METROLOGY FOR HIGH VOLTAGE DIRECT CURRENT STATE-OF-ART AND CURRENT DEVELOPMENT

A. Bergman [1]
[1] SP Technical Research Institute of Sweden, Borås, Sweden
E-mail: anders.bergman@sp.se

Abstract – Energy transmission by high voltage direct current – HVDC - is steadily increasing in the world, both at the highest power levels, but also at medium power, for example in connections of remote wind-parks to the main a.c. grid. Although principles for d.c. side measurements are known since long, support from metrology is not on par with the needs. An overview of available technologies and the challenges for metrology shows that advances are needed in determination of power losses in convertors, traceability for transmission line voltage measurement, power quality and d.c. side metering. Response to these challenges is given by seven national metrology institutes, one university and one industrial partner, in a project funded by the European Union under Article 169. The research will provide traceable calibrations and measurements in the assigned areas, and capability of measurement will extend to transmission line levels including 1000 kV d.c.

Keywords High voltage direct current, metrology.

1 INTRODUCTION

An initial controversy between alternating and direct current in electrical grids was resolved a century ago in favor of alternating current. The success of alternating current derives from the ease of transforming the power from one voltage level to another. This comparative advantage is today no longer so evident in the face of advances in power electronics, making direct current transmission viable at virtually all transmission levels. Trunk lines with direct current have been on the scene for more than 50 years, first based on mercury arc rectifiers which were supplanted by thyristors starting from the 1970-ies. Today the thyristor technology is complemented by, or even replaced by, power transistor technology. This latest phase of development permits a voltage source capability of the convertor stations, which enables a high degree of control, and permits the building of true high voltage direct current grids.

Two major areas need to be addressed to enable true d.c. grids: a reliable d.c. breaker is needed to isolate faulty sections, and quality assured measurements of d.c. grid quantities are needed both for operation and for commercial purposes. The first area is outside the scope of this paper, but the second will be addressed in detail.

2 MEASUREMENT NEEDS IN D.C. GRIDS

2.1 General

Operation of an electrical grid requires good knowledge of the parameters of the grid, i.e. accurate measurements of current, voltage, power etc. are needed. Here we will divide these needs into four groups and discuss them separately and explore the relevant requirements for each case.

2.2 Protection

The protection system must be able to discriminate between faults that must be cleared and other disturbances. If a protective measure is required, the system must also determine how the fault is to be cleared.

In this application, fast response of the measuring system is important to ensure timely protective measures and to permit undistorted capture of transient phenomena. The absolute accuracy is however not of paramount importance.

2.3 Control

The power system control primarily strives to keep the system stable, and ensure controlled power flow. In principle this can be achieved without precisely known values for operating parameters. This is however not practical because then control could only be re-active and not predictive and would lead to poor grid stability.

The accuracy of the measurements is thus important, but on the other hand, fast response is not required.

2.4 Metering

Allocation of resources on a market, such as the electricity market, is controlled by supply and demand. The tool for this is the pricing of the commodity, in this case the electrical energy. Energy sold must be billed in a fair way with confidence in, and acceptance of, the metering. The requirement is valid for the whole metering system, voltage and current transducers, the energy meter and the possible effects of wiring.

Disregarding losses, the metering can take place anywhere in the system, but when losses are to be shared proportion to energy sales, care must be exercised to choose the correct billing points. Take as example a d.c. grid with three converter stations and three different owners. In this case they should cover the losses of their own converter stations, and an equitable share of the line losses. In this case, metering will need to be on the d.c. side to obtain sufficient accuracy for the metering of transmitted /received energy, and to be able to calculate the losses incurred in the line.

D.c. side energy meters are today hampered by the lack of written standards and type test requirements. This lack also means that authoritative testing cannot be obtained at any of the existing test houses.

