Progress report on electrical metrology at VTT MIKES between 2021 and 2023

for the 33rd meeting of the Consultative Committee for Electricity and Magnetism (CCEM), March 2023

Organization

National Metrology Institute VTT MIKES (about 60 employees) is a part of VTT Technical Research Centre of Finland Ltd (about 2100 employees), which is a fully state-owned not-for-profit-company. VTT MIKES is one of the five Research Areas of Digital Technologies, which is one of the three Business Areas of VTT. MIKES's Electrical Metrology Team with 15 researchers is responsible for Finland's national metrology activities in fields of electricity, time and frequency, and acoustics.

Applications of Josephson effect in electrical metrology and quantum technologies

VTT MIKES continues development of a Josephson Arbitrary Waveform Synthesizer (JAWS) driven by a pulsed laser and a photodiode for both DC and AC metrology. Our fairly inexpensive optical pulse pattern generator (PPG) has a superior pulse quality compared to systems based on electrical PPGs operating at tens of GHz. A properly designed mode-locked laser (MLL) produces pulse trains with little jitter and narrow amplitude spread of the pulses. We have built a MLL operating at 1335 nm with pulse repetition rate of 2.3 GHz. An optical time division multiplexer is used to increase the pulse rate to 8-10 GHz. Pulse pattern formation can be done by pulse picking, that is by either passing or blocking pulses at the modest base frequency of 2.3 GHz using optical intensity modulators. We have driven a Josephson Junction Array (JJA) with a low critical current of 360 µA at multiple Shapiro steps, and we have performed experiments with pulse pairs whose time interval can be set freely without distorting the shapes of individual pulses even if they are overlapping [2]. Experimental results are in qualitative agreement with theoretical simulations, but there are quantitative discrepancies which motivate an improved integration of photodiodes and JJAs to improve both the understanding and fidelity of pulse-driven JAWS [17]. VTT's recent progress on silicon photonics platform for quantum technologies is an important enabler for integration [6, 9]. VTT's work belongs partly to project SuperQuant of the European Metrology Programme for Innovation and Research (EMPIR) [18].

Considering future quantum technologies in a wider perspective, our optical approach is a potential enabler for fast and energy-efficient pulse drive without an expensive high-bandwidth electrical PPG, and without high-bandwidth electrical cables that yield too high thermal conductance between cryogenic and room temperatures. These aspects are developed in EU FET Open project aCryComm [https://www.acrycomm.eu/] coordinated by VTT. Other partners of the project are PTB, Tampere University, KTH (Stockholm), ETH Zürich, Single Quantum, and Polariton Technologies. The work at VTT is also related to the Finnish Quantum Computer procurement project, in which Finnish quantum technology company IQM has already built Finland's first quantum computer, superconductor-based 5-qubit HELMI, for VTT. A 20-qubit quantum computer is currently under development, with a 50-qubit upgrade planned for 2024. Recently the HELMI quantum computer has been connected with the pan-European 309-petaflop superconductor LUMI located in Kajaani, Finland [https://www.vttresearch.com/en/news-and-ideas/finland-opens-quantum-computer-research-purposes-fusion-quantum-computing-and].

Impedance and graphene

VTT MIKES continues its research towards a universal quantum standard for electrical quantities. In the joint research project GIQS (Graphene Impedance Quantum Standard) of the EMPIR programme, VTT MIKES was developing technologies needed for operation of both a graphene QHR standard and a Josephson voltage standard in the same cryogen-free cryostat. We use a pulse tube refrigerator to liquefy gaseous helium delivered into experimental chambers housing Josephson voltage standard(s). This guarantees the best possible cooling of the Josephson junctions. In the course of the work, it turned out that a major renovation was required for the cryostat. Renovation took longer than expected, but now the pulse-tube cryostat with 8-T magnet is ready for operation, and the first experiments are expected in near future.

High voltage and power metrology

New techniques for traceability for digital substation measurements have been built into VTT MIKES digital sampling setup for calibration of voltage, current and power harmonics. New design of the sampler ADC [12] has been developed and a method for calibration of its timing has been proposed [11]. In addition, methods for linking the digital substation timing to UTC using PTP techniques is under development [10].

The 10 µrad phase displacement accuracy of the VTT MIKES reactor loss measurement developed in EMPIR project TrafoLoss was confirmed in a comparison with respective PTB and VSL systems [13].

New techniques for measurement of the voltage linearity of high voltage capacitors were developed. Performance of different approaches was summarised in paper [15].

Performance of the 400 kV switching impulse voltage (SI) measurement systems of VTT MIKES was improved by applying software correction for systematic errors in the high voltage divider response [1]. A new lightweight universal divider was developed [5, 14]. Measuring system based on this new divider will be used for on-site calibration of DC, AC, SI, and lightning impulse (LI) customer calibrations up to 400 kV; until now four different systems have been needed for the purpose.

VTT MIKES has one of the 200 kV direct voltage divider modules built 10 years ago in EMRP project "Metrology for High Voltage Direct" (HVDC). The stability of the scale factor of the 1000 kV setup has been followed, and it has had a linear drift of 0.4 ppm/year [16].

Overview papers on the outcome of EMPIR projects with VTT MIKES as a partner have been published for two projects: FutureEnergy [3] and HV-com² [4].

Comparisons

The final report of BIPM-MIKES on-site comparison of 10 V Josephson arrays, BIPM.EM-K10.b, was published in 2021 [19]. The relative deviation of the MIKES result from the BIPM value was $(+2.19 \pm 4.94) \times 10^{-10}$, which supports CMC claims of MIKES.

Final reports of comparisons EURAMET.EM-S33 (AC up to 200 kV) and EURAMET.EM-S34 (Capacitance and dissipation factor up to 200 kV) appeared in 2022 [20, 21]. The results of VTT MIKES are good and support CMC claims.

