Progress report on Electrical Metrology at VSL (2023 – 2025)

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Subfield DC and LF

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 ADC 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 a reference SAMU.

Within the current Digital-IT project, that started in 2021, the bandwith of the setup has been improved, by replacing the SAMU from the future grid project with a commercial powermeter, enabeling charaterization of SAMUs following the IEC 61869-13. Extensive characterization of the delays with respect tot PTP have been done on the commercial power meter.

The setup consists of a three-phase generator capable of generating arbitrary voltage and current signals. A grandmaster PTP clock with PRP enabled switched are used to synchronise the setup These signals are supplied to both the reference meter and the mergingunit under test. Various tools have been developed to extract the relevant information from the IEC 61850 streams.

On the side of this project two digital-input energy meters have been characterised. A paper about the performance was published at the CPEM 2024 [24].

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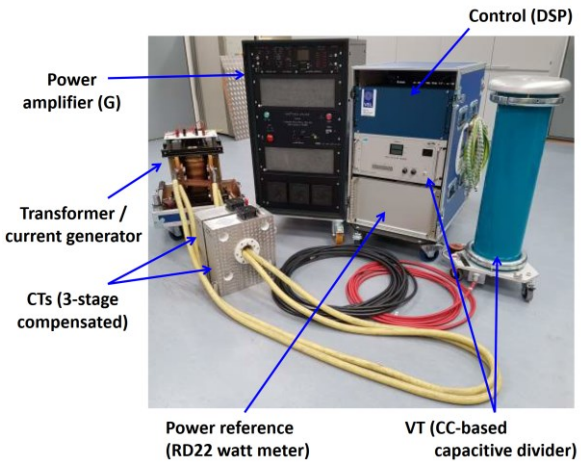
Transformer Load Loss

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.

Within the follow-up EPM project ENSURE (started June 2024), VSL will extend the bandwidth of the reference load loss setup to at least 2 kHz for the determination of the impact of grid harmonics on power transformer losses with a target uncertainty of better than 1 % of the loss power. A literature study has been performed, and further discussions with the transformer manufacturers and grid operators are planned. Calibration on an active high voltage divider unit with a high voltage capacitive bridge (HVCB) is studied up to 2 kHz, which is the key component for loss measurement system at a wideband frequency range.



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Improved HV testing (LI and AC HV)

In the EMPIR JRP FutureEnergy (started in June 2020), VSL 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 was calibrated by RISE in 2021, and further research was carried out at VSL in 2022 to minimize the influence of temperature change and environmental noise. The VSL reference system was then 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. Several peer-reviewed papers have been submitted to the ISH 2023 and the CPEM 2024 to present the research works and comparison results. VSL had its CMCs in the BIPM KCDB approved for LI in 2023.

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.

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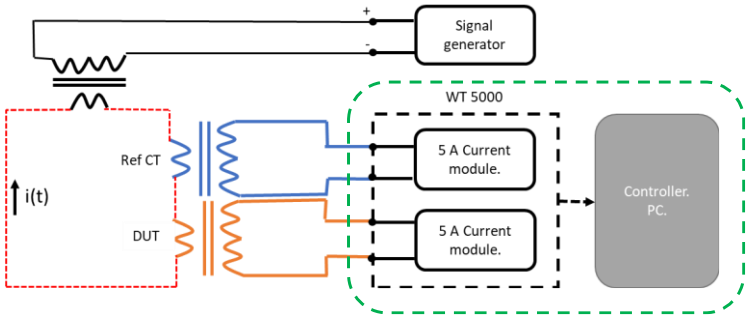
Instrument transformers for PQ measurements

Within the context of the EMPIR project IT4PQ, that ended mid-2023 [6][7], VSL has developed and demonstrated a reference system for the calibration CTs or VTs used for PQ signals up to 5 kHz based on a precision power analyser as comparator [8].



In the follow-up EPM project ADMIT, which started in 2023, VSL has been involved in a review of literature and standards for testing instrument transformers (ITs) used for broadband PQ measurements [9]. Further work of VSL in this project focused on the development of a broadband generator for distortion currents for CT calibration extending the IT4PQ work. So far, for single-tone signals up to 14 A at 150 kHz have been demonstrated and used for initial testing.

