Power Transmission with HVDC at Voltages Above 600 kV

U Åström, L. Weimers, V. Lescale and G. Asplund

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 thyristor valves and DC filter capacitors. However, equipment without resistive DC grading, like bushings and converter transformers, need additional R&D and verification. Also station external insulation and line insulation must be carefully considered. In order to meet the demands, ABB has started an R&D program with the goal to develop and test equipment needed for 800 kV HVDC.

Index Terms—800 kV HVDC, Bulk power transmission, Converter stations, HVDC, HVDC External insulation, HVDC Equipment, HVDC Systems, HVDC transmission economy, Insulation coordination, UHVDC

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 China large hydropower resources are available in the Western part of the country and the power will be transmitted to the industrialized regions in the Eastern and Southern areas of China

In India transfer of the hydropower generated at the Bramaputra River Basin in the North- Eastern part of India will have to be transmitted to the southern part of the country where the power is needed.

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

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

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].

In order to meet the requirements from the market, ABB is at present working with development of equipment for 800 kV HVDC.

II. ECONOMY

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.

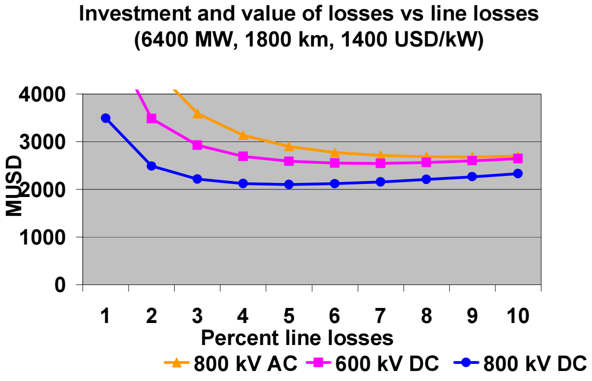

Fig 1. Cost comparison 600 kV HVDC and 800 kV HVDC

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 the 800 kV DC is the most cost effective alternative depending on a 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.

III. AVAILABILITY AND RELIABILITY

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

A. Line faults

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 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 couple of 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, however at higher losses. Switching stations along the line allows for simultaneous line faults on different segments along the line. For the Itaipú HVDC project, with two bipoles in parallel, the two converters can be connected in parallel to one bipole, in order to minimize the loss of power at bipole line outage.

B. Converter station

The structure of the present control and protection system, cable routing and auxiliary systems should be revised, reflecting the different requirements on reliability and availability and also the new configuration. It is envisaged that 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. This should also be applied for the AC-yard configuration, with possibility to entirely disconnect the areas that are needed for each separate pole.

Each twelve pulse group will have a separate valve hall with six double valves and six single phase two winding transformers penetrating into the hall, i.e. the same arrangement as for the recent ± 500 kV, 3000 MW projects.

IV. CONVERTER CONFIGURATION

The rating of the transmission, 6400 MW, makes it necessary to have more than one converter group per pole. This will minimize the disturbances at faults and increase the reliability and availability of the transmission. Another reason for dividing into more groups is the transport restrictions (size and weight) of the converter transformers. A scheme with more than one group per pole is not new, in fact it was used in the mercury arc valve projects from the mid 60's where six pulse groups were connected in series to achieve the desired voltage. Each group had a by-pass breaker, should one mercury arc valve be out of order. The Itaipu ± 600 kV HVDC project is the only project with thyristor valves that has two groups per pole and the operation experience is excellent.

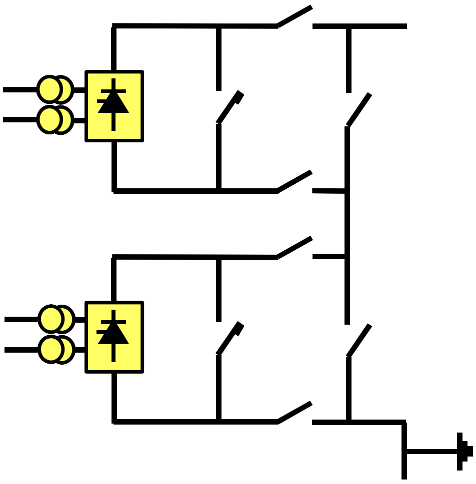

Fig. 2 Converter arrangement with two 12-pulse groups in series per pole

The arrangement on the DC-yard will be almost the same as for the ± 500 kV projects but with all equipment rated for ± 800 kV. The only "new" equipment is the by-pass arrangement with disconnectors and high-speed breakers for each group, see Fig. 2.

