Progress report on Electrical Metrology at VSL (2019 – 2021)

Report prepared for the 32nd meeting of the
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Helko van den Brom, hvdbrom@vsl.nl

Subfield DC and LF

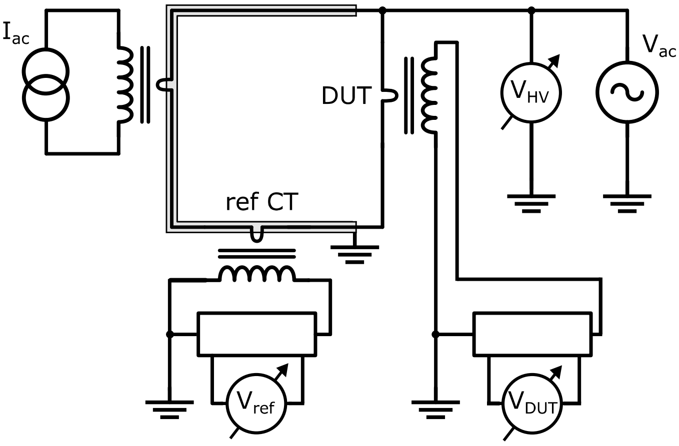
AC Josephson

After finishing the EMPIR project QuADC in 2019 the VSL system was upgraded by means of a new 1 V array from NIST and a corresponding probe to drive the four 250 mV arrays connected in series on-chip. Several routes to improve the margins were investigated, including use of a FIR filter to improve the pulse amplitudes to be more equal and equalizers to improve the effect of distortions caused by the cables. Unfortunately, after initial testing the array was damaged, and the project was temporarily postponed.

Contact: Ernest Houtzager (Ehoutzager@vsl.nl)

Current transducers under distorted conditions

Within the context of the EMPIR project MyRailS, which finished early 2021, at VSL a setup was developed based on a sampling current ratio measurement system to determine the voltage dependence of the ratio error and phase displacement of current transformers (CTs) used at medium voltage (MV) for railway applications (see figure 7) [1],[2]. A grounded shield prevents the reference CT to sense the high potential applied to the primary current circuit. A novel method was developed to first determine the influence of the applied voltage on the ratio error and phase displacement of the reference circuit [2]. The device under test (DUT) is an MV or HV CT. The overall uncertainty of the system is about 10 ppm (or 0.001 %) for currents up to 5 kA and voltages up to 25 kV. The newly developed reference setup was subsequently used to determine the voltage dependence of a commercial 2500 A class 0,2S MV CT. The voltage dependent error was found to be more than two orders of magnitude larger than for the reference circuit, and well outside the specified limits of 0.75 % and 0.9 crad set in the IEC 61869-2:2012. This demonstrates that the voltage dependence of MV CTs should be seriously considered for testing.



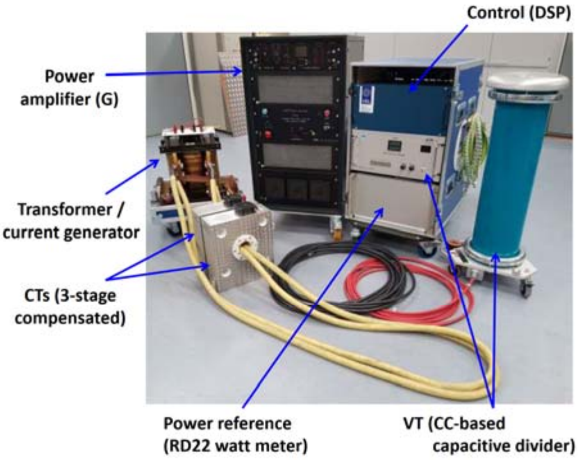
Following up on earlier work on the calibration of DC current sensors under distorted conditions, the calibration setup was improved to include high-current chopped signals occurring in the braking stage of conventional DC railway traction unit, the corresponding energy of which is dissipated in rheostat resistors [3]. Preliminary results indicate that the reference transducer used in this setup can accurately measure chopped signals with magnitudes up to at least 250 A and pulse repetition rates up to 500 Hz with uncertainties better than 0.01 %, whereas currents up to 600 A are currently envisaged.

