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Verification of equipment for ± 800 kV HVDC

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Abstract: The use of Ultra High Voltage Direct Current (UHVDC), i.e. voltages above the highest in use, 600 kV, has been found to be economically attractive for power blocks up to 6000 MW for distances above 1000 km, Furthermore the use of 800 kV as transmission voltage will be achievable within the near future with a limited amount of development work. None of the AC equipment, auxiliary equipment or control and protection will be affected by the increase of DC voltage. Also most of the DC equipment is easily modified for 800 kV, such as voltage dividers and DC filter capacitors. Station external insulation and line insulation must be carefully considered. In order to meet the demands, ABB is running a R&D project for verifying equipment for ± 800 kV HVDC. The program includes manufacturing and type and routine testing of all critical components. The equipment has been installed in a test circuit for long term energisation at 855 kV.

Key Words: 800 kV HVDC, UHVDC, UHVDC converter stations, UHVDC equipment

INTRODUCTION

In order to meet the increasing interest for bulk power transmission with HVDC at voltages above 600 kV, ABB has launched a R&D program in order to develop and qualify equipment for ±800 kV HVDC. The R&D program includes complete system design of a 6400 MW transmission, as well as design, manufacturing, type and routine testing of all critical apparatus [1].

During the development work, it was found that also a long term test is essential to qualify the equipment. Thus, after type and routine testing, all the prototypes manufactured have been installed in a test circuit and will be exposed to 855 kV for at least six months. This paper summarizes the most important findings during the development process.

The test circuit will be energized early November 2006.

AVAILABILITY AND RELIABILITY

Transmission of 3000 – 6000 MW bulk power into heavy load-centers like for example Guangzhou means that the reliability of the transmission is very important and has to be a major design parameter.

For comparison the requirements for the converter stations in the Three Gorges - Shanghai 3000MW transmission are shown below in a table, together with the foreseen requirements for a new 6400MW transmission

Forced outage rates	3GS	6400MW
Single pole trips per year	5	4
Bipolar trips per year	0.10	0.05

Availability		
FEU	0.5%	0.5%

From the figures, it can be seen that serious improvements have to be made: Regarding single pole trips, the improvement from five to four would appear moderate, but the added complexity of the 800kV pole configuration speaks against a better figure. Regarding bipolar trips, the task is even harder: halving the outage rate that is state of the art requires radical improvements.

The different phenomena that have in the past caused disturbances or trips, and at the same time, the different subsystems are being carefully considered in light of the new requirements. One of the keywords is separation: between converter groups, and even more stringently, between poles. The two poles in each station are regarded as practically two stations that happen to be neighbors.

The experiences from the Itaipù ± 600 kV HVDC project, also having two 12-pulse bridges in series per poles is have given important input for the structure of the system, like the control, protection converter sequences and auxiliary systems.

HVDC Line faults

Of course, a chain is no stronger than its weakest link, and the converter stations as well as the transmission line have to be investigated. The scope of this paper is limited to the converter stations, but some considerations on HVDC lines are in order here. The frequency of line faults is dependent on the length of the line. Bipolar faults can occur e.g. at tower failures or due to icing and wind at extreme weather conditions, but are rare. The majority of the pole line faults are cleared easily within some periods by retarding and restart. During the retard time the healthy pole compensates the power loss on the failing pole. At rare occasions the line will stay tripped for longer periods, and will recover within a few hours. The time needed for dead line maintenance will be added to the line unavailability.

For some DC systems special arrangements have been done to increase the power availability. In the Inga-Shaba HVDC project, the two converters in the bipole can be paralleled and the power can be transmitted on one pole line. Switching stations along the line allow for continued transmission even for simultaneous line faults on different segments along the line. For the Itaipú HVDC project, with two bipoles, the converters can be connected in parallel to one bipole, in order to minimize the loss of power at bipole line outage.

Converter configuration/station layout

The configuration of the HVDC main circuit has been carefully analyzed,. For example, the pole configuration, with two converter groups in series halves the power loss upon loss of a converter group, and with adequate switchgear, ensures that a group outage will not result in a pole outage.

