Progress report on Electrical Metrology at VSL (2021 – 2023)

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Subfield DC and LF

AC Josephson

After finishing the EMPIR project QuADC in 2019 the VSL system was upgraded by means of a 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 the use of an FIR filter to improve the pulse amplitudes to be more equal and equalizers to improve the effect of distortions caused by the cables. The possibility to go cryogen free is being investigated as well as investing in a new pulse generator.

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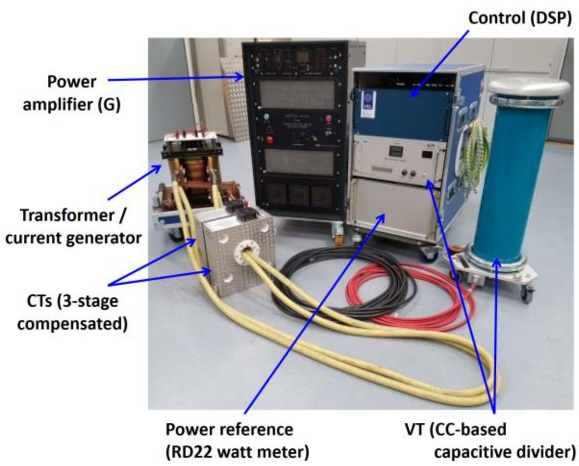
Transformer Load Loss

Within the EMPIR TrafoLoss project (completed in 2021), a setup for on-site system calibration of commercial Power Transformer Loss Measurement Systems (TLMS) has been realised. Major improvements have been made 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. To confirm this uncertainty, VSL has participated in the CCEM-K5 and EURAMET-K5 comparisons.

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. The final agreement of the two methods is better than 6 μrad for voltages up to 100 kV and has been published in a IEEE TIM paper. 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 have underpinned the improved CMC of VSL for on-site TLMS calibrations.

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.

The new setup has been extensively used for on-site calibrations at customer sites in Europe. Furthermore, a cooperation was started with NIM (China), KRISS (Korea) and a commercial calibration company to realise similar setups at their institutes / company.

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. This finding is subject of further studies.

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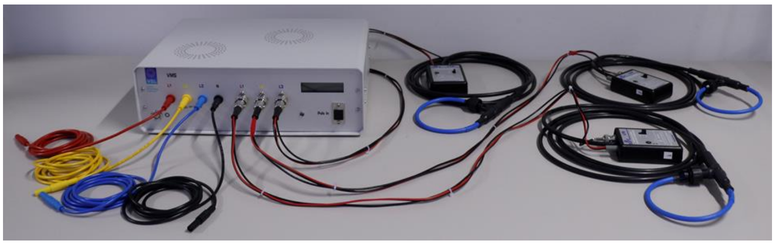
Static electricity meters

Within the context of the EMPIR project MeterEMI, which ended mid-2021, a flexible phantom power testbed was developed at VSL for the testing of electricity meters with arbitrary current and voltage waveform distortions in the frequency range up to 150 kHz. Furthermore, A home-built waveform recorder with a specific trigger mechanism was developed for onsite applications or as a benchmark electricity meter in case of metering disputes.



The testbed has been used to test a large series of different electricity meters in the Netherlands. So far, the test waveforms were recorded in the laboratory when testing isolated household appliances. In a new study, performed in collaboration with the University of Twente, UPC, and JV and published in IEEE TEMC, 16 different meters from all over Europe were exposed to real-world disturbance signals as measured at various European metered supply points. The results show that also real-world waveforms can cause measurement errors as large as several hundred percent, even for meters that pass the present EMC standards. Furthermore, to enable the adoption of potential new test waveforms in future standards for electricity meter testing, artificial test waveforms were constructed based on real-world waveforms using a piece-wise linear model. These artificial test waveforms were demonstrated to cause meter errors similar to those caused by the original real-life waveforms they are representing, showing that they are suitable candidates for use in improved standardization of electricity meter testing. Alternative artificial waveforms based on wavelets were suggested together with NPL and the University of Twente.

Discussions with Cenelec TC13 WG1 on suitable test waveforms for improved electricity meter testing are still ongoing.