The accuracy of onsite measurements of the energy dissipated in braking rheostats in DC railway systems was further envisaged in collaboration with INRIM, University of Campania, NPL, and Strathclyde University [4]. The implementation and further test measurements were performed in collaboration with INRIM, University of Campania and CMI [5].

Contact: Helko van den Brom (HvdBrom@vsl.nl)

Transformer Load Loss

Within the EMPIR TrafoLoss project (started in 2018), significant progress has been made in the improvement of a setup for on-site system calibration of commercial Power Transformer Loss Measurement Systems (TLMS). Already in 2017, the VSL reference system [6] has been successfully compared to the system of PTB, showing an agreement of better than 20 µW/VA in amplitude and 20 µrad in phase [7]. Stimulated by these good results, major further improvements have been made in the past 2 years to reliably achieve overall uncertainties of 20 µW/VA on-site for voltages up to 230 kV and currents up to 2000 A.



First of all, the uncertainty of the power measurement in the setup has been improved from 15 µW/VA to better than 10 µW/VA, mainly via improved characterization of the voltage transformer and current transformer in the VSL primary power measurement setup.
A similar improvement was made in the calibration of the voltage channel in the VSL TLMS reference setup. This voltage channel is a current-comparator-based capacitive voltage divider (CVD). An extensive comparison was done of the calibration results of the CVD components with those of the CVD as a whole [8]. The final agreement of the two methods is better than 6 µrad for voltages up to 100 kV [9]. The 230 kV HV capacitor used in this verification has a known voltage dependence of 4 µF/F / (200 kV)2 in capacitance value and less than 5 ppm change in DF up to 230 kV, so that overall voltage scaling uncertainties of better than 10 µV/V are reached for voltages up to 230 kV.
The results of these improvements underpin the improved CMC of VSL for on-site TLMS calibrations [10]. An additional paper was published on the estimation of uncertainty in loss measurement of power transformers [11].

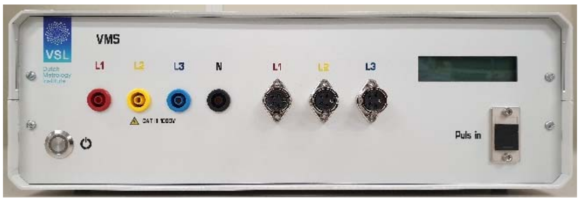
Significant effort has been spent to improvement of the digital feedback loop of the system, designed to generate the 2 kA test current with a stable and known phase with respect to the applied 100 kV test voltage. Major improvements concern the digital algorithm to correct for DC offsets and the PID control for controlling the phase. This particularly led to improved noise for higher currents, between 1000 A and 2000 A, where capacitive compensation is required to compensate the inductance of the primary current loop. At present, a noise in the measurements of better than 10 µW/VA (10 µrad) in a 10-second averaging period can be achieved under all test conditions.

Finally, the effect of non-sinusoidal test signals on the accuracy of transformers loss tests has been studied. It appears, that for the highest voltages in no-load loss (NLL) measurements, the transformer starts to generate harmonic power, reducing the overall measured loss power.

Contact: Gert Rietveld (GRietveld@vsl.nl)

Static electricity meters

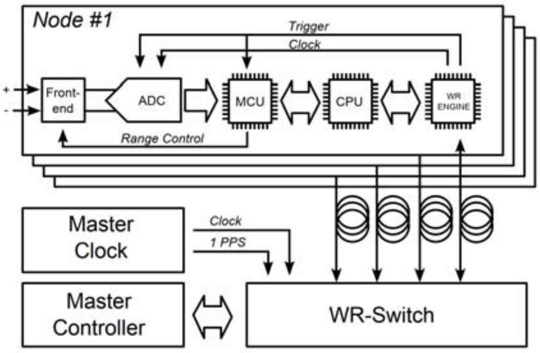
A flexible phantom power testbed was developed at VSL early in the EMPIR project MeterEMI, which ends 2021. This testbed was designed for testing electricity meters with broadband conducted EMI and arbitrary current waveforms in the frequency range up to 150 kHz without the need for the actual physical disturbing non-linear loads causing these waveforms to occur. In the meantime, using this testbed a large series of electricity meters has been tested [12]. Statistics on meter reading errors for about 60 different types of meters showed that meters using Rogowski current sensors are the most sensitive but reading errors are found for meters with Hall sensors, CTs or shunts as well. From the results it can be concluded that the most disturbing waveforms causing the meters to show these reading errors consist of current distortions with dI/dt values above 0.5 A/µs, although the maximum current, the peak (a)symmetry, the phase between current and voltage and distortion in the voltage waveform also play a role.