V. INSULATION COORDINATION

A. General

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; ie. 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. There is a human factor in the latter aspect, though: Adding margins may save some engineering costs. 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

B. Case study

An insulation coordination study has been performed for the dc side of an 800kV HVDC transmission system. The data for the system has been assumed based on the best available estimates to the authors colleagues, with regard to preliminary design of the equipment expected for such an installation. Further, as the study progresses, 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.

C. Protection scheme (controlling the stresses)

In addition to the use of modern, highly effective arresters permitting very good ratios between steady state voltage and protective levels, the protection scheme arrived at included more arresters than are usually applied at HVDC schemes of, e.g. 500kVDC. The reason is that even relatively small gains in stresses result in significant savings in equipment. The arresters beyond the "usual" ones were located to directly protect:

- Valve side of converter transformers at the uppermost 6-pulse bridge

- 800kVDC bus outside the upper smoothing reactor protected with several arresters at specific locations on the bus
- Smoothing reactor on pole side
- 800kVDC bus on valve side of smoothing reactor The cost to benefit ratio of this arrester proved to be sensitive to station design parameters, and its use will have to be decided on a case-by-case basis

Another important aspect comes from the mentioned splitting of the smoothing reactor. By balancing the inductance it is possible to reduce the ripple appearing on the arresters in the upper 12-pulse group, making it possible to lower their protective level.

The third aspect is that controlling the incoming lightning surges is also profitable. Apart from the normal shielding at the station, it is important to optimize the line design for the towers nearest the converter stations

Still another aspect is the location of arresters close enough to the protected equipment, so that distance effects will be negligible. The combination of this principle with the natural distances between different pieces of equipment in an 800kVDC station leads to more arresters, even at the same bus, and for the same protective levels.

D. Insulation margins (Deriving withstand from stress)

At the resulting stresses for 800kVDC equipment it is extremely important to have economy-dictated margins. There is no room for additional margins based on subjective appreciations.

Perhaps even more important: there is no rationale for increasing calculated withstand levels to “the next higher standard level”, since there is no interchangeability of equipment between different stations as is normal for ac equipment.

At lower voltages, where high engineering and testing costs cannot be justified, a simplification is often applied by forcing a ratio between the insulation withstands to switching and lightning surges. At the levels necessary for equipment at 800kVDC, the voltage stresses for all kinds of phenomena and transients are carefully calculated. So are the internal stresses for equipment designed to withstand them, and so are the tests that verify them. At UHVDC, the equipment should be designed to withstand the specified stresses. Then, depending on the materials, and the internal configuration of parts of different resistivities and dielectric permitivities, the ratio between withstand capabilities may or may not be close to the traditional factors Therefore such relationship factors have no reason to exist in 800kVDC insulation coordination. They increase the cost of equipment, yet only give a false sense of security.

Another reasoning taken slightly out of context leads to insulation margin levels that are not quite justified. Specifically, for thyristor valves, by extension, the same insulation margins used for conventional equipment have been required in some HVDC transmissions. There are a couple of important points why the same margins need not be used in the thyristors, and not in the grading circuits. One point is the extremely well known voltage grading along the valve, transiently, dynamically, and even as a function of time after application of a dc field, and even as the years pass. This is also different from conventional equipment. Because of the above, the insulation margins for the thyristor valves need not cope with the same uncertainties as for, eg transformers.

