Final Publishable JRP Summary for JRP ENG07 HVDC
Metrology for High Voltage Direct Current

Overview

High Voltage Direct Current (HVDC) energy transmission is crucial for a successful uptake of renewable energy sources in the grid. The project provided 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 was a combined effort of seven European national metrology institutes (NMIs), one university and one industrial partner; along with three collaborators, who agreed to support 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). In addition, transmission losses, which already account for 10% of all energy generated, are increasing towards levels that will make future transmissions impractical. Not only is new transmission capacity required but it needs to be capable of transmitting electricity generated from renewable energy sources in remote locations and with highly variable generation outputs. HVDC transmission is universally regarded as the solution for these essential grid extensions because the HVDC technology offers: i) Lower losses and reduced demands for right-of-way corridors as compared to a.c. transmission, ii) Enhanced stability of associated a.c. grids, iii) Economically viable transmission of renewable energy from awkward locations; and iv) Power quality correction of polluted grids.

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

Need for the project

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 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 likely to increase to such an extent, that transmission would be impractical. HVDC transmission is an essential technology both for grid extensions and the integration of renewable energy sources into the infrastructure. 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). At present several HVDC interties (HVDC links) exist in Europe, with many new projects in planning or in construction.

A metrology infrastructure was therefore needed to ensure reliable measurement of HVDC parameters to support its implementation.

Scientific and technical objectives

The project set out to develop a 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

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measurement of high d.c. voltage, iii) Metering, and iv) Power quality. From these overall goals, a number of objectives were identified:

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.

Results

Objective 1 Loss measurement

The energy losses of an HVDC transmission system can be directly evaluated in economic terms and minimising losses also reduces emission of greenhouse gases. For investors deciding on transmission system alternatives, an accurate knowledge of expected losses forms an important part of the investment evaluation. The overarching objective of the research was to improve the measurement of losses in HVDC systems, so that the present practice of calculating losses could be replaced by actual measurements, with known uncertainties.

One of the dominating contributors to loss in an HVDC transmission is the a.c./d.c. converter valve. The latest generation of d.c. Voltage Source Converter (VSC) valves utilises a technology where Insulated Gate Bipolar Transistors (IGBT) are used to achieve full controllability. These devices, however, created new challenges compared to previous power semiconductor generations, in that they have faster switching rates (kHz rather than power frequency), which demand accurate measurement of fast changing voltage and current signals when determining losses. The project developed state-of-the-art methods and instrumentation to evaluate losses under these fast signal conditions, as well as techniques to estimate the losses at the design stage, in order to support the needs of converter developers. These findings were then applied during the work of a university collaborator, at the Technische Universitaet Braunschweig, Germany, for measurements on converter components and subsystems.

The achieved scientific and technical objectives of the research were:

- a test circuit for single switching elements (IGBTs) of HVDC valves,
- a test circuit for sub-modules of HVDC valves, including traceable measuring systems,
- characterisations of single elements (IGBTs), stacks and sub-modules; and
- an IGBT stack model with identified parameter values of the model.

Together, these components form a test bench that allows for measurement of losses of components of voltage source converters.

The project had direct representation on the relevant IEC committee for convertor loss and brought results to bear on the preparation of documentary standards for loss evaluation of voltage source convertors.

The required measurement systems were also developed and experimental work on measurements of the IGBTs and systems was performed as part of the university collaborator’s research, providing a first stage of effective reference instrumentation to application engineers and achieving optimised IGBT converter operation and a prediction of IGBT loss. A separate study was made on methods to measure losses of converter stations and has found a practical application in an investigation, on behalf of Svenska Kraftnät, to define achievable uncertainties in the measurements of loss in the South-West Link converter station, where two converters will be connected in a provisional back-to-back configuration, where power will be circulated between them, with the losses supplied by the grid.

Objective 2 High d.c. voltage measurement and calibration

There was a particular focus on d.c. voltage measurement at very high voltage in convertor substations. This measurement was not sufficiently accurate for metering purposes or loss determination; and a new measurement infrastructure was developed for on-site calibration of the wide-band d.c. dividers installed in converter stations, as well as for industrial laboratory references to provide the essential traceability.

An in-house (in NMI) 1000 kV reference divider was realised, based on components from a previous 1000 kV precision divider developed in the UK, and was complemented with new components and mounting hardware to enhance its stability and precision. The performance target of 0.004 % uncertainty was met successfully, proven by final testing performed with two other dividers. The new reference divider will be used as a stable reference, to verify the stability of the on-site modular divider over time.

An on-site modular divider was also designed, also for a 1000 kV operating voltage, comprising five 200 kV modules that were built through a concerted effort, involving virtually all project partners. An extra four modules were also produced. The target of 0.01 % uncertainty at 800 kV was met; and indeed has been surpassed as it has been estimated to 0.005 % at 1000 kV, even for on-site use.

This task was an excellent example of a fruitful cooperation between several of the European NMIs and an industrial partner, where the outcome could not have been realised by any single partner alone. A large number of scientific papers have been produced in the context of development and verification of these dividers.