The testbed was also used to calibrate a home-built waveform recorder modified to operate as static electricity meter. This instrument uses high-precision Rogowski coils and an eight-channel 16-bit digitizer unit with 1 MHz sampling rate, suitable for performing three-phase voltage and current measurements. Using proper hardware settings (in specific a broadband and capacitively-shunted resistance voltage divider) in combination with specific high-pass filtering compensation techniques, its reading errors were reduced to below 1.0 % for all signals investigated [13], though this will remain dependent on the waveform details. The instrument can be used as a waveform recorder with specific trigger mechanism for onsite applications or as a benchmark electricity meter in case of disputes.

Contact: Helko van den Brom (HvdBrom@vsl.nl)

Synchronized distributed digitizers



Within the context of the Future Grids II EMPIR project (started 2018), VSL has developed distributed digitizers with metrological precision of the individual measurement nodes. A master controller aggregates the data of the nodes and performs all computational tasks. A crucial part of the system is the synchronization of the individual nodes at nanosecond level using White Rabbit technology. Fiber-optic communication is used to reduce interference and to obtain high isolation. When operated on battery power, this allows for special applications such as the measurement of currents in high-voltage lines. First results show that a phase error of a few µrad can be achieved with a resolution of better than 0.1 µrad. The results have been published in IEEE TIM [14].

Next to the work on the distributed digitizers, work has started on the development of a reference stand-alone merging unit (SAMU). A key part of this development is the calibration of the delays between the internal DAC unit and the external time synchronization signals. Work is progressing together with colleagues from the time & frequency department to realize traceability in phase of better than 100 µrad (300 ns).

Contact: Ernest Houtzager (Ehoutzager@vsl.nl)

Phasor measurement units (PMUs)

In the EMPIR JRP ROCOF (finished in 2019), the importance of rate of change of frequency (RoCoF) measurements in electrical power grids has been investigated along with its measurement challenges. Work has been performed together with NPL and University of Strathclyde on measurements of frequency and ROCOF measurements in the presence of phase steps [15]. Furthermore, a report has been written on ROCOF events taken from a series of measurements in distribution and transmission grids. Based on these measurements, waveforms have been proposed for future PMU testing to guarantee they can perform reliable ROCOF measurements [16][17].

In collaboration with Eindhoven University work performed in the past has been extended on dynamic line rating of cables by using PMUs at both ends. An algorithm has been developed to estimate the line parameters [18] and uncertainty calculations have been performed to predict the local temperature of the cable real-time [19].

Contact: Gert Rietveld (GRietveld@vsl.nl)

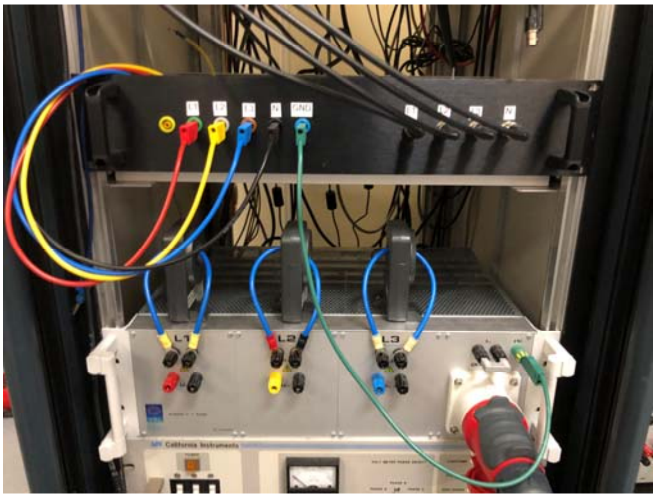
Instrument transformers for PQ measurements