2.5 Loss evaluation

Current source converters using thyristors can be evaluated as to their losses from component calculations, following the IEC standard IEC 61803: 1999, Determination of power losses in high-voltage direct current (HVDC) converter stations. For modern voltage source converters using insulated gate bipolar transistors (IGBT) there is no generally accepted method to perform such calculations. The most straight-forward method to verify the losses of a bi-polar convertor station would be to connect the two poles in back-to-back configuration. The converter control could then be set to any transferred power between the poles, and only the losses would need to be supplied from the external grid. The resolution and accuracy of this method is certainly adequate, but it cannot be generally applied. Measuring the losses of components, especially the IGBTs and their associated circuitry is feasible, but requires accurate measurements both at low voltage and high current, at high voltage and low current and during the switching process between the states.

3 OVERVIEW OF TECHNOLOGY FOR D.C. MEASUREMENTS

3.1 General

The high voltage and high current quantities of the main circuit need to be converted to a quantity useable by control and protection systems. These converted quantities have usually been analogue signals at low voltage and current, mirroring the primary circuit. There is however a trend that conversion is made from analogue quantities in the primary circuit into a digital bit-stream already in the primary transducer. Both technologies have their place and provide distinct advantages. However, the primary transducer must in each case be able to mirror the primary quantity as to magnitude and time parameters and these requirements are independent on the signal transfer technology, be it analogue or digital.

3.2 High d.c. current

Measurement of current at high voltage requires that the secondary circuit is isolated from the primary voltage. An early such technology was the saturable reactor system – the transductor, see Figure 1.

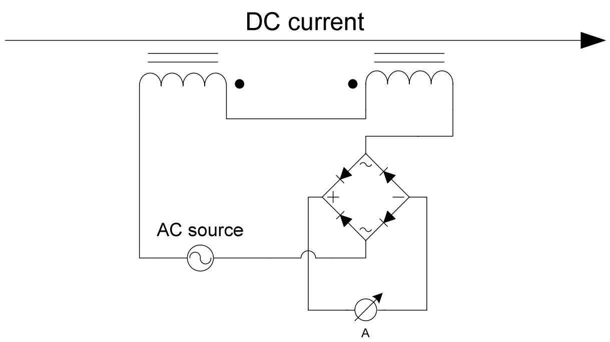

Figure 1. Transductor operation

The operation of the transductor is founded on the non-linear magnetic properties of ferrous metals. As the d.c. current increases, the reactance of the two reactors will decrease and the resultant a.c. current through the rectifier bridge and the instrument will increase. This type of device was widely used in HVDC applications up to the 1970-ies but is today seldom seen.

Research in Canada and Jugoslavia in the 1960-ies had resulted in a new type of current transformer – zero flux transformer – that exhibited excellent properties for d.c. current and also good properties for a.c. This was used extensively in magnet supplies in CERN accelerator designs. The existing designs were modified around 1979 to fit the needs of HVDC. The principle is shown in Figure 2.

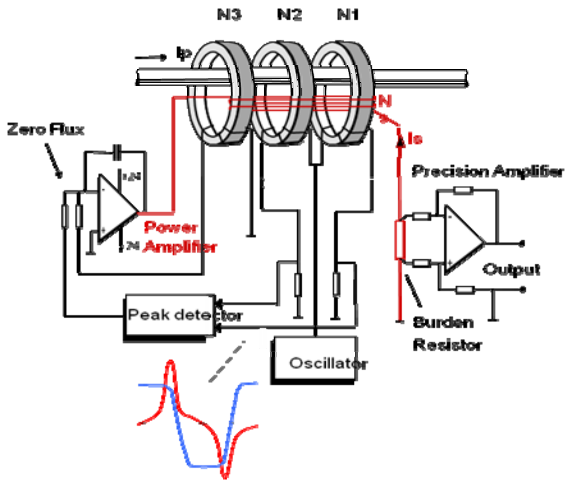

Figure 2. Principle of zero flux transformer for measurements of d.c. and a.c. current

Consider a d.c. current *I*p flowing in the primary conductor. This will cause a net magnetization in the cores N1 through N3. The cores N1 and N2 are intentionally driven with an a.c. voltage large enough to drive the cores into saturation. When there is no net magnetization in the cores, the saturation will be symmetrical, but even at a very small magnetization a distinctly larger saturation current will flow in one of the half-periods of excitation voltage. A peak detector is used in a negative feedback circuit to balance the ampere-turns of the primary and secondary circuits for d.c.. The core N3 provides negative feedback for ac current. Performance for d.c. can approach parts pteer million and the bandwidth can be 10’s to 100’s of kHz.