Special attention has been devoted to the dc neutral. It is normally regarded as one electrical point, and is electrically common to both poles, but it is also a potential source for bipolar trips. The neutral circuit configuration has to provide separable neutrals, allow for maintenance, and, even more important, it has to ensure faults can be detected and cleared independently on each pole, even in normal operation, when the neutral has no voltage.

The ac switchyard and configuration is also under scrutiny. Again, a very important aspect in the considerations is avoiding single or even double failures that can cause bipole outages

Control and protection

A very important aspect has to do with ac system faults close to the inverter station: If an ac fault is close enough to the station, it causes commutation failures in the converters. It is very essential that the converters will not block for such events, because if they do, the HVDC power will not be restored when the fault is cleared. The valves produced by the author’s group have a firing system capable of operation as soon as the ac system has enough voltage for the thyristors to start conducting, even if the voltage was zero for a very long time before that, and the valve control system can resume operation in less than a microsecond. This ensures that this requirement is fulfilled, and thus need no new considerations.

The structure of the present control and protection system, has been revised, reflecting the different requirements on reliability and availability and also the pole configuration. It is envisaged that, in the new control structure, the two poles will be totally independent and that the groups in each pole will have a minimum of interactions. Ideally, the bipole should be built as two separate monoples.

The philosophy of the transducers feeding the control and protection system is also being scrutinized, as is the routing of the cables feeding signals in, and actions out.

Auxiliary systems

Station service power is being restructured, with proper separation between the associated poles and groups, and proper management of incoming supplies via the circuit configurations and control and protection. The physical power cable routing is also under scrutiny and rules are being defined.

The valve cooling systems are also being provided with proper separation between poles and groups: one cooling system per 12-pulse group, and with attention against human errors.

In the fire protection systems the main areas of review have to do with ensuring secure yet reliable sensing, and with the actions the protective systems can cause, directly and secondarily.

EQUIPMENT DEVELOPMENT

General

In this section a summary of the R&D status, early October 2006, of the different 800 kV HVDC apparatus is presented. Since the main focus for 800 kV development has been on converter transformers, bushings and external insulation, also these issues are in focus for this presentation

The equipment affected by the increased voltage level is of course limited to apparatus connected to the pole bus, such as converter transformers, wall bushings, thyristor valves, DC-voltage divider etc. The main part of the equipment within the converter station is not exposed by DC, such as AC yard apparatus, control and protection and auxiliary systems.

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 insulation systems the situation is more complicated, since it is not possible to arrange the DC grading with physical resistors, but the DC grading must be secured by utilizing the different material parameters, that usually are temperature and time dependant.

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 tress. Thus, the internal design of all the equipment for 800 kV HVDC has been subject to careful design review.

Test levels

For 800kVDC stations, the basic ideas for insulation coordination are the same as those applied for lower voltages; i.e. to have equipment with withstand characteristics above the expected stresses. Then, as is normal in medium or high voltage, the expected stresses are controlled by a combination of arresters and shielding. The difference for 800kVDC is that it is economically beneficial to control the expected stresses to an even higher degree, and to revise the steps leading from the expected stresses to the desirable insulation withstand; i.e. the insulation margins.

One has to remember that both aspects aim at improving the economy of a given system. Too loose control results in costly equipment, and too tight control results in costly arrester schemes and shielding. Regarding margins, a similar situation appears: too small margins result in costly equipment failures, too large margins result in costly equipment. Insulation coordination studies has been performed for the dc side of an 800kV HVDC transmission system, by different institutions, including ABB. The data for the system has been assumed based on the best available estimates, with regard to preliminary design of the equipment expected for such an installation. Further, as the study progressed, it became apparent that one fine adjustments to the configuration would yield significant benefits: Splitting the smoothing reactor function in two equal inductances, one at the neutral, and one at the pole.

The different studies performed end up with very similar results, and the test levels used for design of the 800 kV equipment are summarized below in table 1. These test levels have been the basis for the testing of the prototypes developed.

