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Glossary

HV	high voltage (usually exceeding 1 kV)
HVDC	High Voltage Direct Current
a.c.	qualifier pertaining to alternating electric quantities such as voltage or current, to devices operated with these, or to quantities associated with these devices
d.c.	qualifier pertaining to time-independent electric quantities such as voltage or current, to devices operated with direct voltage and current or to quantities associated with these devices
NMI	National Measurement Institute
CT	Current Transformer
OCCT	Openable Core Current Transformer
TSO	Transmission System Operator
VSC	voltage source controlled
IGBT	Insulated gate bipolar transistor
CMRR	Common mode rejection ratio
PSPICE	An electronic circuit simulation program
VNIIMS	Russian NMI
CAD	Computer aided design
PQ	Power quality
PCC	Point of common coupling

1 Executive Summary

Introduction

The research has aimed to underpin the EC directives 2003/87/EC (greenhouse gas emission allowance scheme), 2004/101/EC (amendment including Kyoto Protocol) and helps to meet the requirements to generate 20 % of energy needs from renewable sources by 2020 (Directive 2009/28/EC). It is an important factor to realise a common internal market in electricity (Directive 2003/54/EC). The main thrust of the project has been to ease the introduction of HVDC for energy transmission in Europe. To this end a metrology infrastructure is needed to: ensure HVDC can be reliably measured for grid protection and billing purposes; enable monitoring of its power quality with sufficient precision; and to enable manufacturers of transmission equipment to determine and reduce energy losses.

The problem

Europe has an urgent need to reduce dependence on fossil fuel. The introduction of renewable energy sources is hampered by insufficient transmission systems for electrical energy, to transport the energy from often remote production sites to major population sites. Energy transmission by high voltage direct current (HVDC) is seen as one of the necessary means to enhance the European energy system, but needs support from measurement technology to realise its full potential.

The solution

The response to the challenge posed has been to develop measurement technology that supports energy transmission by means of HVDC.

The main thrust points have been:

- reliable and traceable measurement of energy losses of the converters and of their constituent components,
- reliable and traceable measurement of ultra-high d.c. voltages up to the highest system voltage contemplated in the world,
- investigation of methods and evaluation of power quality parameters associated with HVDC, and, lastly,
- support of new systems to meter electrical energy at HVDC for billing purposes.

Impact

New services for calibration of measurement systems for HVDC converter losses have been developed at PTB for the benefit of European industry. These include state-of-the-art references for the calibration of current and voltage transducers used for measurements on converter subassemblies and on systems for measuring the efficiency of HVDC converters. New methods have also been developed to measure losses on converter components. Measurements are now possible over a very large dynamic range and long time frame. The methods developed also enable determination of on-state losses both over (relatively) long time periods and over fast switching phenomena.

New services for the calibration of high d.c. voltages up to 1000 kV at extremely low uncertainty have been introduced, not only for in-house applications at European national metrology institutes, but also as a mobile service that can be offered on-site anywhere in the world. This both supports dielectric testing of components and apparatus for HVDC transmission and provides a firm foundation for acquisition of the voltage value needed for d.c. side energy metering. The on-site calibration service is already in use, as attested by several commercial on-site calibrations that have been carried out by SP and MIKES.

Special transducers and methods to capture signals from the high voltage grid have been developed. These new transducers and methods have been used for investigations of power quality parameters in an existing HVDC station, where new information could be gained on the actual performance of the station. The methods and results have been published and are available for future investigations.

New services have been made available for the calibration of d.c. energy meters. A foundation for future standardisation of d.c. energy meters has been developed in the form of proposals of requirements for energy meters both with analogue input and digital input. These proposals have been made available for the international standardisation body, IEC technical committee 13, dealing with electrical energy measurement and control.

A prototype current transformer intended for deployment as a non-invasive reference for on-site current transformer calibration has been developed, using state-of-the-art techniques to achieve virtually error-free transformation.

2 Project context, rationale and objectives

2.1 Background

HVDC energy transmission is crucial for a successful uptake of renewable energy sources in the grid. This project provides improvements for the present HVDC metrology infrastructure: accurate measurement of HVDC, determination of losses in HVDC systems, on-site power quality measurements at HVDC substations, and d.c. metering. It is a combined effort of seven European national metrology institutes, one university and one industrial partner. In addition three collaborators from the research and industrial sectors supported the project.

In Europe, generation and transmission of electricity has reached near capacity levels (in particular the European north-south “back-bone” links are already fully loaded). This is exacerbated by transmission losses, which already account for 10 % of all energy generated and are increasing towards levels that will make future transmissions impractical.

In addition, there is an urgent need for the introduction of new energy sources with low greenhouse gas emissions. Renewable energy sources, often located remotely in relation to main population zones, are seen as the environmentally acceptable answer to maintaining security of supply. HVDC transmission is universally regarded as the solution for these essential grid extensions because the HVDC technology offers: a) lower losses and reduced demands for right-of-way corridors as compared to a.c. transmission; b) enhanced stability of associated a.c. grids; c) economically viable transmission of renewable energy from awkward locations; and d) power quality correction of polluted grids.

The metrology infrastructure to support HVDC at the proposed 800 kV working levels has been created within this project to ensure that HVDC can be reliably measured for grid protection and billing purposes, to enable monitoring of its power quality with sufficient precision, and to empower the manufacturers of transmission equipment to determine and reduce energy losses.

2.2 Rationale

The electricity grid is an indispensable infrastructure of today’s society, without which all community functions will cease. In Europe, both generation and transmission are near the capacity limit, leading to a risk of collapse if a disturbance occurs. Furthermore, transmission losses, which already account for 10 % of all energy generated, are in some cases threatening to increase to such an extent that transmission would be impractical. In both cases, energy transmission by d.c. can help to ameliorate the situation.

HVDC transmission is an essential technology for the integration of renewable energy sources into Europe’s energy supply, therefore it directly contributes to the greenhouse gas emission allowance scheme as described in the EC directives 2003/87/EC (greenhouse gas emission allowance scheme), 2004/101/EC (amendment including Kyoto Protocol) and helps to meet the requirements to generate 20 % of energy needs from renewable sources by 2020 (Directive 2009/28/EC). It is also an important factor to realise a common internal market in electricity (Directive 2003/54/EC).

However, no metrology infrastructure existed to support HVDC at the proposed 800 kV working levels. Consequently HVDC could not be reliably measured for protection or billing purposes, its quality could not be monitored and the manufacturers of equipment could not determine and reduce energy losses.

2.3 Scientific and technical objectives

This research has developed metrological infrastructure to support a wide implementation of HVDC transmission in Europe. The research addressed metrological challenges that support a reduction of losses in HVDC transmission, ease the introduction of renewable energy sources, enhance the stability of electric power grids, support low loss long distance energy transmission and ensure fair trade between organisations employing the grid. The main areas of research were i) Loss evaluation, ii) traceable high-voltage measurements, iii) Power quality and iv) Metering. These areas were selected because of their importance for the development of HVDC energy transport for the following reasons:

- Reducing energy losses of an HVDC transmission system is essential not only to increase system efficiency but also in terms of reduced emissions of greenhouse gases. For investors deciding on transmission system alternatives, accurate knowledge of expected losses forms an important part of the investment evaluation. One of the dominating contributors to loss in HVDC transmission systems is the a.c./d.c. converter valve. The latest generation of d.c. Voltage Source Converter (VSC) valves utilise a technology known as Insulated Gate Bipolar Transistors (IGBT) and are used to achieve full conversion controllability. These devices, however, create new challenges compared to previous power semiconductor technology in that they have faster switching rates that require accurate measurement of fast changing voltage and current signals in order to determine losses.
- HVDC transmission systems are inherently based on the ability to make measurements of high d.c. voltages. Prior to the project these high voltages could not be measured with sufficient accuracy for loss determination or metering purposes.
- The fast switching a.c./d.c. converters, important for keeping losses low, create high frequency interference that has to be mitigated by suitable filters to avoid lowering the power quality in connected grids and end-user systems. The performance and acceptability of these mitigation methods can only be verified by accurate and robust measurements.
- Correct metering is a prerequisite for energy billing and for fair trading. Providing metering on the d.c. side of an HVDC intertie is, in many cases, the logical point between buyer and seller in a d.c. grid. However, there is a lack of consensus on correct measurement principles and on accepted technical solutions, making this metering option unusable at present. The projected increase in HVDC links and the resulting escalation in financial transactions between nations and commercial operators creates a need for accurate d.c. side metering, which is necessary to allocate the significant cost of converter station losses to the proper party.

From these issues a number of **objectives** were identified and translated into research packages:

1. **The development of instruments and methods for loss measurement on converter valves** to replace the present practice of loss estimation based on theoretical calculations. Methods to measure loss enable stricter requirements on permissible losses, which in turn support energy reductions.
2. **The extension of calibration capability for traceable d.c. voltage measurements from a few 100 kV, up to a target of 1000 kV**, at an uncertainty of 0.004 %, with benefits for insulation coordination of HVDC stations, measurement of high d.c. voltage on-site and energy metering at the d.c. side.
3. **The development of methods to assess the detrimental effect of poor power quality**, caused by HVDC convertors, on the performance of grids; and measurements of actual power quality in an HVDC station, using sensors characterised for harmonic frequencies.
4. **The development of calibration methods and test systems for d.c. electricity meters to enable d.c. side metering**, which underpins fair trade by permitting a separation of infra-structure losses from the energy transfer in d.c. transmission; the construction of a demonstration prototype of a d.c. electricity meter; and the development of pre-normative information to be made available to the relevant standardisation bodies. Furthermore, development of a novel sensor for in-situ calibration of existing current transformers in the a.c. grid, to enable proper migration of metering from the a.c. side to the d.c. side.

3 Scientific and technological results and foreground

3.1 Objective 1: Measuring power losses in HVDC systems

3.1.1 Introduction

One of the most important issues in purchase of new energy systems and equipment is the power loss incurred in use. Precise and well-accepted methods are needed for a well-functioning market. Practice has been to estimate losses based on theoretical calculations. The research has aimed at providing the tools to measure losses both on single components of HVDC converter stations, on subassemblies and on entire stations. Test benches, reference equipment, calibration services and on-site capability to measure loss have been created.

The research has been divided into two main paths, one for the development of measurement infrastructure (traceability) and one for development of test benches for converter components and subassemblies.

A fundamental outcome of the project is an operational test field for d.c. voltages up to 15 kV and a few hundred amps that has been built up at TUBS. In cooperation with PTB an electrical power loss measurement system has been established to characterize and determine high power Insulated gate bipolar transistors (IGBT) module switching and loss behaviour as single switch, IGBT stack or in sub-module configuration [1].

IGBTs are capable of fast switching between on- and off-state. For switching process, a time delay between electrical measured current and voltage signals can lead to a significant miscalculated power loss value. A digital transient recorder system with measuring heads connected via optical fibres is used to achieve galvanic isolation in the high volt d.c. test field. Test objects are high power IGBT modules. Solutions for time delay compensation at measurement system components are presented at conferences [2, 3].

On-state loss is a relevant amount of IGBT total loss. For on-state loss determination the time delays of some nanoseconds have low relevance. The challenge in precise on-state loss measurement for IGBT modules lies in the abrupt break-down of the collector-emitter voltage from up to 1000 V (or more) to a few volts. A two channel data acquisition system has been introduced for precise voltage measurement in this wide measuring range [4]. The first low sampling rate (LR) channel is supplied with a discriminator allowing a chopping of the high voltage portion of the transient. The second high sampling rate (HR) channel acquires high gradient voltage/current transients during IGBT switching.

A PSPICE IGBT converter model was introduced. The IGBT switch-on energy losses, switch-off loss as well as conduction loss are processed separately. A sub-model of a switch-on energy loss acquisition circuit is equipped with a peak detector and pulse chopper allowing for a simultaneous processing of voltage/current quantities at switch-on. Experimental data of the switch-on loss are converted with Delaunay triangulation to construct a 3D surface of the loss in dependence on IGBT voltage and collector current at commutation. The introduction of the interpolation function of the Delaunay surface in SPICE model allows a continuous processing of the switch-on energy loss with high accuracy [5]. The processing of the switch-off loss is performed in the same way taking into account opposite sequence of the chopped voltage/current transients.

Experiments and simulations were successfully performed to provide a first stage of effective reference instrumentations to application engineers to achieve optimised IGBT converter operation and the prediction of IGBT loss.

3.1.2 Construction of a voltage and current measuring system for ohmic and switching losses

A digital recorder system has been calibrated and adapted for measurements of IGBT loss and calibrated for d.c. in all ranges with d.c. levels of 95 %, 10 % and 5 % of the ranges. The relative deviation is less than 0.5 % for all measurements. In a.c. calibration, all ranges were calibrated with three a.c. voltage levels with frequencies of 100 Hz, 1 kHz, 10 kHz and 100 kHz. The relative deviations were less than 1 % for all measurements and less than 0.5 % for the majority of the measurements. Impulse voltage calibration: All ranges were calibrated with positive and negative impulses 0.84/60. The relative deviation of the peak voltage was less than 1 % for most of the measurements. The relative deviation of the front time was less than 0.7 % and of the time-to-half value was less than 0.6 % respectively. A 2 kV probe for IGBT measurements was tested with step voltages and impulse voltages. The relative deviations were less than 1 %. The test setup is shown in

Figure 1. The subject was further discussed at the 17th ISH in 2011 [1].

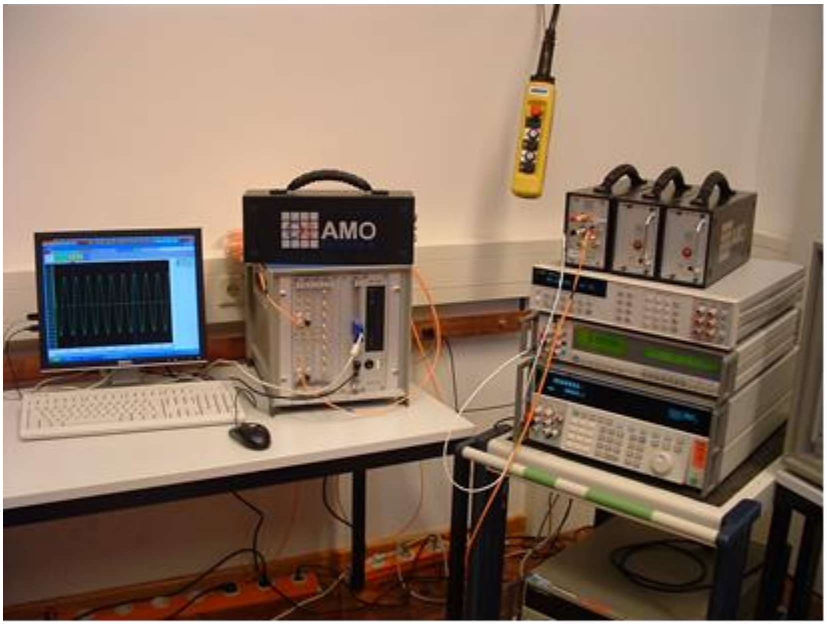

Figure 1: AMO Saturn in DC-measurement setup

A voltage limiting circuit for use in IGBT loss measurements during the conducting condition of the IGBT has been developed and verified. The circuit is used by TUBS for loss measurements. The results are shown in an IEEE publication presented at the AMPS 2012 in Aachen under the title "*Discriminative Acquisition of Power IGBT Low Rate Transients*" [4].

For fast current measurements a Pearson probe Mod. 110 with a 10:1 attenuator was tested and verified. The results are published at PCIM Europe 2012, 08-10 May 2012 Nürnberg, Authors: Ole Binder, Johann Meisner, Michael Kurrat, Matthias Schmidt, Martin Kahmann. Title: "*Impact of time delayed current and voltage signals on IGBT loss measurement*" [2].

3.1.3 Development of a loss power measurement system

A simplified schematic for the loss measurement setup for voltages up to 20 kV (peak) and currents up to 200 A (peak) is shown in Figure 2. Various a.c. and d.c. voltage and current transducers adapt the high voltage and high current to the ranges of the multi-channel power analyser.

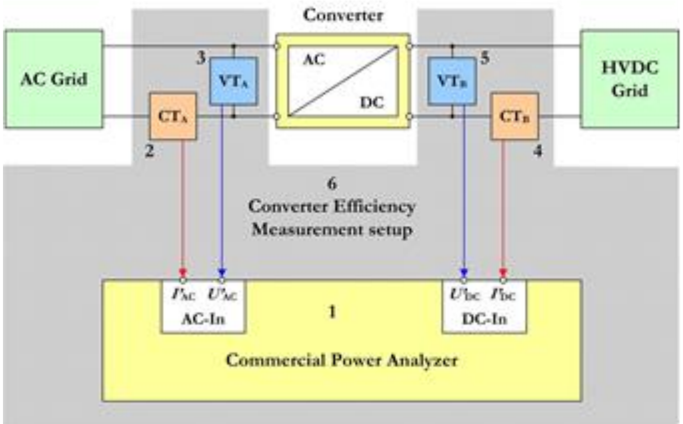

Figure 2: Simplified schematic for the converter loss measurement system for determining the efficiency.

For power measurements at the d.c. side of HVDC converters two 20 kV Ross dividers were bought and investigated. To remove influences from the input impedance of the measuring devices, a buffer amplifier was built. A linear integrated circuit which is matched to the output resistance of the Ross-Dividers (10 MΩ) was constructed and assembled. The frequency response was measured with a calibrator and two precision digital multimeters. The matching of response at high and low frequency is not perfect and could possibly be adjusted. On the other hand, these dividers are to be used to measure d.c. voltage, where the high frequency content is negligible, and therefore no impact on the measurement uncertainty is foreseen. Generation and measurement of superimposed ripple was further discussed in [6].