The insulation margins advocated by the authors are:

Insulation margins			
Insulation type	Oil	Air	Valves[1]
Lightning	20%	20%	10%
Switching	15%	15%	10%

[1] Across single valve

E. Study results

From the studied transmission the stresses resulting, or more accurately, the resulting protective levels, for the most important equipment are listed below:

Protective levels (kV)		
Location	Switching	Lightning
Converter transf. Valve side	1320	1453
Smoothing reactor. Across	NA	1800
Smoothing reactor. To earth	1345	1625
Thyristor valve. Across	406	386
Thyristor valve. Top to ground	1320	1500

With the results found, as given above, and the margins advocated, the following test voltage levels are proposed for the main components:

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 thy valve, top to ground	1518	1800	NA	1040 (3 hs)	NA
Wall bushing	1518	1800	1000 (one minute)	1235	1030
Smoothing reactor Across To earth	 NA 1546	 2160/n 1950	 NA NA	 NA NA	 NA NA

VI. EQUIPMENT CONSIDERATIONS.

A. General

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 for HVDC equipment.

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 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 tress.

B. Thyristor valves

The thyristor valves are built up by a number of equal thyristor positions connected in series, each of them has a certain voltage capability, depending on the thyristor parameters. The snubber circuit as well as DC grading resistor, Fig 3, secure equal voltage distribution between the individual positions. The voltage distribution within the thyristor valve is only slightly disturbed by the stray capacitances to ground. Thus, thyristor valves can easily be designed for higher voltages than 600 kV by extrapolation, that is just addition of more thyristor positions, and still each thyristor position will be subject to equal stresses as in a 500 kV valve or 600 kV valve. Thus, the DC voltage is not decisive for the valve design, this will be handled by adding sufficient number of thyristor positions.

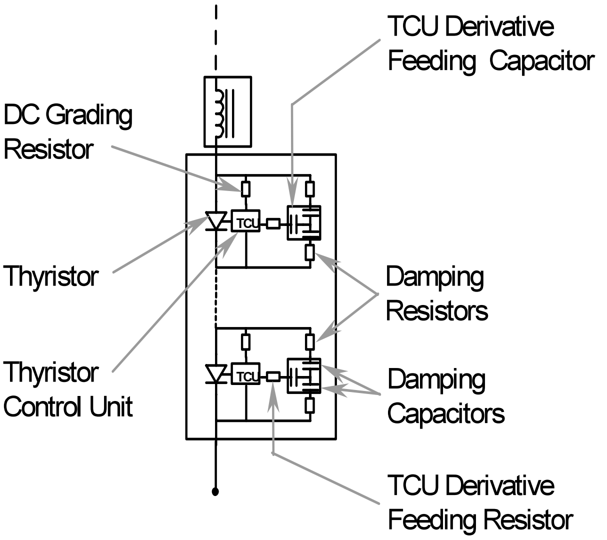

Fig. 3. The components of a thyristor valve. The electrical stresses are defined by passive components at each thyristor position

The ABB experiences from more than 14000 thyristor positions in commercial operation using the 5” thyristor is excellent, not one single thyristor failure has been reported.

C. DC harmonic filter capacitors

The DC harmonic filter capacitors are built up by several capacitor units connected in series in order to achieve the needed voltage withstand capability, and a number of strings in parallel to get the capacitance needed for the filter. Each of the units has its internal resistors to provide the DC-voltage grading. The resistance shall be selected such that the current through the grading resistors is significantly bigger than the maximum expected external leakage current. Also for the harmonic filter capacitors, the higher DC voltage is easily handled by adding more capacitor units in series.

The mechanical design for harmonic filter capacitors will thus be quite similar to the filter capacitors recently supplied to the 3G 500 kV projects. The main difference will be the height, 35 m for 800 kV compared to 20 m for 500 kV.

D. RI filter capacitors

Although the RI filter capacitors are enclosed in a hollow porcelain insulator, they are basically built up equivalent to the harmonic filter capacitors with internal grading resistors. The difference is that in this case, each unit is not a metal can, but an insulator containing the capacitive elements and the grading resistors. Due to the effective DC grading also RI-capacitors can easily be extrapolated to higher DC voltage by adding more modules in series.

E. DC Voltage divider

For the DC voltage divider the resistive grading is inherent by the resistive divider itself. The voltage dividers used today are enclosed in a composite insulator. The external leakage current on a composite insulator is in the range 10-100 µA, far greater than the resistive current through the voltage divider, usually 2 mA. In order to ensure a proper voltage grading also for transient voltages, there are built in capacitors in parallel with the resistive elements. The capacitive and resistive elements are assembled in modules connected in series. Thus, also the voltage dividers can be extrapolated to higher DC voltages by adding more modules in series.