Table 1 Test levels (kV)

Equipment	**SI**	**LI**	**AC_{rms}**	**DC**	**DC** Polarity reversal
Transformer valve side	1518	1744	900	1250	970
Transformer bushing Valve side	1518	1744	900	1250	970
Multiple thyristor valve, top to ground	1518	1800	NA	1040 (3 hs)	NA
Wall bushing	1518	1800	1000 (one minute)	1235	1030
Smoothing reactor:					
Across	NA	2160/n	NA	NA	NA
To earth	1546	1950	NA	NA	NA
Pole bus at the line side of the smoothing reactor			1000 (one minute)	1200	1000

Insulators

It has been found that all outdoor insulation in the DC-yard, including post insulators for air core smoothing reactors, can be done by using composite insulators. Insulators for all applications have been developed within ABB, and are qualified according to Chinese standards.

By utilizing the water repellant properties of composite insulators, the total height of the 800 kV insulators will be about the same as what is used for 500 kV porcelain insulators. The high surface resistivity of the composite insulators are an important factor that must be considered at the design, especially for the design of equipment with an internal voltage grading and composite external surface exposed to the uncontrolled environment. The surface accumulation of charges will be an important factor for the radial DC-field. A special DC field probe is available at STRI, that automatically scans along the surface of the insulator in order to measure the charge accumulation on insulators surface as well as the associated electrical field, figure 1.

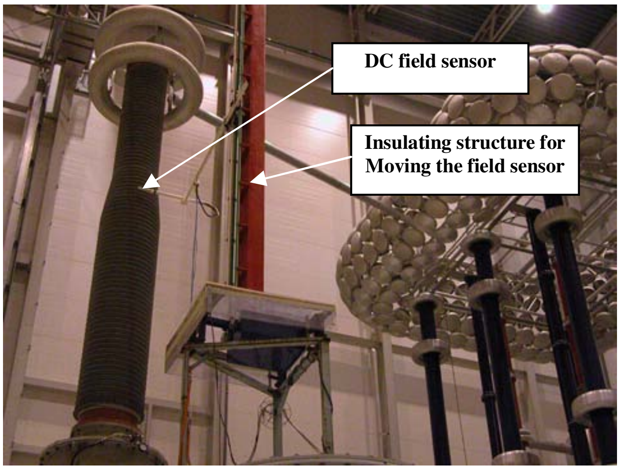

Figure 1: DC field probe, measurement on transformer bushing

Converter transformers

As has been described above, for most equipment using real resistors does the DC grading. This is not the case for the insulation inside the converter transformers. The insulation system in the transformers is built up by a system of oil and paper, and thus the resistivity of these materials will determine the DC- grading, in the same way as the dielectric permittivity will give the transient voltage distribution.

In analogy with other equipment, the stressed volume in a converter transformer is split up in sub volumes by cellulose barriers. The electrical stress is calculated in each sub volume, and the stress in each point should be well within the acceptable criteria.

Since resistivity of oil and paper vary with temperature and aging, also the voltage grading will vary. Thus the voltage distribution must be calculated for several different conditions, in order to ensure that the design will also be adequate at the worst possible combination of parameters. Also, the resistivity of the media is time dependent. The electric conduction in oil is done by electrons as well as by ions. When a DC field is applied across an oil gap, the ions will be drained out after some time, and thus the resistivity will change. Thus, to be able to calculate the actual stresses and time constants during polarity reversal for example, a calculation model including the ion conduction must be used. Such a calculation tool has been developed by ABB and is used for converter transformer design.

A simplified transformer prototype has been manufactured, Figure 2, including all the insulation details for an 800 kV converter transformer. The initial testing of the transformer prototype so far includes :

DC withstand	1250 kV
AC withstand	900 kV

The tests were successfully passed.

Figure 2: Transformer prototype in test room

Transformer bushing

The transformer bushings are of the same design as in the installations of recent HVDC projects. The main insulation on the valve hall side is obtained by gas, while the interface to the transformer is a capacitive core. The insulator on the air side is a hollow composite design increasing the overall mechanical strength. The general design is used for projects up to 500kV. Since the grading of a bushing is arranged both axially and radially, and the resistivities of the materials govern the field distribution, one of the important challenges when increasing the size is to keep the internal and external field stresses balanced for a large number of operational conditions. The design for 800kVdc is thus based on known materials and concepts having thorough experience from the field.

