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## Progress report on electrical metrology at VTT MIKES between 2017 and 2019

for the 31st meeting of the Consultative Committee for Electricity and Magnetism (CCEM), March 2019

### Organization

National Metrology Institute VTT MIKES (62 employees in the end of 2018) is a part of VTT Technical Research Centre of Finland Ltd (about 2400 employees), which is a fully state-owned not-for-profit-company. VTT MIKES is one of the five Research Areas of Knowledge Intensive Products and Services, which is one of the three Business Areas of VTT. MIKES's Electrical Metrology Team with 17 researchers (at present) is responsible for Finland's national metrology activities in fields of electricity, time and frequency, and acoustics.

### Quantum current standard and other applications of single-electron effects

Benefitting from VTT's excellent clean-room facilities, MIKES has continued developing silicon-based single-electron pumps. Characterization of the first VTT-fabricated single-electron pumps based on Si quantum dots is in progress as a part of the project e-SI-Amp of the European Metrology Programme for Innovation and Research (EMPIR).

We have also continued activities with quantum phase slips (QPS) in superconducting nanowires (SNWs), so far with rather limited resources. Especially, we have fabricated and studied SNWs based on disordered silicides. In MoSi nanowires, a size-dependent crossover from conventional superconductivity to transport influenced by thermal and quantum fluctuations was observed [8,24].

During the reporting period, MIKES has not continued development of the SINIS hybrid turnstile towards a quantum standard of electric current. Instead, MIKES in collaboration with PTB and Aalto University demonstrated that a SINIS-based single-electron trap excited by individual photons originating from the electromagnetic microwave background can be used to obtain spectral information of cryoelectronic devices at millimeter wave frequencies with extremely low signal levels [1,37,38]. Also, MIKES with other teams of VTT developed cryogenic refrigeration using a variation of a micro-SINIS device (not nano), in which the normal-metal (N) island is replaced by a sub-chip of highly doped silicon supported by superconducting thin-film aluminium wires and Al-Si tunnel junctions. Refrigeration of a millimeter-scale Si sub-chip by about 80 mK from a starting temperature of about 240 mK was demonstrated [11,23,38].

In addition, MIKES develops thermometry applications of single-electron tunneling in close collaboration with Aalto University. Using the primary Coulomb blockade thermometer (CBT), combined standard uncertainty ( $k = 1$ ) below 0.5% has been reached in determining the thermodynamic temperature in the temperature range from 20 mK to 200 mK [5].

### Applications of Josephson AC voltage standard

VTT MIKES has started development of an ac voltage standard based on a pulsed laser and a photodiode connected to a Josephson voltage standard at 4 K [26]. This work is part of an ongoing EMPIR project QuADC in which we have received help from PTB (Josephson array), JV and USN (4 K photodiode assembly). The main goal is to design and build a fairly inexpensive optical pulse pattern generator (PPG) with superior pulse quality compared to systems based on electrical PPGs operating at tens of GHz. A properly designed mode-locked laser (MLL) is known to produce pulse trains with little jitter and narrow amplitude spread of the pulses. We have built a MLL operating at 1350 nm with pulse repetition rate between 2-2.5 GHz. An optical time division multiplexer is used to increase the pulse rate to 8-10 GHz. Pulse pattern formation is done by pulse picking, that is by either passing or blocking pulses at the modest base frequency (2-2.5 GHz) using optical intensity modulators. We have successfully demonstrated quantized voltage plateaus using unmodulated pulse trains (dc voltages). Testing of the modulation apparatus is going on with a target of realizing pure arbitrary waveforms up to 100 kHz signal frequency.

The development of an ultra-stable semiconductor-based arbitrary waveform generator DualDAC (commercially available from Aivon Ltd, Helsinki, Finland) has been continued. We have worked towards wider signal frequency range (0.1 Hz to 100 kHz), larger dynamics (1 mV - 14 V), improved capability to drive low-impedance loads (like 100 ohms) and better signal to noise ratio. We are currently testing the new developments. The short-term (200 s) amplitude stability of the source in audio frequency range is some parts in  $10^8$ , and within 2 parts per million in a year-long term. We are investigating if the ac signal amplitude stability could be traced to simple measurements of internal dc voltages. We believe the source can be useful in various metrological experiments, like impedance bridges, ADC calibrations, thermal converter measurements, etc.