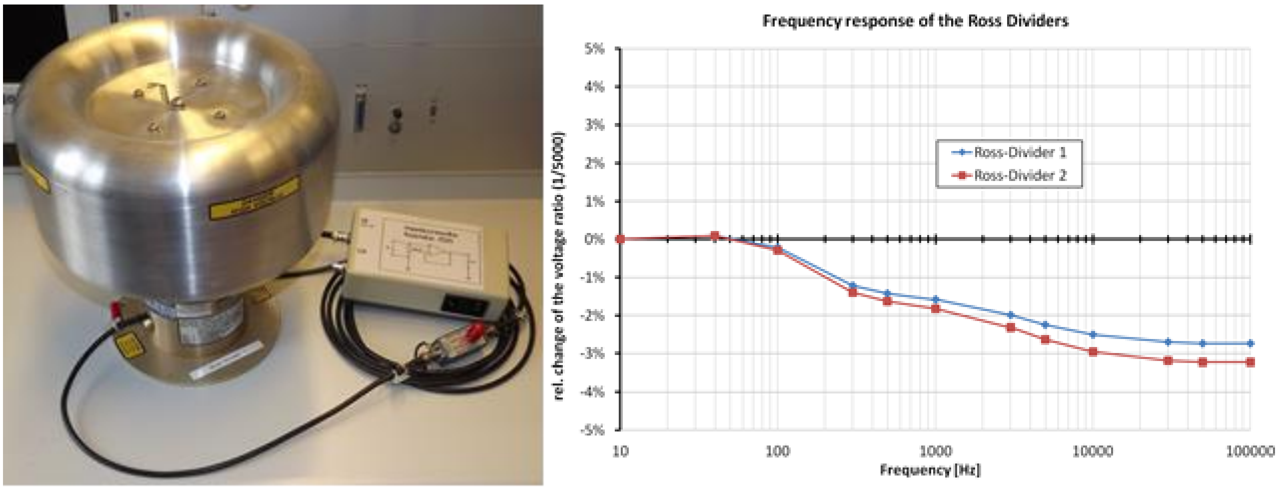

Figure 3.Left: Ross-Divider with the active impedance converter Right: Frequency response of the Ross Dividers

The results of the linearity test and the influence of humidity and temperature are shown in Figure 4 below. The results are good and prove that the dividers exhibit a negligible sensitivity to the environmental parameters tested.

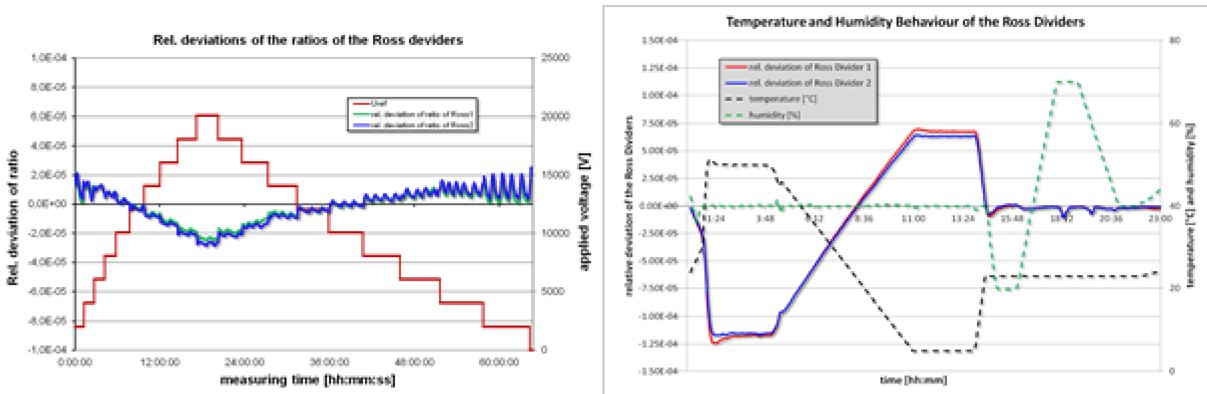

Figure 4: Linearity over voltage range (left) and temperature and humidity behaviour (right) of the Ross 20 kV dividers

Zero-flux transducers equipped with high-precision shunt resistors at the secondary side were used to measure the high d.c. currents. The shunts were developed and calibrated for this purpose and the self-heating tests show a temperature coefficient of less than 0.001 %. The calibration circuit of the LEM zero-flux current transducers is shown in

Figure 5. This was a new calibration setup for d.c. current transducers up to 2000 A that was built up at PTB. The deviations of the calibrated devices at d.c. for different test points between 5 % and 100 % are below 0.01 % with a measuring uncertainty of 0.005 %.

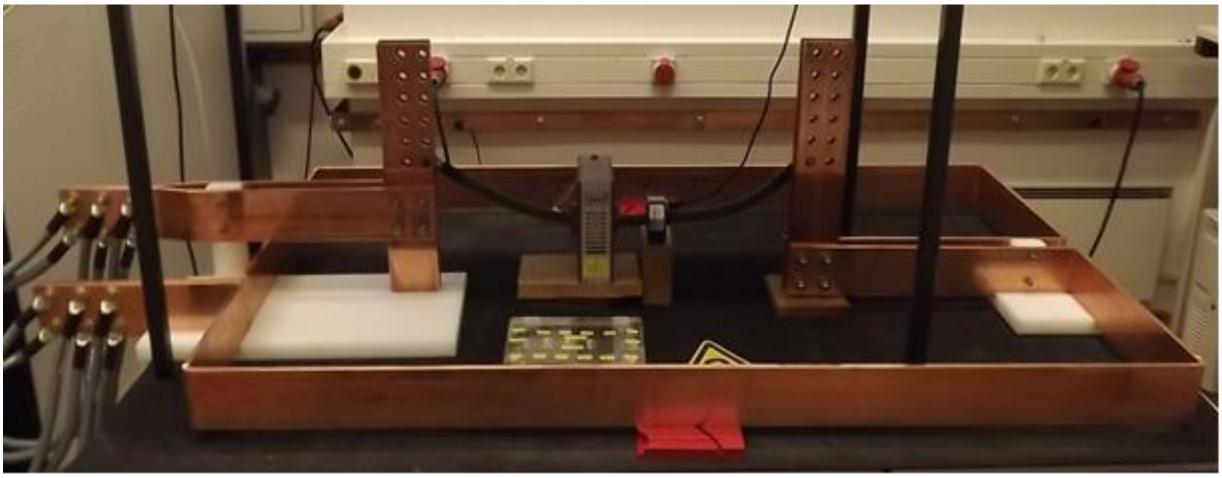

Figure 5: Calibration of the LEM CT

Software to control the power analyser LMG500, and to capture the relevant data has been created in the frame of a student thesis. The work has been reported by Mosquera: "*Erstellung einer grafischen Benutzeroberfläche zur Messdatenerfassung und Bedienung eines Leistungsmessgerätes*", available on the project web-site. A Zimmer LMG500 has been chosen as reference measuring instrument for loss power measurements. It has been calibrated and has been reported within the project.

The power analyser is calibrated for all relevant inputs at a.c. and d.c.. The essential results are:

The power analyser consists of four independent channels, which can be extended to an 8-channel device using an additional slave device. Each channel provides:

- two separate voltage inputs,
- three separate current inputs.

The expanded uncertainty of the complete loss power measurement system including the d.c. and a.c. sensors as well as the power analyser is 0.04 % (k = 2). In order to also include effects that could be correlated, the expanded uncertainty was increased to 0.06 %.

The performance of the loss power measurement system (LMG 500 and a.c. 12kV / 100 A transducers) was checked with a combination of a pulse-width modulated multilevel converter from Siemens, see Figure 6, and a 3 MW motor from ATB Schorch GmbH, Figure 7. This represents an alternative to usually well-filtered HVDC converter.

Figure 6: Photo of the 3 MVA Siemens ML converter - [http://www.automation.siemens.com/mcms/large-drives/en/converters/medium-voltage-converters/perfect-harmony/pages/perfect-harmony.aspx]

Figure 7: Photo of the Schorch 3 MW drive. - [*http://www.schorch.de/html/f,31,High-voltage-machines.htm*]

3.1.4 Creating a reference standard for the quantity "power converter efficiency"

During the project, a reference for the calibration of a multi-channel power analyser was built up. It emulates the typical output signals of current and voltage sensors with an analogue bandwidth up to 20 kHz. The 8-channel generation system can source voltages up to 10 V as well as currents up to 2 A. To achieve this purpose a wideband 3-channel transconductance amplifier was designed with ranges from 1 mA up to 1 A. In order to measure the currents with the voltage inputs of the sampling system with negligible phase distortion, a three-phase shunt with associated three-phase amplifiers with (LF) time constants well below 1 ns were designed. The sampling system makes use of a commercial wideband digitizer (NI 5922). This is a designed sampling controller with integrated instrumentation amplifiers with outstanding common-mode rejection (CMRR > 100dB up to 20 kHz), a dual 8-channel relay matrix, a bipolar d.c. reference voltage and integrated digital circuitry with µC is used as a front-end for the NI digitizer. The performance of the two-channel digitizer has been published in [7].

The reference standard emulates typical a.c. and d.c. waveforms of converters with uncertainties below $20 \cdot 10^{-6}$ for the r.m.s. of the generated a.c. or d.c. voltage or current waveforms and below $40 \cdot 10^{-6}$ for electrical a.c. or d.c. power. Due to the high correlation between the generated a.c. and d.c. power a state-of-art uncertainty of $40 \cdot 10^{-6}$ for the measurement quantity "efficiency" could be achieved with this system. The work will be published by E. Mohns: "Kalibrierensemble für Messsysteme zur Bestimmung des Wirkungsgrades an HGÜ-Umrichtern", as Ph. D, thesis, TU Braunschweig, 2013 (expected to be published in 2014).

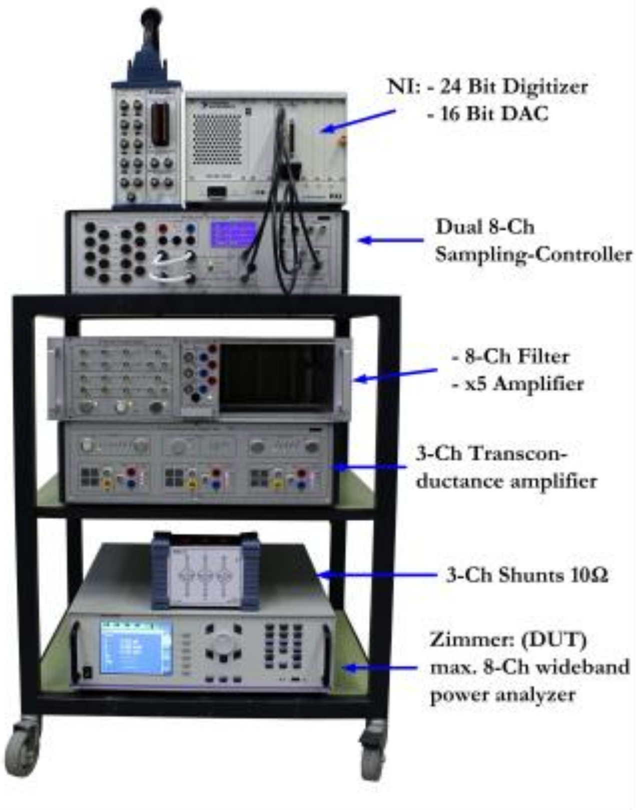

Figure 8: Photograph of the reference standard for the calibration of the converter efficiency.

3.1.5 Analysis of metrological requirements for electrical measurement of HVDC station losses

A scientific paper has been published in IEEE Transactions on Instrumentation and Measurement [8], discussing the requirements on a measuring system intended to measure the losses of switching elements under dynamic conditions and gives background to determine the necessary accuracy in terms of time response. An analysis is also given on methods and requirements needed to measure losses of an HVDC station from a.c. input to d.c. output power. Finally a viable method for measurement of total losses utilizing a back-to-back configuration of two converters is analysed. This last method has been adopted by Svenska Kraftnät (National Grid in Sweden) as the method to prove guarantees on losses in a new HVDC intertie.

3.1.6 Design and construction of test circuit for single IGBT and IGBT stacks

A test circuit for single IGBT and IGBT stacks was built up at TUBS. It was constructed assuming an inductive operation mode. It includes a high voltage d.c. power unit, consisting of three-phase adjustable transformers and a six pulse rectifier that charges a capacitor bank. The experimental investigations were carried out with the large capacitor bank delivering enough energy for a pulse sequence. The bank comprises an array of high voltage capacitors connected together over a low-inductance plate-type transmission line. The storage system consists of 60 µF capacitors with a rated voltage of 2.5 kV. The total capacitance of the storage bank amounts to 18 mF. To quantify the energy losses, voltage probes and current sensors were used to measure the voltage and current signals with a digital recorder (see task described in 3.1.1). Different IGBT test configurations are possible like a classical half-bridge setup with inductive load or a resistive chopper configuration. The test circuitry and measurement system were presented at ISH 2011 conference [1] in cooperation with PTB.

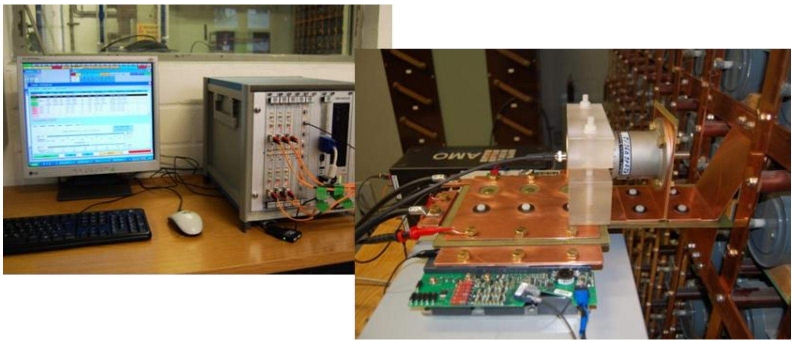

Figure 9: Digital recorder – part of PTB measurement system (left). An IGBT test configuration in the new TUBS HVDC test field (right).

3.1.7 Design and construction of test circuit for sub-modules

An advanced IGBT test bay was constructed for investigation of energy loss of semiconductor arrays and sub-modules. Power circuitry includes the regulation and conversion units for continuous delivery of HVDC energy. IGBT test side includes two HV columns, each consisting of series connected semiconductor stages that can be adapted for different IGBT and sub-module test configurations. The introduced topology enables a variable number of stages as well an introduction of the inductive and resistive units, which allows both modes of the operation. The test circuit provides a number of enhanced investigation opportunities compared to the test circuit established in task described in 3.1.6. The operational advanced test field increased the highest possible d.c. operating voltage to 15 kV.

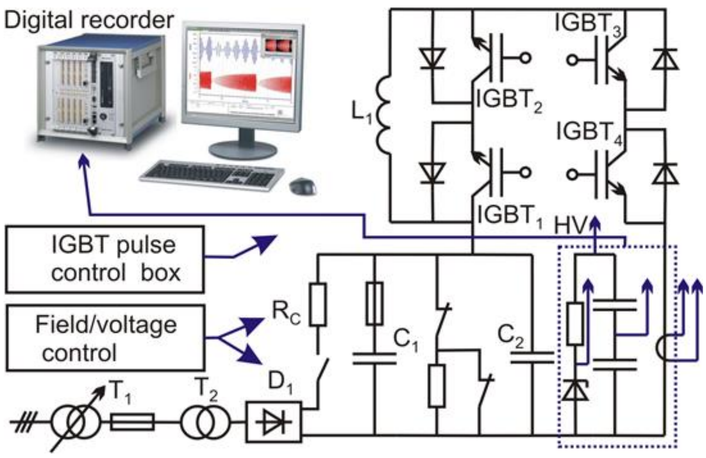

Figure 10: Advanced test field for characterization of IGBT samples, IGBT stacks and sub-modules.

3.1.8 Characterisation of IGBT samples, IGBT stacks and sub-modules

IGBT samples, IGBT stacks and sub-modules were characterized. The experimental tests were performed with a half bridge converter setup in inductive operation mode. Switch-on and switch off transients were acquired with broad-band modular voltage probe TT-HV 250 made by co. TESTEC and a Pearson current monitor of model 110 made by co. Pearson Electronics. The voltage/current quantities were converted with digital transducer of type Saturn System made by co. AMOtronics at a sampling rate of 100 MS/s. The voltage transients in the conductive stage of the IGBT operation were acquired with a novel Zener discriminator allowing necessary measurement precision. See Figure 11. This characterisation procedure with two channel data acquisition was presented by TUBS and PTB at AMPS conference 2012 [4].

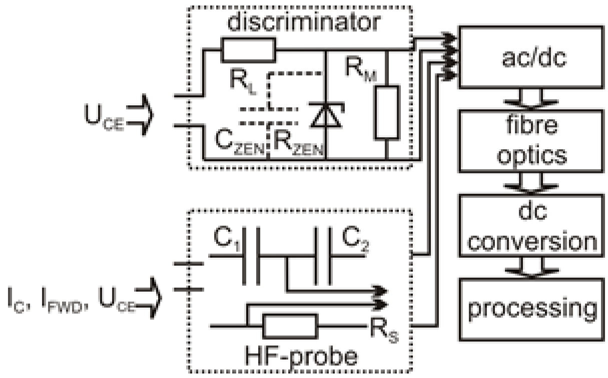

Figure 11: Two channel data acquisition system.

3.1.9 *Parameter identification and development of an IGBT stack model*

A simulation model was introduced based on a model of the IGBT converter built-up in PSPICE. The switching loss and conduction loss were processed separately in the proposed model. The SPICE model includes sub-circuits that chop of voltage/current transients to the acquisition period. In the following the data was used for an acquisition of the loss with 3D surfaces. Processing of the energy loss set in 3D space with Delaunay triangulation and following the approximation of the surfaces with analytical functions enabled a prediction to be made of the switching loss in the entire space of the IGBT settings. This knowledge was published by TUBS and PTB in IEEE [5].

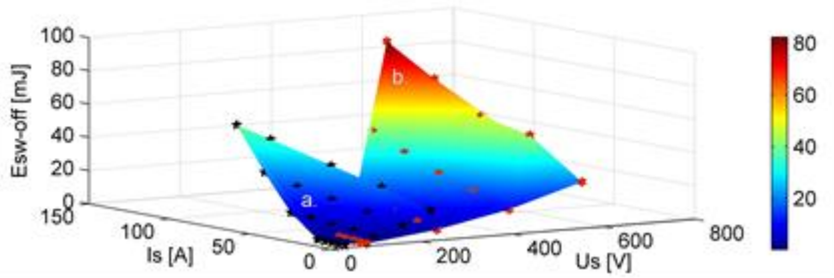

Figure 12: Acquisition of the loss with 3D surfaces. Switch-off loss of IGBT (a.) and stack loss (b.).