A prototype of the transformer bushing for the highest 6-pulse group has been produced, fig. 3. The bushing has passed all type and routine tests.

Figure 3: Transformer bushing testing

Wall bushings

Also the wall bushing design is based on the well proven design that is used for the recent installations at 500 kV. Besides the electrical requirements, the length of the wall bushing, 18 m, figure 4, has been a mechanical challenge. However, all electrical and mechanical type and routine tests have passed successfully. Also the seismic withstand has been verified by calculations. The design and manufacturing of the 800 kV wall bushing is completed, and the completed bushing is installed in the 800 kV test circuit.

Other pole bus equipment

The other pole bus components for 800 kV HVDC has also now been designed, manufactured and tested:

- Pole arrester, fig. 5
- By-pass breaker, fig. 6
- Pole disconnector, fig. 6
- DC RI capacitor, fig. 7
- DC voltage divider, fig. 7
- Composite support insulators, fig. 7
- DC optical current transducer
- Smoothing reactor mock up

In order to meet the requirements of a safe current contact in the disconnector, also at high wind load and at seismic events, each side of the disconnector comprises three composite support insulators in order to give a very rigid and safe structure.

All the equipment as above have been installed in the long term test circuit.

Figure 4: Valve hall bushing testing

Figure 5: Pole bus arrester testing

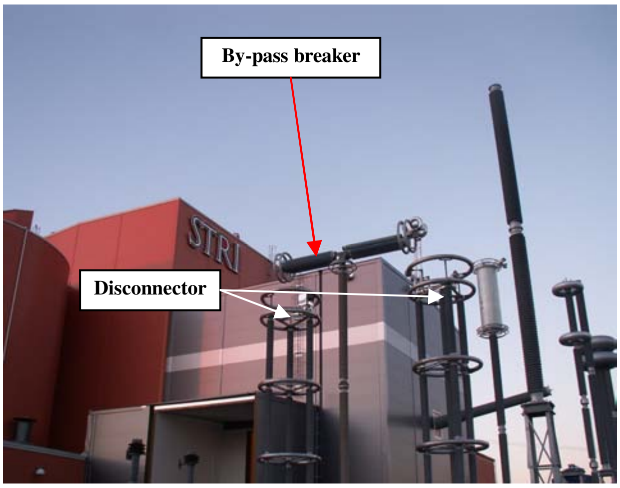

Figure 6: By-pass breaker and discconnecter installed at the 800 kV test circuit at STRI, Ludvika

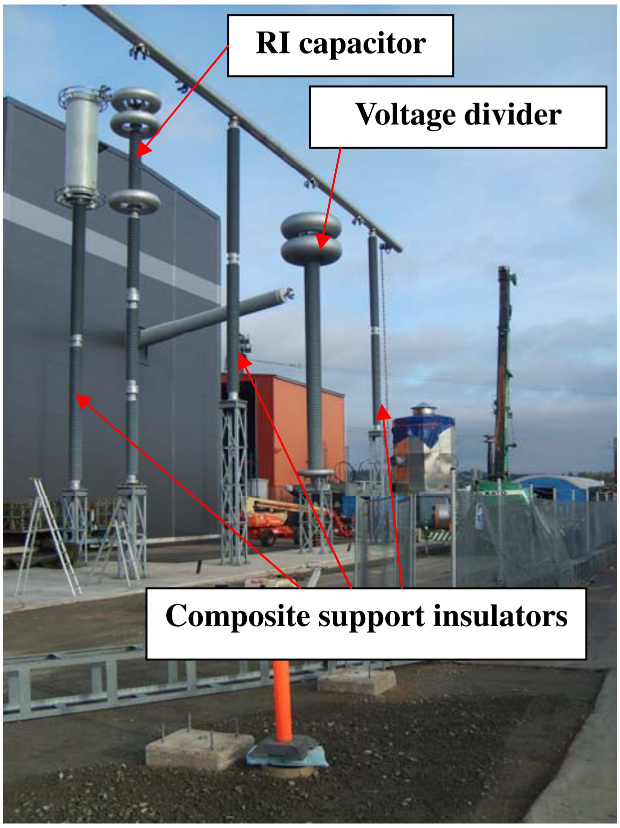

Figure 7: RI-capacitor, voltage divider and composite support insulators installed at the 800 kV test circuit at STRI, Ludvika

