

Converter Stations for 800 kV HVDC

U Åström, and V. Lescale

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Authors

U. Åström ABB Sweden

V. F. Lescale ABB Sweden

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 6400 MW for distances above 1000 km. Several utilities in China, India and Brazil are at present planning for the use of 800 kV as transmission voltage. In order to meet the demands, ABB has been running an R&D program with the goal to develop and test equipment needed for 800 kV HVDC. The R&D work has focused on equipment connected to the pole voltage, with special attention to converter transformers, bushings and external insulation. Due to the large amount of power transmitted by these transmission systems, special attention must be given to reliability and availability. Thus a thorough review of equipment, station layout, control and protection and auxiliary systems has been done.

I. INTRODUCTION

Worldwide there is an increasing interest in the application of HVDC at voltage levels above what is presently used. The main reason is that most of the hydro power resources that are within convenient distance to the consumer centers have been exploited by now, and in order to meet the increasing demand for clean, renewable energy, remote hydro generation plants are built. This asks for efficient means for long distance, bulk power transmission, a typical scenario is 6000 MW to be transmitted 2000-3000 km.

In India hydropower generated at the Bramaputra River Basin in the North- Eastern region will have to be transmitted to the region around New Delhi and also to the southern part of the country where the power is needed. In this case, also the geographical restrictions ask for a very narrow right of way. See Fig. 2.

In China, after completion of the hydro power plant at Three Gorges, hydro resources further west are under development, like in Jinsha River 1000-2000 km from the load centers. Also, one 800 kV DC connection is planned to connect the Yunnan grid with Guangdong, distance 1500 km.

In Africa there is a great potential for power production at the basin of the Congo River near the location of Inga. Part of the power is planned to be transmitted to South Africa

In Brazil vast hydropower resources exist in the Amazon region, while the power consumer centers are located along the eastern coast.

The driving force to increase the voltage is of course the economy, but also the desire to limit the environmental impact. In several investigations that have been carried out in the past, the common conclusion has been that for these big amounts of power and long distances the use of 800 kV HVDC is the most economical solution. [1], [2].

The total cost for a HVDC transmission system is composed of the investment in converter stations and line and the capitalized value of the losses. For a given power the cost for the stations increases with the voltage, while the line has a minimum combined cost at a certain voltage.

A comparison of the total cost for transmitting 6400 MW over 1800 km at 800 kV AC, 800 kV DC and 600 kV DC has been done. 1400 USD/kW has been applied when calculating the value of the losses. The result is that 800 kV DC is the most cost effective alternative because of higher line capacity and lower line losses. The total cost for the 800 kV alternative is 25 % lower than for 600 kV, see Fig. 1.

The environmental impact for transmission of 18000 MW is compared for different transmission alternatives, AC and DC at different voltage levels, see Fig 2. It is obvious, that 800 kV HVDC is a very attractive alternative, compared with 800 kV AC due to the reduced need for transmission lines and the reduced Right-Of-Way.

Several aspects of 800 kV HVDC that have been discussed earlier [3] will not be repeated in this text.

