Progress Report on Electrical Low and Radio Frequency Metrology at CENAM-Mexico 2021 – 2023

Report prepared for the 33rd meeting of the Consultative Committee for Electricity and Magnetism (CCEM), March 2023

1. Low frequency

1.1 Programmable Josephson Voltage Standard (PJVS) at CENAM

Significant improvements were obtained in 2022 for calibrating reference thermal converters AC-DC voltage against the CENAM's Programmable Josephson Voltage System, PJVS. In December 2021 we carried out the last calibration of CENAM´s reference thermal converter at 1 V from 60 Hz up to 1 kHz using a PVJS was carried out. Differences between calibration of the reference thermal converter carried out at PTB and the CENAM PJVS in 2021 are below 0.5 µV/V in the above-mentioned frequency range, with an uncertainty of ± 1.2 µV/V for k = 2.

In 2022 CENAM could not get liquid helium to run the PJVS. CENAM decided to get DC voltage traceability from NIST and AC-DC thermal transfer standard difference at 1 V from PTB.

CENAM is developing a research line for the characterization of analog-to-digital converters of high resolution by means of PJVS. The characterization includes effective resolution, noise content on the digitizing process, 1/f noise measurements, linearity at full scale, linearity near the zero-crossing at nV levels, zero-crossing performance, synchronization effects, timing effects, triggering, among others. This work was done in three of the key technologies available at the metrology level: Fluke 8558A, H.P. 3458A, and PXIe DSA Delta Sigma Cards. This research line stands still since 2021 due to the lack of liquid helium. The results of this characterization process have impacted the uncertainty levels of other national measurement standards such as electric power, electric energy, power quality, magnetic properties of materials, ac current.

To reduce the impact of the shortage in the chain supply of liquid Helium, CENAM has purchased a free liquid helium cryogenic cooling system. This process is ongoing. It is expected to have the cryocooler by august 2023 and fully operational in early 2024.

A peer review of CENAM CMCs for DC voltage took place in early 2022, having the confirmation of our CMCs in DC Voltage, this peer review was conducted by Dr. Stephane Solve. It is pending to submit the CMCs for AC voltage based on the PJVS. During 2022 CENAM participated in the CCEM-WGLF task group on the "update of the BIPM Josephson comparison protocol (BIPM.EM-K10) towards AC voltages", it is expected having our Cryocooler fully operational to participate in the BIPM.EM.K10 early 2024.

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1.2 Measurement Standard of Power Quality Disturbances and Synchrophasors

This measurement standard provides traceability to the measurement of power quality quantities like sags, swells, interruptions, harmonics, both current and voltage, and flicker (IEC 61000-4-30:2018). Currently, CENAM has developed a high-accuracy digital sampling system for the disturbances above based on a real-time platform (PXI). During 2021 the optimization of the first real-time measurement prototype was completed, with measurement capabilities of up to 50 harmonics in 200 ms observation windows. The main components of uncertainty in the real-time power quality measuring standard are related to AC current and voltage transducers along with the ADC performance. The ADC characterization was made using the PJVS directly. The resistive transducer for the measurement of ac current signals was replaced with a three-stage current transformer allowing the reduction of the measurement uncertainty.

This system is the basis of the national measurement standard for power quality to provide traceability of spectral measurements under static and dynamic conditions. In 2022 we proposed a collaboration with NRC was proposed for a pilot study, it is expected that the PQ traveling standard will be fully operational in April 2023. The pilot study aims at leading a comparison like the CCEM K13 in harmonics of voltage, current and power within the SIM region by means of a traveling reference portable measurement system instead of using a bulky high-accuracy PQ generator. This pilot requires further discussion with Dr. Branislav Djokic of NRC to prepare a pilot study.

In November 2021 a peer review was conducted by Dr. Branislav Djokic to confirm the power and energy CMCs at CENAM. It is expected to have a complementary peer review for PQ quantities by the end of 2023.

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1.3 Quantum Hall Effect (QHE) at CENAM

During 2022 there was a severe shortage of liquid helium in Mexico. To ensure CENAM's traceability to the SI ohm, it was necessary to calibrate a pair of high stability 10 kΩ resistors at BIPM in December 2022. To reduce the impact of the shortage of liquid Helium, CENAM is purchasing a cryogenic cooling system. It is expected to have the cryocooler by the end of 2023, and fully operational in early 2024. In mid-2023, the electrical resistance laboratory will have a Peer Review where the CMCs will be evaluated from 1 mΩ to 100 GΩ.