The on-site divider met with approval from the end users during the second half of the project, with commercial calibrations being performed at the 600 kV level, and at the end of the project a 1000 kV calibration was performed in Japan, with the modular divider having been air transported to the site and erected on the outdoor test area as shown in the figure.

Calibration of any high voltage divider starts at low voltage, using well established references, followed by investigations of linearity over the voltage range. For d.c. this proof of linearity is difficult, and apart from the methods employed for characterisation of the 1000 kV dividers, supplementary investigations were performed to determine the potential of using other independent methods to measure d.c., and thus further support the calibration procedure. A demonstrator was built up to 20 kV, using band-gap devices that produced a very promising estimated uncertainty of 0.0003 %.

Objective 3 Power quality

Converters used in HVDC systems can produce harmonics and inter-harmonics, which are injected into the grid system. Existing grid codes (grid requirements) largely concentrate on limiting harmonic pollution from such systems; however, there are issues with inter-harmonics that have not been measured or regulated. The effect of such inter-harmonics could have a significant influence on the grid power quality (PQ), giving rise to increased losses, amongst other undesirable effects.

A measurement campaign was performed in the HVDC intertie SWEPOL link between Sweden and Poland, courtesy of Svenska Kraftnät. A powerful transient recorder developed in a previous project (iMERA-Plus JRP T4.J01 Power & Energy) was used in this campaign. To capture the events occurring on the high voltage grid, current signals were obtained from existing current transformers, whereas voltage signals were obtained from capacitive voltage dividers comprising existing capacitive taps on high voltage equipment, complemented by low voltage arms, specifically designed and constructed for the purpose. This set-up enabled precise measurements of power quality phenomena in this HVDC station and serves as a model for future measurements of power quality parameters on a high voltage grid. The results of these measurements were submitted for publication in a peer reviewed journal; and the measurement system is permitted to stay in the station at least until 2014, providing new data that can be utilised in later research projects.

Work was started on developing and implementing new capabilities for the on-site assessment of harmonics and inter-harmonics and on studying their detrimental effects. In order to design filters for HVDC stations that mitigate the effect of such harmonics, knowledge of the impedance of the grid across the relevant frequency range was required. New methods were investigated to determine this impedance with sufficient precision to enable effective mitigation and prevent component failure.

Objective 4 Metering in d.c. grids

Correct metering is a prerequisite for correct 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 different commercial operators support the need for correct d.c. side metering, which is necessary to allocate the significant cost of converter station losses to the proper party.

Calibration services for primary current and voltage transducers for revenue metering on the d.c. side have been created. The specifications and test methods for d.c. side electricity meters have been identified and suggested for future inclusion in publicly available written standards.

Pre-normative research was conducted to define the basic requirements for d.c. electricity meters, both for present-day analogue input circuits, as well as for current and voltage transducers with digital output signals. Test methods were explored and a calibration demonstration facility was built to implement test procedures for both kinds of d.c. energy meters.

A barrier to d.c. side metering has been the lack of suitable energy meters. A d.c. energy meter demonstrator was built and tested, according to the principles laid down in the project; and a peer-review paper was published on this subject. The prototype meter has been connected in the Lindome Scanlink 1 HVDC Station, which is part of an HVDC link between Sweden and Denmark. Preliminary results and comparison to AC 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 not been possible because the station has been out-of-service for an extended period. The grid operator has furthermore decided to decommission the test circuit and therefore it has not been possible to achieve further results.

A novel type of non-invasive current transformer (CT) for calibration of the a.c. current transformers has also been developed and will be used to characterise installed instrument CTs. This will make it possible to evaluate their energy metering performance, e.g. in an HVDC station.

Actual and potential impact

The project's outputs were disseminated via various routes:

- Contacts with standardisation bodies have been plentiful, with experts from the project participating in committees and working groups at more than 20 meetings during the project. Standardisation bodies targeted were IEC TC14, Transformers, IEC TC22F Losses in HVDC Converters, IEC TC42 High-voltage and high-current test techniques, as well as working groups D1.35 and D1.36 for pre-normative work in the frame of CIGRE. These bodies were informed of the activities of the project and of the results bearing directly on their respective bodies.
- The results of the project have been presented in 26 presentations, mainly at international conferences. 24 scientific papers have been published and another 6 are in various stages of review.
- A training activity for the use of the power meters was held in Berlin.
- Information about the project activities was also provided by press releases and an exhibition. As a result 15 organisations elected to support this project as stakeholders

Intermediate and early impacts were achieved from having the outputs of the project used by a number of different communities:

- Several new calibration services have been realised from the project, including: i) an unprecedented on-site service for 1000 kV d.c., with a best uncertainty of 0.005 % and based on an in-house reference, also with an uncertainty of 0.005 %; and ii) a new calibration facility for d.c. energy meters. Calibrations have been conducted for a number of commercial organisations.

- 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 furthermore 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. 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.

Wider long-term impacts

The impact of the project centres on a high level in the energy transmission system, with apparent boons available for manufacturers of equipment and for transmission system operators, featuring, for example, reductions in losses incurred in the energy transmission, leading to a “greener” energy system. A secondary effect is expected to be more economical, and reliable, supply of electrical energy to the general consumer.

List of publications

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