The Faraday Effect observed in certain crystals couples electrical current to rotation of polarization of transmitted light. Resolving the transmitted light with respect to polarization can therefore be used to measure current using purely optical paths. Such systems are today available on the market with properties at least suitable for control and protection purposes. Use for metering is possible, but not extensively used.

Systems using shunts as measuring elements are available on the market since many years. When used for high voltage applications, digitizing circuits at high voltage convert the shunt voltage to a digital bit-stream that is transmitted over an optical fibre. The same fibre can be used to transmit energy in the form of short wave-length light to the electronics at high voltage. The properties systems are suitable for control and protection, but with careful design, they have been proved to be useful also for metering purposes.

Calibration of d.c. current measurement can be made with very good accuracy up to several kA, and is available in many countries.

3.3 High d.c. voltage

In principle, the task is to “determine the line integral of the electric field from the high voltage terminal to earth” (D. Gabor 1927). In practice no perfect technology exists to perform this, although several alternatives are found.

The most common method to measure high d.c. voltage is to use a resistive voltage divider, which is almost always built as a parallel RC divider to provide response also for higher frequencies. It is an example of engineering need to compromise between conflicting performance requirements. A high resistance is strived for to limit self-heating and resistance change due to temperature, on the other hand this may lead to too high influence form unavoidable leakage currents. Also a.c. performance is easier to obtain at lower resistance values.

Electro-optical effects are possible to use, especially if the line integral evaluation is approximated by using several sensors to sample the electric field. The technology is attractive because the frequency response can be good, but there could be long-term stability issues related to zero point drift in d.c. applications.

Calibration of d.c. voltage is available in Europe up to 300 kV with good accuracy, and with limited accuracy up to 400 kV. Above this level no facilities are now traceable. There is thus a gap up to currently highest line voltage of 800 kV.

3.4 D.c. side power and energy measurement

The straight-forward solution to energy measurement at d.c. is to accumulate the instantaneous products of current and voltage, taking into account the interval between readings. The input signal can be either an analogue signal that is processed in the circuits of the energy meter, or in the other extreme, the primary quantity is digitized already in the transducer and analyzed in a computer. In the latter case the “meter” is just a program in a computer and has no associated hardware.

In either case, primary transducers for voltage and current are needed and are in general the ones described above. In principle many a.c. energy meters can be modified for d.c. application with only minor hardware changes.

Metering systems for power and energy from d.c. must take into account not only steady-state quantities, but must also ensure adequate handling of varying voltage and/or current.

3.5 Loss measurement

Losses in convertor stations using thyristor technology are usually based on calculations on individual components of the station, based on written standards. The new technology that uses Insulated Gate Bipolar Transistors poses new challenges to overcome, and it is not clear if calculations are satisfactory. The losses represent an important economical aspect on the purchase of HVDC equipment and traceable measurement of the losses will be important to the players on the market.

4 CURRENT RESEARCH IN EMRP

Response to the above challenges is given by 7 national metrology institutes, one university and one industrial partner who combine in a research program that aims to provide solutions both the hardware needs, background for future written standards and metrological infrastructure.

The work has received funding from the European Union on the basis of Decision No 912/2009/EC, and identified in the European Metrology Research Programme (EMRP) as Joint Research Project (JRP) ENG07 HVDC, Metrology for High Voltage Direct Current.