3.1.10 *Impact of operating parameters*

The influence of the stray inductance was estimated using a SPICE model of the sub-circuit. The switch-on and switch-off transients were compared with the experimental data.

The efficiency of the power converter is affected by two groups of factors. The first one includes characteristics of the IGBT. Its transfer characteristic affects conduction loss as well as the switching and gating parameters influence directly the switching losses. Converter topology and voltage/current/gating setting form the second group of parameters influencing converter efficiency. The gating frequency and impulse duty cycle affect the voltage quality as well play important role for distribution between switching and conduction loss. In the process of converter design, the IGBT gate control is of primary importance due to its impact on the switching voltage/current transients. The gate voltage and driver impedance are counted among the parameters of gating. Stack packaging and feedback topology are external characteristics of the converter affecting its efficiency as well. Proper design of the stack allows mitigating the voltage surges during switching, in this way reducing demands on over-voltage protection. Well-designed feedback circuitry contributes to the voltage quality as well to the reduction of the energy loss.

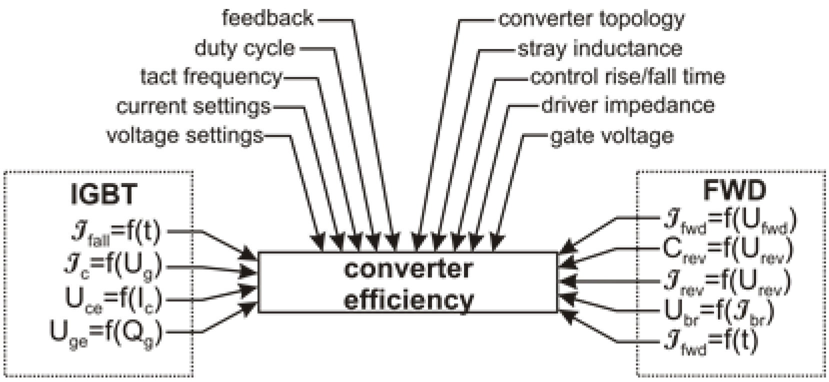

Figure 13: Operation parameters affecting converter efficiency.

3.1.11 Progress beyond the state of the art for measurement of converter loss

The project made considerable advances in the measurement of losses in HVDC converters, developing traceable measurements of loss power, both for components and subassemblies, but also for entire converter stations. New reference standards for calibration of loss measurements were developed and verified. The work has been performed in cooperation between PTB and TUBS. Measuring systems have been developed at PTB and have then been used at TUBS for the experimental work on converter components.

A fundamental outcome is the operational test field for IGBT and IGBT assemblies operating at d.c. voltages up to 15 kV and a few hundred amps that has been built up at TUBS. In cooperation with PTB an electrical power loss measurement system has been established to characterize and determine high power IGBT module switching and loss behaviour as single switch, IGBT stack or in sub-module configuration [1]. The measuring systems were verified and calibrated by PTB.

Among the advances made at PTB can be mentioned development of a reference for loss power, which enables calibration of measuring systems for convertor efficiency.

IGBT are capable of fast switching between on- and off-state. For a switching process, a time delay between electrical measured current and voltage signals can lead to a significant error in calculated loss power value. It was proven that for the switching process in the 100 ns range, a time delay between measured electrical current and voltage signals can lead to an error that is approximately 4 % per 10 ns of time delay. Solutions for time delay compensation of measurement system components were presented at conferences [2, 3]. A digital transient recorder system with measuring heads connected via optical fibres was used to achieve galvanic isolation in the high-voltage d.c. test bay. The test objects were high power IGBT modules.

On-state loss constitutes a significant amount of IGBT total loss. For on-state loss determination the time delays of some nanoseconds are negligible. The challenge in precise on-state loss measurement for IGBT modules lies in the abrupt break-down of the collector-emitter voltage from 1000 V or more to a conduction mode level of a few volts. A two channel data acquisition system has been developed for precise voltage measurement in this wide measuring range [4]. The first low sampling rate (LR) channel is equipped with a discriminator that allows disregarding the high voltage portion of the transient. The second high sampling rate (HR) channel acquires high-gradient voltage/current transients during IGBT switching.

A PSPICE IGBT converter model was developed. The IGBT switch-on energy loss, switch-off loss as well as conduction loss, are processed separately. A sub-model of the switch-on energy loss acquisition circuit is equipped with a peak detector and pulse chopper allowing for simultaneous processing of voltage/current quantities at switch-on. Experimental data of the switch-on loss are converted with Delaunay triangulation to construct a 3D surface of the loss in dependence on IGBT voltage and collector current at commutation. The introduction of the interpolation function of the Delaunay surface in SPICE model allows a continuous processing of the switch-on energy loss with high accuracy [5]. The processing of the switch-off loss is performed in the same way taking into account opposite sequence of the chopped voltage/current transients.

Experiments and simulations were successfully performed to provide a first stage of reliable reference instrumentation to application engineers charged with achieving optimised IGBT converter operation and to predict IGBT loss.

A scientific paper has been published in IEEE Transactions on Instrumentation and Measurement [8], discussing the requirements on a measuring system intended to measure the losses of switching elements under dynamic conditions and gives background to determine the necessary accuracy in terms of time response. An analysis is also given on methods and requirements needed to measure losses of an HVDC station from a.c. input to d.c. output power. Finally a viable method for measurement of total losses utilizing a back-to-back configuration of two converters is analysed. This last method has been adopted by Svenska Kraftnät (National Grid in Sweden) as method to prove guarantees on losses in a new HVDC intertie.

3.2 Objective 2: Extending high voltage calibration capabilities - laboratory references to ± 1000 kV

3.2.1 Introduction

A prerequisite for measurement of losses of HVDC converter equipment, reliable dielectric testing and metering of energy transmitted on HVDC interties is the accurate and reliable measurement of high d.c. voltages. European traceability for d.c. voltages has been extended to much higher voltages through this research. To ensure reliable and accurate calibration of d.c. voltages up to 1000 kV, a dual approach was chosen to develop a laboratory reference that will be used only in-house at the national metrology institute SP in Sweden, and a modular divider system that can be transported to any location in the world, to bring the traceable calibration to where it is needed by industry. The laboratory reference is described in this section.

3.2.2 Extension of the maximum voltage of an existing HVDC divider

The overall d.c. specifications for accuracy of the 1000 kV Laboratory reference divider are better than anything else built up to now for this purpose. However, the results for the modular divider also produced in the project, and reported in section 3.3, rival the results for the Laboratory reference. The laboratory reference is a purely resistive divider, compared to the modular divider which has a strong capacitive shield. This makes the laboratory system more sensitive to charges such as caused by corona. Charge build-up was indeed observed during the characterization at Aalto University in June 2013 as a charging of a floating middle joint (see Figure 14) in the SF_6 pressurized tube encasing. It manifested as noise in the measurement. This led to a decision to repaint the tubes with a semi-conductive paint intended to conduct the charges to earth. The conductivity of the paint gives about 1/5 of the current floating on this skin compared to the 100 μA through the precision resistors at full 1000 kV and is expected to hinder charge build-up.

Figure 14: The Laboratory reference divider in the circuit at Aalto University in June 2013.

3.2.2.1 Background

Components of a precision voltage divider originally manufactured by Central Electricity Research Laboratory in UK, for application to the calibration of the dividers for the Cross-Channel d.c. Link to France, was acquired by SP, with the intention to increase SP's calibration range up to 1000 kV d.c. The divider comprised 24 modules for 25 kV each, i.e. 600 kV at 100 µA. (It was originally intended for 160 µA at 1000 kV, but this lead to a fair amount of self-heating and thus to unnecessarily large errors.) The components of this divider are identical to the components of other dividers (manufactured by Vishay in the 1990ies) already in use at SP, and another 12 modules have been manufactured using spare Vishay resistors available at SP. The full set of 40 modules was achieved by using one 25 kV spare Vishay module augmented by 3 modules constructed with the same resistor type as used in the modular divider designed for on-site application. The new divider assembly has 1000 kV capability and a precision goal of 0.004 %.

3.2.2.2 Characterisation of the components for the 1000 kV reference HVDC divider

A thorough characterisation was undertaken of the components to be used for the reference divider. The 24 modules acquired from UK were characterised in a temperature chamber, as shown in Figure 15. The temperature coefficient (TC) was found to be (1.5 ± 0.9) 10^{-6}/K.

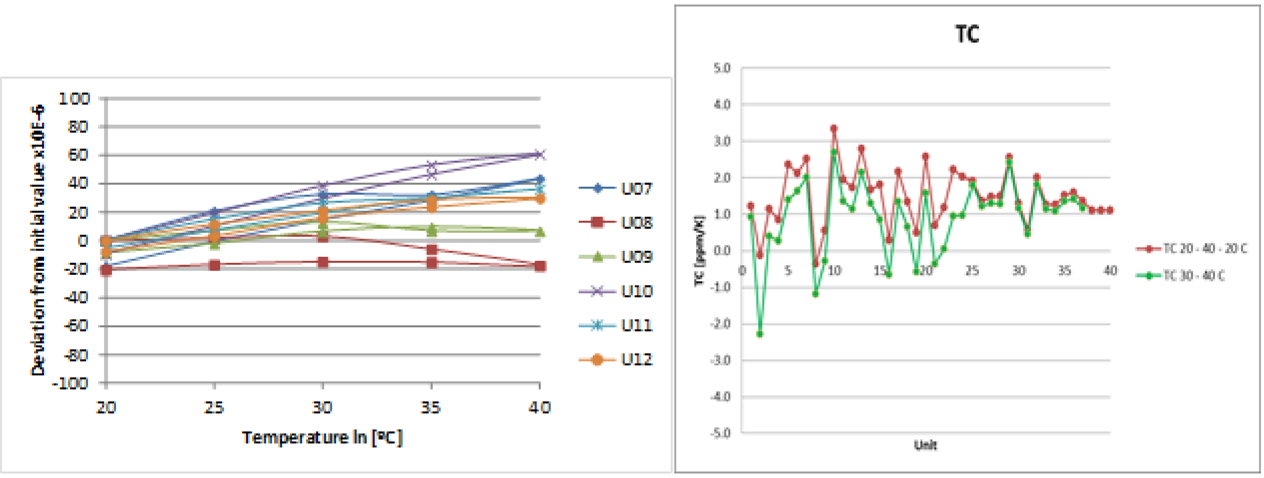

Figure 15: Left graph shows the temperature-induced resistance change for six of the 25 kV modules obtained from UK. The right graph shows the analysed TC of all 40 modules.

These TC values were obtained after replacement of 11 broken resistors using individuals from 330 spare resistors purchased at the time when Vishay-Mann ceased the production of voltage dividers and this type of wire wound precision resistor. A plot of the TC from these spare resistors is given in Figure 16, and the result was a TC of (1.5 ± 1.3) 10^{-6}/K.

Further characterization, based on measurements of the resistance of each of the 600 resistors from UK at 10 V and 1000 V (rated voltage of the resistors), led to replacement of another 18 resistors showing unstable values - defined as changes by more than 0.001 %. The remaining 300 spare resistors were used to build another 12 modules. Yet three modules were manufactured using spare Caddock resistors purchased for building the modular 1000 kV divider. Adding a complete 25 kV module also purchased as spare, provided the required 40 modules for nominal 1000 kV rated voltage of the divider.

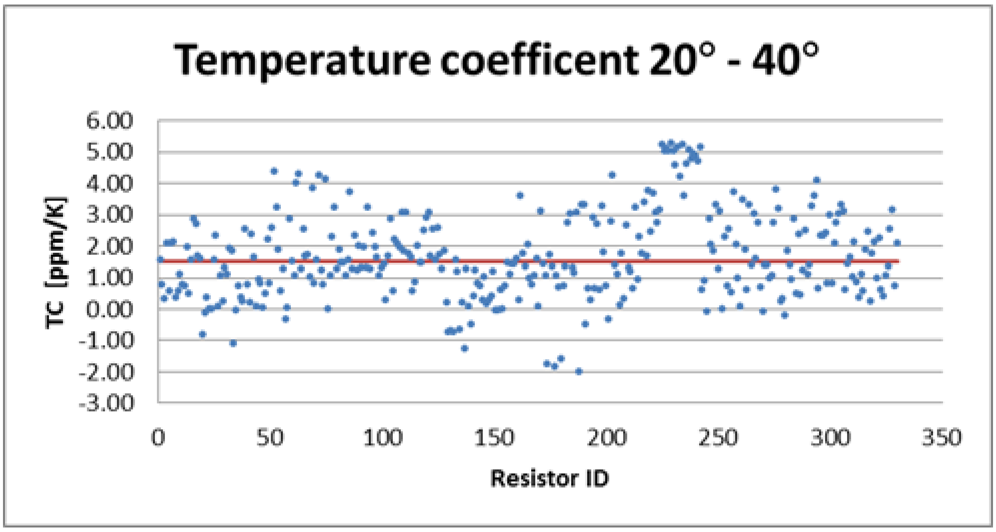

Figure 16: The plot shows the factory measured TC of the spare resistors. These were used for replacement of broken resistors in the UK set and to build another 12 units.

Final testing was performed in June 2013 in Aalto University in Finland, where several 1000 kV dividers were characterised and intercompared. The comparison between dividers of different topology and different divider elements made it possible to verify the respective performance with a high degree of precision. The intercomparison resulted in agreement between predicted and measured values down to 0.001 %, providing a very good basis for further uncertainty estimates.

The divider is intended to be used as the main traceability source in Europe for d.c. high voltage at levels up to 1000 kV.

3.2.3 Characterisation of an existing HVDC divider

MIKES has characterized the 1200 kV divider at Aalto University up to 800 kV in April 2012. The divider at Aalto University consists of 4 modules; each of these modules was characterized up to 200 kV by using MIKES's reference divider with maximum voltage of 200 kV. By combining the results, it was possible to reach an uncertainty of 0.05 % at 800 kV.

The Aalto divider is oil filled, which reduces the self-heating effect during measurement session. It measured to less than 0.01 % for 20 min application of 500 kV. However, the temperature of the oil follows the ambient temperature of the high voltage hall with a long time constant, measured in days rather than hours. In practice this means that for precision measurements, the scale factor should be determined for each calibration task separately.

3.2.4 Literature study of possible alternative methods for providing traceability for high d.c. voltage calibration

A literature search has been conducted to identify physics principles that can be used for measurement of high d.c. voltages. Many of the principles have been known for a long time, although few are in contemporary use. A paper discussing the various principles and their potential has been drafted and will be submitted to IEEE Transactions on Instrumentation and Measurement. Several possible applications have been found among which a method using laser to measure speed o ions seems to have potential and would merit further research.

3.2.5 Development of a new type of high-voltage reference standard

UME developed a new type of high voltage “Zener” reference based on the use of bandgap references (in HVDCZENER-project). The work has been well performed and reported. The results show potential to provide another avenue to establish traceability for measurement of high voltage d.c.

The UME-20 high voltage measurement standard, being tested in MIKES, Finland, proved its extremely high performances. The device may be used as a powerful instrument for high voltage dividers and measuring systems calibration for d.c. high voltages. It gives possibility to calibrate the other references with a high reliability.

The original design of VNIIMS from 1990's was based on temperature compensated Zener diodes. By replacing those with state of the art using the shunt type voltage references, the performance is improved by more than an order of magnitude from 0.006 % to 0.0003 %.

The better performance is due to a number of improvements. The dynamic resistance is lowered from 280 ohm/kV to 40 ohm/kV, which means that the sensitivity to changes in the operating current is improved by a factor of seven. Due to lower operating and applied temperature compensation scheme the self-heating effect is improved by more than an order of magnitude, from c. 0.0015 % to c. 0.000 %.

The temperature dependence of UME-20 less than 0.00003 %/°C is maintained by compensating the each bandgap cell cluster of 500 V using classical Zener diodes.

A custom-made current stabilizer can be replaced by standard equipment, thanks to introduction of new precision instruments into the market. This device gives high current stability in sink operation and the easy applicability. The component cost of this measurement device is c. 20 €/kV and the cost of current source used for stabilizing the current is c. 7 €/V regarding to compliance voltage at the bottom of the device.

3.2.6 Progress beyond state-of-art

A reference divider with excellent characteristics has been developed by SP. It has an uncertainty of better than 0.004 % at 1000 kV, which is the best ever made. It is intended as laboratory reference divider at SP high voltage laboratory, and will see an important use as long-term reference for the calibration of the 1000 kV modular reference divider also developed in the project.

A high degree of confidence could be attributed to the final calibrations at the 1000 kV level because several dividers with different design and components were available at the same place. It is quite probable that they would exhibit different behaviour under high voltage, so that effects should be separable. Especially valuable was the presence of the SP Vishay type divider, together with the modular divider comprising of a total of nine modules. Two major setups of the modular divider were investigated, one comprising the five modules included in the project and one comprising the four modules manufactured by SP. These were compared both with each other and with the SP Vishay divider. The agreement between the dividers over the voltage range up to 1000 kV was an astonishing 0.002 %. A first analysis of the results of the comparison has been made and it proves that the goals of the project are definitely fulfilled. It is however felt that a final analysis could lead to appreciably lower uncertainties and further work is being undertaken after the project. A presentation of this made at CPEM 2014.

3.3 Objective 2: Extending high voltage calibration capabilities - on-site calibration with wide-band d.c. dividers

3.3.1 Introduction

As discussed in section 3.2, new capabilities for measurement of high d.c. voltages have been created. A 1000 kV modular divider has been designed, manufactured, characterized and calibrated with impressive results. A collaboration of five participating NMI’s has brought this work package to its fruition. The objective was to design a 1000 kV modular divider for on-site calibration purposes, having a bandwidth of tens of kHz intended to provide measurement capability also for transients and harmonics but also to protect against transients. The goal for measurement uncertainty was set to be better than 0.01 % at 800 kV d.c. The outcome of the project surpasses the goal as the divider has a measurement uncertainty better than 0.005 % at 1000 kV and a bandwidth surpassing 100 kHz. SP, who invested in four extra modules to achieve 1000 kV capability on their own, has already performed a successful on-site calibration to 600 kV in England in the spring of 2013. MIKES did the same in Finland immediately after the final project meeting in June 2013 in Helsinki. In October 2013 SP demonstrated the full capability of the modular concept with a 1000 kV calibration in Japan (Figure 17).

