Progress Report on Electrical Metrology at METAS from 2023 to 2025

Report prepared for the 34th meeting of the Consultative Committee for Electricity and Magnetism (CCEM)

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1. Electrical Quantum Standards & DC/LF Metrology

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1.1 Fundamental Impedance Metrology

The Dual Josephson Impedance Bridge (DJIB) is the result of a joint development with NIST. It consists of using the sampling bridge technique with two independent voltage sources based on Josephson Arbitrary Waveform Generator Synthesisers (JAWS). JAWS display quantum-accurate distortion-free voltage waveforms over frequencies between a few hertz and 1 MHz. Thanks to the independence of the sources, a single bridge can compare any impedance in the complex plane as arbitrary voltage ratios or phase shifts can be generated. The DJIB has been optimised and is now fully functional in the 1 kHz to 80 kHz frequency range. It displays remarkable agreement with a classical calibration chain, with uncertainties ranging between 0.01 ppm and 0.23 ppm (k = 1) for impedance ratio 1:1, and 0.04 ppm and 0.35°ppm for the 1:10 ratio. [1-3]

The operation of the DJIB has been improved by introducing an automated procedure to increase the Quantum Locking Range (QLR) of the bridge. In this procedure, the finite-impulse-response filters used to shape the excitation pulses applied to the Josephson arrays are systematically modified in order to obtain a robust quantisation of the Josephson waveforms. The QLR, i.e., the interval of the input pulse amplitude for which the output remains quantised is used as an indicator. In future work, the optimisation algorithm will be further improved by introducing Machine Learning methods [4].

1.2 Graphene for AC impedance standards

The study of graphene-based QHR samples as AC impedance standards has been further extended through the design of a dedicated bridge for the determination of the longitudinal impedance Z_{xx} as a function of frequency [5]. The setup has been used for a bilateral comparison with PTB with very satisfactory results. This tool will be of use for theoretical work investigating the AC quantum Hall effect by providing reliable measurement data.

The current developments aim at using graphene for the reference impedance standard of the bridge, whereby the DJIB relies on three quantum references.

1.3 Integral nonlinearity of digitisers

A high precision method of assessment of the integral nonlinearity (INL) of digitisers used in coaxial bridges has been developed. The effort was motivated by the importance of the INL contribution to the uncertainty budget of impedance bridges, which, if precisely characterised, shall lead to an uncertainty improvement of electronic bridges of standard design. A patent has been filed for the developed method.

1.4 Computational traceability

Simulations have been used in several collaborations with the industry in order to establish traceability for impedances across the RF-LF gap, typically between 100 kHz and 500 MHz,, where traceability using classical artefacts had not been achievable. In particular, the physics of a Haddad-type resistor standard has been by means of FEM simulations and mathematical modelling, taking into account the EM-field propagation and the dominant effect of connectors above 30 MHz.

In order to further refine the quality of the low-frequency model, an improved description of the cables has been introduced. Furthermore, the geometrical conformity of the coaxial impedance standards to the formal 4-terminal pair definition has been improved by a new PCB 'connection module'. Presently, the best agreement between model and measurements is better than 0.2 ppm up to 100 kHz, the main uncertainty component being the thermal stability of the standard. Such an improvement is visible at relatively low frequencies, but serves the purpose of increasing trust in the model in the LF-RF frequency gap. [6-7]

1.5 Electrochemical impedance spectroscopy (EIS) for Li-ion cells

Building on the findings of the EMPIR LibForSecUse and Horizon 2020 Nanobat project, the now fully operational setup for the EIS measurement of cylindrical cells (as for instance: type 18650 Li-ion battery) has been enhanced. The measurement setup relies on 4-terminal pair configurations for EIS measurements of battery cells and ensures the traceability of dynamic and multi-tone impedance measurements with this setup. Moreover, a nonlinear frequency response analysis (NFRA) can be performed. Measurement specifications in terms of current and frequency range correspond to max. 5 A and DC – 50 kHz, respectively.

The Horizon Europe Digicell+ project aims at applying machine learning algorithms to large EIS measurement data sets for SoH and SoC assessments in order to ensure traceability of measurement uncertainty propagation.