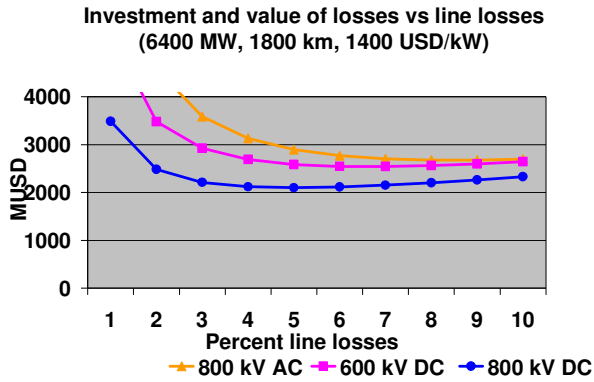


Fig 1. Cost comparison 600 kV HVDC and 800 kV HVDC

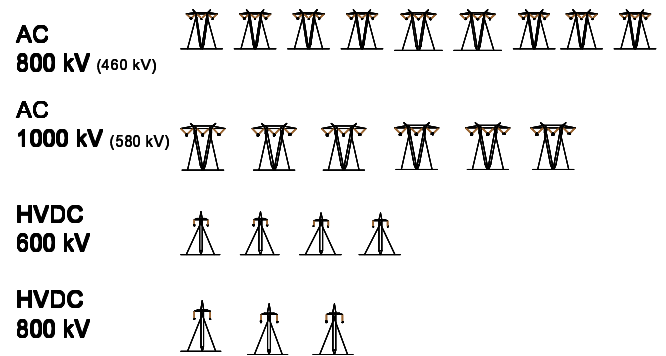


Fig 2. Need for right of way, 18000 MW, comparison HVDC and HVAC

II. AVAILABILITY AND RELIABILITY

Transmission of 3000 – 6000 MW bulk power into heavy load-centers like for example Shanghai 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 authors HVDC group is therefore in the middle of an analysis and synthesis process. 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 review process mentioned above is covering the main following areas:

A. 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.

B. Converter configuration/station layout

The configuration of the HVDC main circuit has been carefully analyzed,. The large total transmitted powers make it necessary to split the system into modules. This is necessary from the point of view of transformers, but also from the point of view of the impact an outage will have on the host system. For example, a pole configuration, with two converter groups in series or in parallel 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.

Figure 3 illustrates the different transmission power levels that can be handled with different configurations.

