Progress report on Electrical Metrology at VSL (2013 – 2015)

Report prepared for the 29th meeting of the
Consultative Committee for Electricity and Magnetism, 12 – 13 March 2015
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New SI

As part of the task of the CCEM task group on the new SI, a paper has been written on the envisaged consequences of the new SI on electrical metrology. The paper has been presented at the NCSLI and CPEM 2014 conferences. It is published in the September issue of the NCSLI magazine "Measure". (see working documents CCEM/15-05 and CCEM/15-06)

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Subfield DC

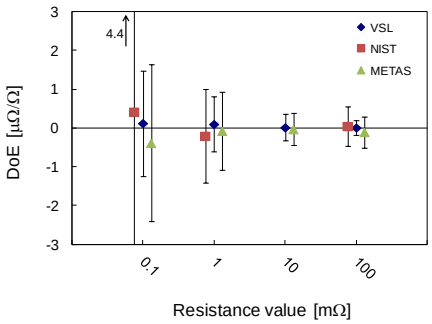
DC voltage and Josephson

Within the JRP "Q-wave" VSL is working on the practical and theoretical aspects of quantum waveform metrology, including generation of arbitrary Josephson signals, the MHz-resonance problem of voltage leads, a Josephson delta-sigma converter, asynchronous sampling techniques and uncertainty calculations. After initial work on changing the inductance of the voltage leads, the MHz resonance was identified as standing wave problem that cannot be suppressed by means of lumped circuit approach.
Preliminary work has been performed on the electronics for the Josephson delta-sigma converter. A thorough study has been performed on sampling properties of the HP3458A.

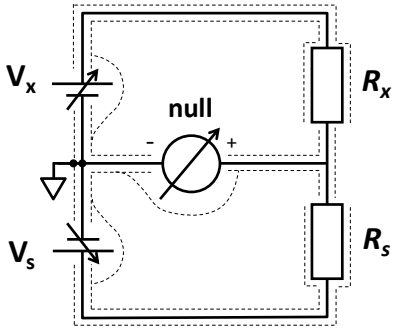
Contact: Helko van den Brom (HvdBrom@vsl.nl) and Ernest Houtzager (Ehoutzager@vsl.nl)

Resistance

An informal comparison was performed with NIST and METAS in the area of low-ohmic resistance measurements. The results of the comparison show excellent agreement between the 3 participating laboratories, well within the combined uncertainties (see the graph).
The results have been published in the IEEE I&M transactions.



An extensive series of evaluation measurements were performed with our improved setup for resistance measurements above 1 GOhm, based on a dual-voltage source bridge (see figure). The bridge is unique in the sense that both voltage and current null-detection can be used, which allows for verification of some systematic effects. The two null-detection methods were compared both in noise and accuracy. A description of the measurement system, together with measurement results have been published in the IEEE I&M transactions.



Based on this work, a joint VSL-METAS-NIST paper has been presented on CPEM2014 on high-precision resistance measurement methods for resistances of 10 MΩ and higher. Discussions with several NMIs worldwide entering this area have been held on details of the VSL measurement setup. Presently, a review paper is in preparation, together with NIST and METAS, summarising the experiences of the past decade(s) in accurate high-ohmic measurements.
Finally, in summer 2014, VSL has performed the measurements of the CCEM.K2-2012 comparison of 10 MΩ and 1 GΩ resistance. Good results with low uncertainties were achieved, better than 1 ppm and 3 ppm at 10 MΩ and 1 GΩ respectively.

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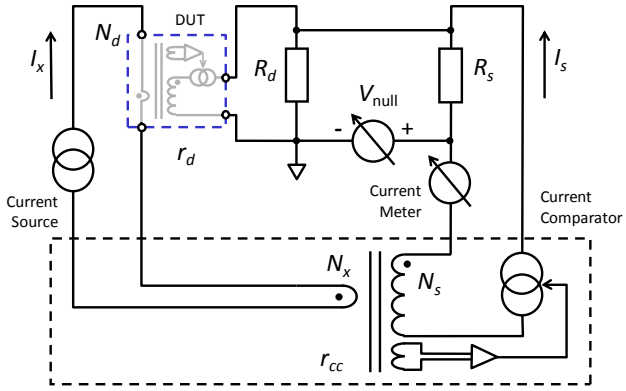
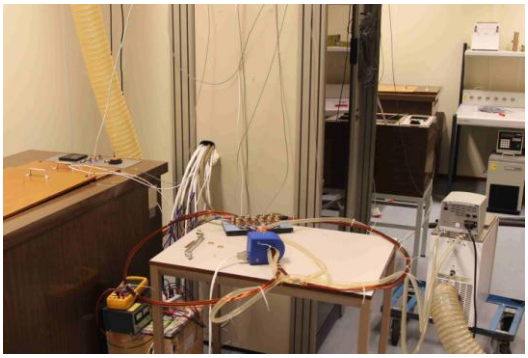
DC current