Withing the EMPIR project IT4PQ, which started 2020, a metrological framework is envisaged to enable the traceable measurement of power quality (PQ) parameters using instrument transducers (ITs), which are currently only tested and calibrated using sinusoidal signals [20]. VSL is leading the work package on definition of PQ parameters and test conditions to envisage in this study, for which preliminary results have been discussed in a stakeholder meeting already. Further VSL work in this project focusses on the development of a comparator unit for the readout and analysis of the reference transducer and the transducer under test. This unit should be accurate but at the same time easy to operate since the aim is to present the design to stakeholders for use in their laboratory. A document with a schematic and list of requirements has been realized as a first step.

Contact: Helko van den Brom (HvdBrom@vsl.nl)

Grid measurements of 2 kHz -150 kHz harmonics

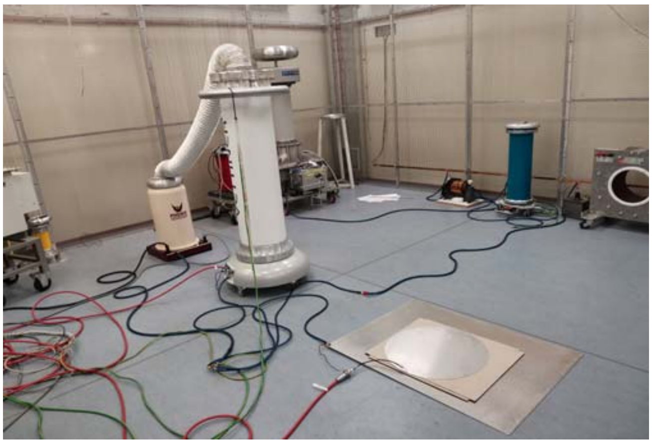
In the context of the EMPIR project SupraEMI, which started 2020, a portable waveform recorder was modified for detecting signals in the frequency range 2 kHz – 150 kHz. This system is currently tested with a new developed laboratory testbed using non-stationary test waveforms. Moreover, with the new proposed measurement method for measuring the harmonics in the frequency range 9 kHz – 150 kHz, the waveform recorder is tested via measuring several selected household appliances using the developed laboratory testbed. The measurement results using the new method need to be compared with the results obtained via CISPR16 method used by LNE. The measurements in the two labs have been done according to the same defined procedure. A measurement campaign is planned in autumn 2021 that the portable measurement instruments will be used to measure the high frequency emissions of the same appliances connecting to the real low voltage grid instead of the laboratory environment.



Contact: Gu Ye (GYe@vsl.nl)

Improved HV testing (LI and AC HV)

In the EMPIR JRP FutureGrid (started in 2021), VSL is working on the realization and comparison of Lightning Impulse systems up to 4 MV. To this end, a 600 kV LI reference system is presently being built, based on a reference divider from NIM and a digitizer system developed by RISE. This reference system will be used later in 2021 to calibrate the 4 MV LI divider of the TU Delft. This calibration will be an important basis for the major measurement campaign planned for autumn 2022, when more than 6 leading LI systems above 1 MV will be brought to the TU Delft premises for intercomparison at voltages between 1 MV and 4 MV.

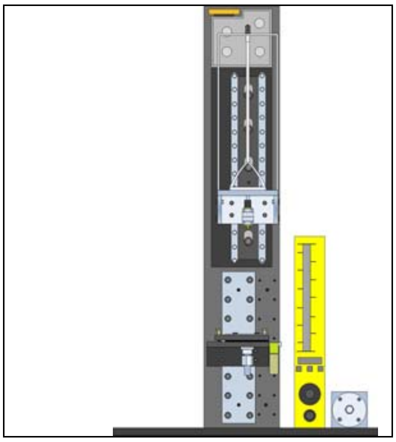


A second line of research in the FutureGrid project is improvement of the traceability at high AC voltages, up to 800 kV. To this end, a capacitive divider has been characterized with better than 10 µV/V uncertainty up to 230 kV. In addition, a field sensor has been developed for linear extension to higher voltages. Initial characterization of this field sensor showed results better than 100 ppm over a range of 10 kV up to 100 kV.