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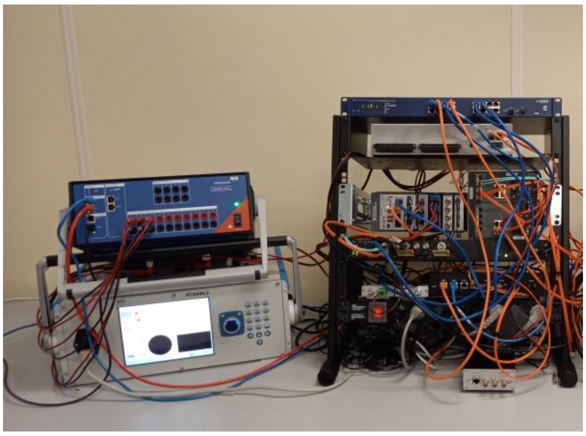
Reference systems for calibration of SV-enabled instrumentation



Within the context of the Future Grids II EMPIR project (started 2018), VSL has developed 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). A complete setup is made which enables the comparison of SAMUs and other IEC-61850-9 enabled equipment with the reference SAMU. Within the current Digital-IT project, that started in 2021, the bandwith of the setup will be improved enabeling charaterization of SAMUs following the IEC 61869-13.

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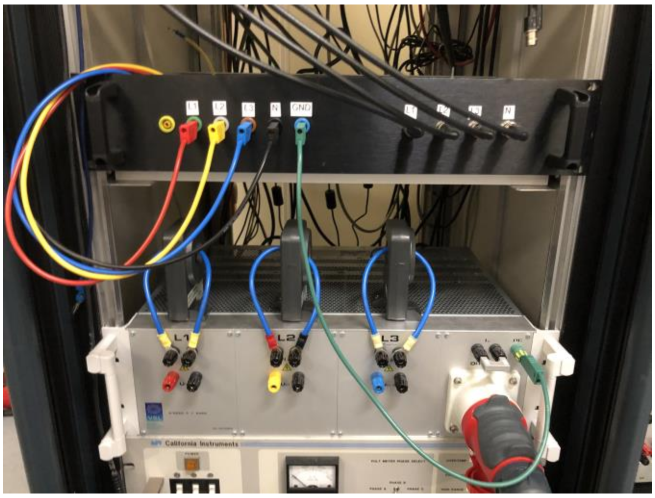
Grid measurements of 2 kHz -150 kHz harmonics



In the context of the EMPIR project SupraEMI, which ended 2022, a laboratory reference setup was developed and an existing portable waveform recorder was modified for detecting signals in the supraharmonic frequency range (2 kHz – 150 kHz). This system uses a new method for assessing supraharmonic emission levels developed in the project by UPV/EHU, NPL, and TU Dresden as a compromise between the existing methods of IEC 61000-4-7 and CISPR 16-2-1. Measurements obtained on-site and in a laboratory environment were compared.

A comparison was performed with LNE to compare the new measurement method with the CISPR quasi-peak method by measuring the emissions of various household appliances. The results show that the two methods are in good agreement for the main emission peaks, considering the reproducibility of the appliances' emissions, the different network impedances, and the measurement uncertainties. In collaboration with NPL, TU Dresden, LNE, and UPV/EHU, the results are compared to the existing compatibility levels to provide an indication of expected supraharmonic disturbance levels in low-voltage networks.

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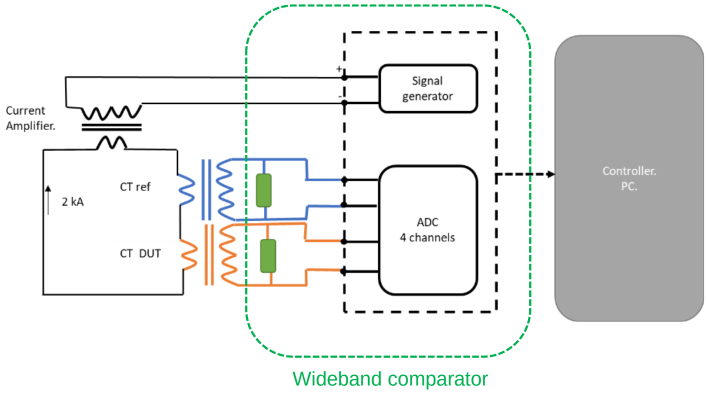
Instrument transformers for PQ measurements

Within the EMPIR project IT4PQ, which will end in 2023, VSL has been involved in the definition of power quality (PQ) parameters and test conditions relevant for testing instrument transformers (ITs) used for PQ measurements, based on a review of literature and standards with INRIM and University of Campania. Further work on the definition of performance indicators, supported by measurements of, among others, INRIM and PTB, has led to a proposal for accuracy testing of ITs for PQ.