A setup has been developed for the accurate measurement of DC current ratios up to 600 A based on a DC current comparator bridge (see the schematic of the setup below). With this setup, VSL has participated in the Euramet.EM-S35 comparison on DC current ratio. The travelling standard in this comparison is a zero-flux based DC current transformer. The picture shows the setup in the VSL laboratory during the comparison measurements.





A description of the new setup and of the results achieved with it has been presented at the CPEM2014 conference and a full paper has been submitted for publication in IEEE I&M. The uncertainty that can be achieved with the VSL DC current ratio system is around 0.5 ppm. In the case of the Euramet.EM-S35 comparison, the final uncertainty was 1 ppm, due to limitations in the behaviour of the travelling standard (stability, current conductor position sensitivity).

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Subfield LF

Impedance

VSL has stopped its developments on the quadrature bridge. As before, VSL will obtain its traceability for capacitance from BIPM or other NMIs.

An improved version of our sampling bridge for impedance ratio measurements has been designed, fabricated and tested. Our first sampling bridge was meant for low-ohmic impedances, and was based on a transconductance amplifier providing the current and two HP3458A's measuring the voltage. After some experiments with higher values of impedance,

the bridge was redesigned to combine both low-ohmic (from the mΩ range) and high-ohmic (upto 20 MΩ) impedance measurements into a single bridge. The voltage sampling is now performed by NI PXI 5922 ADCs. Switching of the ADC inputs is now realized by solid state switches instead of mechanical relays. The switch box includes buffer amplifiers with matched input impedances. Measurement results show that uncertainties of a few ppm can be reached.

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AC/DC Transfer

In March 2014, measurements have been performed for the VSL participation in the Euramet AC/DC current comparison.

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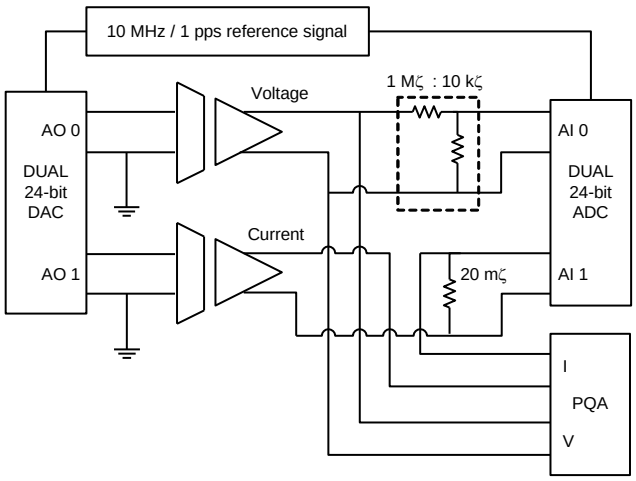
Power Quality

The recently developed PQ calibration setup has been upgraded to a 3-phase system. It is suitable for calibration of PQ analyzers as well as calibrators for a variety of parameters. In collaboration with NMi Certin, a sister organization of VSL and notified body in the Netherlands, we can now also perform compliance tests with respect to the IEC 61000-4-30.



Within the framework of the European EMRP SmartGrid-II project, work has started on the analysis of power quality propagation in distribution grids. Collaboration with TU Eindhoven and DSO Alliander has started on analyzing data obtained from a real grid.

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

Wideband Power

The JRP "ENG62 MESaIL Metrology for Efficient and Safe Innovative Lighting" started July 2014, as a successor of "ENG05 LIGHTING Metrology for Solid State Lighting". In this project, there are two tasks relevant to electrical measurement.