Contact: Ernest Houtzager (Ehoutzager@vsl.nl), Gu Ye (GYe@vsl.nl) or Gert Rietveld (GRietveld@vsl.nl)

Subfield RF&MW

Traceable characterization of precision coaxial air-dielectric transmission line standards



A fully automated measurement system is developed and is operational for traceable calculation of corresponding scattering parameters (S-parameters).
The measurements system allows diameter measurements over the line section's entire length with a minimum step size resolution of 10 µm. The system is suitable for characterizing transmission lines with nominal 2.4 mm, 2.92 mm, 3.5 mm and 7 mm diameters.

Contact: Faisal Mubarak (FMubarak@vsl.nl)

Primary standard for attenuation measurements up to 10 GHz

A primary standard for attenuation measurements is currently under development. The system is suitable for frequencies from 1 MHz up to 10 GHz. The attenuation measurements are based on the IF-substitution method and are traceable through calibrated low-frequency IVD standards.

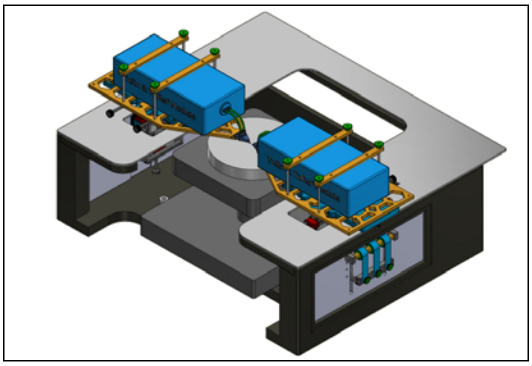
Contact: Faisal Mubarak (FMubarak@vsl.nl)

S-parameter measurement

S-parameter measurements related activities at VSL concentrate on realization of state-of-the-art measurement accuracy for frequencies from 1 kHz up to 50 GHz of connectorized and planar (on-wafer) devices.

- ***Probing-station for nm-size device characterization***

VSL has designed and manufactured a state-of-the-art probing station suitable for measuring the electrical properties of sub-micron devices. The system allows the characterization of 1- and 2-port planar devices. In PlanarCal and TEMMT projects, VSL will extend traceable planar S-parameter measurement capability up to 50 MHz. VSL has also developed a state-of-the-art on-wafer measurements software module, included in FAME, for fully automated probe alignment and contacting procedures.

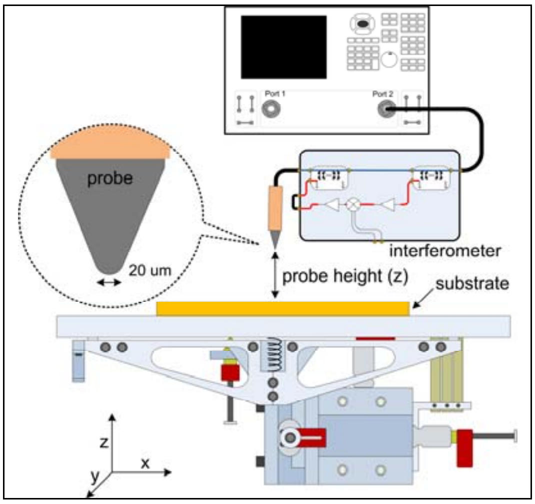


Contact: Fabio Munoz (fmunoz@vsl.nl), Faisal Mubarak (FMubarak@vsl.nl)

- ***Scanning Microwave Microscope (SMM)***

VSL has designed and manufactured a scanning microwave microscope (SMM) system suitable for the measurement of electrical properties of planar devices and materials. The system is fully automated by FAME software.

