Experience from First 800 kV HVDC Test Installation

Abhay Kumar, Dong Wu and Ralf Hartings

***Abstract*--The use of HVDC at 800 kV has been found efficient, environmentally friendly and economically attractive for large point-to-point power transmissions. Worldwide there is an increasing interest in the application of HVDC at 800 kV. With one 800 kV HVDC transmission project already in execution phase, second in bidding and third one in preparation of bidding; it can very well be concluded that 800 kV DC is now a established voltage level for bulk power transmission over long distances. Already realising such a need, ABB not only started with the development for 800 kV equipment to make this possible; but also planned for a long time test circuit installation to establish a confidence in such a voltage step as well in the new technology and newly developed equipment. The long term test circuit installation has been energised at 855 kV_{DC} since November 2006 at STRI, Sweden and has served well its purpose in providing final qualification for the newly developed products and boosting confidence in 800 kV HVDC technology with several utilities around the world. This paper presents the experience from this first 800 kV HVDC test installation in the world.**

***Index Terms*--800 kV, Bulk Power Transmission, Experience, HVDC Transmission, Test Installation, UHVDC, UHV Transmission.**

I. Introduction

DUE to involved economics, interest in application of higher DC transmission voltage than presently used (i.e. 600 kV_{DC}) has increased considerably in recent years for transporting clean and renewable energy from remote hydro-generation plants. 800 kV Ultra High Voltage Direct Current (UHVDC) Transmissions are economic attractive for bulk power transmissions, say above 5000 – 6000 MW, over long distances, say above 1000 – 1500 km [1]. Xiangjiaba – Shanghai ±800 kV HVDC Transmission project rated for 6400 MW to transmit power over a distance of 1935 km by State Grid Corporation of China is presently (July 2007) in bidding phase. Yunnan – Guangdong ±800 kV HVDC Transmission project of China Southern Power Grid, rated for 5000 MW to transmit power over a distance of 1418 km has recently moved under execution phase; while Power Grid Corporation of India Ltd. is currently preparing for bidding of NER/ER – NR/WR Interconnector I ±800 kV Multi-terminal HVDC Transmission project rated for 6000 MW to transmit power over a distance of around 2000 km to feed power into Agra area.

In countries with growing populations and rising economics like India & China, UHV offers the promise to meet challenge to deliver large quantities of electricity from power generating stations to urban centres to meet the increasing intense demand of electricity. UHV is needed to deliver electricity to cities with minimum number of transmission lines. In growing cities where demand is on rise, but room for transmission lines is limited, this is further critical because it means only one power line corridor is needed, not several.

A comparative Life Cycle Assessment (LCA) study performed for 6000 MW power transmission with environmental impact categories as in Table I indicates that 800 kV HVDC transmission infrastructure brings up ecological benefits as well in an overall system's point of view in all categories [2].

TABLE I
ENVIRONMENTAL IMPACT CATEGORIES & INDICATORS FOR LCA STUDY IN [2]

Impact Category	Impact Indicator
Greenhouse Gas Emissions	Global Warming Potential (GWP) of the whole balance system [kg CO_2-Equivalent/a]
Acidification of soils and waters	Acidification Potential (AP) of the whole balance system [kg SO_2-Equivalent/a]
Eutrophication of soils and waters	Eutrophication Potential (EP) of the whole balance system [kg PO_4-Equivalent/a]
Use of Land	Right of way [m]

II. Equipment Development

In order to meet the demands for such large projects, ABB has been running an R&D programme, well in advance, with the goal to develop and test equipment needed for 800 kV HVDC. The R&D work had focused on equipment connected to the pole voltage, with special attention to converter transformers, bushings and external insulation [3, 4]. The most significant difference between equipment for HVDC compared with equipment for HVAC is the need for proper DC grading.

When applicable, HVDC equipment is built up by modules where each module is provided with a proper resistive voltage grading resistor as well as an AC/transient grading capacitor. With a proper voltage grading, the voltage stress in the modules will be the same, regardless the module is part of an 800 kV apparatus or a 500 kV apparatus. For oil/paper

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insulation systems the situation is more complicated, since it is not possible to arrange the DC grading with physical resistors: the DC grading must be secured by other measures.

For outdoor equipment exposed to pollution and rain/fog, the coordination between the internal and external voltage grading is an important issue. Bad coordination can result in damage of the insulators due to radial voltage stress.