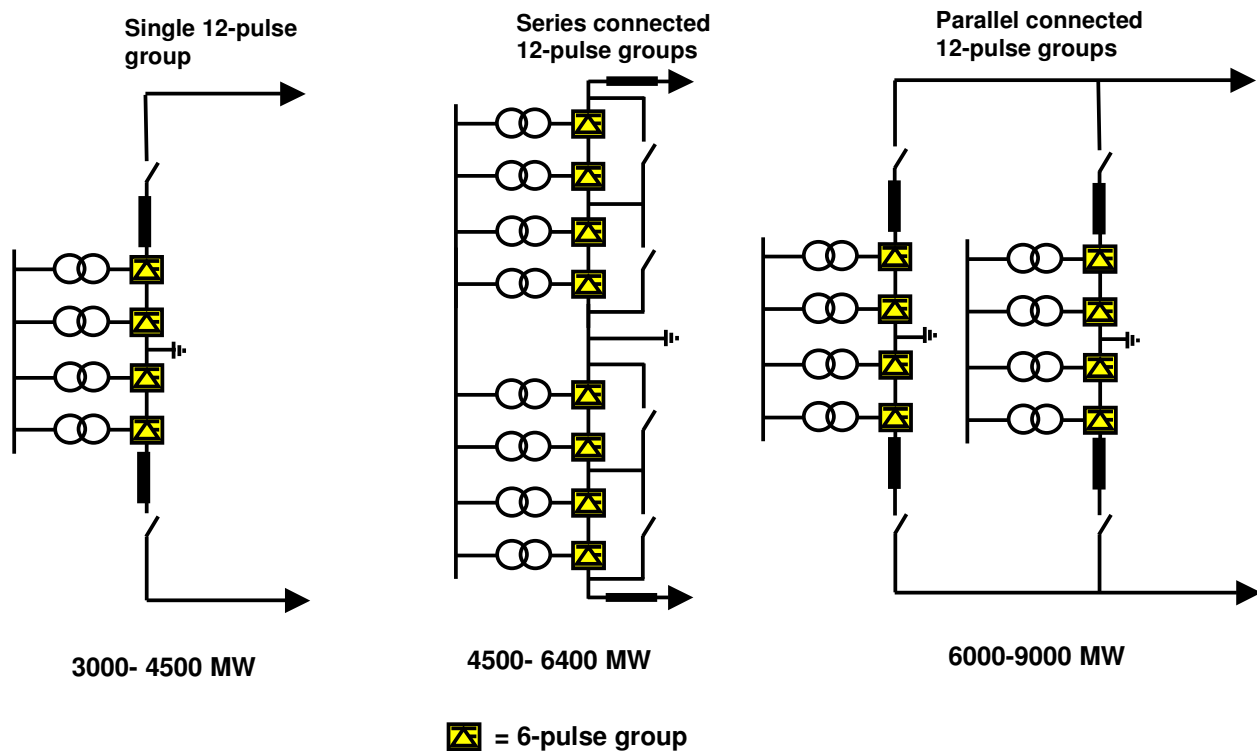


Figure 3. Comparison of different configurations

A parallel configuration will have a higher cost than a series configuration, since part of the insulation cost of the groups is independent of the power. However, such configuration gives additional flexibility in terms of geographical location of the two converter bipoles. Additionally, if there's uncertainty as to when the full power will be needed, the transmission losses during a half-power stage will be lower.

In addition to the converter configuration, special attention has been devoted to the dc neutral. It is usually 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.

C. 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 essential that the converters will not block for such events, else, 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 needs no new considerations.

The structure of the present control and protection system, is being 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 monopoles. This should also be applied for the AC-yard and DC neutral configurations, with possibility to entirely disconnect the areas that are needed for each separate pole.

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.

D. Auxiliary systems

Station service power is being restructured, with proper separation between the associated poles and converter 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 converter 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.

III. EQUIPMENT DEVELOPMENT

A. General

In this section a summary of the R&D status, early June 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 to 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, 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.

B. 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. There is a human factor also: Adding margins may save some engineering costs. However, for 800kVDC, mainly due to the high non-linearity in the relationship between withstand and necessary clearances, the savings in engineering are far outweighed by the savings in equipment by a judicious choice and application of margins

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 for series connected converters end up with very similar results, and the test levels used for design of the 800 kV equipment are summarized in the table below:

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 (1 minute)	1235	1030
Smoothing reactor Across	NA	2160/n	NA	NA	NA
To earth	1546	1950	NA	NA	NA

C. Station 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. This has been verified by seismic studies of the different apparatus. This means, that by utilizing the water repellent 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 for outdoor design and moderate pollution.

D. Converter transformers

As has been described above, for most equipment real resistors takes care of 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.

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.



Fig 4. transformer prototype in the test laboratory

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.

Furthermore, 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 [4].

A simplified transformer prototype has been manufactured, including all the insulation details for an 800 kV converter transformer. The transformer prototype has been tested (See Fig. 4):

- DC withstand 1250 kV
- AC withstand 900 kV

The tests were successfully passed.

E. 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.



Fig 5. Testing of transformer bushing

A prototype of the transformer bushing for the highest 6-pulse group has been produced, Fig. 5, and the initial testing done so far is:

- DC withstand 1456 kV
- AC withstand 1032 kV

The complete type and routine test of transformer bushing together with the transformer prototype is planned to be completed within short.

F. Wall bushings

The design and manufacturing of the 800 kV wall bushing is completed, the bushing has passed the pressure testing and the dielectric testing will start within short.

G. Miscellaneous pole equipment

The status for the prototypes for the remaining equipment is summarized as:

- Pole arrester: Design and manufacturing completed, RI testing completed
- RI capacitor: Design completed, manufacturing ongoing
- Pole disconnector: design completed, development tests completed, manufacturing ongoing
- Voltage divider: Design completed, manufacturing ongoing
- By pass breaker: Design completed, manufacturing ongoing

The equipment as above will be delivered during the summer 2006 to be installed in a long term test circuit at STRI, Ludvika.