F. DC pole arrester

The ABB HVDC arresters used for the 3G projects is built up by modules, each module containing a number of ZnO-blocks, with a Si-rubber enclosure. The arrester leakage current through the arrester blocks is about 1 mA, well above the maximum leakage current on the insulator surface. Also, the nonlinear characteristics of the ZnO-blocks will ensure that the voltage across each of the arrester modules is quite equal, thus giving a linear voltage distribution. The capacitive grading along the arrester is done by external rings.

DC pole arresters for higher voltages can easily be produced by adding sufficient number of arrester modules in series. The proper energy capability of the arresters will be achieved by adding sufficient number of arrester columns in parallel.

G. DC current measurement equipment

Today optical current transducers, OCT, have replaced the large diameter porcelain enclosed transducers used in the earlier HVDC converter stations. The communication to ground potential is done using a very slim composite insulator containing the optical fibers. The only modification needed to convert the existing 500 kV OCT:s to higher voltages is to increase the length of the optical link. Since the diameter is small, and since there are almost no practical limit for the creepage distance of the optical link, OCT:s for 800 kV are easily realized.

H. Pole bus disconnector

Requirements on high specific creepage distance for post insulators in combination with 800 kV DC will result in very long insulators. With conventional design insulator length up to 12 m is feasible, corresponding to specific creepage distance 42 mm/kV at 800 kV DC. In case higher creepage is desired, or in case the seismic requirements gives restrictions on the insulator length, alternative solutions must considered, such as using parallel porcelains or pantograph disconnectors. With extreme requirements an indoor DC-yard will be considered.

I. Smoothing reactor

At present, the idea is to use air core smoothing reactors. The higher DC voltage has no influence on reactor itself, only on the support insulators. Thus, the development of smoothing reactors for 800 kV DC can be reduced to designing a proper support structure. The support structure used for the capacitor banks in AC series compensators is well suited for this purpose, and can easily be modified for the needed creepage distance. This design is also suitable for seismic stresses by using special dampers.

J. Wall bushing

The trend for selection of through wall bushings has lately been focused on reduction of combustible material in the converter valve hall. A suitable design that may be selected is built with hollow composite insulators filled with insulating gas. The main internal insulation relies on the properties of the gas, and to control the field grading is arranged. The design is today used up to 500kV DC, and the flexibility to produce suitable insulators enables the design to be expanded up to 800kV DC.

K. Transformer valve side bushings

The proposed 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. Designing for 800kVdc will thus be based on known materials and concepts having thorough experience from the field

L. 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, see fig 4. The electrical stress is calculated in each sub volume, and the stress in each point should be well within the acceptable criteria.

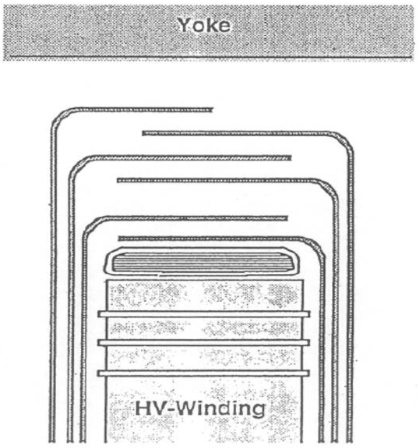

Fig. 4. Transformer main insulation

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 [3].

VII. EXTERNAL INSULATION

A. General

The study of external insulation is considered as one key topic for the research program related to 800 kV HVDC [4], for the transmission line as well as for the converter equipment. The research project on the external insulation for 800 kV was awarded to STRI in 1992 by ABB. A large numbers of experiments were performed in STRI's laboratory with pollution test ability up to 1200 kV DC.

As a result of the combined efforts on evaluating existing converter stations, performing laboratory tests and technical achievements on equipment, design rules for HVDC insulators has been established up to 800 kV.

B. Operation experience

ABB has performed a review on the operational experience of the existing HVDC stations worldwide. Some of the outcomes of these studies were published successively since 1993 on various international conferences [5]-[11].

