Progress report on Electrical Metrology at VSL (2017 – 2019)

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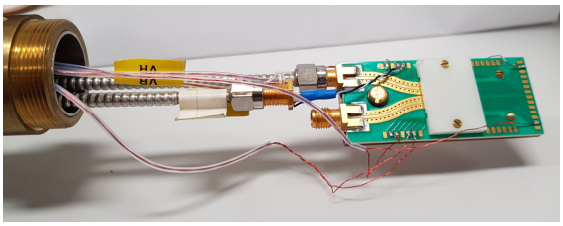
Subfield DC and LF

AC Josephson

Within the JRP "QuADC" (started in 2016) VSL is working on the practical and theoretical aspects of quantum waveform metrology, including generation of arbitrary Josephson signals, the deviation problem of voltage leads at higher frequencies, a Josephson delta-sigma converter, voltage scaling and uncertainty calculations. The work has focused on the problem of measuring AC voltages up to 1 MHz, for which the length of the voltage leads in the cryoprobe is the major problem for obtaining low uncertainties. Impedance matching was proposed as a new solution and the practical details have been simulated, showing that uncertainties on the order of 10 ppm are within reach for frequencies up to 1 MHz [1]. Simulations have been performed using a simplified procedure as well; presently the theoretical predictions are being verified in real measurements, using an extra 50 Ω termination resistance close to the array and measuring the AC voltage using a semirigid coaxial cable.



Furthermore, work has been performed on the electronics for a Josephson delta-sigma converter [2].

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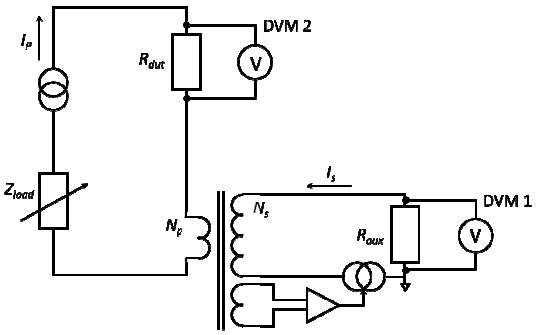
DC current sensors with distorted signals

Within the MyRailS project (started in 2017), to assess the reliability of DC energy measurement equipment on board trains, a setup was developed to characterize DC current transducers under distorted operating conditions **Error! Reference source not found.**,[4]. The operating principle is based on a current ratio measurement technique. The reference sensor is a high-precision zero-flux current transducer in combination with a broadband high-precision current shunt. The influence of AC distortion on this reference sensor was found to be within a few parts in 10^6 using an initial version of the setup, in which AC distortion was applied through a separate winding.



A revised version of the setup employs a programmable electronic load to apply dynamic currents up to 600 A. The setup was used to characterize the dissipative heating, the intrinsic current dependence and the effect of AC distortion for a 100 μΩ high-current shunt

resistor [5], among others by exposing it to a dynamic current profile that was recorded during a trip between two successive underground train stations of Metro de Madrid.
Future work will concentrate on even more demanding current signals, such as chopped signals, and on other types of sensors and measurement systems. The results have been presented at CPEM 2018 **Error! Reference source not found.** and ESARS-ITEC 2018 [5] and published in IEEE TIM [4].

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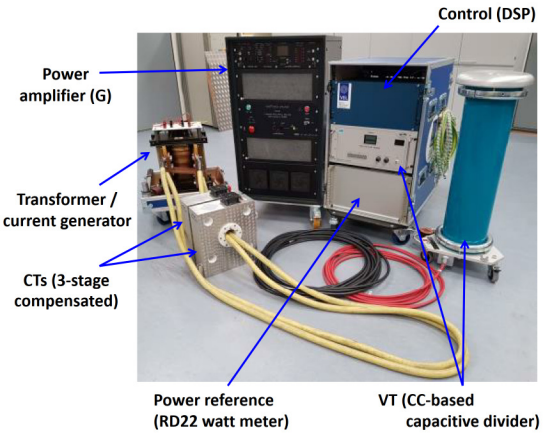
Transformer Load Loss

Within the EMPIR JRP ELPOW (finished in 2018) and its successor TrafoLoss (started in 2018), significant progress has been made in the realisation of a setup for on-site system calibration of commercial Power Transformer Loss Measurement Systems (TLMS). The VSL reference system is extensively described in a paper presented at the ISH 2017 conference [6].