As it was early realized that stray capacitance will influence the frequency response of the divider, and a concept with two separate divider branches was chosen. A centrally placed precision divider was designed with very high quality resistors mounted on a ceramic support that also acted as a parallel capacitive divider together with appropriate low voltage arm capacitors. A capacitive divider was located as three columns in a triangular pattern surrounding the precision divider column. The objective is to shield the precision branch from effects of stray capacitance to earth and to other high voltage electrodes. Bleeder resistors were installed across all capacitors to stabilize the d.c. distribution. The connection between modules for the shield branch is achieved using the upper and lower flanges of each module. The precision branch on the other hand is brought through the flanges with a connector that automatically mates from top flange to bottom flange when stacking the modules, thus effectively isolating the two branches from each other. The low voltage arm for the divider consists of two parallel branches, one that is connected to the precision branch and one to the shield branch. Both low voltage arms have adjustable resistors and capacitors to permit to balance the response over frequency.

The work has been a good example of how results have been achieved by collaborative work between several institutes, leading to advances that could not have been achieved by a single institute. All participants in the work package have contributed, with main input coming from MIKES and SP. Collaboration between partners has been performed in large part by WEB-meetings organised by the Work Package Leader. Ten meetings with all participants have been conducted. In addition about twenty ad hoc web meetings have been organized to clear out details in smaller groups. Final assembly was performed in collaboration between several of the partners, and performing the work at SP.

Figure 17: The modular divider erected for on-site calibration at 1000 kV in Japan.

3.3.2 The complete 1000 kV modular d.c. divider

3.3.2.1 Characterisation

A characterisation of the complete assembly was performed in June 2013 at Aalto University in Helsinki, Finland. The arrangement for calibration is shown in Figure 18. The modular divider stands in the foreground, hooked up to the dark blue generator with its divider next to it, and the blue ±1000 kV Laboratory Reference at the far end of the lab.

Figure 18: Calibration of the full 1000 kV modular divider (foreground) and the 1000 kV reference divider (the blue column in the background) at Aalto University in June 2013. The Aalto divider is on the midpoint.

Each 200 kV module was calibrated against references from MIKES and SP prior to stacking of the full 1000 kV divider. The reference resistor in each of the five low voltage arms was characterized prior to the assembly of the low voltage arms. A balancing of the divider has to be performed before a measurement to reach the high bandwidth of 100 kHz, necessary for prevention of internal flashovers in case of transients in the circuit. The -3 dB bandwidth of the full 1000 kV divider is well above 100 kHz, as shown in the frequency response measurement of Figure 19, being in line with the vague “high kHz range” target set in the contract.

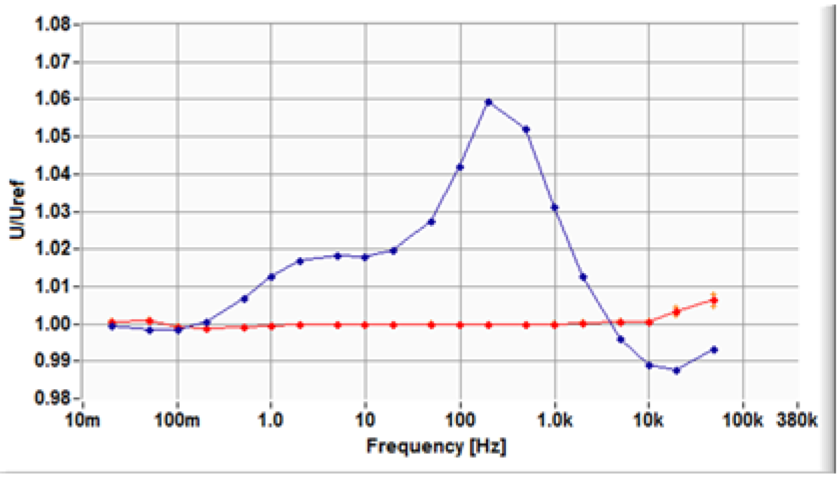

Figure 19: The relative frequency response of a balanced 1000 kV divider. The blue curve is the precision divider response and the red curve the shield response relative a reference divider.

An effect of stray capacitances to other grounded objects in the lab can be observed in Figure 19 as a plateau in the response of the precision response between 1 and 10 Hz. This stray capacitance affects the shield stack balance (not observable in this scale), which works as a capacitive divider in this regime, and couples into the precision stack which has a 5000 times lower capacitance and is therefore more sensitive to stray capacitance. In Figure 27 the response is plotted for a single 200 kV unit, where no apparent effect of stray capacitance can be observed due to the very small difference in stray capacitance from the top and from the bottom of the unit. The grading for the 1000 kV systems is optimized for a typical distance to grounded objects in the lab. Changing the distance will change the amplitude of the plateau and can also shift the effect to give a “recess” in the signal. The scale factor change from 100 Hz to 10 kHz is an effect of stray capacitance between the shield stack and the precision stack, where the precision divider changes from a dominantly resistive to a capacitive divider.

A paper with the title “Design and performance of a wideband 1000 kV HVDC modular reference divider” was presented at ISH2013 in Seoul, Korea [9].

A comparison between the Modular 1000 kV and the Vishay 1000 kV divider is shown in Figure 20. The quotient is stable within 0.002 %. The noise at high voltage is attributable to corona from the high voltage circuit at the highest voltages. It is surmised that noise is predominantly coupled through the Vishay divider. It is expected that the repainting of the Vishay with conductive paint will reduce the noise.

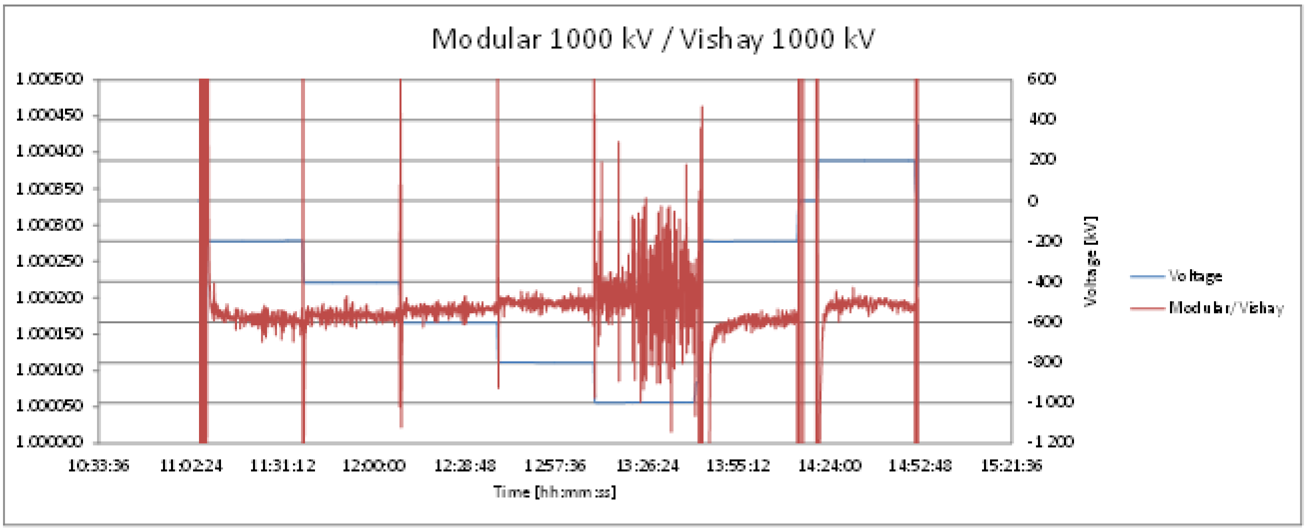

Figure 20: The quotient of the signal between the modular divider and the 1000 kV Laboratory reference divider is shown together with the applied voltage.

The expanded uncertainty (k=2) of the scale factor of the modular divider has been conservatively estimated to be better than 0.01 % at 1000 kV, and the laboratory reference divider is better than 0.004 %. The modular divider has a very high immunity to corona and other transients, whereas the purely resistive laboratory reference divider is affected by it. At lower voltages the uncertainty decreases as expected (see Figure 26 in section 3.3.6).

3.3.2.2 Traceability of the scale factor

Method 1

The scale factor of each divider is calibrated at different voltage level as the ratio of the known input and output voltages. In the measurements performed in June 2013 in Aalto, the measurements traceable to MIKES standards have been performed at 1 kV and 10 kV levels and to SP standards at 40 kV level.

The resistance of the low voltage arm of the precision branch is calibrated in a four terminal arrangement with an Agilent 3458 in comparison with a reference resistor.

The resistance of the high voltage arm of the precision branch is calibrated by voltage/current method as the ratio of the input voltage and current measured by the calibrated low voltage arm resistor.

The scale factor of any stacked setup can now be calculated using the calibrated resistances of the stacked modules and the low voltage arm used.

For the most accurate calibration measurements the linear voltage coefficient, − 0.0009 % from zero to nominal voltage, can be corrected for.

This method has been used for analysis of the measurements of the measurements of June 2013, and it can be used to for any combination of high voltage modules with any low voltage box.

Method 2

The high voltage arms can be used to create a Hamon parallel/series resistor. Five (for example) modules can be connected in parallel to feed one low voltage resistor, and the resistance of this parallel connection can be measured by voltage/current method. As the standard deviation of the resistances of the high voltage modules is less than 0.1 %, the ratio of the resistance in series and parallel connection is known within 0.0001 %. It seems that leakage current and connection wire related uncertainties do not limit the uncertainty in this case. Also, if the same resistor is used for both parallel and series connections, it is not necessary to know its absolute value.

This method has not been tested; it is subject for future work.

Method 3

The resistance of the low voltage arm of the precision branch is measured in a four terminal arrangement with an Agilent 3458 in comparison with a reference resistor. The resistance of the high voltage arm of a module is measured in a Wheatstone type bridge configuration using two calibrators in one branch, the unknown high voltage resistance and a reference resistor in the other and nulling the current by measurement with an electrometer (Figure 21). The scale factor is then calculated from these results.

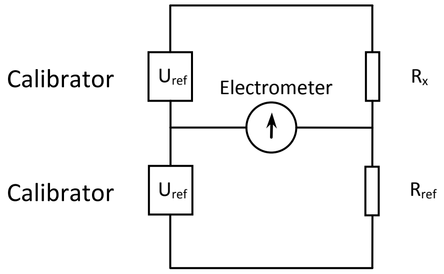

Figure 21: The Wheatstone type bridge set-up for precision measurement of an HV module (250 MΩ - 2 GΩ).

3.3.3 Designing the modular HVDC divider

A 3D CAD software was used for the mechanical design. First draft of the divider drawings was completed by MIKES in August 2011. They were updated according to the feedback from the participants, and the second draft was agreed on in November 2011. The first module was assembled in June 2012. Only minor modifications into the mechanical design were introduced from the experience during the assembly. A complete set of drawings of the design has been developed for use in future development or production.

The general design was complemented by field simulation. These field simulations (see Figure 22) confirmed that the modular structure can handle full voltage without corona. The field simulation provided was also used to obtain values for the grading capacitors of the divider to optimize the high frequency performance.

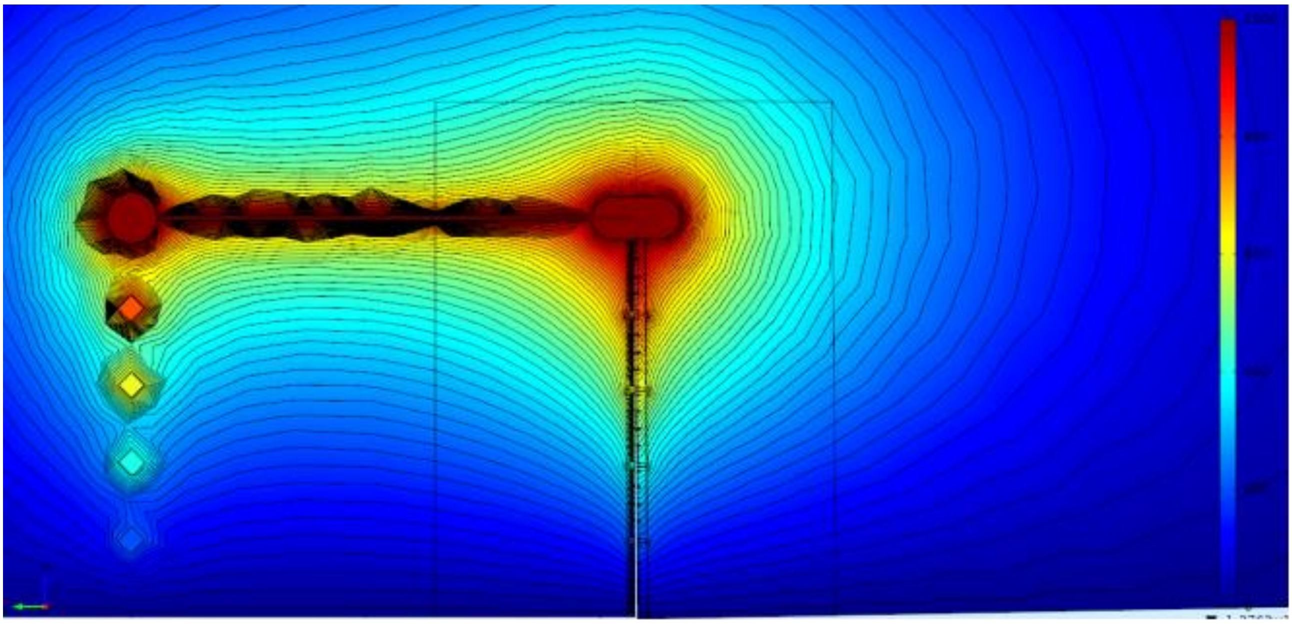

Figure 22. Electric field simulation.. The design divider (in the middle) is in a high voltage hall with a d.c. generator. The electric field distribution is linear along the divider stack.

A paper on the design of the divider [10] and another on the characteristics of the support insulator [11] were presented in the Conference on Precision Electromagnetic Measurements, CPEM 2012, in Washington D.C., USA. A second paper on the field grading was presented at ISH 2103 in Seoul, Korea [12]

3.3.4 Characterisation of components

After a thorough study of possible choices for the resistors, a decision was made to buy these key components from Caddock, USA. An order for 3000 resistors was placed in May 2011, and the first batch of 1500 resistors was delivered in September 2011. VSL characterized 15 % of the resistors in the first batch with respect to temperature, voltage and humidity dependence. The batch was found to perform according to the specifications, and a decision was made in to proceed with the order of the second batch of 1500 resistors.

A paper on the characterization of the resistors [13] was presented in the Conference on Precision Electromagnetic Measurements, CPEM 2012, in Washington D.C., USA.

A characterisation of shield capacitors and bleeders was performed at SP in June 2012 and during assembly in January through March 2013. Some broken capacitors in the shield capacitor banks were discovered during the assembly in March 2013 and were replaced.

3.3.5 Assembly

The first 200 kV module was assembled at SP in June and July 2012, with the help of researchers from UME and MIKES. Only minor problems – e.g. SF_6 leakage due to wrongly chosen O-ring, and droplets of lacquer on fibreglass board – were faced, and quickly corrected. A 50 kV sub-module prototype was on display at SP booth at CPEM 2012 in Washington D.C., USA in July (see Figure 23).

Figure 23. Left: 50 kV sub-module (h = 0.3 m). Middle: 200 kV module internal parts. Right: Complete 200 kV module (h = 2 m).

Ordering and production of the material for the other modules was initiated in September 2012. The assembly work was set to start in mid-January 2013. Some delays in deliveries and quality issues related to the central column were handled and countermeasures were taken. Deliveries of shield capacitors were delayed owing to issues about the grading of the capacitance for the complete 1000 kV stack.

All 200 kV modules of the labs were assembled at SP from mid-January during seven weeks, in a joint effort between MIKES, PTB, UME and SP. Each of the five participating NMI's have ordered one 200 kV module, except for SP who decided to build four additional units at their own expense for a complete 1000 kV system. In total nine 200 kV modules were built. A picture of the precision resistors mounted on the ceramic supports is shown in Figure 24.

Failures of elements in some shield capacitors and bleeders were discovered in March in a characterization of the modules. These capacitors were replaced, and since they were distributed over all modules, the grading of the shield capacitance was adjusted. All modules had to be opened, rebuilt, resealed and re-checked for gas and electrical integrity. This was performed at SP together with MIKES, and finally approved of at the end of April 2013.

Figure 24. The complete set of precision resistors mounted on their ceramic centre columns.

Six low voltage arms were assembled, one for each NMI and one additional for SP. The internal design of the low voltage arm is shown in Figure 25. This box contains one adjustable low voltage arm for balancing of the shield capacitance, one adjustable arm for the shield resistor arm, one adjustable arm for balancing of the precision arm capacitance and a fixed precision resistor for the precision arm. Additionally a micro controller was designed to enable a remote control of the balance of the divider via USB. A sample program was written in VEE and a complete command set is supplied for easy implementation in other environments.

A paper with the title "Optimization of the frequency response of a 1000 kV shielded HVDC reference divider" was presented at ISH2013 in Seoul, Korea [14]. Minimizing the inductance of the shield capacitance in the low voltage arm was the key to achieve the bandwidth surpassing 100 kHz.