In the previous project JRP ENG05, it was established that the source impedance and the presence of harmonics in the AC power supply prevented repeatable measurements of the RMS current, power factor and electrical power consumed by SSL devices at different laboratories. To circumvent this problem, a source impedance stabilisation network needs to be placed between the AC power supply and the SSL so that the device under test sees always the same source impedance. In the first task, the analysis, design, and realisation of such a network will be undertaken.

The aim of the second task is to develop an electronic load with similar electrical behaviour as SSL devices in this project. Key features of the electronic load are rapid stabilization and switchable impedance to simulate typical SSL topologies. This electrical test standard is used to check the reliability of the electrical measurement setup in testing laboratories. The temperature dependence of electrical measurement is investigated. The first prototype with temperature stabilizer is assembled and waiting for test.

An online uncertainty calculation software for electric parameters measurement of SSL is developed.

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HV revenue metering

As part of the EMRP JRP on "Metrology for Smart Electrical Grids", VSL developed a reference set-up for on-site calibration of revenue metering installations in three phase high voltage electricity grids (up to 150 kV and 5 kA). The basis of the VSL reference set-up is composed of three current transformers, three voltage transformers, and a reference power / energy meter. The interconnections between the transformers and the power / energy meter are made with double shielded twisted pair cables to ensure signal integrity. The complete set-up was validated at the Canadian metrology institute, NRC, and was verified to have an uncertainty of less than 0.005 % (50 ppm), k=2, under laboratory conditions. The VSL reference set-up is completed with peripheral components to enable remote read-out and control. After more extensive tests and characterization at VSL it was verified that the set-up has an uncertainty of less than 0.03 % (300 ppm), k=2, for on-site measurements.

The setup has been presented at the CPEM 2014 conference, and a full peer reviewed paper describing the setup presently is in preparation.

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Phasor measurement units (PMUs)

In the new EMRP JRP "Smart Grid II" project, VSL is actively involved in research on PMUs. First of all, the VSL system for testing PMUs are presently being further developed, among others with the aim to include facilities for dynamic testing of PMUs. Subsequently, this facility will be expanded to allow for calibration of commercial PMU calibrator systems. A first series of static tests of a series of commercial PMUs have been performed.
A second major line of research concerns applications of PMUs in on-site measurements in electricity grids, for example with the aim to accurately determine line impedances.

A joint project is started with DELTA, one of the Dutch distribution system operators, on the application of PMUs in distribution grids. In autumn 2014, PMUs have been installed in a 50 kV ring that is heavily loaded by renewable energy sources (wind, CHP). When the PMU data as received by the central Phasor Data Concentrator (PDC) becomes available, these PMU data will be analysed within the EMRP "Smart Grid II" and "GridSens" projects.

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Non-conventional Transducers and Instrument Transformers

The EMRP JRP on "Future grids" started in May 2014. Part of the project aims at adjusting the current measurements setups to accept signals from non-conventional transformers having non-conventional voltage/current/digital outputs. A second part of the VSL involvement in this project is the calibration of commercial transformer test sets suitable for testing non-conventional transformers.

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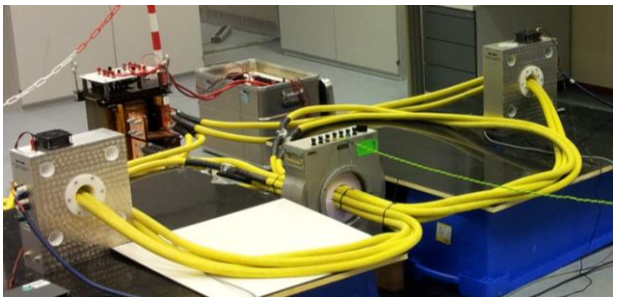
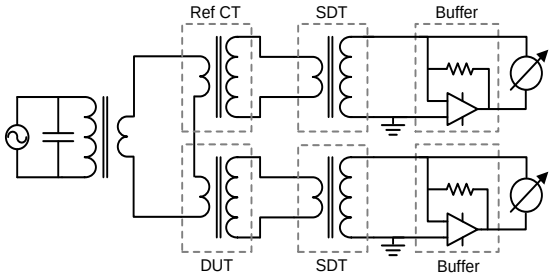
High voltage and high current

The high voltage laboratory has moved to a new laboratory giving more room to work. This laboratory will hold all power related measurement setups.