IV. LONG TERM TESTING

On order to verify the long term behavior of the 800 kV HVDC equipment, all relevant pieces of equipment will be installed in a long term test circuit, and energized at 855 kV DC, for at least half a year. The test circuit will include a “valve hall” where the temperature will be kept at 60° C, to simulate the actual operating conditions for the bushings. The transformer bushing will protrude inside the “valve hall” and be connected to the wall bushing that will be installed in the wall. The remaining equipment as listed in clause III G above, 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 6.

The civil works for the test circuit is ongoing, and the test operation is planned to start during autumn 2006

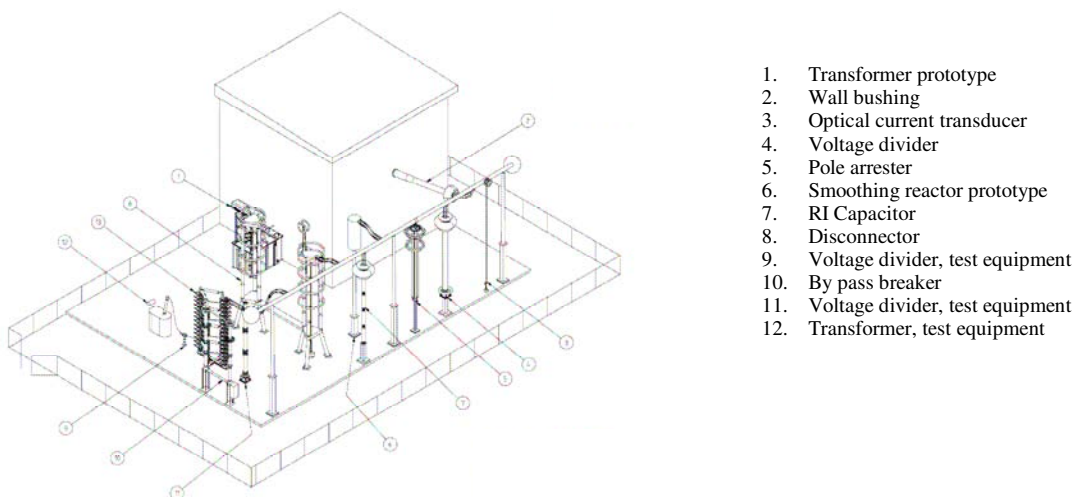


Fig 6. Long term test circuit

V. STATION DESIGN

A. Valve halls

The most decisive factors for the design of the valve hall are if there are one or two 12-pulse bridges per pole, and whether to use double valves or quadruple valves. All these combinations are possible for 800 kV, as long as size of the converter transformers fit into the transport limitations. A valve hall with double valves will in principle look the same as in the Three Gorges projects. However, quadruple valves give 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.

For the alternative with two 12-pulse bridges in series per pole, with double valves, the space factor for the high voltage group will be very low, since 7-8 m 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. Also, a new compact thyristor module suitable for 6" thyristors that is 50% more compact has been developed.

In order to keep the transport dimensions within acceptable limits, single phase two winding transformers is the only realistic alternative for a 6000 MW converter, and the converter should be split up in two 12-pulse bridges per pole, either connected in series or in parallel. Using quadruple valves, this means that the converter transformers should preferably be installed on both sides of the valve hall in order to simplify the bus bar arrangement inside the valve hall.

A proposed valve hall arrangement utilizing quadruple valves and series connected 12-pulse bridges is presented in Fig. 7. This layout also gives very good separation between different poles and between converter groups, as is recommended due to the high reliability requirements. A very similar arrangement of each valve hall can of course be used with the 12-pulse bridges connected in parallel.

The size of the converter area with this layout is approximately 380x145 m.

An alternative layout is presented in Fig. 8, showing a converter station for 800 kV, 3000 MW, using double valves. This layout is very similar to the what has been used for the Three Gorges 500 kV HVDC projects, but upscaled due to the higher DC-voltage. Two converter schemes like this, connected in parallel, will of course deliver 6000 MW. The size of the converter area is approximately 200x150 m.