4.1 Losses

The investment in a d.c. intertie is substantial and both costs and gains must be carefully evaluated. The gains in using d.c. transmission include possibility to connect to weak grids, to lay new high voltage cables, to connect non-synchronous grids etc. These distinct advantages must be weighed against the losses incurred in both d.c. power line and in converter stations. The former is easily estimated from resistance and current, but the latter is complex either to measure or to estimate. The major losses in a converter station relate to the converter itself and to the converter transformer. Of these two, the losses of the converter pose difficult problems, especially for the latest technology with fast-switching high-power transistors. Even determination of losses on a single switch is a challenge, with need both to measure loss at high conduction current (and low voltage), at high voltage (and low leakage current) and during the switching between these states. The measurement must have wide dynamic range, good resolution in both voltage and current and very fast response.

In order to master the measurements on IGBT circuits, simulations and measurement systems have to be developed, that can cope with the fast phenomena (kHz).

The overarching objective of the research is to improve the measurement of losses in HVDC systems. Measurement of loss of especially HVDC convertors is one of the most important figures of merit for a convertor valve.

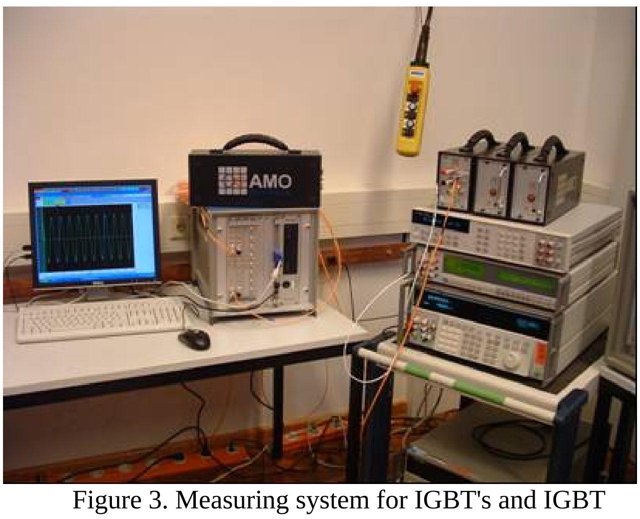

Figure 3. Measuring system for IGBT's and IGBT modules

The scientific and technical objectives of the research are:

- To develop a test circuit for single switching elements (IGBTs) of HVDC valves,
- To develop a test circuit for sub-modules of HVDC valves,
- To perform characterisations of single elements (IGBTs), stacks and sub-modules,
- To develop an IGBT stack model and to identify parameter values of the model.

An investigation has been performed to study the valve topologies in common use today and to determine the needs of the test circuit used to characterize the switching elements under realistic conditions. An existing platform for such measurements has been modified to fit the new requirements and is currently prepared to include the new measurement capability being developed. A number of precision instruments and transducers have been investigated in order to build a precision acquisition system for the voltages and currents occurring in the switching elements of HVDC voltage source convertors. Such equipment has now been defined, purchased and characterised, and is now available to measure losses of switching elements, see Figure 3.

4.2 D.c. Voltage measurement

The measurement of d.c. voltage in convertor substations is important for most aspects of station operation. This measurement is not yet sufficiently accurate neither for metering purposes nor for loss determination. Work is therefore under way to provide new measurement infrastructure 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.

Figure 4. 200 kV reference divider

To support these, at least two voltage dividers in national laboratories will be qualified as master references. In both cases, the target voltage has been raised to an unprecedented 1 MV to prepare for expected increase in future HVDC schemes.

Candidates of resistor elements for the precision divider have been investigated and a decision to use Caddock resistor type USF370 has been reached. Detailed design work is on-going and is supplemented by both theoretical analyses and experiments. Behaviour over the low frequency range has proven to be crucially dependent on the presence of non-guarded parasitic capacitances, and a shielded design has been adopted with dual divider chains, one precision chain shielded by large electrodes that are connected to a capacitively controlled resistor chain.