Work has progressed very well on the upgrade of the VSL AC high voltage measurement facilities. A current-comparator based measurement bridge has been successfully tested and calibrated. This has led to improved CMCs in this area from previously 100 ppm down to presently 20 ppm. The setup has already been successfully used for an on-site calibration at a customer's site.

We also finalized the development of our new sampling measurement setup for the accurate ratio measurement of AC current transformers (CTs) for primary currents up to 5 kA at a frequency of 50 Hz or 60 Hz. The schematic of the bridge is as follows:

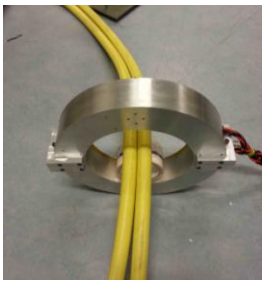




At CPEM a presentation was given on the final evaluation of the system, including the results of a comparison with NRC. The results of this comparison confirm the claimed uncertainty for CT calibration of $5 \cdot 10^{-6}$ in magnitude and 5 µrad in phase at 50 Hz or 60 Hz (k=2).

Within the European Joint Research Pproject on "HVDC", VSL has been involved in the development and final testing of a high voltage divider capable of measuring 200 kV. The divider is part of a larger divider capable of measuring 1 MV. The performance has been proven at Aalto university (Finland, see photo below), showing an accuracy of better than 10 ppm at 200 kV. Some further characterization of the VSL 200 kV unit has been performed at the VSL laboratories.

Within the same project, VSL has finished the work on the non-invasive measurement system for on-site accurate measurement of AC currents. An openable core CT (OCCT) has been made with magnitude error less than 10 µV/V and a phase error of 20 µrad at 2000 ampere. The OCCT has been presented at the CPEM 2014 conference.
A future project will add remote readout and phase measurement capabilities to this CT.



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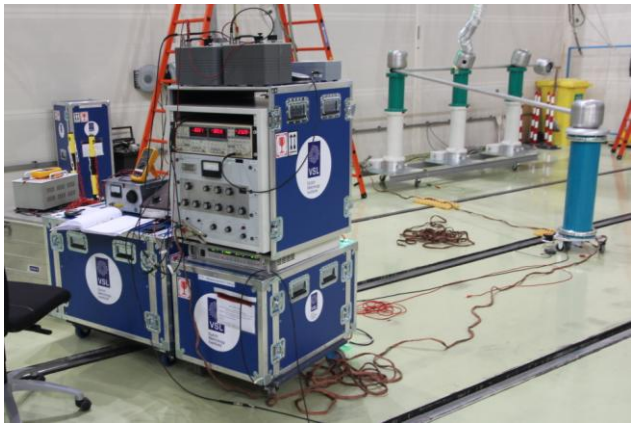
Transformer Load Loss

A calibration of a Power Transformer Load Loss Measurement system has been performed on-site at the customer's location. These measurements involved both CT and VT calibrations at the level of 30 – 80 ppm and 30 – 50 µrad. For this exercise the several VSL calibration setups have been made transportable and rugged.
Present work concentrates on developing a reference setup for complete on-site system validation of transformer loss measurement systems. This work will be part of the new European research project "Metrology for the Electrical Power industry" (ElPow)



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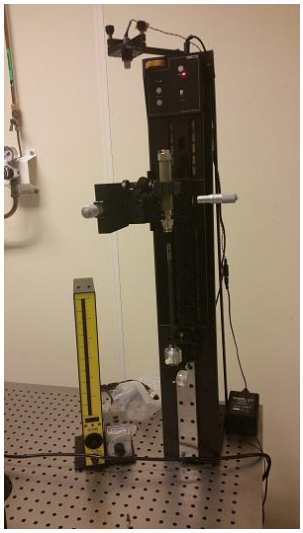
Subfield RF&MW including EM fields

RF & MW

Primary standard for dimensional measurements of precision coaxial airlines

A number of facilities are clustered together for traceable dimensional measurements of precision coaxial airline standards for traceability purposes at primary level. This facility is meant for achieving NMI-level traceability.