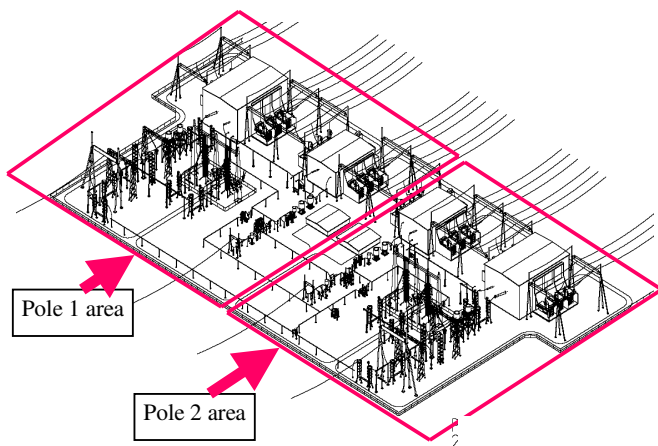


Fig 7. 800 kV 6000 MW converter with two 12-pulse groups per pole with quadruple valves and converter transformers on both sides of the valve hall

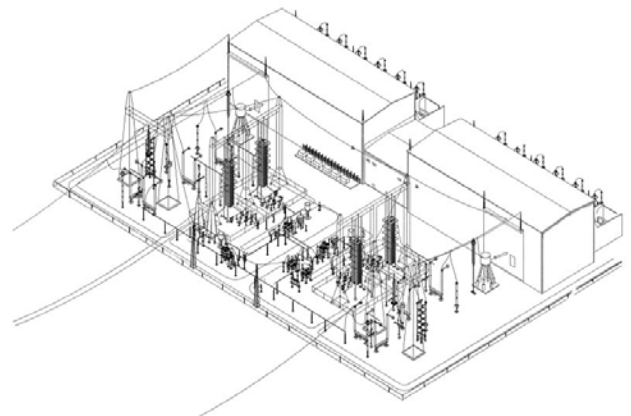


Fig 8. 800 kV converter with one 12-pulse group per pole with double valves and transformers on one side of the valve hall

B. 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 $\geq 0.1 \text{ mg/cm}^2$, indoor DC yard should be considered.

The experiences from the indoor DC yard at Zhenping converter station, the receiving end of the Three Gorges-Changzhou 500 kVDC transmission system, are very good.

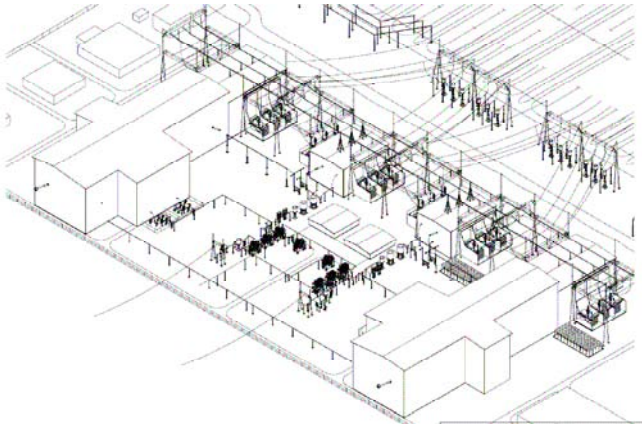


Fig 9. 800 kV converter station with indoor DC yard

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 eliminated. Also the pollution inside the building is moderate. A proposed indoor DC yard for an 800 kV converter station is presented in Fig. 9. In this case, illustrating a converter station with two 12-pulse groups in series per pole, only the 800 kV part is indoor, and the 400 kV interconnections between the two series connected groups are outdoor. For one 12-pulse group per pole the size of the DC yard will be the similar.

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

The buildings for the DC yard will have the dimensions $L \times W \times H \sim 125 \times 30 \times 30 \text{ m}$. The expected extra cost is less than 1%, thanks to the savings in equipment and the elimination of additional support insulators.