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PQ and electricity metering for LV DC grids

Mid-2024, the EPM project DC grids, coordinated by VSL, was completed with the organisation of a workshop with over 135 participants. Within the context of this project, VSL developed a reference system for DC power quality and for DC electricity meter testing for signals up to 2 kV and 900 A in the presence of broadband disturbances up to 150 kHz. The setup was validated by a DC PQ comparison between VSL and METAS for sinusoidal and triangular ripple and a comparison between VSL, METAS and INRIM for DC power in the presence of distortion [10].

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, an urban DC microgrid in the Green Village in Delft [11], and a parking garage in Utrecht [12]. Apart from ripple and specific frequency content, also transients and voltage fluctuations were registered. The measurement results have been used in collaboration with the

University of Campania to develop further analysis tools aiming to support grid operators and surveyance authorities for compatibility level surveys [13].

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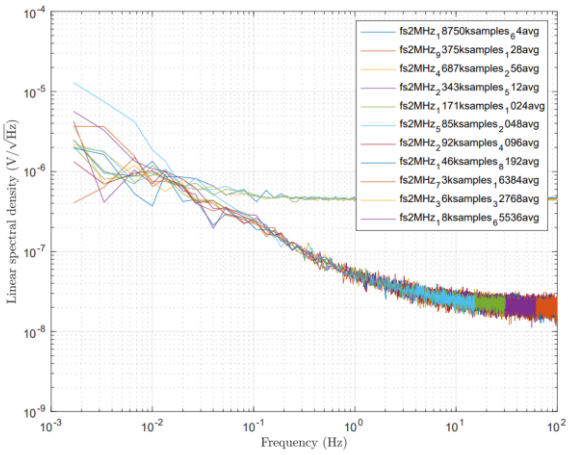
True 8-digit

In 2022 the EPM project True8Digit started. This project aims at collecting ideas on how to improve the resolution and accuracy of digitizers and perhaps to surpass the unprecedented accuracy and resolution of the HP3458a. In a follow-up project together with a partner this might lead to a new metrology class digitizer.



VSL is involved in both the design of the front-end module as well as the timing distribution and a low noise power supply.

Some commercial high isolation power supplies have been characterized and found suitable for this project. Some effort is put into the design of a dual battery supply. Since that will ultimately have the best isolation and lowest noise. For the timing VSL focuses more on the long-distance timing, while others in the project focus more on the board timing.
Some results of a newly developed ADC board show promising results in reaching the goal of true 8 digit resolution.

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Efficiency measurement of power converters used in DC transport systems

Within the EPM project e-TRENY (started June 2023), VSL has been involved with developing, calibrating and applying **on-site setups and algorithms** for the measurement of the energy losses of **non-conventional AC/DC substations** with an overall on-site target uncertainty of 10 % of losses. The Energy Efficiency Measurement System (EEMS) had been designed for AC/AC transformer, AC/DC rectifier and DC/DC energy storage system. The components of the EEMSs had been selected and purchased and are currently under calibration. The on-site campaign was planned to be performed in May 2025, and then further data analysis will be performed.

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Electric vehicle charging systems

The EPM project Met4EVCS, which is being coordinated by VSL, started in mid-2024. The project focuses on the development of metrology capabilities for the traceable evaluation of EVCSs under realistic operating conditions. In this project VSL concentrates on performing onsite measurements at DC and AC charging systems, using the experience obtained in the DC grids project and the MeterEMI project. For this purpose, a breakout box and dedicated measurement equipment is under development.

Furthermore, VSL helps Elaad develop a traceable testbed for EVCS under real-world conditions, i.e., in the presence of real-world conditions, with further support from University of Twente.

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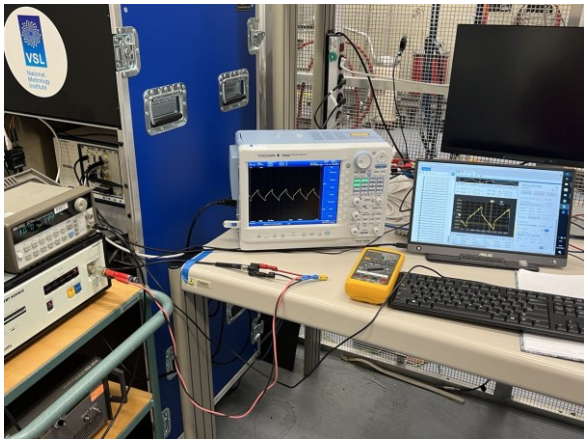
Supercapacitors



Within the EPM project MetSuperCap, which started mid-2024 [Zucca 2x], VSL started working on the development of a setup for the characterisation of supercapacitors. The setup uses the principle of galvanostatic charging and discharging to determine supercapacitor parameters such as the capacitance, series resistance, and leakage resistance. This work will support supercapacitor modelling which will be performed in collaboration with University of Twente. Furthermore, traceability will be provided for the electrochemical impedance spectroscopy system of Twente.