- A new air gauging facility is developed for diameter measurements of precision coaxial airlines. All measurements will be traceable to VSL primary standards for dimensional measurements.
- Microscope based optical measurement facility will be used for measurement of connector parameters.
- Modelling of coaxial airline based on dimensional measurements, including the connector effects. The resulting calculated s-parameters are used in multi-line calibration method.

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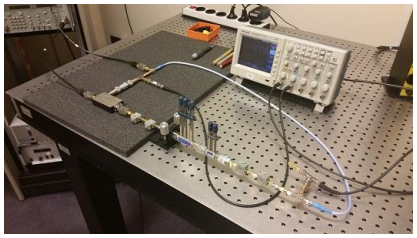
Primary standard for attenuation measurements up to 50 GHz.



A primary standard for attenuation measurements is currently being developed for operational frequency up to 50 GHz. Measurement systems will be based on the substitution method and attenuation measurements will be traceable via calibrated low frequency IVD standards.

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S-Parameter Measurements:

Traceable measurement

S-parameter metrology related research activities concentrated on realization of traceable S-parameter measurements up to 50 GHz of devices with precision coaxial connectors.

Advanced calibration techniques

A new multi-line calibration technique is developed to allow inclusion of connector effects. A significant enhancement of measurement uncertainty is achieved. A number of coaxial connectors are supported, such as type-N, 3.5 mm and 2.4 mm connectors.

Measurement & Uncertainty Software

Advanced S-parameter measurement and uncertainty software is developed.

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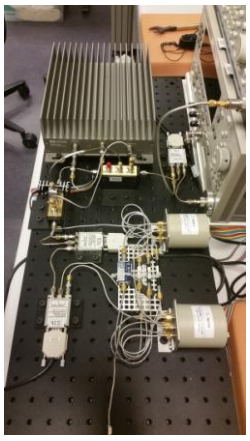

Power measurements:

A power sensor calibration facility

A fully automated power sensor calibration facility has been developed. The measurement method is based on the direct-comparison technique and covers frequencies from 1 kHz to 50 GHz in a single sweep. The measurement facility is supported by advanced measurement and uncertainty software, capable of calculating the calibration factor and the corresponding uncertainty values instantaneously.

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SIB61-High Frequency Circuits

A European joint research project (JRP) dedicated towards development of traceability chain for VNA coaxial measurement up to 110 GHz and up to 1.1 THz for waveguides.

VSL is working towards improvement of airline based ripple technique used for uncertainty evaluation of a calibrated VNA. Connector effects are also considered in the proposed modified method. Detailed description of the technique and results are published.
Measurement results of connector parameters are used for calculation of connector effects. A number of different optical measurement methods are investigated for dimensional measurements of coaxial connector.

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14IND02-PlanarCal
A European joint research project (JRP) is dedicated towards development of traceability chain for planar S-parameter measurements and extension towards nanoscale devices.

The project is currently planned to start by July 2015 and is expected to be of 3 years duration.

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EM-fields

Key comparisons:

- VSL participated in the CCEM.RF-K24.F comparison on E-field measurements. The final report is published in the BIPM website in March 2013.
- VSL participates in the EURAMET.EM.RF-S27 comparison on Antenna factor for Loop Antennas. The final report is published in the BIPM website in May 2014. During the comparison, at VSL a new approach using a one-turn air-core searching coil is developed. This approach has improved the LF magnetic field calibration facility considerably. The upper frequency boundary can now be extended from 1 kHz to 100 kHz.

JRP IND60-EMC Industry
The project started on July 2013 and will last for 3 years.

VSL has characterized five transducers by using an S parameter measurement and LF measurement method. Two voltage dividers (single phase and 3-phase) and three current probes are measured. It is found that the influence resulting from the secondary side on the measurement of transfer impedance is of significant difference for low turns-ratio current probes.

The key issue is deriving the EUT and Grid impedance from measurement. A new approach to measure the grid and load impedance of converters in-situ has been developed. It is called the three-probe approach. This approach allows impedance measurements of power supplies and electric appliances without interrupting their normal operation. The measurement accuracy is guaranteed with proper Fast Fourier Transform (FFT) process to collect both amplitude and phase information in the measurement. With this proposed setup, the equivalent model consisting of both resistive and reactive components can be derived to represent the unknown grid and load impedance in 2 kHz – 150 kHz frequency range. In the frequency range of 150 kHz – 30 MHz, a two-probe approach can be applied. A paper describing the new method is accepted for ICPE Asia 2015.