STATION DESIGN

Valve hall air clearances

One decisive issue for the valve hall design is the valve hall clearances. In the literature there is very little information air clearances for the geometries that are foreseen for an 800 kV valve hall with requirements on switching impulse voltage above 1700 kV. Thus ABB has made extensive tests for various electrode configurations up to 2100 kV switching impulse, which is needed to decide U_{50} at 1700-1800 kV at altitudes at

2000 m. It is known that at these voltage levels complex phenomena show up, since the contribution of the leader process is significant, compared to at lower voltages. The influence of multiple electrodes, as well as support insulators and corners, is significant for the withstand voltage. Also, it was found that the requirements of the electrode surfaces is completely different compared with at lower voltages.

From the test results, design criteria have been established for the different geometries that will be present in an 800 kV valve hall.

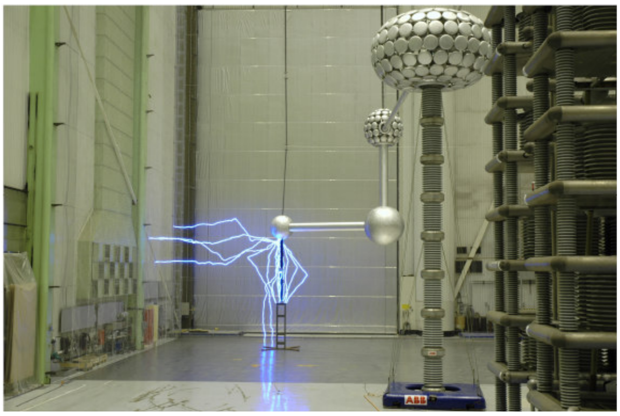

Figure 8: Testing of multiple air gap in corner, several flashovers superimposed in one picture.

Valve design

In order to keep the transport dimensions within acceptable limits, single phase two winding transformers is the only realistic alternative for a 5000 MW converter, and quite often the dimensions and arrangement of the converter transformers gives the length of the valve hall.

Also, an important factor for the design of the valve hall, is whether to use double valves or quadruple valves. Both options are possible for 800 kV. A valve hall with double valves will in principle look the same as in the Three Gorges projects, with one big valve hall for the high voltage 12-pulse group, and one valve hall slightly smaller than the ones used for the Three Gorges project for the 400 kV group. With double valves, the space factor for the high voltage group will be very low, since clearance is needed for 800 kV DC, and similar clearance will be needed at the 600kVDC six-pulse side, also the thyristor valves will be quite small since the voltage across the 12 pulse group is only 400 kV, compared with 500 kV for the Three Gorges projects.

However, using quadruple valves means that the converter transformers must be installed on both sides of the valve hall in order to simplify the bus bar arrangement inside the valve hall.

The thyristor valves will basically be built up with the same type of modules as have been don for the 500 kV projects. The grading circuits at each thyristor position ensures that the stresses on each thyristor position will be well controlled for DC stresses as well for transients. However, the shielding of the valves must be modified to meet the higher electric field stresses to ground in the high voltage 12-pulse group.

A proposed valve hall arrangement utilizing quadruple valves is presented in fig. 9. This layout also gives very good separation between different poles and between converter groups, as is recommended due to the high reliability requirements. The size of the converter area with this layout is approximately 380x145 m.

The quadruple valves alternative gives some advantages:

- The size of the valve hall can be significantly reduced, and thus the civil costs
- The number of valve suspension sections is halved, that also give savings in costs.

