right)$: The calibration of ac-dc current transfer difference of high current shunts $\delta_{I_{\text{ac-dc}}}^{\text{CS}}$ is based on the use of ac–dc thermal converters (TCs) combined in parallel with current shunts (CSs). The $5\,\text{A}$ shunt was coupled in parallel with a $90\,\Omega$ PMJTC.

The ac–dc current transfer difference of the CS-TC combination under calibration, $\delta_{I_{\text{ac-dc}}}^{(\text{CS-TC})^{\text{X}}}$, was calibrated against the ac–dc current transfer difference of the $5\,\text{A}$ ac national current standard, $\delta_{I_{\text{ac-dc}}}^{(\text{CS-TC})^{\text{S}}}$, maintained at an uncertainty of $2.7\,\mu\text{A/A}$, which was validated in the framework of RMO key comparison EURAMET.EM-K12 [33].

The calibration was performed using a home-built automated ac–dc transfer current comparator [16], and the ac–dc current transfer difference of the CS-TC combination under test is calculated from

$$\delta_{I_{\text{ac-dc}}}^{(\text{CS-TC})^{\text{X}}} = \Delta + \delta_{I_{\text{ac-dc}}}^{(\text{CS-TC})^{\text{S}}} \quad (3)$$

where, Δ is the difference of the ac–dc differences of the two CS-TC combinations. The standard uncertainty of a set of twelve repeatable measurement is within $80\,\text{nA/A}$ at almost all frequencies.

Moreover, assuming that the effect of mutual inductance between the shunt and the thermal converter is negligible at low frequencies, i.e. at power line frequency, following [34], the ac–dc current transfer difference of the ac shunt under calibration can be approximated as

$$\delta_{I_{\text{ac-dc}}}^{\text{CS}^{\text{X}}} \approx \delta_{I_{\text{ac-dc}}}^{(\text{CS-TC})^{\text{X}}} - \left(\alpha \cdot \delta_{V_{\text{ac-dc}}}^{\text{TC}^{\text{X}}} + \beta \cdot \delta_{I_{\text{ac-dc}}}^{\text{TC}^{\text{X}}}\right) \quad (4)$$

where $\delta_{V_{\text{ac-dc}}}^{\text{TC}^{\text{X}}}$, $\delta_{I_{\text{ac-dc}}}^{\text{TC}^{\text{X}}}$ are the ac–dc transfer voltage and current differences of the TC, which when coupled to CS works in a mixed mode with coupling coefficients $\alpha = R^{\text{TC}}/\left(R^{\text{CS}} + R^{\text{TC}}\right)$ and $\beta = R^{\text{CS}}/\left(R^{\text{CS}} + R^{\text{TC}}\right)$; R^{CS} and R^{TC} are the input resistance of the TC and CS.

For ac currents higher than $100\,\text{mA}$, $\beta < 0.1$ and term $\delta_{I_{\text{ac-dc}}}^{\text{TC}^{\text{X}}}$ can be neglected. Under these conditions PMJTC behaves as voltage detector and only the term containing $\delta_{V_{\text{ac-dc}}}^{\text{TC}^{\text{X}}}$ must be considered. It is calibrated against the national ac–dc voltage transfer standard with relative calibration uncertainty within $0.5\,\mu\text{V/V}$ from $40\,\text{Hz}$ to about $10\,\text{kHz}$, as reported in [17].

In summary, the calibration uncertainty of the $\delta_{I_{\text{ac-dc}}}^{\text{CS}^{\text{X}}}$ value at $5\,\text{A}$ does not exceed $3\,\mu\text{A/A}$.

c) Phase Angle Error of Current Shunts $\left(\arg(Z_{\text{CS}})\right)$: The phase angle error of the $5\,\text{A}$ ac current shunt was calibrated using an improved version of the digital phase comparator [18], with extended frequency range down to $10\,\text{Hz}$, and a step-up procedure as follows:

- Phase angle calibration of two home-built current shunts of nominal value of $2\,\text{A}$ [35] against the phase angle standard to the rated current of $1\,\text{A}$ and direct comparison between them to the rated current of $2\,\text{A}$.
- Phase angle calibration of two $5\,\text{A}$ shunts against the $2\,\text{A}$ set of shunts to the rated current of $2\,\text{A}$ and comparison between them to the rated current of $5\,\text{A}$.