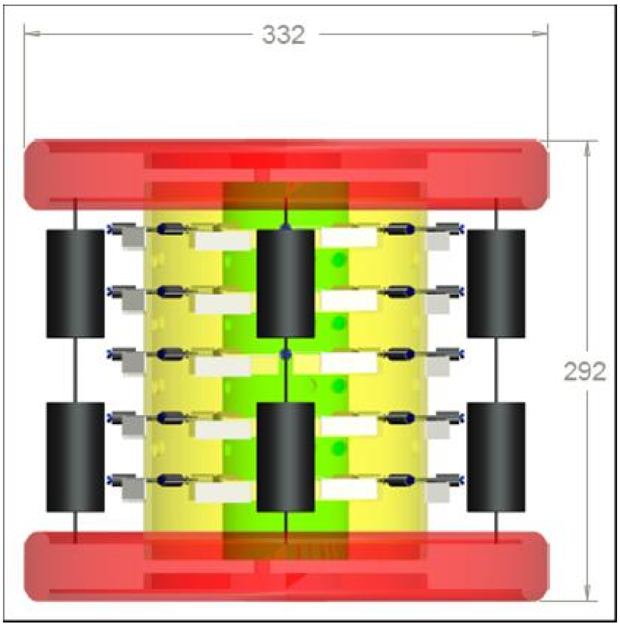

Figure 5. Concept of a 25 kV section of the modular divider for on-site use

4.3 Power quality

Converters used in HVDC systems can produce harmonics and inter-harmonics which are injected into the grid system. Existing grid codes largely concentrate on limiting harmonic pollution from such systems; however there are also anticipated issues with inter-harmonics that are mostly un-measured and un-regulated. The effect of such inter-harmonics could have a significant influence on the grid power quality (PQ), which amongst other undesirable effects, gives rise to increased losses. An effort will be made to develop and implement new capabilities for the on-site assessment of harmonics and inter-harmonics and study their detrimental effects.

Design of filters in HVDC stations needed to mitigate the effect of such harmonics requires knowledge of the impedance of the grid across the relevant frequency range. New robust methods will be developed to determine this impedance with sufficient precisions to enable effective mitigation, and prevent component failure.

The possibility to use existing current or voltage transducers to capture power quality phenomena will be investigated.

4.4 Metering

Figure 6. On-site work will be included in the scope.

Correct metering is a prerequisite for correct billing and for fair trade. Metering on the d.c. side is in many cases the logical point in the interface between buyer and seller in a d.c. grid. Due to lack of consensus on correct measurement principles and of accepted technical solutions, this option for metering is currently not used.

Although suitable candidates for primary current and voltage transducers for metering on the d.c. side are available, there is no calibration service available to prove that they fulfil revenue metering requirements.

Specifications for d.c. side electricity meters are not publicly available and there is no consensus on methods for type and routine tests on such meters. However, with the projected increase in HVDC links and the resulting escalation in financial transactions between nations and different commercial operators, there is a need to allocate the significant cost of converter station losses and this can only be achieved through d.c. side metering.

New measurement capabilities for d.c. side metering apparatus is needed, and will be developed, both for high level laboratory calibration and for calibration needs during manufacture of measuring devices. A further need for verifications in the finished sub-station is also expected.

Pre-normative research on-going to define basic requirements for d.c. electricity meters, both for present-day analogue input circuits, but also for the future using current and voltage transducers with digital output signals. Testing and test methods will be explored and a calibration demonstration facility will be built to implement test procedures for both kinds of d.c. energy meters.

A barrier to d.c. side metering is the lack of availability of suitable energy meters. A demonstration d.c. energy meter will be built and tested according to the principles laid down in the project. The meter will be installed in an actual HVDC station and compared to metering presently installed on the a.c. side.

A novel type of non-invasive current transformer (CT) for calibration of the a.c. current transformers will be developed and used to characterize installed instrument CTs in order to evaluate their energy metering performance in the chosen HVDC station. A survey of technology and industrial competence in this area has been conducted, and a collaborator for this is in the process of being attached to the project.

As part of this package, on-site experiences are planned where the methods and equipment are trialled under realistic circumstances, Figure 6.

5 OUTLOOK

The research program addressing the above research issues started on September 1, 2010 and will have a duration of 3 years. The participants are working in complementary tasks focusing on their specific expertise. The final result will be new calibration capabilities, but also new equipment such as reference dividers for HVDC with assured characteristics, loss measurement platforms and prototype energy meters for d.c. metering.