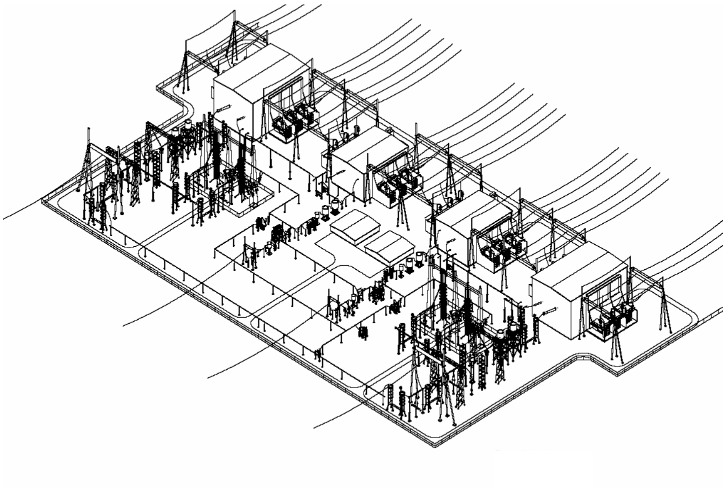

Figure 9: Converter area

DC YARD

Mechanical considerations

Since composite insulators will be used for all outdoor equipment completely new approach to station design must be taken. This has been found during the design and installation of the test station. The mechanical properties of composite insulators are different compared to porcelain. The radial strength and the stiffness of composite insulators can be controlled at the manufacturing, by controlling the pitch of the fibers in the fiber glass tube. Also the thickness of the fiber glass tube is an important parameter. These factors have been carefully considered for the insulators for each application.

However, composite insulators are more flexible than porcelain insulators, which means that movement, of the supported equipment at wind or seismic events will be different compared with a porcelain design. This has been considered at specifying the forces on the terminals of the different apparatus.

Also seismic studies for all equipment has been carried out for all the different equipment, including air core smoothing reactor.

Indoor DC yard

In areas with high pollution level, or in case there is a possible but uncertain future increase of pollution level, indoor DC yard is an attractive alternative. If high specific creepage distance is required, it will result in very long insulators. The diameters of the bus bars in an

800 kV DC yard need to be about 400 mm, and this means that the wind loads will be considerable. In case seismic requirements are added on top of this, the mechanical stresses on the support and apparatus insulators will result in a very elaborate design with two, or even three insulators in parallel. According to the investigations done so far, 10 m insulator length will result in a quite conventional design, and still all expected mechanical requirements will be fulfilled. 10 m insulator length means about 50 mm/kV for composite insulators and about 37 mm/kV for porcelain insulators As a rule of thumb, in areas with expected ESDD level ≥ 0.1 mg/cm^2, indoor DC yard should be considered.

The experiences from the indoor DC yard at Zhengping converter station, the receiving end of the Three Gorges-Changzhou ±500 kV HVDC transmission system, are very good. Initially, there was some corona from some of the support insulators, but after adjustment of the air handling system and coating of the porcelain insulators with RTV (Room Temperature Vulcanized silicone rubber), this problem was completely eliminated. Also the pollution inside the building is moderate. A proposed indoor DC yard for an 800 kV converter station is presented in fig. 5. Only the 800 kV part is indoor, and the 400 kV interconnections between the two series connected groups are outdoor.

For an indoor DC yard for 800 kV special arrangement must be done to handle the loss dissipation from the air core smoothing reactors.

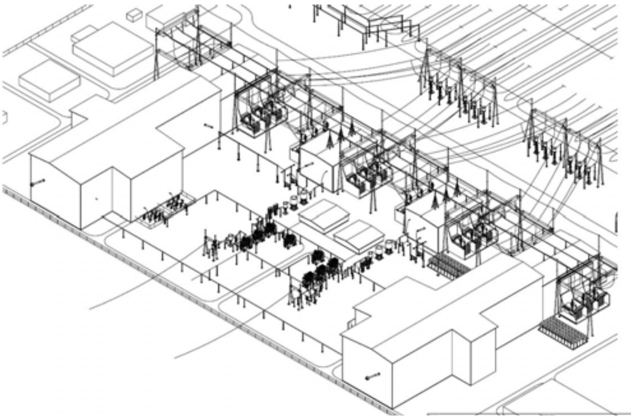

Figure 10: Indoor Dc yard

LONG TERM TESTING

In order to verify the long term behavior of the 800 kV HVDC equipment, all relevant pieces of equipment has been installed in a long term test circuit, and will be energized at 855 kV DC, for at least half a year. The test circuit will include a “valve hall”.