In December 2017, the complete setup was shipped to PTB for a direct bilateral comparison between PTB and VSL. The results of this comparison showed an agreement of better than 20 µW/VA in amplitude and 20 µrad in phase. This results, presented at CPEM 2018 and published in IEEE TIM [6],[8], underpin the new CMC of VSL for this measurand and show that the goal defined in the ELPOW project has been reached.

The 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, has been further improved. Under most actual on-site conditions, a noise in the measurements of better than 10 µW/VA (10 µrad) can be achieved. Present work concentrates on the signal-to-noise ratio when applying low test current signals, which presently increases the noise level up to 20 - 30 µW/VA. Furthermore, the effect of non-sinusoidal test signals on the accuracy of the calibration is being studied.

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Static electricity meters

Following initial studies showing that conducted electromagnetic interference (EMI) can lead to large error readings of static electricity meters, VSL performed a thorough verification study confirming that wideband currents produced by non-linear, fast-switching loads indeed can lead to significant error readings of static meters [9].

In 2018, the normative EMPIR project MeterEMI started for a more detailed investigation on this topic

[10]. Initial analysis on the waveforms together with NPL showed that dI/dt and discrete wavelet coefficients are the key parameters to be used as trigger for capturing the disturbing waveforms in real-life measurements [11]. The influence of the input impedance and the phase-firing angle of a dimmer on the error reading of a series of static electricity meters was investigated, showing some unexpected results, including a strongly non-monotonic dependence on phase for some of the meters [12]. A flexible phantom power testbed was developed for testing electricity meters with conducted EMI and arbitrary current waveforms in the frequency range up to 150 kHz, without the need for an actual load [13].

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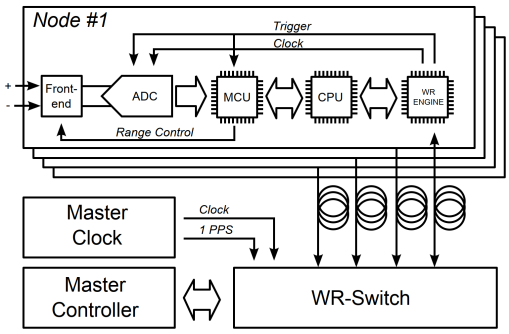
Synchronized distributed digitizers

Within the context of the Future Grids II EMPIR project (started 2018), VSL has developed prototype 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 presented at the CPEM2018 conference [14] and published in IEEE TIM [15].



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Phasor measurement units (PMUs)

The VSL PMU calibration setup has been extensively characterised and the results of this characterisation have been presented at the PowerTech 2017 conference [16]. Present work concentrates on the automation of the VSL PMU calibration setup.

Within the EMPIR JRP Smart Grid II (finished in 2017), an algorithm has been developed by IMBIH and VSL for accurate determination of electricity grid overhead line impedances using synchrophasor data obtained by PMUs located at the two ends of the overhead line [17]. The algorithm was subsequently refined and applied using actual PMU measurements in electricity grids [18].

In the EMPIR JRP ROCOF (started 2016), the importance of rate of change of frequency (RoCoF) measurements in electrical power grids is 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 [19-21]. 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 [22].

