Progress Report on Electrical Metrology at the PTB between 2017 and 2019 on the Occasion of the 31st Meeting of the CCEM

Submitted by Uwe Siegner,
Electricity Division,
Physikalisch-Technische Bundesanstalt,
Bundesallee 100, D-38116 Braunschweig, Germany

1. Electrical Quantum Standards

1.1 Josephson Voltage Standards

The major goal for pulse-driven Josephson junction series arrays is the further increase of the output voltage. Three different approaches have been investigated to this end. First, the number of junctions in a single array has been increased to 15000 SNS Josephson junctions using fivefold-stacked junctions with Nb_xSi_{1-x} barriers fabricated in an optimized standard window process. Second, the development of two different kinds of on-chip power splitters has been started and promising results were already achieved. Third, a pulse drive based on opto-electronics has been investigated together with partners in a project funded by the European Metrology Programme for Innovation and Research (EMPIR). Using an improved electrical set-up consisting of two commercial 8-channel pulse pattern generators, 16 arrays (on 8 chips) containing a total number of 162 000 junctions were simultaneously operated. An RMS output voltage of 2.25 V was demonstrated with a spurious-free dynamic range (SFDR) of better than 120 dBc. In addition, special circuits for pulse-drive operation were developed and fabricated for a German technology transfer project (see below) and the development of Johnson noise thermometry at the PTB. (Oliver.Kieler@ptb.de, Johannes.Kohlmann@ptb.de)

The PTB is advancing the technology transfer of pulse-driven Josephson voltage standards. In cooperation with two German companies and another research institute, all components will be optimized for commercial distribution. The objective is to increase the output voltage and to build a turn-key system for cryocooler operation that can be used by a wide community including industry and research institutes. (Ralf.Behr@ptb.de)

The output voltage of the two-terminal-pair impedance bridge based on pulse-driven Josephson arrays was raised from 20 mV to 100 mV. This reduces the type-A uncertainty of a single measurement to less than 1 nV/V after 100 s of measurement time. The setup was used to link a 10 nF capacitance standard to the quantum Hall resistance with a similar agreement as reported before (less than 2 parts in 10^8). Moreover, the impedance bridge was used to directly link a 1 nF capacitance standard to the quantum Hall resistance. The agreement with conventional measurements was 3 parts in 10^8 and was limited by the measurement voltage of 10 mV at the quantum Hall side (10:1 measurement ratio). (Stephan.Bauer@ptb.de)

Two pulse-driven Josephson systems were used to calibrate inductive voltage dividers (IVD) with a difference method. One system delivered a 100 mV sinewave to the input of the IVD and the second was used as the reference for measuring the error at the output taps of the IVD. For measurement times of 100 s, the type-A uncertainty was below 1 part in 10^9 at the three frequencies investigated (120 Hz, 225 Hz, and 497 Hz). The agreement with the conventional bootstrapping method was better than 1 part in 10^8. (Jonas.Herick@ptb.de)

In cooperation with PTB's thermometry department, a two-channel pseudo-random Josephson voltage noise source is under development for use in a practical quantum-voltage-based Johnson noise thermometer for the temperature range 273 K to 1000 K. The two-channel approach is used to reliably assess the type-B uncertainty contributions at the µV/V level in the frequency range up to 700 kHz with 10 mV RMS voltage amplitudes. (Franz.Ahlers@ptb.de)

1.2 Single-Electron Transport, Quantum Current Standards, and Quantum-Enhanced Measurements

The clean room fabrication of GaAs-based single-electron pumps has been optimized allowing reliable device fabrication with high yield. New pump geometries with two electrostatic gates for the definition of the quantum dot and an additional electrostatic tuning gate have been implemented to optimize the low-temperature device performance. Based on these optimized pumps, quantum circuits with two serially connected pumps and a fast single-charge detector in between have been fabricated and characterized. These devices represent a major step towards a pA self-referenced quantized current source. (Niels.Ubbelohde@ptb.de)

In September 2018, PTB presented the Ultrastable Low-Noise Current Amplifier (ULCA) in an invited lecture in the workshop entitled "The next generation of ionization chambers for radionuclide metrology", jointly organized by the BIPM and NIST in Gaithersburg (USA). Aim of the workshop was to discuss possible methods for improved traceable small-current measurement methods on ionization chambers. Further activities are underway to coordinate future international studies, involving experts in radionuclide and electricity metrology from the Consultative Committee for Ionizing Radiation (CCRI) and from the Consultative Committee for Electricity and Magnetism (CCEM). (Hansjoerg.Scherer@ptb.de)