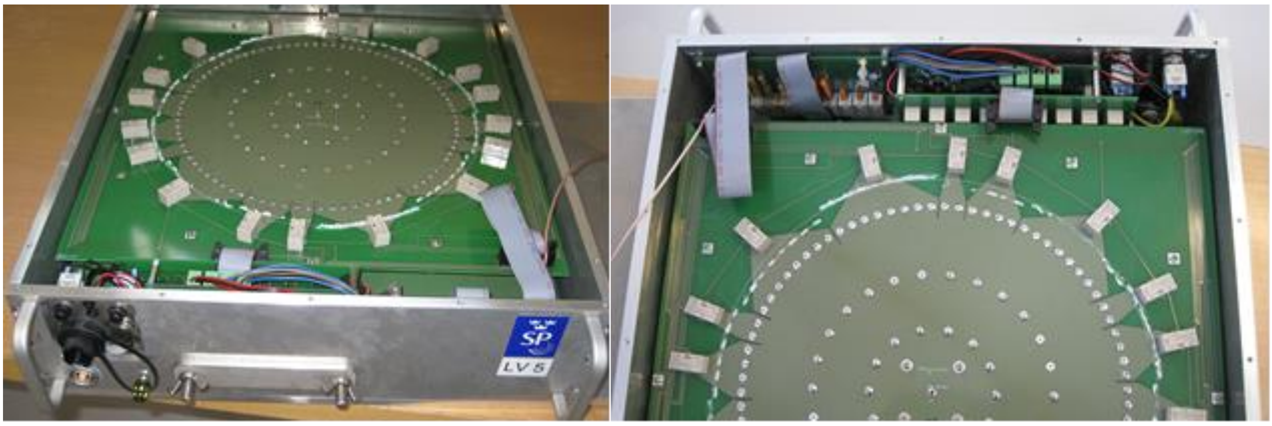

Figure 25: A low voltage arm with the top cover removed. The large board is the low voltage arm of the coaxially built shield capacitance. The other boards are mounted inside of the front panel. The settings are remotely controlled via a USB connector.

3.3.6 *Characterisation of the 200 kV modules*

The characterisation of the first module started at SP in June 2012 and continued in July at PTB. Preliminary results are in line with the original design goal. According to preliminary measurements at SP (see Figure 26) the d.c. uncertainty of the 200 kV module is less than 0.001 %, which is well below the 0.01 % target set for complete 800 kV system.

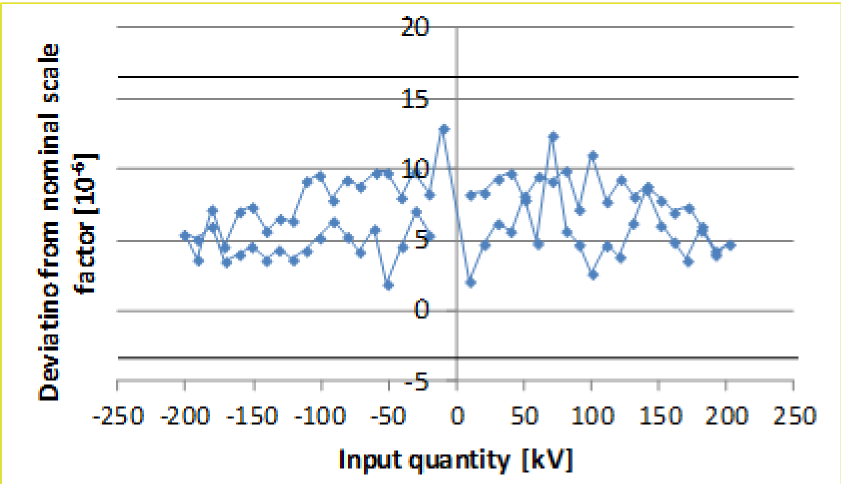

Figure 26. The divider shown in Figure 23 was compared with SP reference divider. The voltage was raised from 10 kV to 200 kV, and then lowered from 200 kV down to 10 kV; and then this was repeated using negative voltages. The black horizontal lines show 0.001 % deviation.

The -3 dB bandwidth of the 200 kV module is well above 100 kHz, as shown in the frequency response measurement of Figure 27, being in line with the vague “high kHz range” target set in the contract. The other modules were characterised and calibrated by MIKES at Aalto University in May 2013.

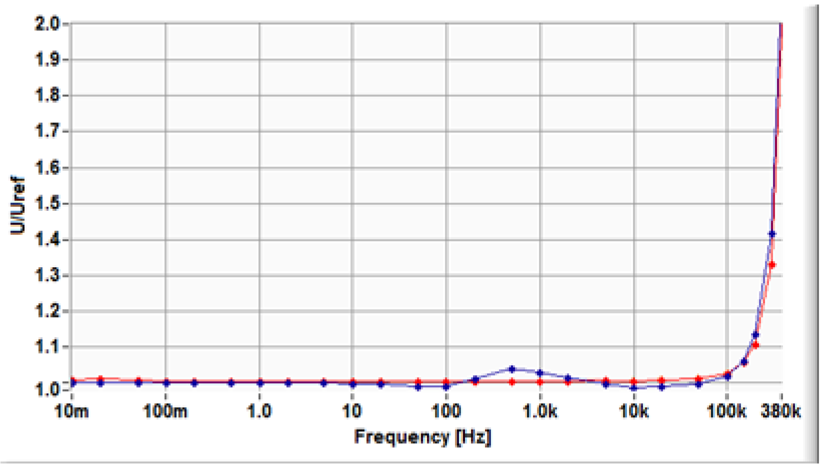

Figure 27: The relative frequency response of a balanced 200 kV module. The blue curve is the precision divider response and the red curve the shield response relative a reference divider.

3.3.7 Progress beyond state-of-art

A mobile reference divider with excellent characteristics has been developed with an uncertainty of better than 0.01 % at 1000 kV, which rivals the best designs ever made and was achieved even for on-site calibration. That it fills a real need is clear since already during the project there were two commercial calibrations at 600 kV carried out, followed by another one at 1000 kV immediately after the project.

3.4 Objective 3: Assessment and analysis of the detrimental effects of poor power quality generated in HVDC substations

3.4.1 Introduction

Poor power quality in an HVDC station can cause disturbances in surrounding grids and possibly lead to interference with other technical systems. Filters are therefore an integral part of such stations and measurements are needed to verify that proper filter performance has been achieved.

The work has centred on installation of power quality measuring equipment in a classical HVDC station. The task was delayed due to unexpected problems to get access to a station. Another station than originally planned was chosen and the measuring system had to be slightly re-engineered to fit the parameters of the new site. Installation was completed in late September 2012 and measurement results were obtained through to the completion of the project.

3.4.2 Assessment of the detrimental effect of typical harmonics and inter-harmonics emitted by HVDC Converters

The HVDC technology is made possible by the development of the power electronics and of solid state switching devices, which for their intrinsic non-linearity, produce fast changes in the currents and the voltages with the result of not negligible distortions. Consequently, the presence of harmonics in the converters from a.c. to d.c. and vice-versa is a normal operative condition for these systems and methods for their reduction have to be designed and implemented.

The modelling of various convertor configurations was carried out with the aim at calculating the harmonic current injected into the transmission system by the HVDC station. These currents combine with the system impedance to produce undesirable voltage harmonic distortion on the system.

Two types of systems: the line commutated converters (LCC) and the voltage-source converters (VSC) have been modelled in which the generation of harmonics, the mitigation by means of filters and the influence on the transmission line impedance and resonance were considered. By applying a distributed line parameters model, the effect of the current harmonics generated by converters was simulated.

In order to understand the impact on power quality, other elements beyond the converters were taken into consideration, such as the transmission line (grid) impedance and the harmonic mitigation filters.

The transmission line has to be modelled by distributed parameters for the frequencies of the harmonics. This means that, when the impedance is not adapted, there can be non-negligible resonances, which can greatly amplify the effects of some harmonic components. Therefore, criteria for an effective design of the filters have been investigated and simulated taking into account both the distortions produced by the converters and the interface with the line.

The possible presence of resonance peaks, which can produce harmonic voltages beyond the limits expected, underlines the importance of grid impedance measurement (3.4.5) over the operational frequency range. Such information is critical to system operators and planners such that the required mitigation filters can be designed and additional precautions taken to avoid such effects.

The results of the study were valuable in preparing and planning the site measurements described in 3.4.3 and 3.4.5. The results of this Task have been submitted for publication in the IEEE Transactions in a paper “Detrimental effects of HVDC converters on the power quality in connected transmission lines”.

3.4.3 On-site measurements of harmonics and inter-harmonics related to HVDC converters

Cooperation has been established with the Swedish Transmission System Operator Svenska Kraftnät (SvK) to enable on-site measurements in an operating HVDC link. The original station selected was the Lindome site in western Sweden and a site visit was been done to plan the measurement campaign, which was planned to start in May 2012. Unfortunately, in April, the site operator subsequently cancelled the measurement for safety reasons due to the presence of heavy civil engineering on the site.

In cooperation with SvK, SP searched for an alternative site with a planned outage and the Sweden-Poland HVDC link (SWEPOL) was selected. A site visit was carried out in August 2012 and a measurement plan was developed and the measurement equipment was installed in the last week of September 2012 corresponding to a 5 day station outage. Measurements were made on two sites (part of the same circuit) located some 0.5 km apart as shown in Figure 28 and Figure 29. Preparations for the measurements included the fabrication of two digitizers, transducers and the procurement of cables and auxiliary equipment.

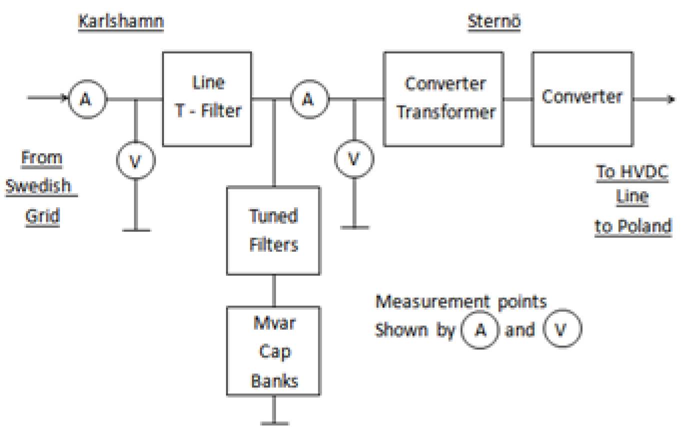

Figure 28. Single-line diagram schematic of the PQ measurement setup at the Sternö HVDC station on the Sweden-Poland HVDC link.

Figure 29. HVDC station measurement installation

Data was obtained from the station up until the end of the JRP. Analysis was performed in order to understand the nature of the power flow on the HVDC link and any correlation with observed PQ events. The results give an interesting insight to the operational characteristics of the HVDC link which show the export of power during the daytime hours between Sweden and Poland.

Associated with the link operation are a number of PQ effects that can be seen at the point of common coupling (PCC) with the Swedish grid.

Firstly, there is a 1.5 % decrease in grid voltage at the PCC proportional to link current when the link was operated. In the context of normal system voltage variations, this increase is not significant and is well within statutory limits. At the moment of link energization, a further step change in voltage of approximately 2 % was observed. Once again, this is not significant in the context of the usual system variation, but may be considered so as an individual system load.

Levels of converter-current harmonics as measured before the mitigation filters (Fig.6) are smaller but similar to that predicted by theory. These harmonics are filtered and the level of current injected to the PCC will give rise to voltage distortion. Voltage distortion measured at the PCC is strongly correlated to link current. The largest converter harmonic, H11 was measured at the PCC as approximately 0.25 % of system voltage.

Harmonics at frequencies non-characteristic of the converter at H3, H5 and H7 were also observed to increase when the link was operated. Increases of approximately 0.2 % in these low-order voltage harmonics at the PCC were estimated, a possible cause being harmonic magnification caused by resonances between the filter banks and the inductance of the grid.

The results will be published in a paper accepted for publication in the IEEE Transactions on Power Delivery.

3.4.4 Characterization of voltage and current transducers for a Frequency Range up to the 50th Harmonic

Shunts have been fabricated to measure the current on the secondary of the installed current transformers. Six of these devices (for two three-phase measurement locations) have been built using multiple parallel metal film resistors to increase power rating and reduce inductance. They are individually housed in coaxial enclosures and the two sets of three further mounted in boxes for protection during the installation on site. The shunts have been fully characterized and have error of less than 0.001 % beyond the 50^{th} harmonic. These devices are shown in Figure 30.

Figure 30. Three current shunts in their box.

The installed CTs cannot be removed from the station for characterization as they form part of the critical infrastructure of the station and are installed in a 400 kV switch yard. In order to determine the frequency response of the CTs a type test was carried out on a similar CT, selection of which was only possible once the site-test station was selected (August 2012). A suitable device was located and permission obtained to move it from SvK (it is heavy and large). However SvK did not allow the CT to leave Sweden and it was necessary for PTB to travel to SP to conduct the calibration. The results of the calibration have been documented in a PTB report.

Voltage measurement were be made using capacitive taps on HV equipment on both sites. Following the selection of the Station, SP fabricated the lower capacitive arm (see Figure 29), used on the tap to form a 230 kV to 200 V divider. The 200 V is then directly measured using the digitizer. Capacitive tap bosses have been purchased (3 off – Figure 29) and PCBs for the lower arms have been fabricated; these were used to measure voltage at one site. Wall mounted, environmentally protected, terminal boxes were to house the lower arm. These can be seen in Figure 29 mounted of the wall of the transformer building. A similar arrangement was used in conjunction with capacitive taps on CTs on the second site.

3.4.5 Determination of grid impedance at harmonic frequencies for the optimal design of PQ mitigation filters

The measurement configuration at the Sternö HVDC station was configured to measure the impedance of the circuit across the line tee-filter shown in Figure 28. This filter consists of line resistance and inductance and capacitance to earth.

Impedance measurements are of particular interest to system designers so that they can design the optimal filter to suppress harmonics generated by the HVDC convertors. This requires that the impedance of the network is measured over a range of frequencies, such that resonant points can be clearly identified, which is corresponding to frequencies of harmonic generation could give rise to serious over voltages and system failures. Generally, the impedance of the network is variable according to configuration of loads and generators connected to the network and a complex plot of impedance at different frequencies includes bounded areas indicating the range of variability in the impedance.

In order to measure the impedances, the voltage drop across the filter was measured using the difference between the two digitizers' measurements on the three phases. The current through the line impedance was also measured. In principle it should be possible to calculate the impedance of the line using these measurements provide that the network is passive, i.e. there are no spurious current or voltage sources at the measurement frequency ii) the three-phase system is balanced.

Such a technique requires that the measurement circuit is energized at the frequency of interest. Whilst the system operates at 50 Hz, there are no other sources of energization except for the convertor harmonics at H11, 13, 23, 25 etc. which are available when the HVDC station is operating.

Tests were carried out using the measurement data and it was found that both of these conditions were compromised to some extent and as a result would introduce variability and uncertainty into the measurement.

Impedance measurements were made over a number of days and whilst their mean values were broadly in line with expected results (from the component values of the filters), the results were highly affected by noise. This is a particular problem because the kernel of the calculation is a small voltage obtained by the difference of two separate 400 kV measurements. Noise at either or both measurement sites often caused big changes in this difference measurement leading similar proportion noise in the impedance measurement.

Signal processing techniques involving thresholding and moving averages were successful in improving the measurement noise to some extent.

An example of the results at H11 (550 Hz) are shown in Figure 31 for the three phases L1, L2 and L3. The results are highly variable during times of no link operation at approximately 17h and 21h. This is because there is no H11 signal when the link is off and these results should be disregarded. The three phases have impedances that are broadly coincident and each tracks the same trend as would be expected. Non-coincidence indicates a level of unbalance in the system. L2 is always lowest, but L1 and L3 alternate as the highest impedance. Changes in level are unexplained; it could be due to the impedance changing although it is more likely that spurious harmonic sources in the system are causing the step changes such as that observed at 00h. This is also probably the cause of the change at 04h when the link current is reduced.

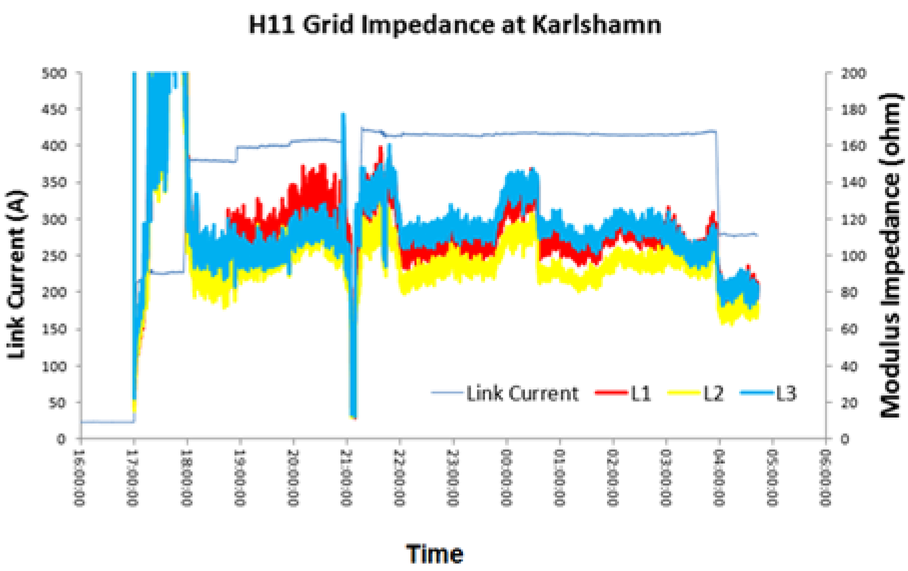

Figure 31, Grid based Impedance measurements at H11 (550 Hz)

The conclusion is that grid impedance at harmonic frequencies is a difficult measurement beset with noise and hindered by the lack of a controllable energization voltage. Further work is required beyond this project in order to improve the measurement technique.

A journal paper, discussing line impedance versus frequency and in the presence of HVDC-generated harmonic frequencies, has been submitted to IEEE Transactions on Power Delivery.

3.4.6 Progress beyond the state of the art for PQ measurements

WP4 was successful in making traceable metrological grade measurements of PQ on a classical HVDC station giving an unprecedented insight into the operation of the link and correlations to various PQ events. Development of the capability, associated measurement equipment, and practical techniques are important for future field-measurements on these HV systems which will be used by system operators and planners to ensure system operation within quality bounds.