The step-up procedure enables the phase angle error calibration of the $2\,\text{A}$ and $5\,\text{A}$ set of shunts at lower and nominal current. Variations within $\pm 0.3\,\mu\text{rad}$ were found, most likely due to level dependence of the shunts at $53\,\text{Hz}$. Such a variation is taken into account as uncertainty contribution. The phase angle error calibration uncertainty of the $5\,\text{A}$ shunt was within $3\,\mu\text{rad/rad}$.

C. RVD Ratio Calibration

RVD ratio calibration covers a crucial aspect, since its accuracy is directly reflected to ac voltage measurements needed for power measurements.

The RVDs calibration method employs a true-rms high impedance thermal voltmeters [25]. The calibration uncertainty of the calibration method was further improved by using an ac-dc voltage transfer standards and coaxial range resistors. The consistency of the thermal method was checked with a second comparison experiment, which consists in comparing the RVD ratio against the ration of a calibrated inductive voltage divider (IVD)‡ using the two digital sampling multimeters of the DSPS [21].

The difference between the RVD ratio calibration methods was within 3×10^{-6} at nominal frequency of $53\,\text{Hz}$. The difference was taken into account in the RVD ratio uncertainty budget.

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†The DCC bridge is a commercial Measurement International model 6010B. During the comparison experiment the ration of DCC bridge was set to 1:1000 and the power dissipated, $P = I^2 \cdot R$, over the resistance standard and the high-current shunt at $5\,\text{A}$ nominal current was $4\,\text{mW}$ and $4\,\text{W}$, respectively.

Brand names are used for identification purpose. Such identification does not imply recommendation, nor does it imply that the equipment identified in this paper is necessarily the best available for the purpose.

‡The IVD is a two-stage inductive voltage divider having twenty output-taps designed to carry out precise characterization and linearity test on sampling digital multimeters and RVDs characterization up to $120\,\text{V}$. Its in-phase and quadrature errors are within 2×10^{-6} and 5×10^{-6} for voltages from $10\,\text{V}$ to $100\,\text{V}$ and frequencies from $53\,\text{Hz}$ to $400\,\text{Hz}$. The calibration was performed against:i) an IVD at $80\,\text{V}$ and $53\,\text{Hz}$ using two DSMs; and ii) by using a system for ac voltage ratio absolute calibration [36] at $10\,\text{V}$ and $400\,\text{Hz}$.

D. RVD Phase Angle Calibration

Th phase angle errors of the set of RVDs were calibrated according to the step-up procedure described in [19]. The two digital sampling multimeters of the DSPS were configured as an asynchronous phase comparator and the phase angle of the set of RVDs with ratio from 1:3 up to 1:101 was recalibrated.

The phase angle error due to DSM input capacitance loading effects was compensated for 1:51 and 1:101 RVDs and a residual phase angle error less than $1\,\mu\mathrm{rad}$ to $53\,\mathrm{Hz}$ with combined standard uncertainty better than $3\,\mu\mathrm{rad/rad}$ was reached.

VI. COMPARISON RESULTS AND MEASUREMENT UNCERTAINTY

A simplified schematic of the experimental setup employed for the comparison between sampling power standards is reported in Fig. 3. It was employed during INRiM participation in the EURAMET.EM-K5.2018 comparison, during which both DSPS and MSPPS setups were used to measure the power error of the traveling standard, i.e. Radian RD-22 power meter, during the whole month of stay.

The relative difference between the active power measurement performed with the traveling standard, P_X, and the INRiM's power reference standards, P_S, with respect to the nominal apparent power, $S = U \cdot I$, is computed as follows

$$\Delta = \frac{P_\mathrm{X} - P_\mathrm{S}}{S} \qquad (5)$$

The measurement model for active power measurement under sinusoidal conditions using the DSPS setup can be stated as

$$P_\mathrm{S} = U_\mathrm{ac} \cdot I_\mathrm{ac} \cdot \lambda \qquad (6)$$

where U_ac and I_ac represent the rms value of the applied voltage and current and λ represents the power factor. The power factor under sinusoidal condition corresponds to the absolute value of the active factor, $\lambda = |\cos \varphi|$, which in turn is equal to the cosine of displacement angle, $\cos \varphi$, between voltage and current.