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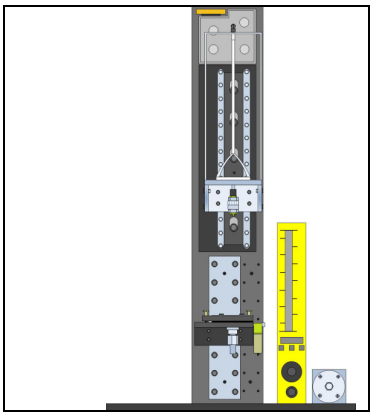
Subfield RF&MW

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 entire length of the line section with minimum step size resolution of 10 µm. The system is suitable for characterization of transmission lines with nominal 2.4 mm, 2.92 mm, 3.5 mm and 7 mm diameters.

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Primary standard for attenuation measurements up to 50 GHz

A primary standard for attenuation measurements is currently under development. The system is suitable for frequencies from 1 MHz up to 50 GHz. The attenuation measurements are based on the IF-substitution method and are traceable through calibrated low frequency IVD standards. The system is currently validated for frequencies up to 18 GHz and is expected to be extended up to 50 GHz.

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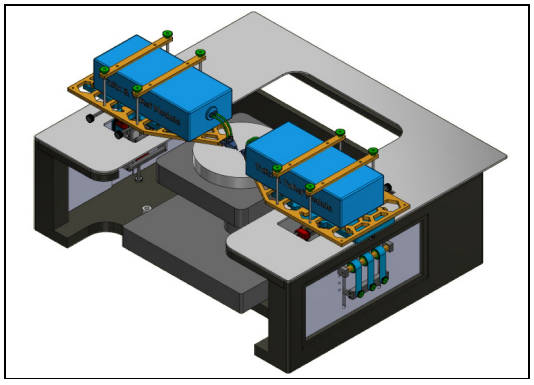
Scattering parameters measurement



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.

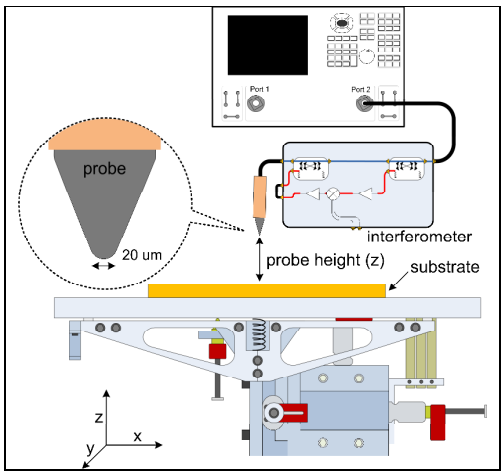
Probing-station for nm-size device characterization

VSL has designed and manufactured a state-of-the-art probing-station suitable for DC-THz measurements of electrical properties of sub-micron devices. The system allows characterization of 1- and 2-port devices.

In framework of TEMMT project, VSL will jointly extended traceable planar S-parameter measurements to 1 THz barrier. VSL will develop fully automated probe planarization and contacting methods to realize accurate device contacting in the THz domain.

Scanning Microwave Microscope (SMM)

VSL has designed and manufactured a scanning microwave microscope (SMM) system suitable for measurement of electrical properties of planar devices and materials. The systems is fully automated with advanced measurement software designed in MATLAB environment.



RF-interferometer for low-noise measurements

VSL has developed measurement and calibration techniques to support ultra low-noise VNA measurements in conjunction with RF-interferometers. To preserve true broadband measurement capability of a VNA, advanced measurement software is designed in MATLAB environment.

In framework of PlanarCal project (14IND02), VSL extended low-noise S-parameter measurements to highly mismatched nano-scale devices. VSL and Delft University of Technology have developed a broadband interferometer-based VNA measurement system suitable for highly mismatched measurements.

VNA measurement & uncertainty software

VSL is extending the VNA S-parameter measurement capability with advanced measurement software. The measurement software is suitable for extraction of uncorrected measurement data from the VNA and included range of calibration techniques. The software includes automated algorithms for assessment of VNA uncertainty contributions and subsequently automatically calculates total measurement uncertainty.