### Resistance and graphene

An important improvement in MIKES's resistance metrology infrastructure took place in the end of 2017 when the new CCC probe purchased from Magnicon GmbH was delivered. Since then, the CCC probe has been used together with the earlier-acquired Magnicon CCC Drive system, which can also be used with the low-frequency current comparator (LFCC) that MIKES has developed for room-temperature operation at frequencies below 1 Hz [3].

MIKES's research activities in resistance metrology and metrology applications of graphene have been rather limited during the reporting period. Reasons for this low-activity period are the retirement of Dr Alexandre Satrapinski in spring 2017 and temporary lack of research funding for resistance metrology. Research activities on graphene-based resistance metrology will be continued when the EMPIR project GIQS (Graphene Impedance Quantum Standard) will start in June 2019. In that project, the main task of MIKES is to develop the technologies needed for the AC operation of both a graphene QHR standard and a Josephson voltage standard in the same cryogen-free cryostat. That would be an important step towards a universal quantum standard for electrical quantities.

## Power and energy

MIKES has developed a single-phase calibration setup for calibration of voltage, current and power harmonics [10,30]. A phantom power source is used for generation of the test signals. The setup can be used for calibration on voltages up to 350 V and currents up to 20 A. Measurement is based on capacitive-resistive voltage dividers, two different kinds of resistive current shunts, and a custom digitizer. Magnitude and phase errors of reference voltage and current sensors and digitizer inputs are determined and compensated in measurement software or in calculations. The system is able to measure power at expanded uncertainty of 30  $\mu\text{W}/\text{VA}$  at unity power factor up to 10 kHz. With smaller power factors the uncertainty increases. At 10 kHz, with zero power factor the uncertainty is 160  $\mu\text{W}/\text{VA}$ . Further work is still needed to lower the uncertainty of the current measurement.

Theory of a new method for suppressing Rogowski coil temperature dependence has been studied. The method has been verified with a proof-of-concept measurement using a commercially available Rogowski coil. The TC compensation approach allows both optimization of the damping ratio of the coil, and adjustment of temperature coefficient to practically zero at low frequencies. Monte Carlo analysis shows that effects of modelling errors can be kept to a minimum when the coil is properly terminated, which makes it easier to compensate for the response with signal processing methods. Further work is still needed to improve the TC around resonance frequency in order to reduce the uncertainty budget at high harmonic frequencies [6].

Another demonstration worked out together with TUBITAK improves Rogowski coil immunity to winding position and ambient magnetic fields. Together with the applied temperature compensation, the mutual inductance varies less than  $\pm 30 \mu\text{H}/\text{H}$  and the phase displacement less than  $\pm 2 \mu\text{rad}$  regardless the conductor position within temperature range from 15 to 35 °C. Maximum current of the demonstration design is 600 A. The drawbacks of the design are increased weight, and limited current range compared with Rogowski coil without the introduced shielding [13].

A concept was developed in EMRP FutureGrid project for measurement of high current using Faraday effect in optical fiber. The sensor system was designed for a wavelength around 635 nm, in contrast to commercial systems running at 1310 or 1550 nm, in order to increase the sensitivity. Doping with Terbium nanoparticles of the fibre material was attempted to increase the Faraday Effect, but was not successful probably owing to absorption of light by dopant itself [18]. The full potential of the setup was not reached, and the work continues slowly.

An advanced loss-measuring system for measurement of high voltage reactor losses was developed. System can be used for measurement of losses of single-phase reactors using voltages up to 200 kV. With power factor of 0.001, total expanded uncertainty of 5 % ( $k = 2$ ) for active power was achieved. The high magnetic field posed challenges to instrumentation. More work has to be done for characterization and protection of the measuring setup to high external magnetic field to reduce the uncertainty. The systems was used for measurement losses of an air-core shunt reactor during temperature rise tests. Results were compared to the losses calculated according to theoretical formulae in IEC 60076-1. Calculated changes of resistance were systematically lower than the ones measured with the loss measuring system [34].

## High voltage metrology

The lightning impulse voltage is distorted due to attenuation in the (typically about 15 m long) coaxial cable connecting the high voltage divider in the high voltage hall to digital recorder in control room. A model was built based on telegrapher's equations and transmission line theory, and the results were compared with measurements [15,29]. The first results seem to indicate that the typical estimates for lightning impulse front time calibration are too optimistic. This work continues slowly, too.

A commercial charge-sensitive preamplifier, originally designed for particle detection applications, was introduced for calibration of PD calibrators below 1 pC. The use of charge-sensitive preamplifier significantly improves the signal-to-noise ratio of PD detection, making low-level measurements possible. Expanded overall uncertainty for the tested setup is less than 1 % from 20 pC down to 0.1 pC, and less than 3 % at 0.01 pC ( $k = 2$ ). This extends the lower calibration range by over one order of magnitude from those currently available from National Metrology Institutes. The measured results are in line with the traditional method on PD levels from 1 pC to 20 pC [9,27].