3.5 Objective 4: Metering and billing in d.c. grids

3.5.1 Introduction

Transmission grids are almost exclusively built on a.c. transmission, even though d.c. has several distinct advantages such as ability to connect grid areas over weak links or connections between asynchronous grids. Two main technological advances are vital for building true d.c. grids, development of breakers for high d.c. power and ability to meter, and bill, the transmitted energy on the d.c. side. The latter has been in focus in this research, and it brings advantages over a.c. side metering since losses in the converters are not included in the metered energy and therefore leads to a clear definition of energy sold and bought, ensuring equitable billing. At present, documentary standards are lacking in this area.

The work package is pre-normative for HVDC electricity metering, and covers both analogue and digital meters. It has provided lists of requirements and test equipment for such meters. A test bench for analogue meters has been produced as well as one functional test bench for digital meters. An analogue meter HVDC meter demonstrator has been designed and evaluated. It has been installed in an actual HVDC station. The work package also incorporates design and construction of an openable a.c. current transducer to be used for combined a.c. and d.c. measurement for e.g. efficiency measurements of HVDC converters. There were some difficulties in acquiring industrial cooperation, which was solved by opting for an in-house design.
A summary of the work with HVDC metering has been published in IEEE Transactions on Power Delivery [15]

3.5.2 D.C. electricity meters with analogue inputs, pre-normative research

After a pre-normative research a catalogue of requirements for d.c. electricity meters with analogue input was created and released as an internal report, which will be placed at the disposal of IEC TC13 and CENELEC TC13 to support future standardisation. The results are also discussed in an IEEE paper [15].

A survey of the properties of signals from primary transducers was made. The suggested requirements were given with the aid of EN 50463 series which is the standard for Railway applications – Energy measurement on board trains [16, 17] and the general requirements for electronic measuring instruments from the International Organization of Legal Metrology (OIML) [18] as well as the draft for Metrological and Technical Requirements (OIML TC 12/ R 46-1) for a.c. meters [19].

In essence an HVDC meter does not differ from an HVAC meter regarding environmental requirements such as temperature, humidity and mechanical requirements. The requirements for metrological markings are also basically the same. These requirements in this catalogue of requirements are therefore taken directly from OIML [18]

The accuracy requirements were given in a form adapted from EN 50463, where Area 1 represents the full accuracy conditions; while gradually lower accuracy is allowed for the other areas, see Figure 32. The main question has been how to set the lower bounds for both voltage and current and a set of suitable bounds are given in

Table 1.

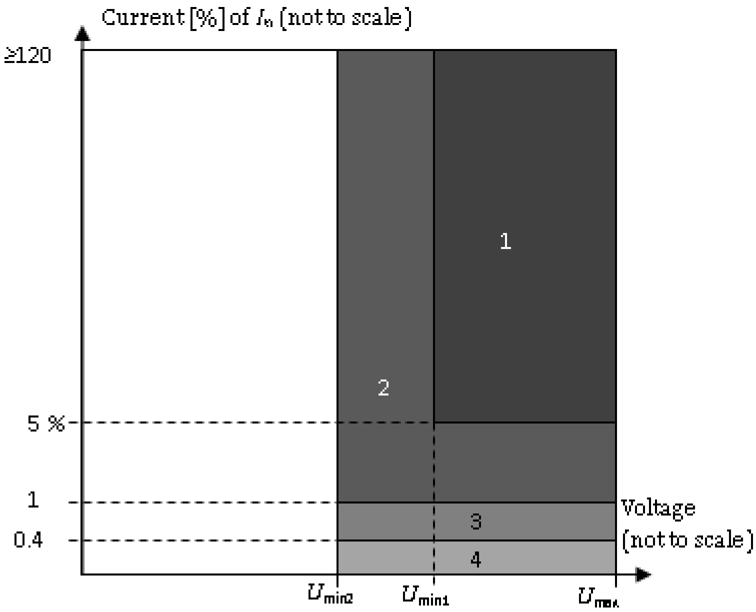

Figure 32. Accuracy requirements for different voltage and current levels.

Table 1. Proposed accuracy requirements

Accuracy class	**± Maximum percentage energy error**				
	Area 1	**Area 2**	**Area 3**	**Area 4**	***I_n* = 0 A**
D	0,2	0,4	1,0	maximum percentage error not defined. Arrangement between manufacturer and customer	Energy calculation shall not count energy
C	0,5	1,0	1,5		
B	0,75	1,5	2,0		
A	1,0	2,0	3,0		

The lower bounds of voltage U_{min1} and U_{min2} are left open to manufacturer, as it may vary with the application. The lower bound for current is rather set by what is technically possible, and is similar to the metering standards for d.c. trains. It is not anticipated that HVDC lines will be driven as low as these boundaries are set.

3.5.3 D.C. electricity meters with digital inputs, pre-normative research

There are several important differences between a traditional a.c.-metering system and a digital measurement system that affect the standardisation. In a digital energy-meter system, the primary transducers for high voltage and high current transmit the secondary values in a digital form to the merging unit. This unit collects the data, time-stamps it, and converts it into the standardised protocol described in IEC 61850-9-2 [20]. At the end of this measuring chain, there is a data processing unit (i.e. essentially a computer with calculation program) and a displaying device that provides indication of the measurand in units of energy, a device which could be regarded as the meter in the system. A “digital energy meter” is thus essentially a calculation program running in a computer. The process of conversion from analogue to digital environment, which is usually associated with a measuring instrument, is now performed before the data reaches the “meter”. This is in contrast to analogue metering systems where the interface between transducers and meters are analogue, typically 100 V and 5 A.

In the case of transducers with digital output we can regard the transducer as a measuring instrument rather than a transducer, providing the instantaneous values of voltage or current for each instance of time. The final measurand, energy, is achieved by combining these digital signals in a computing device, the “digital energy meter”. However, no A-D conversion or analogue signal processing is performed at this stage; therefore, it may be argued that it is not a measuring instrument, nor a meter. No traditional accuracy requirements can be set on the digital meter itself, only functional requirements.

The mechanical and electrical requirements as well as the reference conditions have been summarized for meters that are physical devices. A demand for requirements for meters that are realised as embedded software may be anticipated but will rather be a data security problem than a measurement problem and therefore they are not given in this Catalogue of Requirements.

The transmission of the digital data between merging unit and the meter is covered by the IEC 61850-9-2 standard. There are however a number or optional settings that could influence the metering functionality and which should be verified:

- IEC 61850-9-2 leaves room for two sampling frequencies 4000 S/s or 12800 S/s. (The latter is mainly for power quality purposes.)
- IEC 61850-9-2 leaves room for different numbers of transformers connected to one merging unit.
- IEC 61850-9-2 leaves room for a time/phase angle delay which may be set to any value within a certain range
- It should be considered that voltage data and current data may come from separate merging units.

At the moment it is not decided or there is no information on how the HVDC transducers should be mapped in the merging unit, especially for a multi-pole HVDC station. If the meters have several options available for this, they should all be checked.

The tests for the above items should preferably be done with a simulation unit, and representative curve-forms. An optional such curve-form is given in a PTB report issued for 3.5.4 [21].

The results of this work is presented in a PTB internal report “Requirements for d.c. ”meter“ with digital inputs”, which will be placed at the disposal of both IEC TC13 and CENELEC TC13. Discussion of these results is also given in an IEEE paper [15]

3.5.4 Testing and test methods for d.c. electricity meters

3.5.4.1 Test of meters with analogue inputs

The test set-up hard-ware for meters with analogue input has been purchased and assembled. It is shown in

Figure 33 below. The details of the set-up, which is built of by commercially available instruments, is given in a PTB report [21].

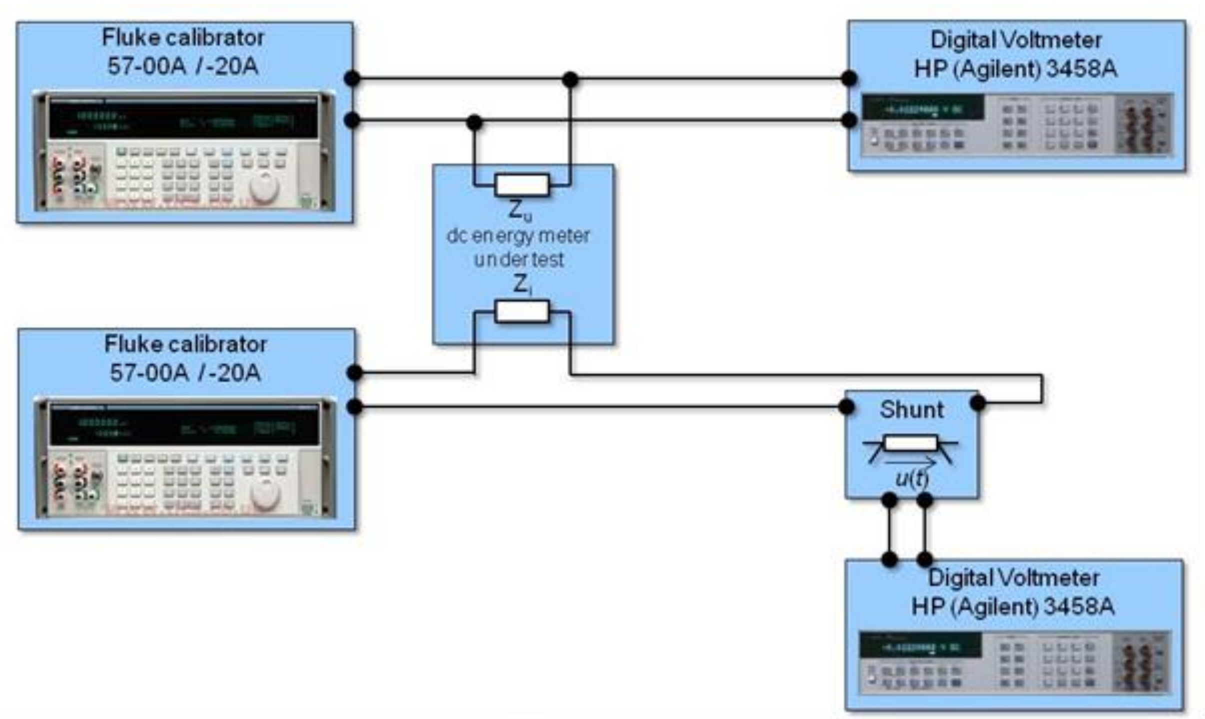

Figure 33. Test set-up for d.c. meters with analogue inputs

Since there have not been any HVDC meters available for evaluation, a commercial a.c. and d.c. wattmeter has been used as a test object during the verification of the test set-up. The result of an accuracy test on this test object is shown in Figure 34.

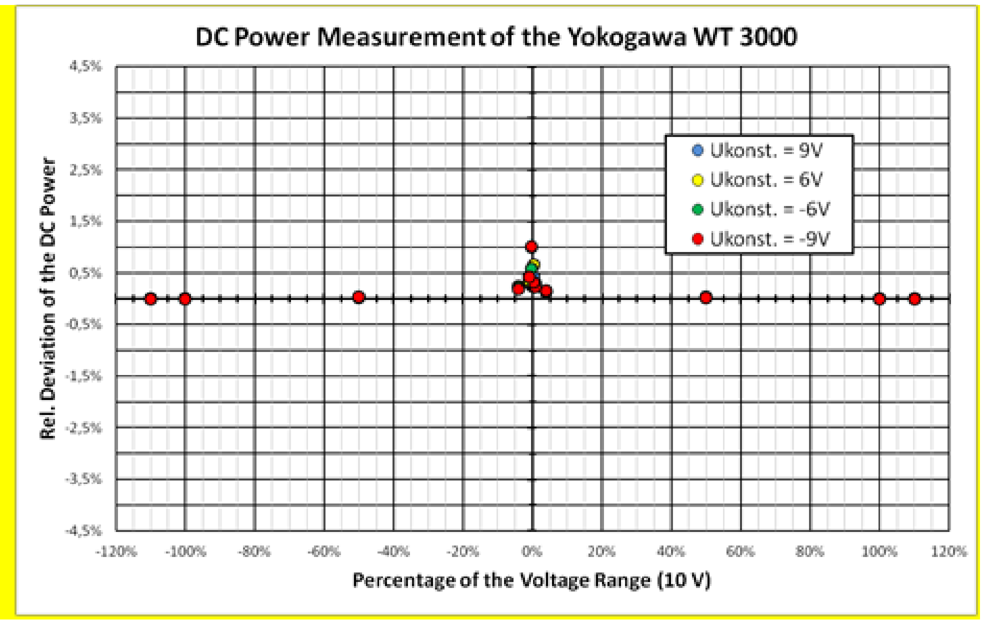

Figure 34. Test result for a “d.c. meter”

The test results show very evidently that the main accuracy problems are at the lowest part of the range and are most probably due to offset voltages.

3.5.4.2 Test of d.c. meters with digital input

For meters with digital input, a data simulation unit has been built in cooperation with Schniewindt GmbH and Landis&Gyr. It simulates the data stream from a merging unit to a d.c. “meter” with digital inputs.

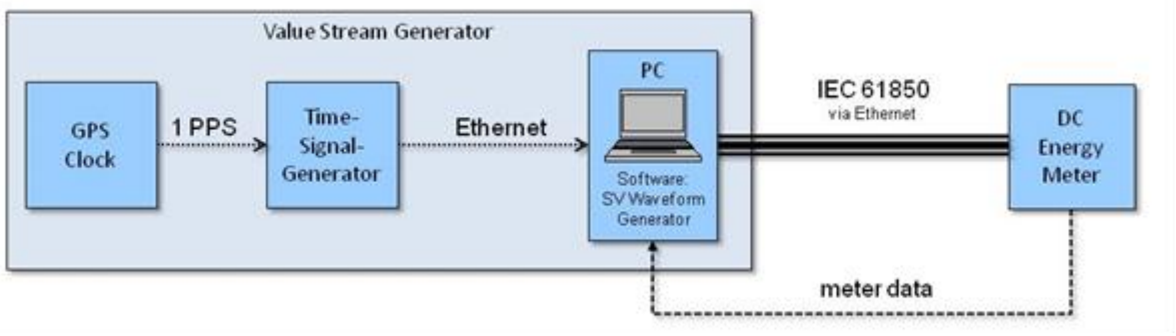

Figure 35. Transducer data simulation unit for the test of d.c. “meters” with digital input.

Figure 36. The value stream generator, simulating data from current and voltage transducers

The block "value stream generator" consists of three parts. Using a GPS clock, which provides a PPS output signal (pulse per second), and a time signal generator to synchronize the computer, and thus the software "SV Waveform Generator". This software is used to combine the signals generated by a user interface into the IEC 61850-9-2 protocol. This program was created from information in “*Implementation Guideline for Digital Interface to Instrument Transformers Using IEC 61850-9-2*” from UCA International Users Group [22]. It was simulated by 256 samples per 50 Hz, a sampling rate of 12.8 kHz were used. The protocol in this case contains 8 pairs of values, which could stand for four voltages and four currents in a HVDC transmission system. As an example, a bipolar HVDC link two current and two voltage measurements could be included.

The main features of the voltage and current waveforms in HVDC are the following:

- Constant value of the d.c. current and voltage.
- Superimposed ripple signal.
- Energy flow direction changes within a one minute period.

A curve-form incorporating these features can be simulated by the simulator and would look like in Figure 37 below.

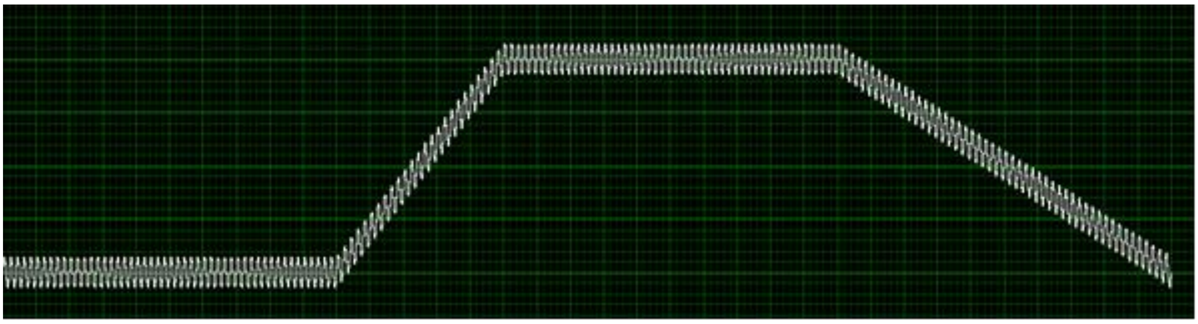

Figure 37. Example of curve-form with the most common dynamic features of a HVDC transmission.