The conducted immunity test-setup is realized using a bulk current inject probe. A smart meter is used as DUT for the conducted immunity test. The influences on the smart meter are determined by comparing the reading from the smart meter and from the reference meter. Although resonance will occur when the disturbance meets the resonant frequency for the combination of an inductive source and a capacitive load, such resonance has no obvious effect on the smart meter. The injected disturbance is injected in the 2 kHz - 150 kHz range.

VSL designed a conducted emission reference source for round-robin tests. A digital synthesizer is used to provide flexible output level. The phases of all frequency components are adjusted to achieve the lowest crest factor of the waveform. For frequency band above 30 MHz, a crystal oscillator + Schmitter trigger + coupling capacitor/RF transformer method is adopted.

The output signal is compared with an AC standard. Non-linearity and frequency flatness have been measured. A paper, presented at the IEEE EMC 2014 Conference, raised good interest.

Project website: www.emc-industry.com

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Participation in comparisons

- CCEM.RF-K5c comparison on S-parameter measurements in coaxial 3.5 mm connectors. The VSL measurement results are submitted.
- CCEM.RF-K24.F comparison on E-field measurements. The final report is published on the BIPM website in March 2013.
- CCEM-K2.2012, Comparison of resistance standards at 10 MΩ and 1 GΩ. VSL measurements performed June – July 2014.
- EURAMET.EM-K12, AC/DC current transfer. VSL measurement results have been submitted to the coordinator.
- EURAMET.EM-S31, Comparison of capacitance (at 10 pF and 100 pF) and capacitance ratio, draft A circulated to the participants in 2012.
- EURAMET.EM-S32, Comparison of resistance standards at 1 TΩ and 100 TΩ. Final report available, see list of publications (B. Jeckelmann et al., Metrologia, 2013)
- EURAMET.EM-S35, Comparison of High-Current Ratio Standard. VSL measurements Feb – Mar 2013.
- EURAMET.EM.RF-S27: Antenna factor for loop antennas. Final report available, see list of publications (F. Pythoud et al., Metrologia, 2014)

List of publications

[1] G. Rietveld, "*Vibrating reed electrometer with attocoulomb charge resolution and sub-attoampere current resolution*", IEEE Transactions on Instrumentation and Measurement **62**, pp. 192 – 198 (2013).

[2] Gert Rietveld, Jan H. N. van der Beek, Marlin Kraft, Randolph Elmquist, Alessandro Mortara, and Beat Jeckelmann, *"Low-Ohmic Resistance Comparison: Measurement Capabilities and Resistor Travelling Behavior",* IEEE Transactions on Instrumentation and Measurement **62**, pp. 1723 – 1728 (2013).

[3] E. Houtzager, G. Rietveld, and H.E. van den Brom, "*Switching Sampling Power Meter for Frequencies up to 1 MHz*", IEEE Transactions on Instrumentation and Measurement **62**, pp. 1423 – 1427 (2013).

[4] Gert Rietveld, Leendert Jol, Helko E. van den Brom, and Eddy So, "*High-Current CT Calibration Using a Sampling Current Ratio Bridge*", IEEE Transactions on Instrumentation and Measurement **62**, pp. 1693 – 1698 (2013).

[5] Gert Rietveld and Jan H. N. van der Beek, "*Automated High-Ohmic Resistance Bridge with Voltage and Current Null-detection*", IEEE Transactions on Instrumentation and Measurement **62**, pp. 1760 – 1765 (2013).

[6] Marjan Popov, Gert Rietveld, Vladimir Terzija, and Zoran Radojevic, "*An Efficient Algorithm for Fault Location on Mixed Line-Cable Transmission Corridors*", Proceedings of the 2013 International Conference on Power Systems Transients (IPST2013), Vancouver, Canada, pp. 1 – 6 (2013).

[7] Andrew J. Roscoe, Graeme M. Burt, and Gert Rietveld, "*Improving frequency and ROCOF accuracy during faults, for P class Phasor Measurement Units*", Proceedings of

the IEEE international workshop on Applied Measurements for Power Systems (AMPS), Aachen, Germany (2013).