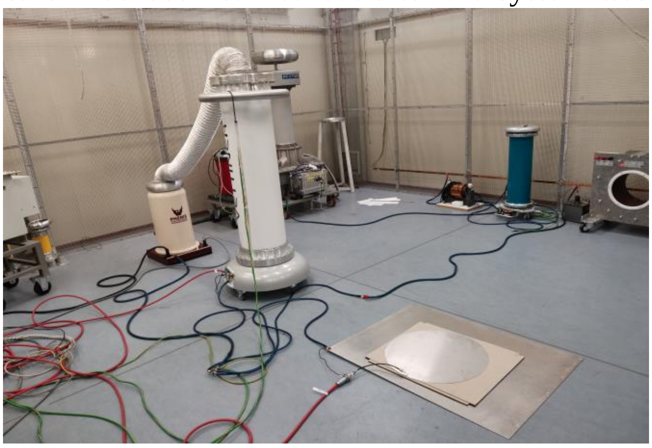


The work of VSL in this project was focused on the development of a broadband comparator for industrial and/or on-site IT characterization up to 9 kHz. The comparator digitizing part is based on a commercial precision power analyzer, with input modules up to 30 A and 1 kV and a sampling rate of up to 2 MSa/s. Software was developed to calculate the performance indicators, in particular the ratio of harmonics. Preliminary tests have been performed to assess its accuracy performance when it is used to acquire dual-tone current waveforms; the measured deviations are lower than 50 µA/A up to 10 kHz. An onsite demonstration using the comparator for industrial applications of CTs and VTs is planned.

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

Improved HV testing (LI and AC HV)

In the EMPIR JRP FutureEnergy (started in June 2020), VSL has established a 1200 kV lightning impulse (LI) reference measuring system. The reference system was built based on a reference divider from NIM and a digitizer system from RISE. The whole system had been calibrated by RISE in 2021, and further research had been carried out after the system was setup at VSL in 2022. The temperature coefficient of the divider, the attenuator, the terminator, and the digitizer were checked to minimize the influence of temperature change on the measurement result. Currently, the power supply and grounding systems are being studied to enhance the anti-interference ability from environment noise. The VSL reference system has been used as the reference to tune and calibrate the Haefely 4000 kV damped capacitive LI divider of the TU Delft. This calibration was an important basis for the major measurement campaign carried out in October 2022, and more than 8 leading LI systems from RISE, VTT, PTB, NIM, Haefely, TAU, TUD, and VSL were brought to the TU Delft premises for intercomparison at voltages between 400 kV and 3000 kV. A peer-reviewed paper has been submitted to the 23rd International Symposium on High Voltage Engineering (ISH 2023) to present the comparison results. The comparison results are also a good support for VSL to apply for new CMCs for LI.



A second line of research in the FutureEnergy project is the 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.

VSL has developed the field sensor based on the double-sided PCB (Printed Circuit Board). The uncertainty, which has been measured against the VSL voltage divider, is within 40 ppm, which corresponds to the results of project partner VTT (Finland). This is much more accurate than the needs of the industry. Currently, the sensor is being made more mechanically robust. A final test will be carried out with the final design of the sensor. This is expected to be finished in the first half of 2023.

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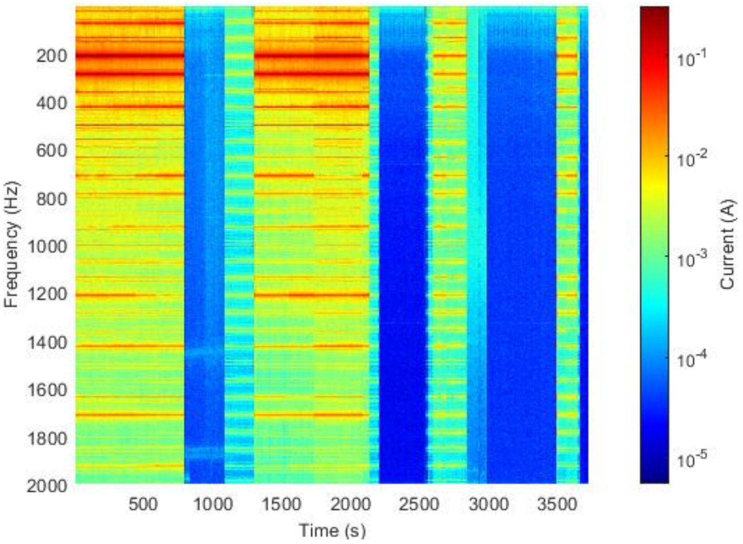
PQ and electricity metering for LV DC grids

Mid-2022 a new project coordinated by VSL was started on standardization of measurements for DC electricity grids, with a focus on the definition of PQ parameters for DC, reference systems for these parameters, and DC electricity metering in the presence of distortions. Within the context of this project, a reference system was developed for DC electricity meter testing in the presence of broadband disturbances. Preliminary characterization shows that the system is robust against distortions with amplitudes up to 20 % and frequencies up to 100 kHz for voltage and current levels up to 100 V and 10 A, respectively. The setup will be upgraded to higher voltage and current levels and be used as a reference for upcoming DC PQ parameters.