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1.4 Measurement standard of high AC voltage and high AC current

During 2021 and 2022 CENAM has developed a measurement system for ac voltage up to 100 kV at 60 Hz and ac current up to 1 kA at 60 Hz along with their respective CMCs. The basis of the ac voltage measurement standard is a capacitive divider characterized by amplitude and phase along with a digital impedance bridge developed in CENAM. The basis of the ac current measurement standard is a two-stage reference current transformer, a three-stage electronically enhanced current transformer, and a recently developed digitally assisted current comparator. The impedance bridge was developed during 2020-2021 and now is under characterization to assess its uncertainty. During 2022 the digitally assisted current comparator was built and the characterization is ongoing. In 2023 CENAM is developing a current transformer based on a cascade array of three-stage current transformers to reach 3 kA at 60 Hz.

These capabilities aim at providing calibration services for potential transformers, current transformers, transformer comparator measurement systems, electronic burdens, and dissipation factor measurement systems, all of them in amplitude and phase. It is expected to have a peer review for including these new services in 2024.

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1.5 Coaxial digitally assisted four-terminal-pair impedance bridge

A digitally assisted four-terminal-pair impedance bridge was developed to establish the values of impedance standards maintained at CENAM´s Electrical Impedance Laboratory in a frequency range of up to 10 kHz. This development will help to solve the metrological needs of the electrical, electronic, and automotive Mexican sectors. In the long term we aim at the measurement of standard resistance values of 100 kΩ at a frequency of 1592 Hz, with traceability to the quantum Hall effect.
In 2022, the topology of the digital impedance bridge was redefined in order to ensure the overall coaxial feature of the entire bridge, minimizing leakage currents in the detector and achieving the definition of impedance measurements at 4-terminal pairs at the reference standard impedance and at the impedance under calibration. The bridge is integrated by a double-stage IVD that provides the voltage ratio and a set of injection and detection transformers that, together with variable amplitude and phase signal generators, achieving the bridge balance in an automated manner. The detection stage of all balance points of the bridge consists of a lock-in amplifier in conjunction with a homemade modular coaxial multiplexer, which achieves isolation of at least -165 dB between channels. In an automated way, the bridge can perform 1:1 and 10:1 ratio measurement in a frequency range of 150 Hz to 10 kHz. The uncertainty of the bridge at the frequencies of 1 kHz and 1.592 kHz is less than two parts in 10^7 and less than 1 part in 10^6 over the entire frequency range.
It is expected that from the knowledge acquired with this development, a Quadrature Bridge will be implemented. This will allow obtaining the traceability of the capacitance magnitude to the quantum Hall effect reproduced in CENAM.

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1.6 Magnetic flux density measurements

CENAM has established reference measurement values at 500 mT aiming at taking part in an international comparison of magnetic flux density standards. The CENAM's reference at this level is a Nuclear Magnetic Resonance (NMR) magnetometer. The characterization of the reference system is ongoing, and a bilateral comparison with the INRIM of Italy has been proposed in 2023 oriented to support the CENAM CMCs.

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Participation in international comparisons

- **SIM.EM-S13**, Voltage, Current and Resistance Comparison. Attending the suggestion from the CCEM-WGLF review of Draft B. During 2024 is planned a bilateral comparison with NIST, on AC-DC voltage transfer difference, to link the CENAM's results with the on-going key comparison CCEM-K6.a.2018 and CCEM-K9.2018.
- **CCEM.K5 key comparison power.** Along with PTB and VSL, CENAM is part of the coordinating group od this comparison. In 2022 we participated in a couple of meetings for the analysis of measurement data during the comparison

Publications

A.H. Pacheco-Estrada, F.L. Hernandez-Marquez, J. Rodríguez-Reséndiz, C. Duarte-Galvan, L.M. Contreras-Medina, "Review of Scanners for DC to 20 kHz electrical metrology applications", Measurement, Volume 187, 2022, 110297, ISSN 0263-2241, https://doi.org/10.1016/j.measurement.2021.110297.

A.H. Pacheco-Estrada, R. D. Carranza-Lopez-Padilla, "Physical phenomena that affect electric impedance measurments – (Fenómenos físicos que afectan las mediciones de impedancia eléctrica)", Memorias del Simposio de Metrología 2022.

M. Rodriguez, PhD Dissertation: Reference measurement method for power quality and Synchrophasors in stationary-state and no-stationary state – (Método de referencia para calidad de la potencia y sincrofasores en estado estacionario y no-estacionario)", Universidad Autónoma de Querétaro, August 2022.

A.H. Pacheco-Estrada, PhD Dissertation: Electrodynamic coaxiality in a digitally-assisted impedance bridge to improve uncertainty and frequency scope in standard impedance measurements, (Coaxialidad electrodinámica en un puente de impedancia digitalmente-asistido para mejorar el alcance en frecuencia e incertidumbre de mediciones de impedancias patrón)", Universidad Autónoma de Querétaro, December 2022.