A coaxial cable current step generator for producing well-defined, rectangular, fast and steep current steps of up to 100 A with rise time less than 5 ns was developed. The duration of the stable current is about 1  $\mu\text{s}$ . The generator for calibration of the step response and dynamic resistance of impulse shunts by substitution method using a fast current sensing coil for transfer. Measured differences between the dynamic (at 800 ns) and dc resistances of the four tested shunts ranges from 0.3 % to 6 % [31,33,39].

MIKES's lightning impulse voltage measurement system now has FFT-based deconvolution correction for non-ideal impulse digitizer front-end response. Good signal to noise ratio for the correction was achieved by averaging a large number (> 50) of step responses. Performance of the digitizer correction was verified by comparison with a calculable impulse voltage calibrator. The correction reduced systematically the errors of the measured voltage and time parameters to less than  $\pm 0.1\%$ , which is clear improvement from the typical scatter magnitude of  $\pm 1\%$  for impulse digitizers. Correction has been in use for over one year and calibration results have been stable within  $\pm 0.1\%$  for all parameters [12].

A fast high voltage divider for puncture testing has been presented. The design of the divider is based on using ceramic disk resistors. The divider has a nominal maximum voltage of 600 kV for measurement of transients shorter than 0.5  $\mu\text{s}$ , and the nominal full lighting impulse voltage withstand is 400 kV. The measured rise time of the complete divider is less than 2 ns [19]. In an informal comparison a scatter of 3 % was found in measurement of 200 ns pulses with 300 kV peak value [35].

## Comparisons

MIKES has participated the following key or supplementary comparisons whose final or draft report appeared during the reporting period: EURAMET.EM-S33 (AC up to 200 kV), EURAMET.EM-S34 (Capacitance and dissipation factor up to 200 kV), EURAMET.EM-S35 (High DC current ratio) and EURAMET.EM-S37 (Current transformer calibration systems up to 10 kA) [22]. The results of MIKES are good and support CMC claims. MIKES is supporting RISE in running EURAMET.EM-S42 (Lightning impulse voltage up to 700 kV). MIKES measurements were performed in November 2016 at PTB; MIKES is responsible for analysing the comparison results.

In an informal bilateral 1 mH and 10 mH inductance comparison with PTB, an excellent agreement in measurement results was reached within the overall uncertainty of the comparison that varied from 14  $\mu\text{H}/\text{H}$  to 62  $\mu\text{H}/\text{H}$  in the frequency range 100 Hz to 2 kHz [4].

Some other informal comparisons where MIKES has participated were on lightning impulse voltage on 1000 V level [32], partial discharge down to 0.1 pC [36] and 300 kV submicrosecond impulses [35].

## Publications 2017 -

### Publications in refereed journals

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- [9] J. Havunen and J. Hällström, *Application of charge-sensitive preamplifier for the calibration of partial discharge calibrators below 1 pC*. IEEE Trans. Instrum. Meas., in press (2019), doi 10.1109/TIM.2019.2895437.
- [10] T. Lehtonen, *Harmonic power standard of VTT MIKES*. IEEE Trans. Instrum. Meas., in press (2019).
- [11] E. Mykkänen, J.S. Lehtinen, L. Grönberg, A. Shchepetov, A.V. Timofeev, D. Gunnarsson, A. Kemppinen, A.J. Manninen, and M. Prunnila, *Efficient thermionic operation and phonon isolation by a semiconductor-superconductor junction*, arXiv:1809.02994, submitted for publication (2018).

### International conference papers

- [12] J. Havunen, J. Hällström, A. Bergman, and A.E. Bergman, *Using deconvolution for correction of non-ideal step response of lightning impulse digitizers and measurement systems*, Proc. 20th International Symposium on High Voltage Engineering (ISH 2017), Buenos Aires, Argentina, 28 August - 1 September, 2017, ISH2017\_381.
- [13] J. Hällström, B. Ayhan, E.-P. Suomalainen, and A. Valero, *Rogowski coil with reduced immunity to conductor location and stray magnetic fields*, Proc. 20th International Symposium on High Voltage Engineering (ISH 2017), Buenos Aires, Argentina, 28 August - 1 September, 2017, ISH2017\_561.
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#### Other publications

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