The Josephson traveling-wave parametric amplifier (JTWPA) will be further developed within the project "ParaWave", funded by the European Metrology Programme for Innovation and Research (EMPIR) The project was launched in July 2018 and is coordinated by PTB. ParaWave aims at the advancement of JTWPA devices, characterisation of the amplifier noise, integration of JTWPAs with quantum sensors with the purpose of achieving quantum sensitivity and the development of associated metrological techniques. First circuits fabricated in niobium technology at the PTB and tested at a temperature of 4.2 K achieved a gain of up to 20 dB at 5 GHz. (Ralf.Dolata@ptb.de)

1.3 Quantum Hall Effect

For quantum Hall metrology based on epitaxial graphene devices on silicon carbide (SiC) substrates, PTB has further optimized the growth process to realize ultra shallow mono-atomic surface steps in the SiC substrate supporting the atomically thin graphene films. The graphene films reveal a highly isotropic electrical resistance indicating a very weak impact of the monolayer SiC steps on the graphene transport properties. These optimized graphene sheets will be used to develop stable graphene-based quantum standards for electric resistance and impedance. (Klaus.Pierz@ptb.de)

The quantized anomalous Hall effect shows resistance quantisation without an external magnetic field. PTB has measured the quantized anomalous Hall resistance (QAHR) of a 10 nm thick Vanadium-doped $(Bi,Sb)_2Te_3$ layer at temperatures below 100 mK and current levels of up to 50 nA. The resistance was traced to R_K using a 100 Ω transfer standard. The agreement of the QAHR with R_K was confirmed at an uncertainty level of 2.5 parts in 10^7. Further studies of the quantized anomalous Hall effect will be performed within the 5-year Horizon-2020 project TOCHA in cooperation with several European academic research institutes. (Franz.Ahlers@ptb.de)

2. Voltage, Resistance, Current, AC/DC Transfer, and Impedance

In cooperation with a German company, the PTB has started to work on the development of DC standard resistors. The focus is on 10 kΩ resistors with low drift rate. Currently, the drift rate is of the order of a few parts in 10^6 per year, but improvements in the manufacturing process promise to achieve drift rates below 1 part in 10^6 per year. (Bernd.Schumacher@ptb.de)

A new measurement setup was developed for linearity investigations of high-precision bridge amplifiers, which are used in static force and torque measurements. The measurement setup is based on two cascaded inductive voltage dividers (IVD). One of them is an automated 24-bit IVD. This setup allows very detailed linearity investigations with a step size of 1 nV/V. This resolution is 10000 times higher compared to previously used setups. The expanded uncertainty for linearity values in the range ±2.5 mV/V has been determined to be 2 nV/V. (Florian.Beug@ptb.de)

The time constant as well as the sensitivity of planar multijunction thermal converters (PMJTCs) was significantly increased by filling the housing with noble gases, preferably xenon or krypton. The frequency response of the AC-DC transfer difference was significantly reduced below 40 Hz and remained unchanged at higher frequencies, while the sensitivity was more than doubled. Using the lowest manufacturable heater resistance of 90 Ω with the noble gas filling, AC-DC transfer down to 70 mV compared to about 100 mV in air becomes possible. The improved performance was observed sustainedly for more than two years without any degradation. (Torsten.Funck@ptb.de)

The Key Comparison CCEM-K4.2017 (comparison of 10 pF and 100 pF capacitance standards, piloted by the BIPM) has been successfully completed and the final report has been published in 2018. (Juergen.Schurr@ptb.de)

3. Power and Energy

Voltage and current signals of the power grid become more and more nonsinusoidal due to the increasing usage of nonlinear loads and sources. Therefore, the demand for traceability of electric power with harmonics above 1 kHz is continuously growing. To address this need, PTB is developing a measuring system for electric power up to a frequency of 150 kHz. The final goal is to achieve calibration capabilities for maximum currents of 32 A and maximum voltages of 480 V. At present, the measuring system can be used up to a maximum frequency of 20 kHz, a maximum voltage of 230 V, and a maximum current of 14 A. The main challenge of the measurements of power at higher frequencies is the increasing uncertainty of creating a representation of defined phase angles between current and voltage. Consequently, the relative measurement uncertainties of the active power and the reactive power are angle-dependent and are currently in the range between $65\cdot10^{-6}$ and $1600\cdot10^{-6}$ ${}^{W}/_{VA}$ or ${}^{var}/_{VA}$ for angles between ±180° at 20 kHz. (Matthias.Schmidt@ptb.de)