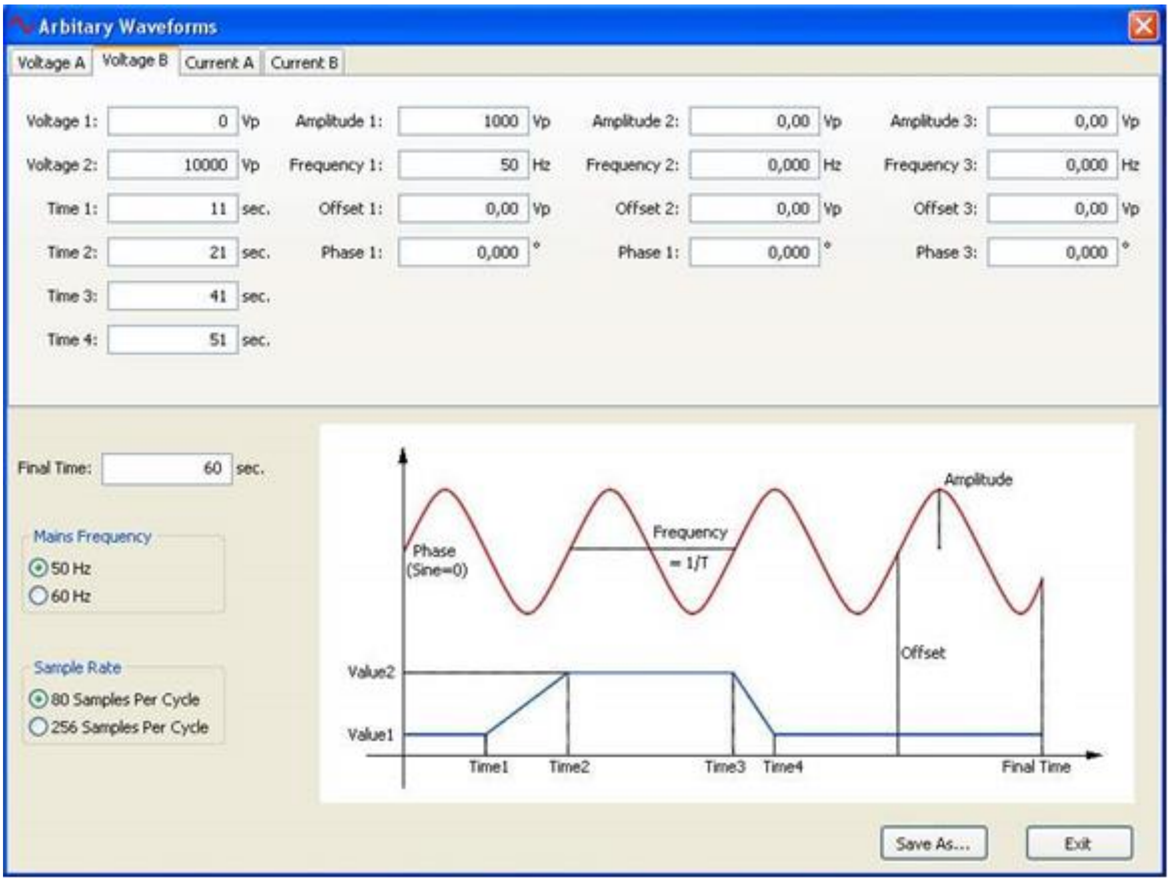

Figure 38. An example of the signal build-up of a simulated curve-form.

Tests on a prototype of a digital d.c. power meter from Landis + Gyr E880 were performed at Physikalisch-Technische Bundesanstalt. The functionality of the counter has been tested for different change rates. The following features were used:

- • Output accuracy under clean d.c. conditions
- • Accuracy for d.c. with superimposed ripple
- • Acquisition of energy during a power flow reversal
- • measuring of reactive ripple power for out-of-phase ripple voltage and ripple current

When the specified tests were performed on the prototype, no errors were observed. Only the definition of the flow direction had to be adjusted by a sign in the display for easy operation. However, this does not affect the calculation of the total energy, including a reversal of the flow direction.

3.5.5 Demonstration of energy meter for d.c. applications

An analysis of the design requirements has been done, based on the result of clause 3.5.2. Due to problems with finding a suitable existing meter platform to modify, a full in-house meter design is done.

Some critical design issues have been especially considered:

- The offset voltages in input circuits and AD converter
- Very high input impedances may be required for some transducers
- Overall accuracy, especially at low currents

The design of new input and AD conversion circuits has been done and the resulting hardware has been tested. This work has been published in CPEM 2012, Conference on Precision Electromagnetic Measurement, in Washington D.C, July 2012 [23], and an extended paper has been accepted for publication in IEEE Transactions on Instrumentation and Measurement.

The design is based on a traditional instrumentation amplifier with high impedance low offset instrument amplifiers and high precision, low offset A/D converters with a sampling rate up to 100 kS/s. In the design a sampling rate of 8 kS/s has been chosen. The design is made for an input of maximum 10 V on both the voltage and current input but may easily be adopted for most other lower inputs ranges.

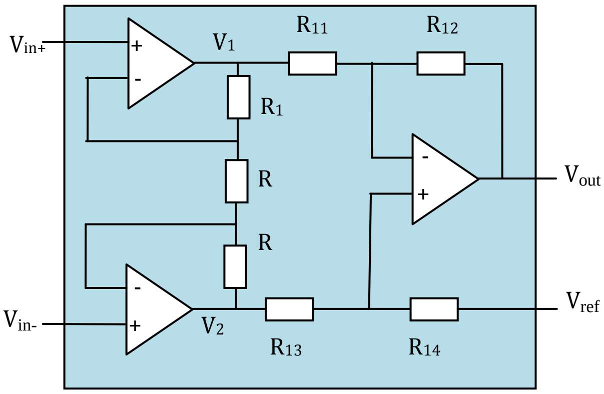

Figure 39. Circuit diagram of input circuits

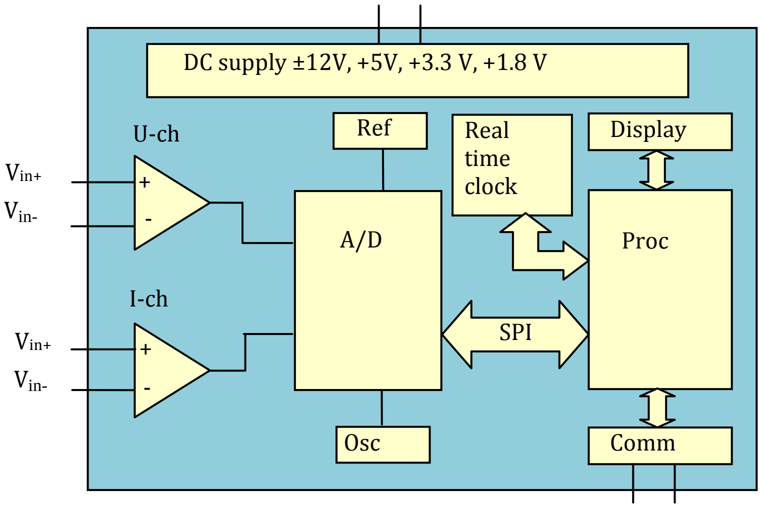

Figure 40. Block diagram of the meter

The multiplication and integration, display and communication part is built around a standard 8-bit microprocessor a two-line display and a real/time clock to handle hourly values, resulting in a design as in the block diagram below.

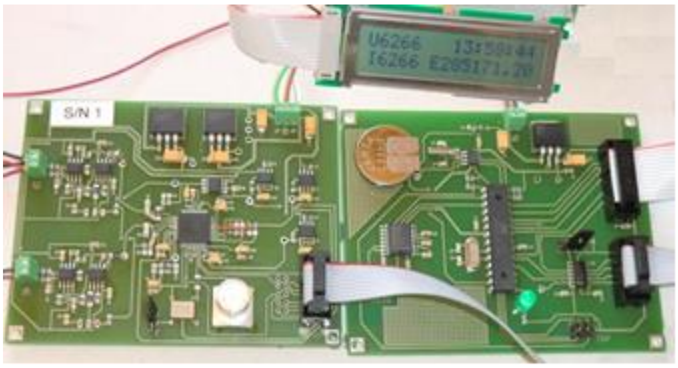

Figure 41. HVDC d.c. meter parts, A/D board, processor board and display.

Some first results have been evaluated:

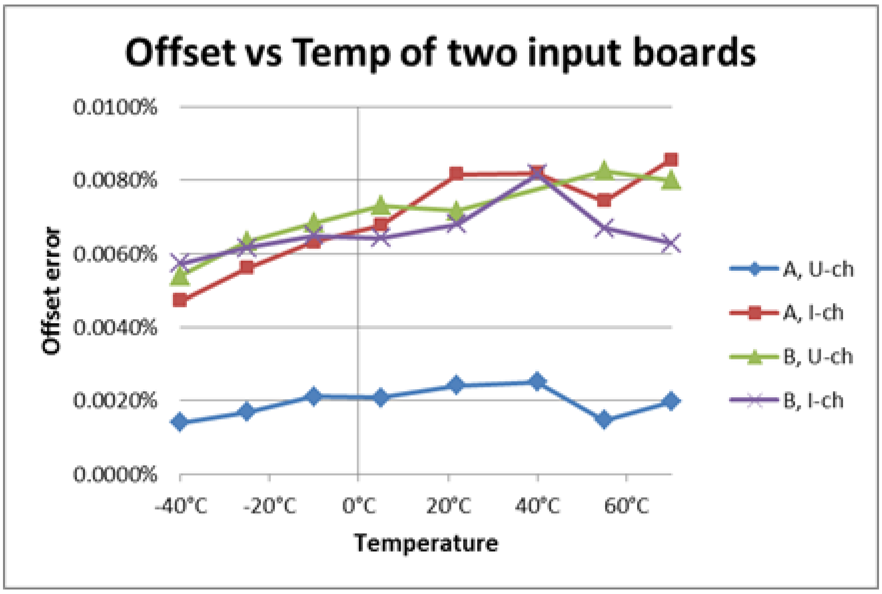

Figure 42. Offset error and its temperature dependence.

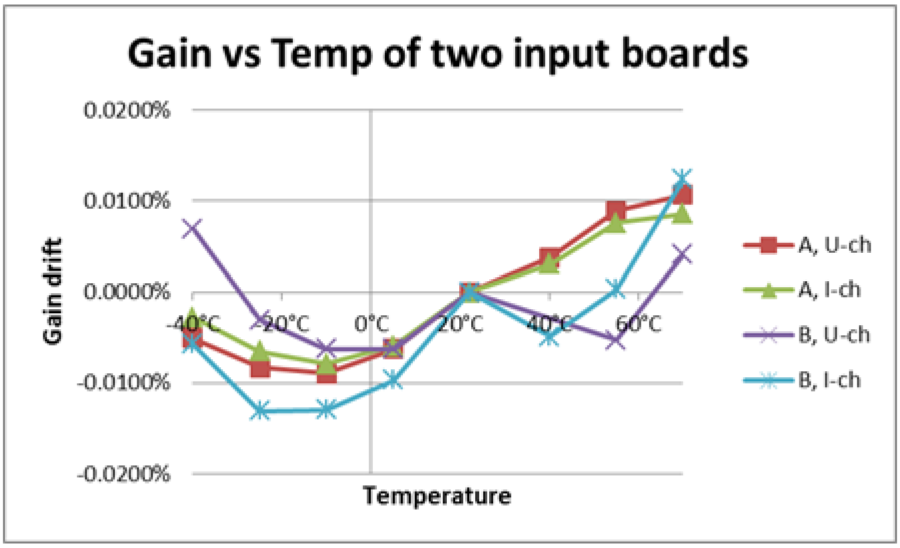

Figure 43.The temperature dependence of the gain of board A and B for different temperatures.

As seen in Figure 42, the offset error varies ±0.002 % with temperature. Long term drift of offset is not yet determined. The result, while seemingly impressive for a first design stage, just barely fulfils the suggested metering requirement of clause 3.5.2 regarding accuracy at low currents. Better resistors in the amplifier stage are expected to remedy the situation. It is possible that the level of accuracy at low currents in clause 3.5.2 should be re-addressed during standardisation. The gain error variation of ± 0.01 % seen in the tests for large temperature variations is not a problem.

A prototype meter has been connected in the Lindome Scanlink 1 HVDC Station that is part of an HVDC link between Sweden and Denmark. Preliminary results and comparison to a.c. metering results indicate a difference between d.c.-values and a.c.-values of 5.1 % at export and 3.9 % at import. The difference between export and import fits well with the expected power direction dependent losses in the station. The systematic difference of about 4.5 % is significantly higher than expected because HVDC station losses during operation should be well below 1 %.The difference should be investigated, but this has been delayed because station has been out-of-service during an extended period.

3.5.6 Non-invasive on-site check of a.c. current transformers

The aim of this work package is the design of a method that can be performed on-site to verify the metrological performance of a CT without opening the current circuits.

The details of this work are presented in the VSL report “Non-invasive current sensing”. The aim is:

1. measurement of 2000 Ampere, 50/60 Hz with an uncertainty of less than 0.01 %,
2. insulation up to 100 kV,
3. insertion without opening the circuit,
4. Remote readout. (preferably wireless)

And if possible

5. ability to measure phase displacement between two of these units,
6. the device should be either battery powered or get its power from the grid,
7. the measurement time should exceed 24 hours,

The size and weight will strongly determine the use. A compact and lightweight design will strongly enhance the usefulness of the device.

The system, see Figure 44, consists of two stages, an openable core with one stage converting 2000 A to 5 A and a second stage to convert 5 A to 50 mA. A digitizer (ADC) measures the voltage across a specially selected burden resistor. The controller sends all the acquired samples to a PC where the data will be analysed. Optionally the digitizer is phase locked to the 1 PPS from the GPS to obtain phase information, which makes it possible to determine the phase difference between different units.

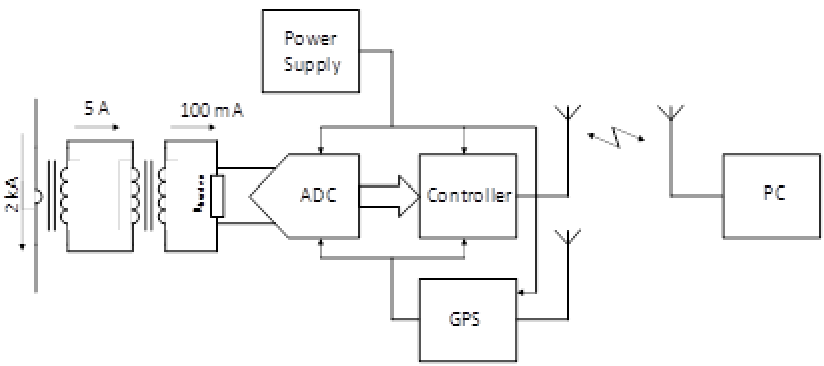

Figure 44. Block diagram of the openable core transformer system

Both transformer stages are of enhanced core type shown in

Figure 45 below. Cutting the core will strongly reduce the effective mu of the core. The two halves of the core must be almost perfectly aligned and the resulting air gap should be smaller than 15 µm.

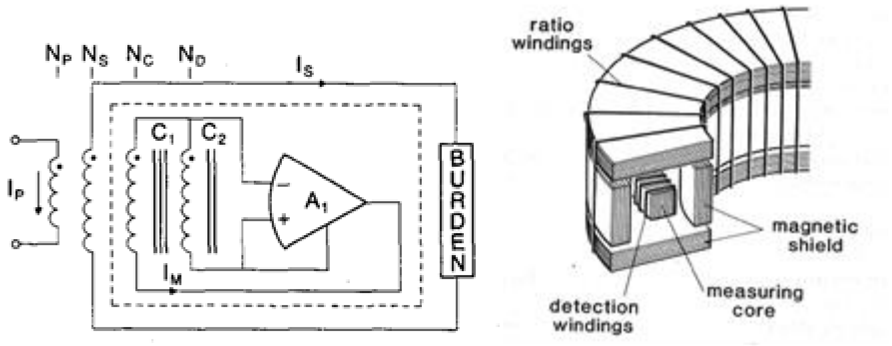

Figure 45. Enhanced core design

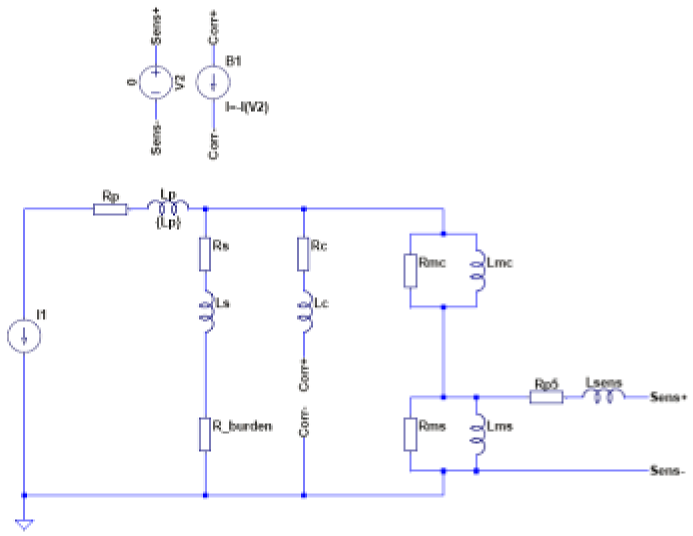

Figure 46. Equivalent circuit diagram of the enhanced core transformer.

In the model shown in Figure 46 it is clear that any current flowing in $R_{mc}//L_{mc}$ + $R_{ms}//L_{ms}$ will cause an error, because this current will not pass the burden resistor. By measuring the current flowing through $R_{ms}//L_{ms}$ we can inject an additional current to counter this error, which is done by a simple operational amplifier circuit as shown in

Figure 45.

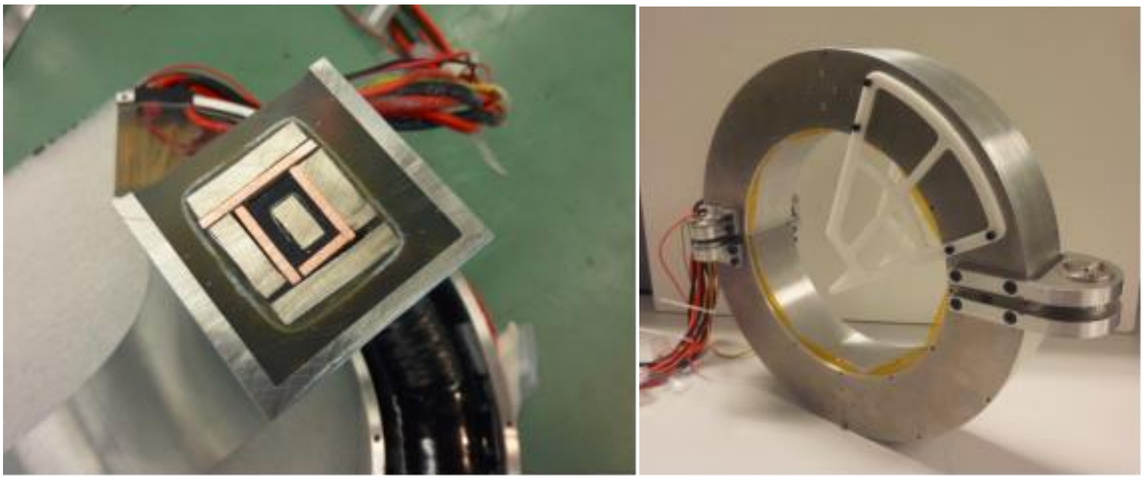

Figure 47. Photos of the cores and the complete openable CT and the core aligning mechanism.