2. Power and Energy

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2.1 Calibration of instrument transformers at non-grid frequencies

While power quality has traditionally been limited to 9 kHz, disturbances of significant levels have been observed up to 500 kHz: supraharmonics from inverters up to 150 kHz and effects owing to narrow-band power line communication (PLC) up to 500 kHz. The EPM ADMIT project addresses these issues by investigating voltage and current transformer performance up to 150 kHz. The main objective of the project is to contribute to the establishment of a guideline for manufacturers of such instruments, their customers and metrology institutes. The project also aims at defining procedures allowing industry laboratories to carry out their own tests without the need for an NMI-type infrastructure. [8]

The results of the project will provide answers to a number of open questions relating to standards (IEC 61869 series) in particular through additional recommendations, linking with transient accuracy requirements, characterising of harmonics and 'intra-harmonics', developing an HF test procedure, and calibrating the HF test system.

2.2 Calibration of DC power in distorted condition'

Measuring DC power is in principle an 'easy' task: $U \times I$. Indeed, the underlying assumption that voltage and current signals are perfectly stationary makes the effect of integration time negligible. In modern DC grids, though, the supply comes from power converters either connected to the AC bulk network or to a renewable energy source (e.g., photovoltaic panels). The converter output signals are no more constant: they depend on the source variability. Moreover, the converter circuitry is likely to inject spurious disturbances in the harmonic and supraharmonic frequency range. In this context, the EMPIR DC Grid project has investigated the definition of DC power and energy in distorted conditions and has set the basis for a rigorous metrology of power quality and revenue metering in modern DC grids. [9-12]

2.3 Calibration of devices using sampled values

In modern digital substations, the signals to be measured are not transmitted in an analogue format from the instrument transformers to the metering devices, but in the form of Sampled Values, digital signals following the standard IEC 61850-9-2. METAS is developing its capabilities to be able to offer calibration and characterisation services for devices of this emerging ecosystem: LPITs with digital output, SAMUs, digital revenue meters and comparators to calibrate SAMUs and LPITs with digital outputs. (LPIT: Low Power Instrument Transformers; SAMU: Stand-Alone Merging Units.) Moreover, METAS is working on the assessment of the quality of the sampled values data stream in terms of synchronisation to an external time reference, and capability of detecting possible anomalies either in the sample series or in the information content (voltage and current level) conveyed by them. [13-17]

2.4 Power grid monitoring

Distributed energy resources and storage systems, which are connected to the power system via dedicated power inverters, are introducing measuring disruptions and consequently the traditional sinusoidal models used to compute the power signal are not valid anymore. This phenomenon calls for new measurement procedures and development of instruments with more precision. In this context, the QUINPORTION project funded by the Swiss Federal Office of Energy involves the development of a novel PMU prototype, more resilient with respect to harmonic distortion and capable to cope with amplitude and phase fluctuations. Moreover, definition of methods to measure and quantify the existing amount of inertia on the system are being derived. It is also planned to demonstrate the feasibility and reliability of the proposed approaches by means of laboratory testing and hardware-in-the-loop realisation. [18-31]

3. RF & Microwave

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3.1 Impedance and Network Analysis

The VNA metrology software *VNA Tools* (www.metas.ch/vnatools) has been further developed and enhanced. Many bug fixes, small and larger extensions, convenience features and driver updates have been added. The support of non-linear measurements (wave parameters) has made good progress as well. The software has continued to broaden its user base. So far there are close to 3000 registered licensees of *VNA Tools* and more than 350 persons have visited the three-day introductory course, which is provided by METAS. The courses are to an increasing degree being hosted by measurement device manufacturers, such as, e.g., National Instruments (Austin, TX), Tektronix (Portland, OR) and Rohde & Schwarz (Munich, DE). In 2024 a course was also hosted by the US Navy lab in San Diego, CA. This demonstrates the interest in the software by key players in the field. The VNA Tools Real Time Interface (RTI), a stable high-level interface for integration of VNA Tools functionality into an existing software environment, has been licensed for two commercial applications: Option K50 of the Rohde & Schwarz ZNA allows real-time measurement uncertainties to be displayed on the VNA screen using VNA Tools functionality. The VNA software *Insight* by Maury Microwave also uses *VNA Tools* in the background through the RTI.

Developments for 6G, the next generation of mobile communication standards, are gaining traction. The laboratory is participating in the EPM RF46G project and in an industry project to extend the traceability of coaxial S-parameter measurements to 220 GHz or more, using a novel 0.5 mm coaxial connector currently under development. In the RF46G project, novel techniques for the determination of linearity and attenuation up to at least 220 GHz are also evaluated. In addition, a novel type of phase standard for non-linear VNA measurements based on a calculable diode is fabricated and evaluated.