Contact: Faisal Mubarak (FMubarak@vsl.nl)



- ***FAME VNA measurement software***

VSL has developed VNA measurement software FAME for real-time 1-port and 2-port VNA calibration and uncertainty evaluation. Furthermore, a data analysis module is designed to support advanced metrological evaluations with unprecedented speed. The software uses co-variance based uncertainty propogation techniques for accurate uncertainty calculations. Furthermore, the software supports connectorized and on-wafer calibrations.

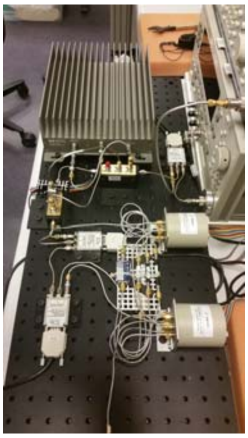
Contact: Fabio Munoz (fmunoz@vsl.nl), Faisal Mubarak (FMubarak@vsl.nl)

- ***S-parameter measurements in cryogenic conditions***

VSL is extending S-parameter measurement capability to cryogenic conditions to support quantum research. In collaboration with Delft University of Technology and Qetech, VSL will extend traceable S-parameter measurement capability to cryogenic environment.

Contact: Faisal Mubarak (FMubarak@vsl.nl)

Power measurements



The automated power sensor calibration facility is fully operational. The measurement method is based on the direct-comparison technique and covers frequencies up to 50 GHz. The measurement system is supported by advanced measurement and uncertainty calculation software.

Contact: Faisal Mubarak (FMubarak@vsl.nl)

Participation in comparisons

- CCEM-K2.2012, Comparison of resistance standards at 10 MΩ and 1 GΩ. VSL measurements performed in 2014. Results published.
- EURAMET.EM-S35, Comparison of High-DC Current Ratio Standard. VSL measurements Feb – Mar 2013. Results published.
- EURAMET.EM-S37, Comparison of AC current ratio. VSL measurements performed in 2014. Results published.
- CCEM.EM-K5.2017, Comparison on LF power. VSL measurements performed in 2021. Measurements finished. Co-piloted by VSL, CENAM, and PTB.
- EURAMET.EM-K5.2018, Comparison on LF power. VSL measurements performed in 2020. Measurements finished. Co-piloted by VSL, PTB, LNE and NPL.
- CCEM.RF-K5c comparison on S-parameter measurements in coaxial 3.5 mm connectors. The VSL measurement results are submitted.

List of publications

[1] Ronald van Leeuwen, Helko van den Brom, Gert Rietveld, Ernest Houtzager and Dennis Hoogenboom, “Measuring the Voltage Dependence of Current Transformers”, *CPEM Conf. Dig.*, Denver, Colorado, 2020

[2] H. E. van den Brom, R. van Leeuwen, G. Rietveld and E. Houtzager, "Voltage Dependence of the Reference System in Medium- and High-Voltage Current Transformer Calibrations," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1-8, 2021, Art no. 1502908

[3] Helko van den Brom and Ronald van Leeuwen, “Calibrating Sensors to Measure Braking Chopper Currents in DC Traction Units”, *CPEM Conf. Dig.*, Denver, Colorado, 2020

[4] Helko van den Brom, Domenico Giordano, Danielle Gallo, Andreas Wank, Yljon Seferi, "Accurate Measurement of Energy Dissipated in Braking Rheostats in DC Railway Systems", *CPEM Conf. Dig.*, Denver, Colorado, 2020

[5] Domenico Giordano, Davide Signorino, Daniele Gallo, Helko E. van den Brom, and Martin Sira, "Methodology for the accurate measurement of the power dissipated by braking rheostats", *Sensors* 2020, Vol. 20, 6935

[6] Gert Rietveld and Ernest Houtzager, "High-accuracy reference setup for system calibration of transformer loss measurement systems", *Proceedings of the 20th International Symposium on High Voltage Engineering (ISH 2017)*, pp. 1 – 6 (2017).