After careful mapping of the material parameters, it was found during the simulations, that in a complicated structure involving several different materials, like oil, paper, epoxy, fiber glass and SF$_6$, thermal equilibrium of the voltage distribution will not be reached until after several months, or even years, unless the testing is done at elevated temperatures. Thus it was decided that the long term test will be performed at least at +60° C, in order to simulate the actual operating conditions. The temperature in the simulated valve hall will be kept at this temperature in order to verify the long term behavior of the equipment.

In the test circuit, the transformer bushing will protrude inside the heated “valve hall” and be connected to the wall bushing that will be installed in the wall. The remaining equipment as listed, will be installed outdoors, together with the voltage generator and a prototype of the air core smoothing reactor. The layout for the test circuit is given in fig 11 and 12 below.

The test circuit will be energized early November 2006.

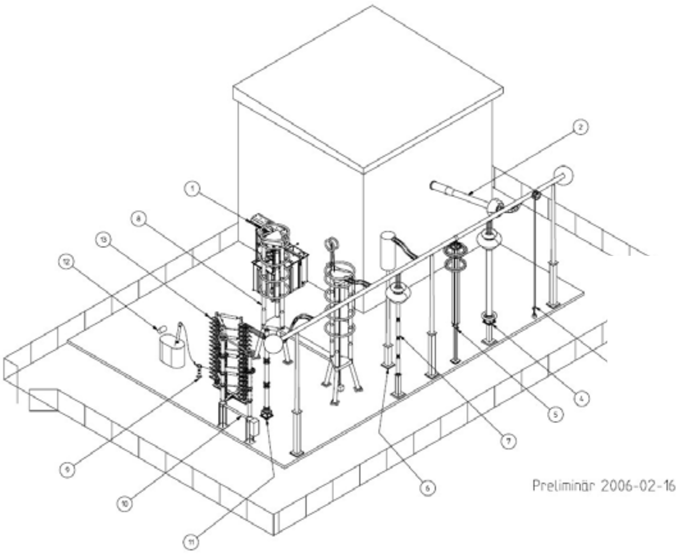

Figure 11. Long term test circuit

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
9. Voltage divider, test equipment
10. By pass breaker
11. Voltage divider, test equipment
12. Transformer, test equipment

SUMMARY

The development, manufacturing and testing of the critical equipment needed for an 800 kV HVDC converter station is completed. The equipment has been installed in a test circuit and will be energized with 855 kV for at least 6 months. During the R&D process essential knowledge has been gained, regarding realization of converters for 800 kV HVDC, such as:

- The complete DC-yard can be realized with composite insulators

- The use of composite insulators will ask for completely new mechanical design criteria for the equipment
- The use of composite insulators ask for careful electrical design due to the high surface resistivity and charge accumulation
- The criteria for valve hall clearances can not be handled by extrapolation only. The complicated structure in a valve hall with many electrodes and walls and corners request comprehensive testing
- In order to qualify complicated structures, such as bushings, comprising several different materials, a long term test at relevant temperature is needed

Figure 12: Test circuit during installation

REFERENCE

[1] Urban Astrom, Victor Lescale, Converter Stations for 800 kV HVDC, 2006 International Conference on Power System Technology, Chonqing, China, 22-26 October 2006

BIOGRAPHIES

Urban Åström was born in Njurunda , Sweden 1946. He received his M.Sc degree in physical engineering from the university of Uppsala, Sweden 1973. In 1974 he joined ABB´s HVDC department and has worked with design, development and testing of control equipment, thyristor valves, valve cooling and converter transformers. From 1995 to 2000 he was manager of the HVDC Converter Valve Development department, when he joined the Three Gorges- Changzhou project team as commissioning manager. Since 2004 he has been manager for the 800 kV HVDC development project

Victor Lescale Victor F. Lescale was born in Mexico in 1944. Graduated as an Electrical Engineer from the University of Mexico 1966. He has more than 30 years of engineering experience, in, among other fields, protection relays and control, high and extra high voltage installation commissioning, power system planning, special projects, HVDC control, HVDC system design, and in international HVDC project engineering and management.