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Subfield RF&MW

S-parameter measurements of connectorized devices

S-parameter measurement activities for connectorized device characterization at VSL concentrate on realizing state-of-the-art measurement accuracy for frequencies from 9 kHz up to 50 GHz and intend to extend towards 110 GHz within the next two years.

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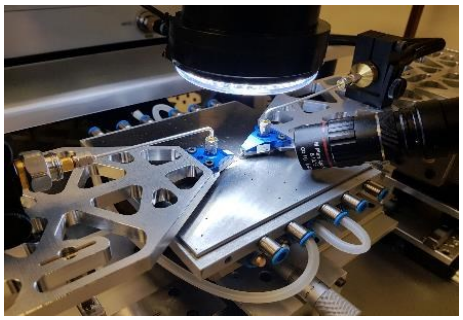
S-parameter measurements of on-wafer devices



VSL is establishing a traceable on-wafer measurement service up to 110 GHz using an in-house designed reference calibration substrate. These on-wafer measurements are performed using the fully automated probing station designed at VSL. For accuracy enhancement, autonomous RF probing is realized using VSL on-wafer measurement software, embedding a wide range of machine learning algorithms for accuracy improvement.

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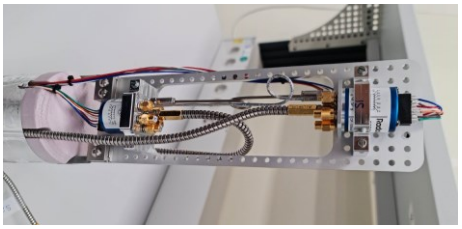
S-parameter measurements at cryogenic temperatures



VSL has developed dedicated facilities for calibrated S-parameter measurements up to 20 GHz at 77K and 4 K temperatures. The system supports coaxial devices with up to 4-ports.

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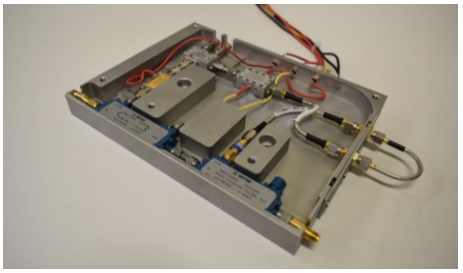
Measurement of active device properties



A measurement system for large-signal active device measurements is currently being developed at VSL and includes the usage of in-house designed active tuners for broadband frequency coverage and automation. VSL's FAME VNA software supports the measurement facility.

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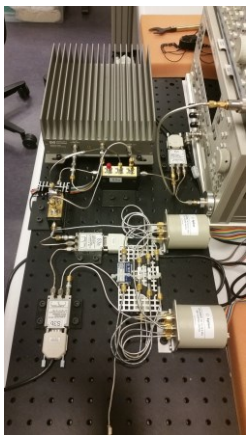
FAME VNA measurement software



VSL has developed VNA measurement software FAME for multi-port VNA calibration and uncertainty evaluation. Furthermore, the software supports connectorized and on-wafer calibrations.

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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, LF power. VSL measurements performed in 2021. Measurements finished. Co-piloted by VSL, CENAM, and PTB.
- EURAMET.EM-K5.2018, LF power. VSL measurements performed in 2020. Co-piloted by VSL, PTB, LNE and NPL.
- EURAMET.EM-S45, Small DC currents. VSL measurements performed in 2024.
- EURAMET.EM-S46, High voltage comparison of DC ratio
- EURAMET.EM-S47, High voltage comparison of high resistance
- CCEM.RF-K5c, S-parameter measurements in coaxial 3.5 mm connectors. The comparison is concluded, and VSL measurement capability is found in agreement with the CMCs.
- CCEM.RF-K5d, S-parameter measurements in coaxial 2.4 mm connectors. VSL measurements were performed in 2024 and 2025. The comparison is on-going at the moment.