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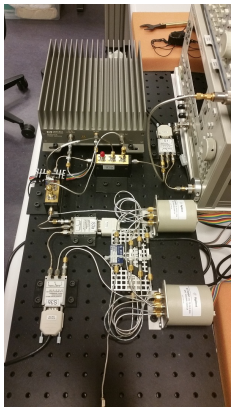
Power measurements

The tradional power sensor calibration facility has been upgraded and is now fully automated. The measurement method is based on the direct-comparison technique and covers frequencies up to 50 GHz in a single sweep. The measurement system is supported by advanced measurement and uncertainty calculation software, capable of calculating the calibration factor and the corresponding uncertainty values instantaneously during the measurement.



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Subfield EM-fields

EM-fields facilities have been stopped at VSL.

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Participation in comparisons

- CCEM-K2.2012, Comparison of resistance standards at 10 MΩ and 1 GΩ. VSL measurements performed in 2014. Draft A report received.
- EURAMET.EM-S35, Comparison of High-DC Current Ratio Standard. VSL measurements Feb – Mar 2013. Draft A report received.
- EURAMET.EM-S37, Comparison of AC current ratio. VSL measurements performed in 2014. Draft B report received.
- CCEM.EM-K5.2017, Comparison on LF power. VSL measurements performed in 2018.
- EURAMET.EM-K5.2018, Comparison on LF power. VSL measurements expected in 2019. 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] Dongsheng Zhao, Helko E. van den Brom and Ernest Houtzager, “Mitigating Voltage Lead Errors of an AC Josephson Voltage Standard by Impedance Matching”, Meas. Sci. Technol. 28, 095004 (11pp), 2017, https://doi.org/10.1088/1361-6501/aa7aba.

[2] Jane Ireland, Jonathan Williams, Oliver Kieler, Ralf Behr, Ernest Houtzager, Ralph Hornecker, and Helko E. van den Brom, “An optoelectronic pulse drive for quantum voltage synthesizer”, Conference on Precision Electromagnetic Measurements, Paris, France, 8-13 July 2018.

[3] Helko E. van den Brom, Ronald van Leeuwen, and Ralph Hornecker, “Characterization of a reference DC current transducer with AC distortion for railway applications”, Conference on Precision Electromagnetic Measurements, Paris, France, 8-13 July 2018.

[4] Helko E. van den Brom, Ronald van Leeuwen, and Ralph Hornecker, “Characterization of DC current sensors with AC distortion for railway applications”, IEEE Trans. Instrum. Meas., 2019 (early access), DOI 10.1109/TIM.2019.2898014.

[5] Helko E. van den Brom, Ronald van Leeuwen, and Ralph Hornecker, “Characterization of DC current sensors under distorted conditions for railway applications”, Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS) & International Transportation Electrification Conference (ITEC), Nottingham, UK, 7-9 November 2018.

[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, D. Hoogenboom, H. Khalilnezhad, Comparison of two Reference Setups for Calibration of Power Transformer Loss Measurement Systems, Conference on Precision Electromagnetic Measurements, Paris,

France, 8-13 July 2018, DOI: 10.1109/CPEM.2018.8501248.

[8] G. Rietveld, E. Mohns, E. Houtzager, H. Badura, D. Hoogenboom, “Comparison of two Reference Setups for Calibrating Power Transformer Loss Measurement Systems”, IEEE Transactions on Instrumentation and Measurement (2019) (early access), DOI: 10.1109/TIM.2018.2879171.

[9] G. Rietveld, D. Hoogenboom and M. Acanski, “Conducted EMI causing error readings of static electricity meters”, Conference on Precision Electromagnetic Measurements, Paris, France, 8-13 July 2018.

[10] P.S. Wright, G. Rietveld, F. Leferink, H.E. van den Brom, F.R.I Alonso, J.P. Braun, K. Ellingsberg, M. Pous and M. Svoboda, “Evaluation of EMI Effects on Static Electricity Meters”, Conference on Precision Electromagnetic Measurements, Paris, France, 8-13 July 2018.