Not just designing or making prototype or testing these 800 kV equipments, ABB has installed them in an energised test circuit to obtain first hand long term 800 kV operational experience [5]. This was to obtain the confidence in the new technology as well to gain the time to resolve if any unforeseen problem is revealed and to verify the dimensioning of various parameters. In ordinary conditions, newly developed equipment is qualified by a series of type tests. Most of the dielectric type tests are short duration tests. Supported by operational experiences of earlier products at similar voltage level, such qualification has been proved to be sufficient. However, as for equipment for 800 kV HVDC, there is no existing experience at this voltage level. To verify the design, it is of importance to examine the equipment in a relatively long time span. A good example is the need to verify the internal and external electric field design.

In AC, the field distribution is determined by the dielectric permittivity (ε, epsilon) of the insulation materials, while in DC the steady state field distribution is controlled by the resistivity (ρ, rho) of the insulation materials. In real service operation an equipment, typically the bushings, will be exposed to both DC and transients of varying frequency. When switching on the voltage, an AC-like voltage distribution will occur, and after a certain time (corresponding to the "overall time constant" of the insulation system, $\tau = \rho * \varepsilon$), the DC-like field distribution will be obtained. Due to the complex nature of the insulation system, the geometry and position of the different parts, the transition from "AC to DC" may occur very differently in different locations inside and outside the bushing.

The resistivity of the insulation materials of a bushing is of course very high. As a result, the typical overall time constant will vary orders of magnitude and can be very long. In fact, hours, days, or weeks are quite typical. Furthermore, the resistivity is normally a function of the temperature, which means that the resistivity may vary several orders of magnitude, with varying temperatures. It is therefore important to verify the electric field distribution also in its "natural" environment, e.g., at a valve hall temperatures of up to 40-50 °C. Thus a long term test using a 'heated valve hall' simulates the real time stresses.

Though the test location is Sweden, however the equipment design is made for the site pollution conditions.

III. Long term test circuit

In order to verify the long term behaviour of the 800 kV HVDC equipment, all relevant pieces of equipment are installed in a long term test circuit at STRI in Ludvika, Sweden (see Fig. 1), and energized at 855 kV DC, since November 2006.

Fig. 1. 800 kV HVDC long term test circuit installation at STRI, Sweden.

The test circuit includes a "valve hall" where the temperature is kept above 50 °C, to simulate the actual operating conditions for the bushings. The transformer bushing protrudes inside the "valve hall" and is connected to the wall bushing that is installed in the wall. The remaining equipment as listed below, are installed outdoors, together with the voltage generator. The layout for the test circuit is given in Fig. 2.

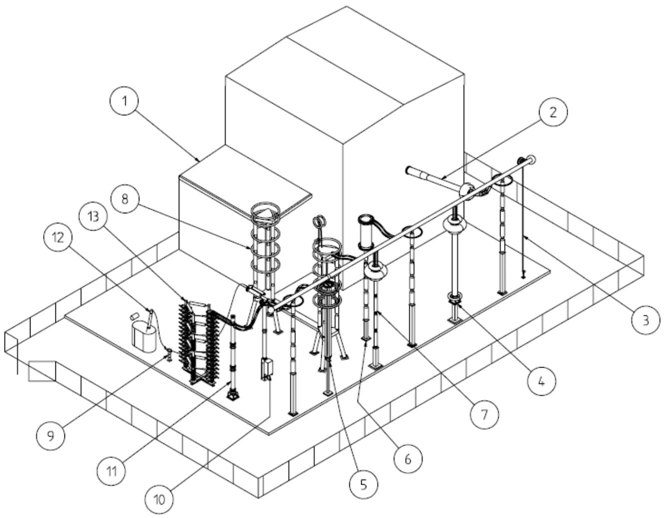

Fig. 2. 800 kV HVDC long term test circuit layout.

Following equipments (test objects) are included in the test circuit installation:

1. Transformer prototype
2. Wall bushing
3. Optical current transducer
4. Voltage divider
5. Pole arrester
6. Smoothing reactor prototype
7. RI Capacitor

8. Disconnector
10. By pass breaker

In addition to the above test objects, following test equipments associated with the voltage source can also be seen on the above layout:

9. Voltage transformer
11. Voltage divider
12. Transformer
13. DC voltage generator

IV. Experience and Measurements

All equipments in the test circuit has been operating as expected and no failure has been reported so far. The polarity of test circuit was changed from positive to negative on May 4, 2007, after several months of successful operation. While making stop at positive polarity, measurement for the electrical field strength around the transformer bushing at 300 kV were performed and as well while starting at negative polarity.