List of publications

[1] W. Zhao, G. Ye, S. A. Madhar, I. Splinter and G. Rietveld, "VSL 1200 kV Reference Measuring System for Lightning Impulse Voltage Calibrations," 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, CO, USA, 2024, pp. 1-2, doi: 10.1109/CPEM61406.2024.10645996.

[2] W. Zhao et al., "Calibration and Fine-Tuning of a 4000 kV Lightning Impulse Generator Circuit and Divider," 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, CO, USA, 2024, pp. 1-2, doi: 10.1109/CPEM61406.2024.10646161.

[3] J. Hällström et al., "Linearity extension of UHV class lightning impulse dividers up to 3000 kV," 23rd International Symposium on High Voltage Engineering (ISH 2023), Glasgow, UK, 2023, pp. 8-13, doi: 10.1049/icp.2024.0414.

[4] D. Giordano et al., "Metrology support for enhanced energy efficiency in DC transportation systems," 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, CO, USA, 2024, pp. 1-2, doi: 10.1109/CPEM61406.2024.10646053.

[5] Alf-Peter Elg, Gert Rietveld, Jari Hällström, Gabriella Crotti, Ángel Ramirez, Jorge Rovira, Vladimir Milojevic, Hanane Saadeddine, Burak Ayhan, Wei Zhao, Juan J. Pérez-Aragüés, Paolo Mazza, Mohamad Ghaffarian Niasar, Eduardo Arcones, Armando Rodrigo Mor, Prasanth Venugopal, Guglielmo Frigo, ”High-Voltage Metrology for Electric Energy and Supply Reliability,” 2024 Conference Precision Electromagnetic Measurements (CPEM), Denver, USA, pp. 1 – 2 (2024). DOI: 10.1109/CPEM61406.2024.10646152

[6] Crotti, Gabriella; Meyer, Jan; Letizia, Palma Sara; Agazar, Mohamed; Istrate, Daniela; Chen, Yeying; Mohns, Enrico; van den Brom, Helko; Muñoz, Fabio; Cayci, Huseyin; Mazza, Paolo; Stiegler, Robert; Luiso, Mario; Tinarelli, Roberto; Mingotti, Alessandro, “Performance Evaluation of Instrument Transformers in Power Quality Measurements: Activities and Results from 19NRM05 IT4PQ Project”, International Conference & Exhibition on Electricity Distribution (CIRED 2023), Rome, Italy, 12-15 June 2023

[7] G. Crotti, P.S. Letizia, R. Styblíková, Jan Hlávaček, M. Agazar, D. Istrate, E. Mohns, H. van den Brom, F. Munoz, H. Cayci, B. Ayhan, P. Mazza, G. D’avanzo, R. Tinarelli, A. Mingotti, M. Luiso, A. Delle Femine, J. Meyer, R. Stiegler, “Characterization of MV Instrument Transformers for Power Quality Measurement: the contribution from the IT4PQ project”, CPEM Conf. Dig., Denver, Colorado, 2024

[8] Fabio Munoz, Saliha Madhar, Helko van den Brom, and Gert Rietveld, “Calibration of Wideband Current Transformers using a Precision Power Analyzer as Comparator”, CPEM Conf. Dig., Denver, Colorado, 2024, DOI: 10.1109/CPEM61406.2024.10646121

[9] Mohamed Agazar, Giovanni D’Avanzo, Guglielmo Frigo, Domenico Giordano, Claudio Iodice, Palma Sara Letizia, Mario Luiso, Andrea Mariscotti, Alessandro Mingotti, Fabio Munoz, Daniele Palladini, Gert Rietveld, Helko van den Brom, "Power Grids and Instrument Transformers up to 150 kHz: a Review of Literature and Standards", Sensors Vol. 24, no. 13: 4148, 2024, https://doi.org/10.3390/s24134148

[10] G. Frigo, R. van Leeuwen, H. van den Brom, D. Signorino, D. Giordano, D. Gallo, and A. Delle Femine, “Inter-Laboratory Comparison of Reference Systems for DC Power Quality Measurements”, AMPS 2024 Workshop Proceedings, Caserta, Italy, 18-20 Sept 2024

[11] H.E. van den Brom, R. van Leeuwen, G. Maroulis, S. Shah, and L. Mackay, “Power Quality Measurement Results for a Configurable Urban Low-Voltage DC Microgrid”, Energies 2023, Vol. 16, p. 4623, https://doi.org/10.3390/en16124623.