C. Audible noise

To limit the environmental impact of installations in general has become more and more important in later years. For converter stations the limitation of audible noise has become a key issue. Thus ABB has spent a lot of R&D to meet the strict requirements that are given in the specifications. It is very important that the correct requirements that must be met are presented at an early stage, because this must be considered already at the design of the equipment and the converter station. Noise reduction efforts as a retrofit usually show to be more costly and less efficient. In recent specifications 50 dB(A) maximum noise level at the site boundary has been requested, and in order to meet this strict requirement several precautions are needed. It should be noted that 50 dB corresponds to the sound level in an ordinary office, and 45 dB corresponds to the background noise level in rural areas! The higher voltage level does not mean that the noise level will increase, but the higher power to be transmitted does. For an 800 kV, 6400 MW converter station, the number of converter transformers will be twice the number of those in a 500 kV, 3000 MW station, thus the number of sound sources will be doubled. The total size of AC filters will be larger, roughly also twice the size. This means that the sound generated will be about 3dB higher for a 6400 MW converter. In order to meet 50dB(A) at site boundary, actions must be taken on most of the equipment:

- Converter transformers: All converter transformers must be boxed in, regardless of valve hall arrangement. Low noise cooling fans must be used
- Smoothing reactors: Air core smoothing reactors should be provided with top- and bottom sound screens, unless they are located indoors
- AC and DC filter capacitors: Acoustical damped filter capacitors should be used
- AC filter reactors: Filter reactors with low current density and careful mechanical design will need to be used. Sound screens can be added
- Valve cooling/Air conditioning: Low noise fans should be used. If needed dampers can be added.

In order to make a proper design that will meet the requirements in a cost efficient way the sound levels must be predicted at the design stage by computer simulations. The computer program used by ABB needs as input a complete 3-D site layout with all the sound sources, also a 3-D model of the topography of the surrounding areas is needed. With proper model loaded, different actions on the disturbing sound sources can be simulated, until the specific requirements are met. An example from a sound prediction calculation for a 500 kV HVDC station is given in Fig. 10.

Several projects have been followed up with measurements in order to provide feedback for further refinement of the calculation procedure. With proper input to the calculation model the sound level can be predicted with accuracy better than 2 dB.

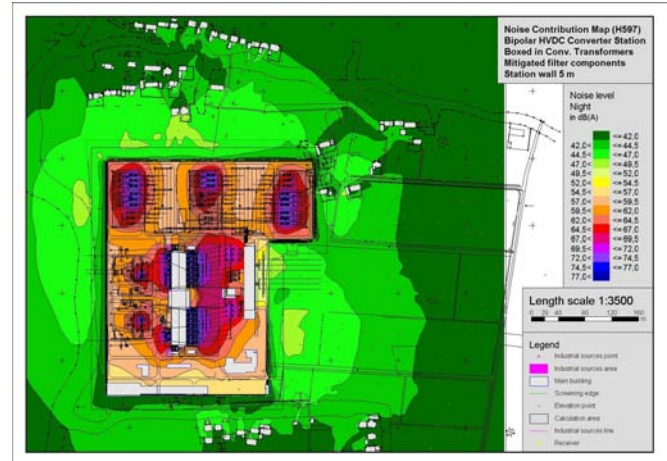


Fig 10. Output from noise level calculation

VI. CONCLUSIONS

800 kV HVDC is economically attractive for bulk power transmission, 6000 MW, over long distances, 2000-2500 km. With the present progress of R&D converter equipment for 800 kV HVDC will be qualified within short. With proper separation and proper structure of the control and protection and auxiliary systems, the reliability and availability will be as good as, or even better than, for converters at lower voltage.

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VIII. 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

urban.astrom@se.abb.com
Lyviksvägen 3
77180 Ludvika,
Sweden



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.

victor.lescale@se.abb.com
Lyviksvägen 3
77180 Ludvika
Sweden