The quantities U_ac, I_ac and λ are computed as follows

$$U_\mathrm{ac} = \mathrm{k_{RVD}} \cdot (1 + \delta_\mathrm{RVD}) \times U_\mathrm{DSM_1} \cdot (1 + \delta_\mathrm{DSM_1}) \quad (7)$$

$$I_\mathrm{ac} = \frac{U_\mathrm{DSM_2}}{R_\mathrm{dc}^\mathrm{CS}} \times \frac{(1 + \delta_\mathrm{DSM_2})}{(1 + \delta^\mathrm{CS})} \qquad (8)$$

$$\lambda = |\cos \varphi| \cdot (1 + \delta_\varphi) \qquad (9)$$

where:

$U_\mathrm{DSM_{1,2}}$: rms-value of the voltages sampled with $\mathrm{DSM_{1,2}}$ in DCV-digitizing mode;

$\delta_\mathrm{DSM_{1,2}}$: gain correction error of $\mathrm{DSM_{1,2}}$;

$\mathrm{k_{RVD}}$: calibrated resistive voltage divider ratio;

δ_RVD: RVD ratio correction error including effects due to long and short-term stability, drift, ac-dc difference

and ratio change due to self heating and applied voltage;

$R_\mathrm{dc}^\mathrm{CS}$: calibrated current shunt dc-resistance;

δ^CS: current shunt correction error comprising effects due to ac-dc difference ($\delta_\mathrm{ac-dc}^\mathrm{CS}$), long and short time stability ($\delta_\mathrm{stab}^\mathrm{CS}$), drift ($\delta_\mathrm{drift}^\mathrm{CS}$) and self heating ($\delta_\mathrm{sh}^\mathrm{CS}$). All corrections are assumed to be zero, within uncertainties $u(\delta_\mathrm{stab}^\mathrm{CS})$, $u(\delta_\mathrm{drift}^\mathrm{CS})$, $u(\delta_\mathrm{sh}^\mathrm{CS})$, expect that for ac-dc difference;

$|\cos \varphi|$: nominal power factor/active factor, φ the displacement angle between current and voltage phase angles, i.e. $\varphi = \varphi_{I_\mathrm{ac}} - \varphi_{U_\mathrm{ac}}$. For $\varphi > 0$ the current phase leads the voltage phase while for $\varphi < 0$ the current phase lags the voltage phase.

δ_φ: correction due to phase shift between the voltage and current. In general, the phase shift is $\delta_\varphi = \delta_\varphi^{DM1,2} + \delta_\varphi^{RVD} + \delta_\varphi^{CS}$, where $\delta_\varphi^{DM1,2}$ phase shift due to digitizers depending from their jitter, bandwidth, sampling frequency, synchronization, etc., δ_φ^{RVD} phase error of the resistive voltage divider and δ_φ^{CS} phase error of the current shunt.

Fig. 6 shows the relative differences between different power measuring systems performed at $U = 120\,\mathrm{V}$, $U = 240\,\mathrm{V}$, $I = 5\,\mathrm{A}$ and $f = 53\,\mathrm{Hz}$.
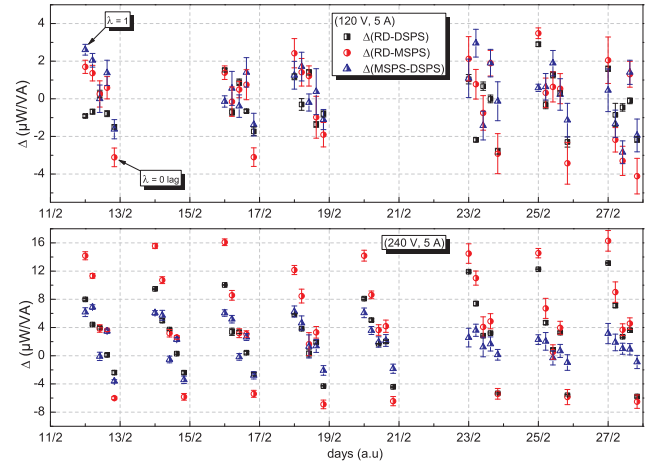

Fig. 6. Relative difference between active power measurements performed with different sampling power standards at different power factors λ, i.e. for each measurement data set from left to right in the following order: 1, 0.5 lead, 0.5 lag, 0 lead and 0 lag.