During these times when all these equipments are kept energised at 855 kV_{DC} in the test circuit installation, several measurements are continuously being recorded. These include

- Ambient conditions
- Surface leakage currents
- Electrical field strengths
- Gas in oil analysis

In addition videotaping of the energizing was performed when snow was laying on the wall bushing. With an infrared camera recoding of the heat transmission through the wall bushing during cold weather was also made.

It is planned that after the long term testing, equipment shall be subjected routine tests again.

A. Ambient Measurements

Regular measurements are made for the ambient conditions. These include temperature, humidity, rain fall, wind speed, wind direction, UV-B intensity and dew-point temperature. In the below Fig. 3, Fig. 4 and Fig. 5, recorded temperature, humidity and wind speed is shown for period May/June 2007.

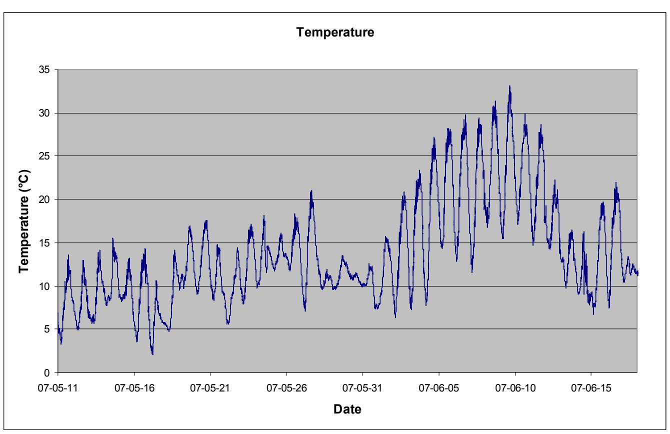

Fig. 3. Record of ambient temperature during May/June 2007

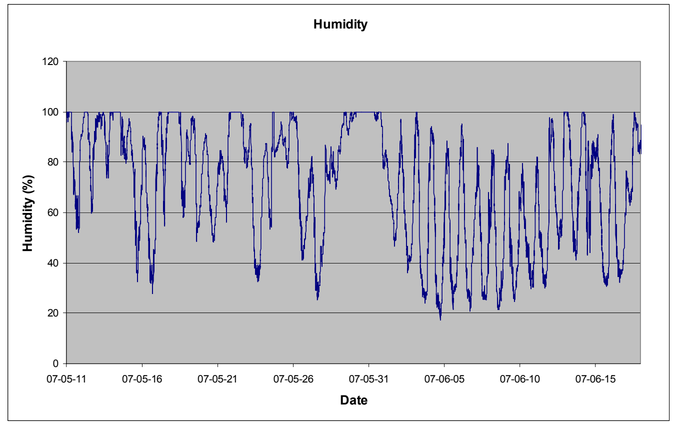

Fig. 4. Record relative humidity during May/June 2007

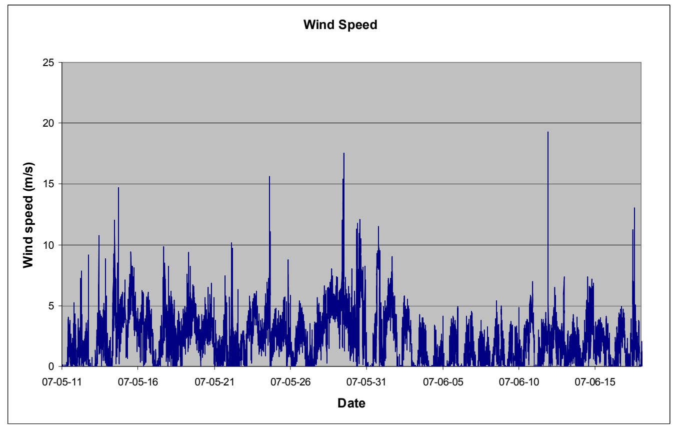

Fig. 5. Record of wind speed during May/June 2007.

B. Leakage Current Measurements

Regular measurements are made for the surface leakage current on the RI Capacitor, Arrester and Wall bushing. In the in Fig. 6 below one of such typical recoding is shown for period May/June 2007 for the wall bushing.