Radiofrequency quantities

1. Radiofrequency (RF) power

Current capabilities in RF power cover the frequency range from 10 MHz to 50 GHz and in RF voltage from 10 kHz to 1 MHz. In former years CENAM developed a calorimeter in Type N connector to cover the range up to 18 GHz and another in 2.4 mm connector which covers the range up to 50 GHz, both through a close cooperation with other NMI's, NIST and KRISS, respectively. RF voltage is obtained by means of a RF-c.c. transfer method. This has allowed having CMC's at a primary level and also those for supporting any request from other slabs of traceability chain; CENAM provides services not only to calibration labs but also to industry labs and conformity assessment labs.

CENAM's current RF power CMC's were peer reviewed from July 18 to 22; as a result from that, CMC's entries at the BIPM KCDB will be updated accordingly.

Main challenges:

Even when domestic industry request for RF power traceability doesn't go further than 50 GHz, one of the challenges is keeping CMC's in good shape as calibration service requests increase year by year and investments in new staff and in renewing equipment has not been possible accordingly to the workload; this recently derived in a more compromised situation as the RF power lab suffered the loss of a well experienced staff in October 2022.

Another challenge is a better support of the CMC's through interlaboratory comparisons in type N, 3.5 mm, and 2.4 mm; we appreciate any help other NMI's could provide to CENAM in this issue.

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2. Reflection and transmission coefficients

Current capabilities cover the frequency range from 10 kHz to 50 GHz. As has been stated in previous reports, calibration and measurement services for reflection and transmission coefficients have continued growing; even when most service requests by customers are in Type N connector up to 18 GHz, the continued strong enforcement of local regulations in telecommunications and electromagnetic field measurements have pushed the demand for services of reflection and transmission properties of components and equipment working in in type 3.5 mm, 2.92 mm, and 2.4 mm connectors. No service requests in waveguide at all, nor higher frequencies.

CMC's for reflection and transmission coefficients were successfully peer reviewed from July 18 to 22; as a result from that, CMC's entries at the BIPM KCDB will be updated accordingly.

Main challenges:

A need of additional interlaboratory comparisons is envisioned for a better support of CMC's; we appreciate any help other NMI's could provide to CENAM in this issue.

Also, domestic regulations for Specific Absorption Rate (SAR) of wireless devices have pushed a demand for traceability of Permittivity and Conductivity properties of Tissue Emulation Liquids (TEL). As these electromagnetic properties can be derived from s-parameter measurements, reference systems need to be developed for addressing this necessity. CENAM s-parameters laboratory has already started providing services for measurement assurance of reflection coefficient measurements of coaxial open-end probes and reflectometers used in conformity assessment labs.

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3. Antenna parameters and electromagnetic fields measurements

Current capabilities in antenna and electromagnetic fields measurements cover the frequency range from 30 MHz to 40 GHz. Antenna factor of dipole-like antennas working in the frequency range from 30 MHz to 1 000 MHz is measured on an open area calibration site compliant with IEC/CISPR 16-1-5 using the Standard Site Method (SSM). Power gain of antennas in the frequency range from 1 GHz to 18 GHz is measured using the Three Antenna Method and the Standard Gain Antenna Method on the same site modified with electromagnetic absorber materials to eliminate ground reflection. Those calibration services address the needs of traceability for telecommunications applications and Immunity and Emissions measurements for EMC applications. This CENAM's lab also provides services of metrological characterization of facilities for performing measurements of E-fields, antenna parameters and EMC conformity assessment testing.

Main challenges:

Being the only laboratory in the whole country which performs this kind of measurements with high accuracy, the workload is full and addressing customer needs in-time while keeping CMC's at a standards laboratory level or to develop new services has become a challenge; additional strategies for overcoming this challenge need to be envisioned. For example, the development of CMC's for calibration of reference dipoles and probes radiating into a media different than air needs to be started in the short-term time as a part of the support for SAR measurements.

Also, a better support of antenna CMC's through interlaboratory comparisons is needed, mainly in the 30 MHz to 1 GHz in dipole-like antennas but also for the 1 GHz to 18 GHz in horn-type antennas; any collaboration from other NMI's will be greatly appreciated regarding this issue.

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4. Electromagnetic compatibility

CENAM has developed a service portfolio for addressing traceability needs of electromagnetic compatibility measurements. This includes Electrostatic discharge (ESD) waveform parameters from 2 kV to 25 kV of peak voltage, absorbing clamp factor of transducers used for radiated emissions from mains cables, and Insertion loss, isolation, and impedance of LISN's used in conducted emissions. Through the years these capabilities have consolidated but had not been yet submitted to the KCDB.

Main challenges:

These CMC's are planned to be subject of a peer review in the next few months, so a peer reviewing needs to be agreed. Also, extending CMC's for supporting more measurements required by IEC/CISPR EMC standards is a task still pending.

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