Impulse voltage measurements are essential for the reliable and safe power distribution in electrical grids. Together with the voltage divider developed in the last years, a new transient voltage measuring system allows PTB to measure lightning impulses up to 1.5 MV with uncertainties of peak value and time parameters of less than 0.6 % and less than 2 %, respectively. The transient recorder is equipped with a new software, which enables a fully automated calibration procedure. The newly designed low voltage attenuators are constructed to counteract negative properties of the digitizer and, furthermore, to allow research of Very Fast Transients (VFT) up to 500 kV. To characterize the entire system, a step generator based on non-destructive avalanche breakdown in semiconductors was designed to produce step voltages with 100 ps rise times at voltage levels of 1000 V. The system enables the study of interferences caused by resonance modes in a shielded laboratory room. Travelling wave propagation in a high voltage lab, which acts as a cavity resonator, is caused by electromagnetic radiation emitted from the impulse generator and potentially affects measurement uncertainties. At PTB, measurements can be performed far below the interference level of 1% stated in the IEC 60060 standard. (Stephan.Passon@ptb.de)

4. Magnetic Measurements

Within the PTB-coordinated *NanoMag* project (funded by the European Metrology Programme for Innovation and Research, EMPIR) the first international comparison of magnetic force microscopy (MFM) calibrations based on nano-scale reference samples has been carried out. The results will form the basis for the first international standard for nano magnetic measurements, which is presently drafted within IEC TC133 “Nanotechnology standardisation for electrical and electronic products and systems” lead by PTB. This standard will represent a breakthrough for quantitative research, engineering, and material development in the field of nano magnetic materials and devices. (Hans.W.Schumacher@ptb.de)

5. High Frequency and Fields

5.1 Electromagnetic Fields and Antenna Measuring Techniques

PTB has made progress both in antenna calibration at lower frequencies (30 MHz – 3 GHz) on its open-area test site (OATS) and at higher frequencies (1 GHz – 50 GHz) using a spherical antenna scanner. At lower frequencies, antenna calibration has been established on the OATS and CMC entries will be applied for in 2019. At higher frequencies, antenna calibration techniques have been investigated to determine the phase center and to suppress multi-path propagation effects. The extrapolation method determining the free-space antenna factor from distance-dependent measurements has been implemented successfully. A CMC entry for the calibration of the on-axis gain of horn antennas up to 50 GHz will be applied for in 2019. Most recent work aimed at implementing near-field to far-field transformation algorithms for antenna calibration. (Thomas.Kleine-Ostmann@ptb.de)

Moreover, PTB has established capabilities of precise on-site electromagnetic field measurements employing unmanned aerial systems (UAS). Extensive measurement campaigns for signals of terrestrial navigation and radar installations were performed to investigate the influence of wind power plants on these services. Ongoing work aims at improving the quantitative prediction of navigation errors of Very High Frequency (VHF) Omni-Directional Range installations caused by wind turbines. (Thorsten.Schrader@ptb.de)

5.2 High-Frequency Measuring Techniques

PTB has extended its measurement capabilities of the RF quantities power and scattering parameter in both coaxial and rectangular waveguides up to 110 GHz. The frequency and the measurement range were extended while several measurement uncertainties have been reduced. Ongoing work is aimed at establishing traceability for the new 1.35 mm connector up to 92 GHz. (Karsten.Kuhlmann@ptb.de)

The joint research project “Microwave measurements for planar circuits and components” (PlanarCal) within the European Metrology Programme for Innovation and Research (EMPIR), coordinated by PTB, has been completed successfully. Among other accomplishments, the major goal of PlanarCal, i. e., establishing traceability for coplanar waveguide calibrations on industrial microwave substrates, was achieved and successfully demonstrated on fused silica substrates. Commercially available impedance standard substrates can be used as application-specific transfer standards. PTB will apply for a CMC entry up to 110 GHz in 2019. (Uwe.Arz@ptb.de)

PTB has further advanced its optoelectronic measuring techniques with femtosecond lasers. An asynchronous electro-optical sampling technique has been developed and implemented to increase the bandwidth and to reduce the uncertainty of measurements of the time response of ultra fast electrical signals generators. The new technique uses two femtosecond lasers with slightly detuned pulse repetition rate allowing electro-optical measurments over a broad spectral range form 76 MHz to 500 GHz. (Mark.Bieler@ptb.de)