The operational experience from existing HVDC stations, from 250 to 600 kV, has shown that the flashover rate of these stations has no direct correlations to the voltage levels of the stations. It has also shown that there is no tendency and need to choose a higher value for the specific creepage distance because of higher voltage level. With suitable design, a very low flashover rate of 0.05 per pole per year has been achieved in total 80 poles (47 stations) around the world supplied by ABB. Good operational experiences with silicone rubber insulators, even with shorter creepage distance than that of porcelain, have also been obtained.

C. Site conditions

The most important factor for insulator selection is the actual site conditions, as well as what is expected for the future since the specific creepage distance will mainly be decided by the site pollution severity. Also factors such as site altitude must be known to allow for proper atmospheric corrections. Long-term on-site measurements on insulators of the same type, and energised under the same voltage, provide the best accuracy for this. However, for practical and economical reasons, such a measurement has seldom been performed. It is very important to map the pollution at a future HVDC site. In order to make this possible, ABB can provide a mobile test station that measures airborne pollution, collects weather data like wind, rain, humidity and temperature. Also high DC voltage (100 kV) is generated to energize insulators to be set up outside the test station, to map the pollution gathered by the energized insulators. Also the leakage current is continuously measured for each individual insulator. In a joint research activity between BDCC of SGC, EPRI and ABB, this flexible test station has been utilized in site pollution measurements for Three Gorges-Shanghai projects. The measurements performed on Huangdo and Guojiagang sites will be presented in a future publication.

D. Laboratory tests

Laboratory tests with pollution and with uneven rain have been performed on different type of insulators. Insulators of different shed profiles have also been compared in laboratory tests. It is also clear from laboratory studies that for a SDD level equal to or higher then 0.05mg/cm^2, a linear relationship holds between the required creepage distance and the applied voltage for the same type of insulator. This fact simplifies the dimensioning of the insulation, when the pollution level is known. The effects of various palliative methods, such as hydrophobic coatings and booster sheds have not only been reviewed in the operational experience but also verified in the laboratory tests.

E. Other considerations

The most effective way to reduce the risk for flash overs in the converter station is of course to reduce the number of insulators. The state of the art is to have the converter transformer bushings protruding into the valve hall, thus reducing the number of wall bushing. Also the old type of direct current transducers has been replaced with optical current transducers in modern converter stations. When possible, composite silicone rubber insulators, with superior surface properties, are used. The ultimate solution of the external insulation complex is of course to build an indoor DC yard, as has been done at Zhengping converter station. This should be considered at sites with high pollution.

VIII. CONCLUSIONS

800 kV HVDC is economically attractive for bulk power transmission, 6000 MW, over long distances, 2000-2500 km. With the present experience of HVDC as a sound base, it is possible to realize an HVDC system for 800 kV with reasonable efforts in R&D by using building blocks that have been used for lower voltages. 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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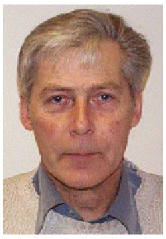

Urban Åström was born in Njurunda , Sweden 1946. He received his M.Sc degree in physical engineering from the university of Uppsala , Sweden 1973. In 1974 he joined ABB´s HVDC department and has worked with design, development and testing of control equipment, thyristor valves, valve cooling and converter 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

Gunnar Asplund was born in Stockholm, Sweden on September 23, 1945. He got his MS in Electrical Engineering at the University of Lund in 1969.

His employment experience is with ASEA and later ABB. He has worked in the fields of high voltage testing, thyristor valve development, project management, commissioning of the Itaipu HVDC project in Brazil, system studies, engineering and since twelve years he is manager of the development of HVDC within ABB.

Victor Lescale Victor F. Lescale was born in Mexico 1944 and graduated as an Electrical Engineer from the University of Mexico 1966. He has more than 30 years of engineering experience, of which 4 years in protection relays and control,3 years in high and extra high voltage installation commissioning, 5 years in power system planning, 4 years in special projects, 2 years in HVDC control, 8 years in HVDC system design and 6 years in international HVDC project engineering and direction.

Lars Weimers, born 1949, graduated from Chalmers University of Technology in Sweden 1975 with a Master Degree in Electrical Engineering. He joined ABB's HVDC department in 1979 and has had leading positions in design, R&D, project management and marketing and is presently manager for HVDC marketing in China. Mr. Weimers is the author of many articles/papers about HVDC and HVDC Light.