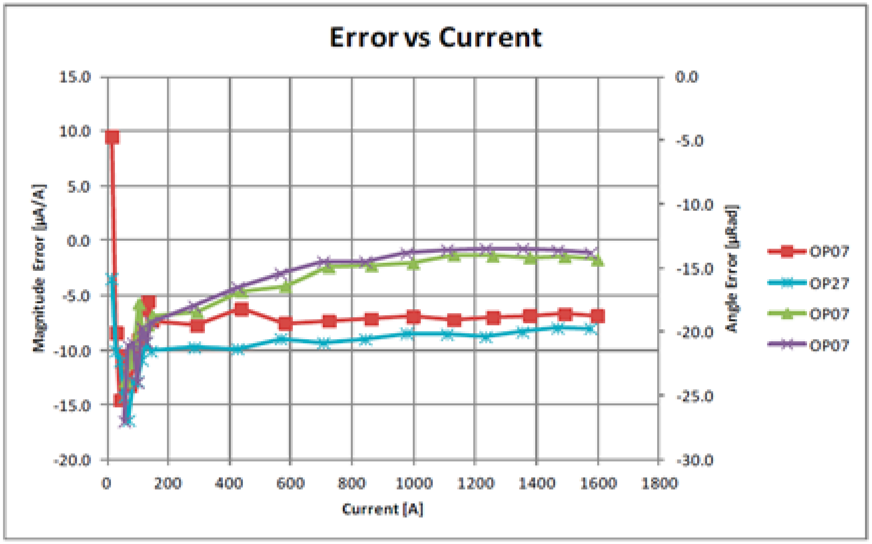

Figure 48. Amplitude /red and blue) and phase displacement (purple and green) of the OCCT

The effects on position on the conductor and the position of the return current conductor should be small. The effects have been measured and are shown in Figure 49 and Figure 50 for the ratio error and phase displacement respectively.

Position	Amplitude Error	Phase Error
	[µA/A]	[uRad]
1	-8.0	+22
2	+8.4	-37
3	2.5	-45
4	7.5	-41
5	-2.0	-41
6	-20	-45
7	-60	+41
8	-26	-57
Center	-12	-50

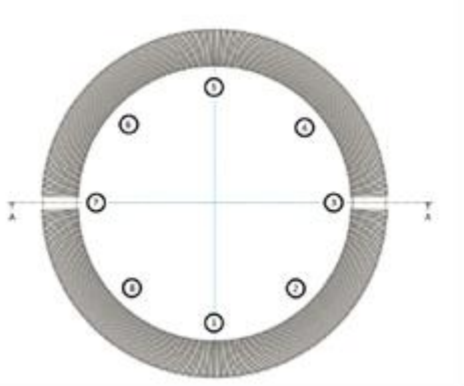

Figure 49. Position dependence of the OCCT

Position	Amplitude Error	Phase Error
	[µA/A]	[uRad]
0.5 m	-10	-45
1.0 m	-24	-50
1.2 m	-2.0	?

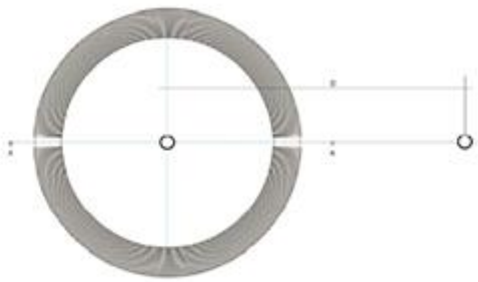

Figure 50. Effect of the return current conductor position on the OCCT.

Reproducibility in the closing of the core is very important to reduce error. The alignment of the cores is very sensitive. Having a proper mechanism to close the core has been developed and shows that after repetitive opening and closing the error of the OCCT is reproducible. In this case care has been taken to have the conductor in the same position between closings.

Table 2. Effects of repetitive closing and opening of OCCT

Rep #	Amplitude Error	Phase Error
	[µA/A]	[µrad]
1	-12	-67
2	-12	-70
3	-12	-70
4	-10	-65
5	-10	-68
6	-12	-73
7	-10	-45

3.5.7 Progress beyond the state of the art

A pre-normative work for HVDC electricity meters with analogue inputs has been finalised and the results will be useful for future standardisation. A new IEC standardisation work has been started for d.c. meters that at the moment does not include HVDC meter. A proposal to include HVDC meters has been brought up, and the HVDC pre-normative work will be handed over to this group.

Also a pre-normative work for HVDC electricity meters with digital inputs has been finalised. Since the standardisation of the transducers are not yet quite finalized by IEC TC 38, a move to present a new work item proposal (NWIP) has been postponed

An analogue HVDC meter that complies with the above requirements has been designed and constructed. A first set of tests has been performed and published.

A test bench for accuracy tests of analogue d.c. meter has been built and tested. A test-bench for functional test of HVDC meters with digital inputs has been built. The test work has been published as a PTB report.

A non-invasive current transformer has been built and verified. It has an accuracy that makes it very suitable for on-site calibration work. The galvanically isolated data transfer has yet to be realised before it can be used for actual on-site work

4 Actual and potential impact

4.1 Main research subjects

The project has developed new metrology capabilities for high voltage direct current in four main areas:

- Losses in HVDC converters, converter valves and valve components
- Measurement and calibration of d.c. voltage up to 1000 kV, both in-house and on-site
- Power quality issues for HVDC converter stations
- D.C. side energy metering

4.2 Scientific impact

4.2.1 Objective 1: Measuring power losses in HVDC systems

The complex wave-shapes encountered in HVDC converter valves create significant measurement challenges. This project has developed traceable measurement systems and calibration services, which together with newly developed test benches enable traceable measurement of losses in converters and in their constituent parts. Measuring systems were developed at PTB and used by TUBS for experimental work on converter components. An electrical loss power measurement system has been established to characterize and determine high power Insulated Gate Bipolar Transistor (IGBT) module switching and loss behaviour as single switch, IGBT stack or in sub-module configuration. A separate study has been made on methods to measure losses of converter stations.

Experiments and simulations were successfully performed to provide a first stage of reliable reference instrumentation to application engineers charged with achieving optimised IGBT converter operation and to predict IGBT losses.

A scientific paper has been published in IEEE Transactions on Instrumentation and Measurement [8], discussing the requirements on a measuring system intended to measure the losses of switching elements under dynamic conditions and gives the necessary background to determine the accuracy in terms of time response. An analysis is also given on methods and requirements needed to measure losses of an HVDC station from a.c. input to d.c. output power. Finally a viable method for measurement of total losses utilizing a back-to-back configuration of two converters is analysed. This last method has been adopted by Svenska Kraftnät (National Grid in Sweden) as a method to prove guarantees on losses in a new HVDC intertie.

4.2.2 Objective 2; Extending high voltage calibration capabilities

Metrology grade measurement and calibration of d.c. voltage was, until the advent of this project, limited to 400 kV in Europe. This level is insufficient in the face of the present trend to ever higher transmission voltages, with 800 kV already being in use and 1000 kV systems being planned. The project undertook the ambitious goal to create an infrastructure in this field based on development of one laboratory reference divider for 1000 kV with a projected uncertainty of 0.004 % plus a modular, transportable, divider that should be possible to use up to 1000 kV and with a projected uncertainty of 0.01 % at 800 kV. The goals were met, and even surpassed as the modular divider met the accuracy goal at 1000 kV. The agreement between the dividers over the voltage range was actually within 0.002 %.

The market response to the new on-site calibration service, made possible by the modular divider, has been very good. During the project two commercial calibrations were carried out at 600 kV by MIKES and SP, and another calibration at 1000 kV was carried out just after the end of the project by SP, at a client's laboratory in Japan. The clients for the calibrations were producers of transmission equipment for HVDC.

This work has benefited European as well as worldwide industry by providing a traceable link from industrial measuring systems for very high d.c. voltage back to the best international realisations of measurement. The confidence of industrial measurement and testing is greatly enhanced as a result of this project.

The introduction of this unique reference system will enable building of calibration infrastructure for HVDC metering dividers. An introduction of accurate measuring systems for power flow across borders is now possible.

4.2.3 Objective3: Assessment and analysis of the detrimental effects of poor power quality generated in HVDC substations

The conversion process between a.c. and d.c. involves semiconductor switches where fast switching is important to achieve low losses. The fast switching does however lead to high frequency interference that has to be mitigated by suitable filters to avoid power quality issues in connected grids. Performance of the mitigation needs to be verified by measurements that have proper metrological support.

The project was successful in making traceable metrological grade measurements of power quality (PQ) on a classical HVDC station giving an unprecedented insight into the operation of the link and correlations to various PQ events. Development of the capability, associated measurement equipment, and practical techniques are important for future field-measurements on HV systems which will be used by system operators and planners to ensure system operation within quality bounds.

4.2.4 Objective 4: Metering and billing in d.c. grids

Prior to this project no infrastructure existed for energy metering HVDC on circuits as a result of a double bind – there was no demand for d.c. side metering because no infrastructure for qualification existed, and there was no pressure to provide such infrastructure because there was no demand. This project has broken this bind by creating the necessary background for d.c. metering standardization and developing verification methods and test benches. Metering requirements were also developed in response to the fact that transducers for the primary voltages and currents are increasingly offered as devices with integrated electronics, providing a digital output. To prove the feasibility of d.c. side metering, a demonstrator was built and mounted in an HVDC station. As a final target in this area, a need to verify existing current transformers for use in a.c. energy metering was identified and solved with a new reference with an uncertainty of 0.05 %.

The project also addressed pre-normative work for HVDC electricity meters with analogue inputs and delivered results that will be useful for future standardisation. At present a new IEC activity on standardisation for d.c. meters does not include HVDC meters, leading to a situation where there are no documentary standards regulating this field. Standardisation would greatly ease wider introduction of d.c. energy transmission. Therefore a proposal to include HVDC meters in current IEC standardisation activities has been made and the HVDC pre-normative work will be handed over to the relevant IEC Technical Committee.

A test bench for accuracy tests of analogue d.c. meter has been built and tested. An analogue HVDC meter that complies with the above requirements has been designed and constructed. A first set of tests has been performed and published. In addition pre-normative work for HVDC electricity meters with digital inputs has been finalised. Transducers for high d.c. current and voltage with digital output instead of analogue signals are under development for use in HVDC transmission systems. This work would benefit from support by documentary standards. Since the standardisation of the transducers are not yet quite finalized by IEC TC 38, a move to present a new work item proposal (NWIP) has been postponed, but will be brought forward at a later date.

The advances achieved in d.c. side metering will strongly support the creation of true d.c. grids in Europe, and will therefore help to achieve the 2020 goals on energy conservation.

4.3 Dissemination

Throughout the project the new knowledge generated and awareness of the new metrology capabilities developed have been disseminated to the industrial, academic and standardisation communities.

4.3.1 Presentations

Table 3. Presentations made to the relevant industrial audiences through various conferences and exhibitions

IEEE PES Conference on Innovative Smart Grid Technologies Europe, Gothenburg, Sweden, 2010	This event occurred at an early stage and an invited key-note speech was held to introduce the aims and plans of the project to an international audience
VDE-Ausschuss Geschichte der Elektrotechnik, Berlin, Germany, 2011	A presentation of the history of HVDC transmission was made to German-speaking audience
IMEKO-MI2011, Cavtat, Croatia, 2011	A presentation was made on the subject of “Metrology for High Voltage Direct Current : State-of-Art and current development”
17th ISH, Hannover, Germany, 2011	Three poster presentations on subjects from the project were made. The audience is both from academia and from industry
HIGHVOLT Kolloquium´11 - Prüfen und Messen an elektrischen Betriebsmitteln der Hochspannungstechnik, Dresden, Germany 2011	The target group for this event is high voltage related industry in German-speaking countries, and was an opportunity to present the project to a wide audience
EMO_2011 (National Electrical Congrees of the Chamber of Electrical Engineers in Turkey), Izmir, Turkey, 2011	The target group for this event is high voltage related industry in Turkey, and was an opportunity to present the project to a wide audience. Two presentations were delivered.
PCIM Europe 2012, Nuremberg, Germany, 2012	PCIM is an event for industry and one poster presentation was held
CLEEN SGEM unconference, Kirkonummi, Finland, 2012	One presentation on “Smart grid related projects in European Metrology Research Programme”
Chalmers Energy Conference, Gothenburg, Sweden, 2012	One presentation was made on “The future role of energy consumers: The value of flexibility.
CPEM 2012, Washington USA, 2012	Six posters and one presentation of subjects from the v project were made. There was also an exhibition booth where the first sub-module for the 1000 kV modular d.c. divider was presented
18th ISH, Seoul, Korea, 2013	A total of four posters were presented at the conference, which has an audience both from industry and academia
PCIM Europe 2013, Nuremberg, Germany, 2013	One poster presentation was made

4.3.2 Publications

In terms of the scientific output the project has already published **24** peer reviewed papers with **6** further papers submitted for publication.

The scientific and academic community were also addressed through international congresses and conferences including CIGRE, ISH, CPEM, IEEE-PES smartgrids, and IMEKO.

4.3.3 Training

Formal training was delivered through an external Power Meter Seminar held in Berlin in 2012.

Several cases of secondments between the partners were organised, e.g. a six-months Researcher Mobility Grant was organised, and furthermore in several work-packages researchers performed experiments and measurements at another partner's premises.

A student has been working for half a year on the task to make an accurate model of an electronically aided dual core, current transformer. The results of this work have been used as input to design of the actual transformer, which has proven to be of interest to the local TSO.

4.3.4 Standardisation

Project partners have a strong presence on several relevant technical standards committees and pre-normative organisations, which will ensure that the results of the project are disseminated and inform the appropriate decision making bodies, e.g.

- CIGRE AG D1.02, Materials and emerging technologies, Advisory group for High Voltage and Current Testing and Diagnostic. Several project partners are active within working groups
- IEC TC13, Electrical energy measurement and control. Some project partners are active in working groups, and have second-hand accession to IEC work through their national organisations
- IEC TC14, Power transformers. One project partner has been active in production of an IEC standard
- IEC 22F, Power electronics for electrical transmission and distribution systems. One project partner is active in production of an IEC standard
- IEC TC38, Instrument transformers. Some project partners are active in working groups, and have second-hand accession to IEC work through their national organisations
- IEC TC42, High-voltage and high-current test techniques. Several project partners are active representing for the national committee, as members of working groups and as convenor of working groups.

In several cases IEC and CENELEC operate in parallel, and in those cases the members active in IEC also impact on CENELEC.

4.3.5 Miscellaneous

Three press releases have been given relating to work of the project.

Based on one of the press releases, .a half-page news item was printed in September 2013 issue of NCSLI Measure journal about the 1000 kV modular divider.

The first sub-module manufactured for the 1000 kV modular divider was exhibited at CPEM 2012 in Washington.

4.4 Early uptake and exploitation

Some of the results of the project are already in use and being exploited:

- Commercial calibrations have been performed using the new calibration capabilities developed. SP and MIKES have used the modular 1000 kV divider for commercial calibrations on-site at three industrial user premises at voltage levels from 600 to 1000 kV and a calibration at 1000 kV was carried out just after the end of the project by SP, at a client's laboratory in Japan. The clients for the commercial calibrations are manufacturers of equipment for HVDC transmission.
- A prototype d.c. energy meter has been developed and was demonstrated at the Lindome Scanlink 1 HVDC Station, proving that d.c.-side metering is feasible.
- A separate study was made, and published, on methods to measure losses of converter stations in-situ. It has found a practical application in an investigation, on behalf of Svenska Kraftnät (National Grid), to define achievable uncertainties in the measurements of a provisional back-to-back configuration of two converters in a converter station, where only loss power is supplied from the grid.
- Svenska Kraftnät in Sweden has, in the purchase requirements for a new domestic HVDC intertie, referred to methods developed in the project, to define verification of losses in a new HVDC transmission. SP has been awarded a contract to perform those measurements.

- A long-term measurement campaign in an HVDC intertie substation has yielded a vast amount of data that has already been used in a publication [24]. The data is also available for further studies and interpretations.
- The project had direct representation in the relevant IEC committee for convertor loss (IEC TC22F, Losses in HVDC Converters) and the project's results have been used in the preparation of documentary standards for loss evaluation of voltage source convertors.
- The project will present a new work item proposal (NWIP) to IEC TC 38 (Instrument Transformers) on digital high voltage d.c. transducers
- Discussions have been opened regarding possible commercialisation of the modular divider developed on the project, and/or building further units at national measurement institutes. The discussions are in a preliminary stage and will take some time to finalise. IPR issues regarding such exploitation have been settled early in the project and the agreement clearly defines how commercialisation shall be handled.
- Measurement methods for switching and ohmic losses of Insulated Gate Bipolar Transistors have been developed and published. These are complemented by calibration facilities at national measurement level. It is expected that the support thus provided for developers, will speed the advent of lower losses in HVDC converters.
- An infrastructure for energy metering in high voltage d.c. circuits has been created and a body of background material for standardization has been developed to underpin the building of true d.c. grids where metering in connection points will be indispensable.

4.5 Socio-economic/policy impact

The driving force behind this project was the EU's requirement to reduce its dependency on fossil fuels. To do so the EU has encouraged the "greening" of the electricity distribution system by switching from fossil fuels to renewables. A successful uptake of renewables will be strongly supported through introduction of energy transport based on HVDC, which is regarded as the most viable alternative for new transmissions.

Introduction of calibration infrastructure based on the technical solutions developed in this project will enable precision measurements where they have not yet been possible. D.C. and HVd.c. revenue metering systems will be more accurate and more widely applied in future. Also, the losses of future HVDC converter stations can be measured with better precision, thus enabling design improvements. Both of these developments will have a huge economic impact, as even a small improvement in the technology will lead to large savings due to the scale of the power industry. Some of this future progress can be traced back to the results of this project.

The social and economic impact of the project is to move Europe closer to the point where it can economically and safely trade electricity across the European distribution system. Ultimately the full impact will depend on the extent to which the EU delivers on its energy policies and to what extend the envisaged international introduction of HVDC transmission is taken up by the community.

The success of the project in the scientific and technological arenas will enable a wide introduction of HVDC energy transmission not only in Europe, but also worldwide. As a result, potential renewable energy sources will become available to the energy market, reducing the dependency on fossil fuels.

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