3.2 RF power and Noise

The consortium for the development of a novel primary power standard based on the electro-optical effect consists of METAS (RF&MW lab and Photonics, Time & Frequency lab), the University of Otago in Dunedin, NZ, and a Swiss company. The project is funded by Innosuisse (Swiss Innovation Agency) and currently underway. Together with theoretical simulations, first test measurements with a prototype electrical resonator have been performed to evaluate the best setup and read-out scheme.

The measurement software for power and noise measurements has been fully transferred from the old LabView code to C#, which allows direct implementation of the uncertainty evaluation based on *METAS UncLib* and the use of software components developed for *VNA Tools*.

It is planned to extend the upper frequency limit of the noise calibration service from currently 33 GHz to 50 GHz in the near future.

3.3 Scanning Microwave Microscope (SMM)

Within the last two years, the METAS SMM activity has developed further and various projects [32,33] have been conducted. The two EMPIR projects FutureCom and ELENA ended in 2024. The main goal in FutureCom was the development of an on-wafer probe with small pitch size based on the capillary pulling technology developed for the coaxially shielded scanning tip in an earlier project. The advances in the project were significant. However, to make the probe commercially exploitable, further work is needed to improve the probe's specifications in terms of robustness and electrical performance. The goal in ELENA was to improve the reliability of nanoelectrical measurements through the establishment of SI traceability. METAS contributed with calibration standards, calibration algorithms and dedicated software for the SMM. The submission of the first CMCs in this area can be expected in the not-so-distant future.

Recently started projects aim at extending the SMM activity into the life science domain and also exploiting the capabilities of SMM measurements at low temperatures. For the latter the Cryo-SMM will investigate Qbits in the EPM MetSuperQ project and topological isolators in the

EPM QuAHMet project [34]. These projects are conducted in close collaboration with the University of Basel, where we obtain access to the necessary cryo-infrastructures.

3.4 Quantum sensing

The laboratory has started a new activity in the area of quantum sensing. In a first step the plan is to use Rydberg states of atoms to measure the electrical field distribution on a planar circuit. This could potentially become an alternative for the traditional probing techniques to determine on-wafer S-Parameters. The first activities are performed at the University Basel in the framework of the EPM OnMicro project. In parallel a dedicated laboratory room at METAS will be built and equipped from scratch. This is part of a long-term initiative of METAS, which will explore the measurement capabilities of Rydberg sensing and quantum sensing in general in different metrological fields.

4. EMC and Antenna

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4.1 Measuring method for 5G New Radio

METAS participates actively in the EMPIR MEWS project focussing on 5G. A traceable measurement method for 5G signals has been developed, including the traceable demodulation of 5G signals. Moreover, new measurement methods have been developed in order to characterise the traffic beam of 5G base stations [35]. The actual methods are today based on the analysis of synchronisation signals, and the maximum exposition is based on an extrapolation. Based on this foundation, new measurement features have been developed and implemented on the measuring instrument Deviser EM860.

A comparison between accredited laboratories of Switzerland will take place in 2025.

4.2 Round robin test device for EMC testing

METAS continues its effort in Proficiency Testing. METAS has now a full set of devices available for proficiency testing: conducted emission, radiated emission (comb generator with antenna), radiated emission (EUT with cabling), conducted immunity according to IEC 61000-4-6, surge immunity according to 61000-4-5, radiated immunity according to 61000-4-3, and burst immunity.

METAS now provides proficiency testing for accredited laboratories in Europe (www.metas.ch/emc).

5. Participation in Comparisons

Comparisons completed since the 2023 CCEM meeting

CCEM.RF-K26: Attenuation in coaxial line up to 40 GHz, coordinated by NMIJ AIST, Japan. [36]

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6. Publication List

Articles published since the 2023 CCEM meeting

[1] Bauer, S., Overney, F., Eichenberger, A. L., Kraus, M., & Pimsut, Y. (2024). Comparison of Josephson Impedance Bridges. In 2024 Conference on Precision Electromagnetic Measurements (CPEM) (pp. 1–2).IEEE. https://doi.org/10.1109/cpem61406.2024.10646026

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