The uncertainty budget of the new DSPS setup at one of the testing point of EURAMET. EM-K5.2018 comparison is reported in table I. The combined standard uncertainty results improved by a factor of two with respect to the MSPPS uncertainty budget declared during the EUROMET EM-K5(2007) comparison [37]. The differences in power measurements between the laboratory's values and the traveling standard values were within the best expanded measurement uncertainties ($k = 2$, coverage factor) of the DSPS setup.

VII. CONCLUSION AND FUTURE WORK

A new modular digital sampling power standard was developed and characterized at INRiM. Its implementation for elec-

TABLE I
UNCERTAINTY BUDGET OF THE MODULAR DSPS SETUP AT 240 V, 5 A AND 53 Hz.

Contribution to uncertainty (y_i)	Standard uncertainty $u(y_i)$	Sensitivity coefficient c_i	Type uncertainty Distribution	Uncertainty contribution at different $\cos \varphi$ (μW/VA)		
				1.0	0.5 lead, lag	0 lead, lag
U_{ac} : ac-Voltage						
Repeatability	0.1	1	A	0.1	0.1	0.1
DSVM Calibration	2.0	$\cos \varphi$	B	2.0	1.0	0.0
RVD (1:101) ratio calibration	4.0	$\cos \varphi$	B	4.0	2.0	0.0
RVD voltage dependence	2.0	$\cos \varphi$	B	2.0	1.0	0.0
U_{ac} measurement setup	3.0	1	B	3.0	3.0	3.0
$\mathrm{RSS}_{U_{ac}}$	5.7			5.7	3.9	3.0
I_{ac} : ac-Current						
Repeatability	1.0	1	A	1.0	1.0	1.0
DSVM Calibration	2.0	$\cos \varphi$	B	2.0	1.0	0.0
Current shunt dc calibration	3.0	$\cos \varphi$	B	3.0	1.5	0.0
Current shunt δ_{ac-dc} difference	3.0	$\cos \varphi$	B	3.0	1.5	0.0
I_{ac} measurement setup	2.0	1	B	2.0	2.0	2.0
$\mathrm{RSS}_{I_{ac}}$	5.2			5.2	3.2	2.2
PF: Power Factor						
Repeatability	0.2	1	A	0.2	0.2	0.2
DSVM phase correction	3.0	$\sin \varphi$	B	0.0	2.6	3.0
RVD phase correction	3.0	$\sin \varphi$	B	0.0	2.6	3.0
Current shunt phase correction	3.0	$\sin \varphi$	B	0.0	2.6	3.0
PF measurement setup	2.0	1	B	2.0	2.0	2.0
RSS_{PF}	5.6			2.0	4.9	5.6
P_{ac} : Active Power						
Combined standard uncertainty				8.0	7.1	6.7
Expanded uncertainty ($k = 2$, coverage factor)				16.0	14.1	13.4

tric power measurement is described and comparison results as well as uncertainty budget are reported. The DSPS traceability is provided by the calibration of its single constituents starting from the electrical dc-quantum standards. When all the transducers and digitizes corrections are removed via software after the calibration procedure, the the DSPS residual error becomes negligible. Validation tests by means of an internal trilateral comparison show that a repeatability less than 1 ppm can be attained at 240 V and 5 A, whereas its accuracy is within the limits of traceability whose overall relative measurement uncertainty ($k = 1$) is better than 8 μW/VA.

More recently the INRiM's primary power and energy laboratory is setting up a new automated measuring bench for testing and verification of static energy meters in presence of harmonic and sub-harmonics disturbances regarding classes as specified in the standards IEC 62053-21,-22 [38] and EN 50470-3 [39]. The DSPS proposed here will be set up and used as reference standard to check the reliability of voltage and current arbitrary waveforms generated with the measuring bench.

Furthermore, in the framework of the project EMPIR 19RPT01-QuantumPower, research activities are in progress with the aim of including a programmable ac-quantum voltage standard to improve the calibration uncertainty of DSPS constituents and further shorten the present traceability chain linking the sampled power measurements to fundamental constants of nature.

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