A broadband DC waveform recorder was developed for on-site measurement campaigns in low-voltage (LV) DC grids. The device was used for measurement campaigns in Lelystad Airport Business Park with mostly streetlights connected and an urban DC microgrid in Delft with solar panels that could be operated in island mode or grid-connected mode. Apart from ripple and specific frequency content, also transients and voltage fluctuations were registered. The measurement results can be used by project partners to develop DC PQ analysis tools and by grid operators and surveyance authorities for compatibility level surveys.

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Subfield RF&MW

S-parameter measurements

S-parameter measurements related activities at VSL concentrate on realization of state-of-the-art measurement accuracy for frequencies from 9 kHz up to 50 GHz of connectorized and planar (on-wafer) devices.

Traceable on-wafer measurements

VSL is in progress to realise traceable on-wafer measurements and includes the development of a reference calibration substrate designed for traceability. Furthermore, the measurement facility is supported by VSL FAME S-parameter measurement and uncertainty calculation software.

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Traceable active device measurements

A measurement system for large-signal active device measurements is currently being developed at VSL and includes the development of active tuners for broadband frequency coverage and automation. The measurement facility is supported by FAME VNA software.

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Autonomous RF probing software for on-wafer measurements

VSL is working towards developing autonomous RF probing software for traceable and accurate on-wafer measurements. Furthermore, it includes automated various necessary alignments and contacting the on-wafer device. The alignment methods are embedded in FAME VNA software by VSL.

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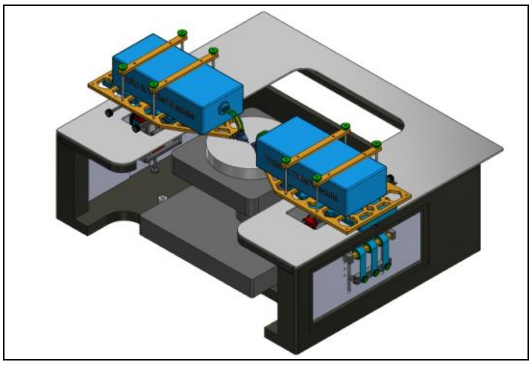
Probing-station for µm-size device characterization

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 the 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.

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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 covariance based uncertainty propagation techniques for accurate uncertainty calculations. Furthermore, the software supports connectorized and on-wafer calibrations.

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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.

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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.

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Participation in comparisons

- 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.
- EURAMET.EM-S46 Supplementary Comparison - High voltage comparison of DC ratio
- EURAMET.EM-S47 Supplementary Comparison - High voltage comparison of high resistance
- CCEM.RF-K5c comparison on S-parameter measurements in coaxial 3.5 mm connectors. The VSL measurement results are submitted.

List of publications

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[8] H.E. van den Brom, R. van Leeuwen, G. Ye, D. Hoogenboom, G. Rietveld, D. Istrate, K. Kasri, A. Gallarreta, and D. de la Vega, "A comparison of the Light-QP method for (2 to 150) kHz emission measurements with the CISPR 16-1-1 method", CPEM 2022, Wellington, New Zealand

[9] S. Lodetti, P.N. Davis, D. Ritzmann, P.S. Wright, V. Khokhlov, J. Meyer, D. Istrate, H. van den Brom, R. van Leeuwen, A. Gallarreta, and D. de la Vega, "Comparison of household appliances voltage emissions to compatibility levels in the 2 kHz to 150 kHz range", CPEM 2022, Wellington, New Zealand

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[13] Helko van den Brom, Julio Melero, Vladimir Cuk, Guglielmo Frigo, Daniele Gallo, Daniela Istrate, Domenico Giordano, Michael Blaz, Brian Stewart, and Xavier Yang, “Traceable Power Quality Measurements in DC Electricity Grids”, CPEM 2022, Wellington, New Zealand

[14] E. Houtzager and G. Rietveld, “Calibration of a precision IVD using a commercial digitizer”, 2022 Conference Precision Electromagnetic Measurements (CPEM), Wellington, New Zealand, pp. 1 – 2 (2022).

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