[12] H.E. van den Brom, R. van Leeuwen, J.M. Warmerdam, and R. Schaacke, “Power Quality Measurements in a Low-Voltage DC Microgrid in an Open Parking Garage,” 2024 International Instrumentation and Measurement Technology Conference, Glasgow, UK, 20-23 May 2024

[13] Antonio Delle Femine, Daniele Gallo, Carmine Landi, Mario Luiso, Helko E. van den Brom, Ronald van Leeuwen, “Assessment of quasi-stationary Power Quality phenomena in DC power systems”, Measurement, Volume 242, Part A, 2025, 115844, ISSN 0263-2241, https://doi.org/10.1016/j.measurement.2024.115844

[14] M. Zucca, N. Al-Zubaidi-R-Smith, L. Bartova, H. van den Brom, L. Callegaro, A. Cultrera, L. Fast, B. Grandinetti, M. Hassanzadeh, A. Mariscotti, A. Masouras, S. Musumeci, G. Nicol, M. Ouameur, G. Rietveld, “The project ‘Metrology for Static and Dynamic Characterization of Supercapacitors’ – MetSuperCap”, CPEM Conf. Dig., Denver, Colorado, 2024, DOI 10.1109/CPEM61406.2024.10646148

[15] Mauro Zucca, Nawfal Al-Zubaidi-R-Smith, Lucie Bartova, Helko van den Brom, Luca Callegaro, Alessandro Cultrera, Lars Fast, Aldo Girimonte, Melika Hassanzadeh, Andrea Mariscotti, Athanasios Masouras, Juan Medved, Salvatore Musumeci, Giovanna Nicol, Mohamed Ouameur, Gert Rietveld, “MetSuperCap: Metrology for static and dynamic characterisation of supercapacitors”, Measurement: Sensors, 2024, 101434, ISSN 2665-9174, https://doi.org/10.1016/j.measen.2024.101434

[16] F. Mubarak et al., "An Interlaboratory Comparison of On-Wafer S-Parameter Measurements up to 1.1 THz," in IEEE Transactions on Terahertz Science and Technology, doi: 10.1109/TTHZ.2025.3537461.

[17] L. Oberto et al., "Measurement and Calibration Approaches for Two-Port Scattering Parameters at mK Temperatures," 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, CO, USA, 2024, pp. 1-2, doi: 10.1109/CPEM61406.2024.10646000.

[18] D. Poduval, F. A. Muñoz, G. Rietveld and F. A. Mubarak, "Evaluating Aging Uncertainty of Impedance Standard Substrate in On-wafer S-parameter Measurements," 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, CO, USA, 2024, pp. 1-2, doi: 10.1109/CPEM61406.2024.10646142.

[19] X. Shang et al., "Some Recent Advances in Measurements at Millimeter-Wave and Terahertz Frequencies: Advances in High Frequency Measurements," in IEEE Microwave Magazine, vol. 25, no. 1, pp. 58-71, Jan. 2024, doi: 10.1109/MMM.2023.3321516.

[20] F. A. Mubarak, V. Mascolo, F. Hussain and G. Rietveld, "Calculating S-Parameters and Uncertainties of Coaxial Air-Dielectric Transmission Lines," in IEEE Transactions on Instrumentation and Measurement, vol. 73, pp. 1-11, 2024, Art no. 8000511, doi: 10.1109/TIM.2023.3338667.

[21] X. Shang et al., "Interlaboratory Investigation of On-wafer S-parameter Measurements from 110 GHz to 1.1 THz," 2023 53rd European Microwave Conference (EuMC), Berlin, Germany, 2023, pp. 624-627, doi: 10.23919/EuMC58039.2023.10290550.

[22] F. Mubarak, F. Munoz and M. Spirito, "A Rigorous Analysis of the Random Noise in Reflection Coefficients Synthesized via Mixed-Signal Active Tuners," 2023 101st

ARFTG Microwave Measurement Conference (ARFTG), San Diego, CA, USA, 2023, pp. 1-4, doi: 10.1109/ARFTG57476.2023.10279048.