[11] Fani Barakou, Paul Wright, Helko van den Brom, Gertjan Kok, and Gert Rietveld, “Detection Methods for Current Signals Causing Errors in Static Electricity Meters”, submitted to EMC Europe 2019, Barcelona, Spain.

[12] Zander Marais, Helko van den Brom, Gert Rietveld, Ronald van Leeuwen, Dennis Hoogenboom, and Johan Rens, “Sensitivity of static energy meter reading errors to changes in non-sinusoidal load conditions”, submitted to EMC Europe 2019, Barcelona, Spain.

[13] Helko van den Brom, Zander Marais, Dennis Hoogenboom, Ronald van Leeuwen, and Gert Rietveld, “A Testbed for Static Electricity Meter Testing with Conducted EMI”, submitted to EMC Europe 2019, Barcelona, Spain.

[14] E. Houtzager, R. Hornecker, and G. Rietveld, “Compact distributed digitizers with metrological precision”, Conference on Precision Electromagnetic Measurements, Paris, France, 8-13 July 2018.

[15] E. Houtzager, R. Hornecker, and G. Rietveld, “Compact distributed digitizers with metrological precision”, IEEE Transactions on Instrumentation and Measurement (2019) (early access). DOI: 10.1109/TIM.2018.2878090

[16] Daniele Colangelo, Dennis Hoogenboom, Erik Dierikx, Gert Rietveld, and Guglielmo Frigo, “Metrological Characterization of a PMU calibrator in the 25 Hz to 3 kHz Range”, Proceedings of the PowerTech 2017 conference, Manchester, UK, pp. 1 – 6 (2017). DOI: 10.1109/PTC.2017.7981109

[17] Vladimir Milojevic, Srdan Calija, Gert Rietveld, Milos Acanski, and Daniele Colangelo, "A Robust Synchrophasor-Based Method for Determining Three-Phase Line Impedance", Proceedings of the IEEE international workshop on Applied Measurements for Power Systems (AMPS), Liverpool, UK, pp. 1 - 6 (2017). DOI: 10.1109/AMPS.2017.8078340

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"Field Testing of ROCOF Algorithms in Multiple Locations on Bornholm Island", Proceedings of the 2018 Conference on Precision Electromagnetic Measurements (CPEM 2018), Paris, France, pp. 1 - 2 (2018). DOI: 10.1109/CPEM.2018.8500805

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[22] Gert Rietveld, Paul Wright, Andrew Roscoe and Kevin Johnstone, “Reliable rate of change of frequency (ROCOF) measurements: use cases, operational parameters and test conditions”, Proceedings of the 2019 CIRED conference, Madrid (2019).

[23] Faisal Ali Mubarak and Gert Rietveld, “Uncertainty evaluation of calibrated Vector Network Analyzers,” IEEE Transactions on Microwave Theory and Techniques, 66, No. 2, pp. 1108 – 1120 (2018). DOI: 10.1109/TMTT.2017.2756881

[24] F. Mubarak, V. Mascolo, G. Rietveld, M. Spirito, K. Daffe and K. Haddadi, "Parameterization Models for Traceable Characterization of Planar CPW SOL calibration Standards", Proceedings of the 2018 Conference on Precision Electromagnetic Measurements (CPEM 2018), Paris, France, pp. 1 - 2 (2018). DOI: 10.1109/CPEM.2018.8500810

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[26] K. Daffe, F. Mubarak, V. Mascolo, H. Votsi, N. M. Ridler, G. Dambrine, I. Roch, K. Haddadi, "On-Wafer Broadband Microwave Measurement of High Impedance Devices-CPW Test Structures with Integrated Metallic Nano-Resistances," 2018 48th European Microwave Conference (EuMC), Madrid, 2018, pp. 25-28. doi: 10.23919/EuMC.2018.8541607

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