[7] G. Rietveld, E. Mohns, E. Houtzager, H. Badura, and D. Hoogenboom, "Comparison of Reference Setups for Calibrating Power Transformer Loss Measurement Systems," *IEEE Transactions on Instrumentation and Measurement*, **68**, No. 6, pp. 1732 – 1739 (2019). **DOI:** 10.1109/TIM.2018.2879171

[8] G. Ye, W. Zhao, and G. Rietveld, "Verification of high voltage divider with $10\cdot10^{-6}$ uncertainty", *Proceedings of the 2020 Conference Precision Electromagnetic Measurements (CPEM2020)*, pp. 1 – 2 (2020). **DOI**: 10.1109/CPEM49742.2020.9191889

[9] Gu Ye, Wei Zhao, and Gert Rietveld, "Verification of a capacitive high voltage divider with 6 µrad uncertainty up to 100 kV", *IEEE Transactions on Instrumentation and Measurement*, vol. **70**, Early Access (2021). **DOI**: 10.1109/TIM.2021.3056647

[10] Gert Rietveld, Ernest Houtzager, Dennis Hoogenboom, and Gu Ye, "Reliable Power Transformer Efficiency Tests", *Proceedings of the 5th International Colloquium Transformer Research and Asset Management (ICTRAM)*, Opatija, Croatia, pp. 1-8 (2019). **DOI**: 10.5281/zenodo.3559845

[11] Anders Bergman, Allan Bergman, Bengt Jönsson, Gert Rietveld, Mathieu Sauzay, Jonathan Walmsley, and John-Bjarne Sund, "Estimating Uncertainty in Loss Measurement of Power Transformers", *Proceedings of the 21st International Symposium on High Voltage Engineering*, pp. 805 – 814 (2019). **DOI**: 10.5281/zenodo.3559837

[12] H. E. van den Brom, G. Rietveld, D. Hoogenboom, R. van Leeuwen, Z. Marais, G. J. P. Kok, S. Sharma and M. G. A. van Veghel, "Towards improved standardization of electricity meter testing", *CPEM Conf. Dig.*, Denver, CO, USA, Aug. 2020

[13] Z. Marais, H. E. van den Brom, G. Kok and M. G. A. van Veghel, "Reduction of Static Electricity Meter Errors by Broadband Compensation of Voltage and Current Channel Differences," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1-11, 2021, Art no. 1501511

[14] E. Houtzager, R. Hornecker, and G. Rietveld, "Compact distributed digitizers with metrological precision," *IEEE Transactions on Instrumentation and Measurement*, **68**, No. 6, pp. 1653 – 1658 (2019). **DOI:** 10.1109/TIM.2018.2878090

[15] Paul S. Wright, Peter N. Davis, Kevin Johnstone, Gert Rietveld, and Andrew J. Roscoe, "Field Measurement of Frequency and RoCoF in the Presence of Phase Steps," *IEEE Transactions on Instrumentation and Measurement*, **68**, No. 6, pp. 1688 – 1695 (2019). **DOI:** 10.1109/TIM.2018.2882907

[16] Gert Rietveld, Paul Wright, and Andrew Roscoe, "Requirements and Test Conditions for Reliable Rate-of-Change-of-Frequency Measurements," *Proceedings of the 2019 IEEE 10th International Workshop on Applied Measurements for Power Systems (AMPS)*, Aachen, Germany, pp. 153-158 (2019). **DOI:** 10.1109/AMPS.2019.8897789

[17] Gert Rietveld, Paul Wright, and Andrew Roscoe, "Reliable Rate of Change of Frequency (ROCOF) Measurements: Use Cases and Test Conditions," *IEEE Transactions on Instrumentation and Measurement*, **69**, No. 9, pp. 6657 – 6666 (2020). **DOI**: 10.1109/TIM.2020.2986069

[18] Ravi Shankar Singh, Helko van den Brom, Stanislav Babaev, Sjef Cobben, and Vladimir Cuk, "Estimation of Impedance and Susceptance Parameters of a 3-Phase Cable System Using PMU Data", *Energies* 2019, Vol. 12, no. 23, 4573

[19] Ravi Shankar Singh, Sjef Cobben, Helko van den Brom and Gert Rietveld, "PMU Data-based Temperature Monitoring of a Power Cable", *2020 IEEE Power & Energy Society General Meeting (PESGM)*, Montreal, QC, Canada, 2020, pp. 1-5

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