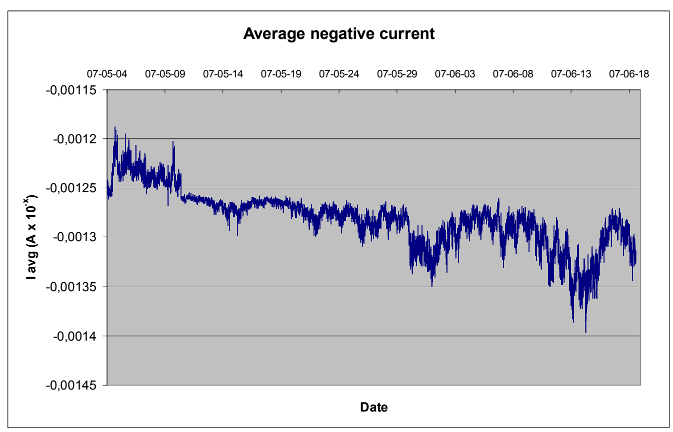

Fig. 6. Record of average negative current on 800 kV wall bushing.
(Note: above measurement is with out correction of initial offset).

With negligible recorded leakage current, these measurements have been as expected and have not revealed any problem with any of the equipment installed in the test circuit.

C. *Electrical field strength Measurements*

In DC applications, the voltage is constant over time and the impact of this constant electric field strength is a continuous driving force on charges and charged particles. These are drawn towards and accumulated on the bushing and these charges will have an impact on the total field distribution, not only on the outside of the bushing, but also on the internal parts of the bushing. It is the electric field distribution, and the lack of "electric field hotspots", which determines the dielectric performance of the bushing. It is therefore of vital importance to know where those charges will and should be accumulated when designing the internal parts of the bushing.

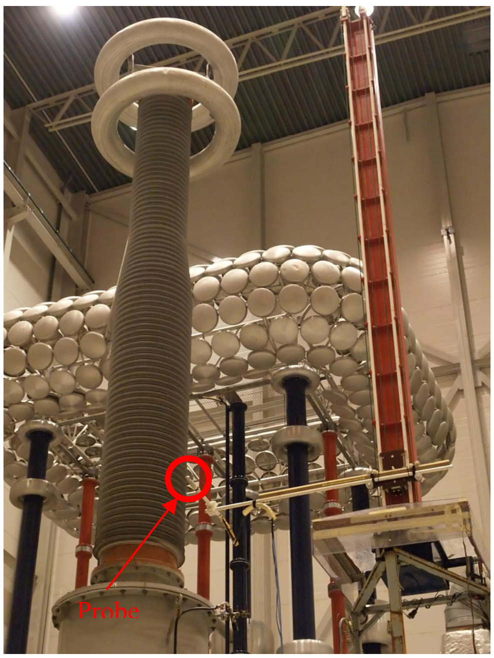

Fig. 7. Test set-up for DC electric field measurements along a 500 kV_{DC} transformer bushing. The field probe is in the middle of the red circle.

Initially, the field distribution was studied along a 500 kV_{DC} transformer bushing. The test set-up for the electric field measurements is shown in Fig. 7.

The rotating field probe measures the axial and radial field along the bushing, by moving the white horizontal rod, holding the probe, along the vertical (brownish) robot pillar. A typical field plot is shown in Fig. 8, measured after the bushing was grounded and thus indirectly showing the amount of charges left in and on the bushing. It is clear that charges are present and that they will influence the field distribution during normal service conditions. Under certain conditions, residual field strengths of up to 500 kV/m were measured locally along the bushing. To integrate this phenomenon into the design of the bushing is a requirement for any HVDC bushing in order to guarantee a life-long problem free operation in service.

The field distribution inside and outside the bushing is controlled not only by the deposited charges on the outside, but of course also by the inner structure of the bushing, the external flanges, the corona rings and the properties of the surrounding air.

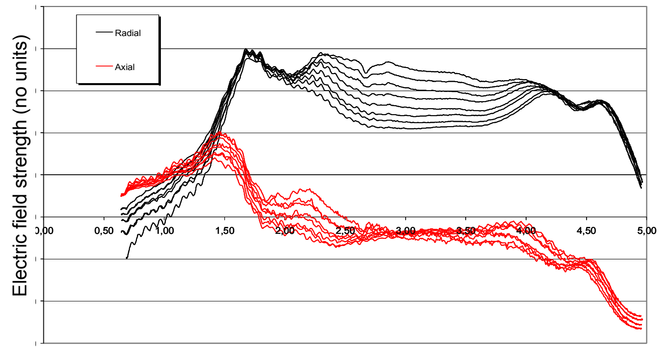

Fig. 8. Axial (red) and radial (black) electric field along 500 kV_{DC} transformer bushing after grounding ($U_{applied}=0$). The different curves represent different measurements in time. Time step is about 1 minute.
Y-axis: Axial and radial field strength in arbitrary units;
X-axis: length along bushing in meter.