[8] B. Jeckelmann B. et al., "*Final report on supplementary comparison EURAMET.EM-S32: Comparison of resistance standards at 1 TΩ an 100 TΩ*", Metrologia 50 Tech. Suppl. 01008, 2013.

[9] Helko van den Brom, Gert Rietveld, and Jan Paepen, "*Small current measurements for a new standard in radionuclide metrology*", Callab Magazine, issue July – Sept 2013, pp. 34 – 39 (2013)

[10] Faisal Mubarak, Gert Rietveld, Dennis Hoogenboom, and Marco Spirito, "*Characterizing Cable Flexure Effects in S-parameter Measurements*", Proceedings of the 82nd Automatic RF Techniques Group (ARFTG) conference, pp. 1 – 7, Ohio, USA (2013)

[11] Faisal Mubarak and Gert Rietveld, "*A Method for De-Embedding Cable Flexure Errors in S-parameter Measurements*", Proceedings of the 83nd Automatic RF Techniques Group (ARFTG) conference, pp. 1 – 5, Florida, USA (2014).

[12] Nick Fletcher, Gert Rietveld, James Olthoff, and Ilya Budovsky, "*Electrical Units in the New SI: Saying Goodbye to the 1990 Values*", Proceedings of the 2014 NCSLi conference, Orlando, USA, pp. 1 – 12, 2014.

[13] Gert Rietveld, Dean Jarrett, and Beat Jeckelmann, "*Accurate High-Ohmic Resistance Measurement Techniques up to 1 PΩ*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 290 – 291 (2014).

[14] Gert Rietveld, Jean-Pierre Braun, Paul S. Wright, Paul Clarkson, and Norbert Zisky, "*Smart Grid Metrology to Support Reliable Electricity Supply*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 680 – 681 (2014).

[15] E. Houtzager, H. E. van den Brom, and E. Dierikx, "*Development of a wide-range sampling impedance ratio bridge*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 230-231, (2014).

[16] E. Houtzager, G. Rietveld, J. Dessens, M. Heemskerk, and H. van den Brom, "*Design of a non-invasive current sensor for application on high voltage lines*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 624 – 625 (2014).

[17] D. Zhao, G. Rietveld, J.-P. Braun, F. Overney, T. Lippert and A. Christensen, "*Traceable measurement of the electrical parameters of solid-state lighting products*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 650 – 651 (2014).

[18] P.S. Wright, J.P. Braun, G. Rietveld, H.E. van den Brom, and G. Crotti, "*Smart Grid Power Quality and Stability Measurements in Europe*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 70 – 71 (2014).

[19] Nick Fletcher, Gert Rietveld, James Olthoff, and Ilya Budovsky, "*Predicted impact of latest h and e values on resistance and voltage traceability in the new SI (Système International)*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 432 – 433 (2014).

[20] Gert Rietveld, Martin Fransen, Nicolas Blanc, Ernest Houtzager, and Eddy So, "*A Reference System for On-Site Calibration of High-Voltage Revenue Metering Systems*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 404 – 405 (2014).

[21] Helko E. van den Brom, Gert Rietveld, and Eddy So, "*Sampling Current Ratio Bridge for Calibration of Current Transducers up to 10 kA with 5 ppm Uncertainty*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 8 – 9 (2014).

[22] Gert Rietveld, Jan van der Beek, and Ernest Houtzager, "*Accurate High-Current DC Current Ratio Measurements*", Proceedings of the 2014 Conference on Precision Electromagnetic Measurements (CPEM 2014), Rio de Janeiro, Brasil, pp. 610 – 611 (2014).

[23] Frédéric Pythoud et al,"*Final report on EURAMET supplementary comparison EURAMET.EM.RF-S27: Antenna factor for loop antennas*", Metrologia, vol. 51, Tech. Suppl., 01007, 2014.

[24] Nick Fletcher, Gert Rietveld, James Olthoff, and Ilya Budovsky, "*Electrical Units in the New SI: Saying Goodbye to the 1990 Values*", NCSLi Measure J. Meas. Sci., Vol. **9**, no. 3, pp. 34 – 39 (2014).

[25] Faisal Mubarak and Gert Rietveld, "*Residual Error Analysis of a Calibrated Vector Network Analyzer*", Proceedings of the 84st Automatic RF Techniques Group (ARFTG) conference, pp. 1 – 6, Colorado, USA (2014).