[23] E. Shokrolahzade, F. Sebastiano, F. Mubarak, M. Babaie and M. Spirito, "Impedance Standard Substrate Characterization and EM model definition for Cryogenic and Quantum-Computing Applications," 2023 IEEE/MTT-S International Microwave Symposium - IMS 2023, San Diego, CA, USA, 2023, pp. 557-560, doi: 10.1109/IMS37964.2023.10188097.

[24] E. Houtzager, P. Van Der Kamp and G. Rietveld, "Calibration of digital energy meters with IEC 61850-9-2 inputs," 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, CO, USA, 2024, pp. 1-2, doi: 10.1109/CPEM61406.2024.10646123.

[25] Idarshan Veerakumar, Aleksandar Boričić, Ilya Tyuryukanov, Marko Tealane, Matija Naglič, Maarten Van Riet, Danny Klaar, Arjen Jongepier, Jorrit Bos, Mohammad Golshani, Gert Rietveld, Mart van der Meijden, and Marjan Popov,

[26] “Improving Power System Resilience with Enhanced Monitoring, Control, and Protection Algorithms,” In Commit2Data. Open Access Series in Informatics (OASIcs), Volume 124, pp. 7:1-7:18, Schloss Dagstuhl – Leibniz-Zentrum für Informatik (2024). DOI: 10.4230/OASIcs.Commit2Data.7

[27] Seyedreza Azizighalehsari, Eduard Aguilar Boj, Prasanth Venugopal, Thiago Batista Soeiro, and Gert Rietveld, “A Distribution of Relaxation Time Approach on Equivalent Circuit Model Parameterization to Analyse Li-ion Battery Degradation”, IEEE Transactions on Industry Applications, vol. 60, no. 6, pp. 9206 – 9215 (2024), DOI: 10.1109/TIA.2024.3430268

[28] Seyedreza Azizighalehsari, Prasanth Venugopal, Deepak Pratap Singh, Thiago Batista Soeiro, and Gert Rietveld, “Empowering Electric Vehicles Batteries: a comprehensive look at the application and challenges of second-life batteries”, Batteries 10 (5), 161, pp. 1 – 40 (2024), DOI: 10.3390/batteries10050161

[29] Weichuan Zhao, Sohrab Ghafoor, Gijs W. Lagerweij, Gert Rietveld, Peter Vaessen, Mohamad Ghaffarian Niasar, “Comprehensive Investigation of Promising Techniques to Enhance the Voltage Sharing among SiC MOSFET Strings, Supported by Experimental and Simulation Validations,” Electronics 2024, 13, pp. 1 – 34 (2024), DOI: 10.3390/electronics13081481

[30] Sohaib Qazi, Prasanth Venugopal, Gert Rietveld, Thiago Batista Soeiro, Udai Shipurkar, Alex Grasman, Alan J. Watson, Patrick Wheeler, “Powering Maritime: Challenges and Prospects in Ship Electrification”, IEEE Electrification Magazine vol. 11, no. 2, pp. 74 – 87 (2023). DOI: 10.1109/MELE.2023.3264926

[31] Keqiu Zeng, Gert Rietveld, and Jelena Popovic, “Measurement System for Accurate Determination of Fast-Changing DC Currents up to 900 A”, IEEE Transactions on Instrumentation and Measurement, vol. 72, pp. 1 – 9 (2023). DOI: 10.1109/TIM.2023.3277995

[32] Madhat Alimawi, Roelof Grootjans, and Gert Rietveld, “An Alternative Calorimetric Approach for Power Loss Measurement of Ultra-efficient Power Electronics,” 2024 Conference Precision Electromagnetic Measurements (CPEM), Denver, USA, pp. 1 – 2 (2024). DOI: 10.1109/CPEM61406.2024.10646036

[33] Kees Koreman, Gert Rietveld, Yanny Fu, “Revenue metering and loss evaluation in meshed HVDC grids”, CIGRE B4 International SC Meeting and Colloquium, Vienna, Austria, pp. 1 – 11 (2023).

[34] Weichuan Zhao, Mohamad Ghaffarian Niasar, Peter Vaessen, Gert Rietveld, “Voltage sharing improvement methods in series-connected MOSFETs for future grid high-voltage applications”, 23rd International Symposium on High Voltage Engineering (ISH 2023), Glasgow, UK, pp. 85 – 91 (2023). IET Digital Library, 2023. DOI: 10.1049/icp.2024.0432