MIKES participated comparisons EURAMET.EM-S46 (High voltage DC ratio up to 200 kV) and EURAMET.EM-S47 (High voltage 2 GΩ resistance). Participants sent their references to RISE, who performed the comparison measurements in March 2022. Draft A is under preparation.

In addition, MIKES acts as the pilot laboratory for worldwide supplementary comparison EURAMET.EM-S36 (Partial discharge), coordinated by RISE. Comparison started in 2022, and the measurements should be completed by the end of 2023.

Publications 2021 –

Articles

[1] Havunen, J. & Hällström, J., *'Reference Switching Impulse Voltage Measuring System Based on Correcting the Voltage Divider Response with Software'*, IEEE Transactions on Instrumentation and Measurement, vol. 70, 1006008 (2021). https://doi.org/10.1109/TIM.2021.3063753

[2] Nissilä, J., Fordell, T., Kohopää, K., Mykkänen, E., Immonen, P., Jabradaghi, R. N., Bardalen, E., Kieler, O., Karlsen, B., Ohlckers, P. A., Behr, R., Manninen, A. J., Govenius, J. & Kemppinen, A., *'Driving a low critical current Josephson junction array with a mode-locked laser'*, Applied Physics Letters 119, 3, 032601 (2021). https://doi.org/10.1063/5.0060804

Conference articles

[3] Elg, A. P., Garnacho, F., Agazar, M., Meisner, J., Merev, A., Houtzager, E., Hällström, J., Lahti, K., Escurra, C. M., Platero, C. A., Micand, T., Steiner, T. & Voss, A., *'Research project EMPIR 19ENG02 future energy'*, in VDE High Voltage Technology 2020: ETG-Symposium (Germany, 9/11/20), pp. 252-257 (2021). https://ieeexplore.ieee.org/document/9275526

[4] Meisner, J., Gockenbach, E., Saadeddine, H., Havunen, J., Schichler, U., Elg, A. P., Garnacho, F., Roccato, P. E., Merev, A., Lahti, K., Backhaus, K., Orrea, A., Gamlin, M. & Steiner, T., *'Standardisierung von Hochspannungsprüfungen mit zusammengesetzten und kombinierten Spannungsformen'*, VDE High Voltage Technology: ETG Symposium (Germany, 9/11/20), pp. 354-358 (2021). https://doi.org/10.7795/EMPIR.19NRM07.CA.20210215

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[6] Cherchi, M., Bera, A., Kemppinen, A., Nissilä, J., Tappura, K., Caputo, M., Lehtimäki, L., Lehtinen, J., Govenius, J., Prunnila, M. & Aalto, T., *'Supporting quantum technologies with a micron-scale silicon photonics platform'*, Integrated Optics: Devices, Materials, and Technologies XXVI. Garcia-Blanco, S. M. & Cheben, P. (eds.). International Society for Optics and Photonics SPIE, 17 p. 120040A. (Proceedings of SPIE - The International Society for Optical Engineering, Vol. 12004, 2022). https://doi.org/10.1117/12.2612182

[7] Aaltonen, L., Lahti, K., Hällström, J. & Havunen, J., *'Improvement and uncertainty evaluation of a 1 MV lightning impulse measurement system*', Proceedings of the 27th Nordic Insulation Symposium. Nordic Insulation Symposium, 6 p. (Proceedings of the Nordic Insulation Symposium, Vol. 27, 2022). https://doi.org/10.5324/nordis.v27i1.4920
[8] Havunen, J., Hällström, J., Meisner, J., Gerdinand, F. & Elg, A-P., *'Design and Verification of a Calculable Composite Voltage Calibrator'*, Proceedings of the 27th Nordic Insulation Symposium. Nordic Insulation Symposium, 5 p. (Proceedings of the Nordic Insulation Symposium, Vol. 27, 2022). https://doi.org/10.5324/nordis.v27i1.4491
[9] Cherchi, M., Bera, A., Kemppinen, A., Nissilä, J., Tappura, K., Caputo, M., Lehtimäki, L., Lehtinen, J., Govenius, J., Prunnila, M. & Aalto, T., *'An unconventional ultra-low loss silicon photonics platform for quantum technologies'*, Quantum 2.0 Conference and Exhibition: QUANTUM 2022. Optical Society of America OSA, QW4A.5. (Optics InfoBase Conference Papers, 2022). https://doi.org/10.1364/QUANTUM.2022.QW4A.5
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[11] Lehtonen, T. & Hällström, J., '*A Method for Absolute Delay Calibration of a Reference Merging Unit*', 2022 Conference on Precision Electromagnetic Measurements (CPEM), Wellington, New Zealand, 2022.
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[13] Rietveld, G., Mohns, E., Havunen, J., Vukadinovic, A., Ye, G., Raether, P., Suomalainen, E-P. & Hällström, J., '*HV Voltage Dividers for Advanced Loss Measurement Systems*', 2022 Conference on Precision Electromagnetic Measurements (CPEM), Wellington, New Zealand, 2022.
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[18] Bieler, M., Priyadarshi, S., Tian, H., Kieler, O., Kohlmann, J., Oberto, L., Enrico, E., Fasolo, L., Arikan, M., Coskun Ozturk, T., Nissilä, J., Selvasundaram, P.B., Fordell, T., Seppä, J., Manninen, A.J., Kemppinen, A., Koepfli, S.M., Leuthold, J., Astafiev, O., Antonov, V., Viheriälä, J., Spirito, M., Sebastiano, F., Bozbey, A. & Razmkhah, S., '*Microwave metrology for superconducting quantum circuits*', 2022 Conference on Precision Electromagnetic Measurements (CPEM), Wellington, New Zealand, 2022.

Comparison reports

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