During the long duration tests, the electric field was measured along the transformer bushing to monitor the transition from purely capacitive AC-field distribution to a steady state resistive DC field distribution, including the impact of accumulated charges, see Fig. 9. The measured electric field distributions also confirm the calculation models based on the resistivity of the insulation materials used.

Fig. 9. Measurement of 2-dimensional DC electric field along transformer the bushing, during the long duration test. The wooden structure is used to put the robot in parallel with the bushing. The position of the probe is indicated by the red circle and it is remotely moved along the bushing.

D. *Corona*

No audible or visible corona has been found except on optical current transducer (OCT) and on DC voltage generator itself. This was already expected as the shielding design for OCT was used from 500 kV without modifications.

The test installation has proved the satisfactory design for the electrode arrangements and bus bars.

E. *DGA Analysis*

Dissolved gas analysis (DGA) is being made for the converter transformer prototype. The main intention of the DGA is to reveal possible partial discharges in the transformer insulation system. Since there is no load-current in the test circuit, changes in the dissolved gas content in the transformer oil can be attributed to partial discharges only, and the absence of gas produced by load current makes it possible to analyze the samples with a very high degree of resolution. During the operation of the test circuit, no changes of the dissolved gas content have occurred, which indicates that the transformer prototype is PD-free.

V. Conclusion

800 kV HVDC is economically attractive for bulk power transmission over long distances. With the present progress of R&D converter equipment for 800 kV HVDC is fully qualified.

Test installation has been operating satisfactorily since November 2006, without any problems and has provided confidence in ABB's design for 800 kV UHVDC equipments including design of electrode arrangements and bus-bars.

With the confidence gained with satisfactory operation of the long term test circuit, the conclusion is that 800 kV DC will account for a significant part of world growth in power transmission capacity over the next several years.

VI. Acknowledgment

The authors gratefully acknowledge the contributions of Urban Åström and Victor F Lescale for their work on the long term test circuit and support extended by them in writing of this paper.

VII. References

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VIII. Biographies

Abhay Kumar was born in Delhi, India in 1961. He obtained his degree in Electrical Engineering from University of Roorkee (now IIT) in 1982. He joined National Thermal Power Corporation Ltd. (NTPC) in 1982 and worked until 1995 as Deputy Chief Design Engineer. He has been involved in the design of Vindhyachal B2B HVDC and Rihand – Delhi HVDC Projects and many other EHV substations. He has also been consulting engineer for Chandrapur – Padghe HVDC Project. From 1995 to 2000 he worked for ABB Ltd. New Delhi as Senior Manager at Power System Engineering and Business Development department. Since May 2000, he has been working for ABB HVDC in Sweden first as the Technical Manager for The Three Gorges – Changzhou ±500 kV DC Transmission Project and presently as the Lead Engineer cum Project Manager for The Three Gorges - Shanghai ±500 kV DC Transmission Project in Sweden.

Dr. Dong Wu was born in China in 1952. He had graduated from Xian-Jiaoton University, received his M.Sc. degree from China Electric Power Research Institute, and gained his Ph.D from the Royal Institute of Technology of Sweden, in 1977, 1982 and 1988 respectively; all in electrical engineering. He has worked at China EPRI until 1991 and STRI in Sweden until 1997. Since 1998 he has been with ABB HVDC in Sweden. He has worked in the areas of power electronics, the design of HVDC converter valves, high-voltage engineering and electrical insulation. He is a Company Senior Specialist on electrical Insulation in ABB. He is a member of several Cigré and IEC working groups on outdoor insulation.

Ralf Hartings was received the M.Sc. degree in electrotechnical engineering from the University of Technology, Eindhoven, The Netherlands, in 1981. From 1982 to 1987, he has worked with circuit breaker research and development at ASEA, Ludvika, Sweden. In 1987, he entered the area of outdoor insulation, first at ABB and in 1989 at STRI in Ludvika, Sweden. From 1995-2005, he was the Research Director and manager of the department for Technology & Consulting Services at STRI. Since May 2005, he is at ABB and responsible for the development of 800kVdc bushings. Ralf Hartings is a Senior Member of IEEE, a member of Cigré and received the Cigré Technical Award in 2002. He is also is a former member of Cigré Study Committee 33 and has written more than 50 international publications and participated in numerous international conferences.