

Power Transmission with HVDC at 800 kV

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SUMMARY

The use of HVDC at 800 kV, has been found to be economically attractive for power blocks up to 6400 MW for distances above 1000 km. Worldwide there is an increasing interest in the application of HVDC at 800 kV in countries like China, India, South Africa/Congo and Brazil, where large hydro power resources available in remote areas will be developed. This paper makes a comparison of the total investment and loss cost for UHVAC and UHVDC and shows that ± 800 kV HVDC is the most cost effective alternative for long distance bulk power transmission.

The very high power rating of the complete transmission, together with the insulation levels, make it necessary to split each pole into two 12-pulse converters. For the host ac systems, for improving the reliability, as the split halves the impact of an outage. For transport, the split reduces the weight and dimensions of the converter transformers. The paper addresses reliability aspects.

The proposed configuration is with two series connected converters. The paper discusses the advantages of this split, as opposed to parallel split. The smoothing reactor function is split equally between the pole and neutral in halves, to reduce the ripple in the high voltage converter. The reasons and advantages of precisely such split are discussed.

An insulation coordination study has been performed for the dc side of an 800kV HVDC transmission system. The paper discusses what cases were considered and why, as well as why some of the traditional cases needed to be adapted to the new conditions. Equipment for 800 kV DC transmission voltage will be achievable within the near future. Most of the DC equipment is easily modified for 800 kV, such as thyristor valves and DC filter capacitors. However, equipment like bushings and converter transformers, need additional R&D and verification..

The operational experience from existing HVDC stations, from 250 to 600 kV, has shown that the flashover rate has no direct correlations to the DC voltage level. The specific creepage distance needed is dictated by the site pollution severity. 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 the authors group. Good operational experiences with silicone rubber insulators have also been experienced.

KEYWORDS

HVDC - 800kVDC - UHVDC - Insulation coordination - Series connected converters - Split smoothing reactor - External insulation

Economical aspects

The total cost for an HVDC transmission system is composed of the investment in converter stations and lines and the capitalized value of the losses. For a given power the investment cost for the stations increases with voltage, while the line can be optimized with regard to investment and value of line losses. Taking these two factors in consideration, an optimal transmission system can be designed with respect to voltage and conductor arrangement.

Besides the traditional economic aspects, investment and cost of losses, also environmental aspects should be considered. The transmission capacity of a line is proportional to the voltage which means that for a certain capacity a high transmission voltage reduces the number of needed lines. Many of the new generation stations are located in mountain areas where it is difficult to find right of ways for the transmission lines and thus a high line voltage is advantageous.

A comparison of the total cost and number of lines for transmitting 6400 and 19 200 MW over 1800 km has been done. 1400 USD/kW has been applied when calculating the value of the losses. The result is shown in the graphs below:

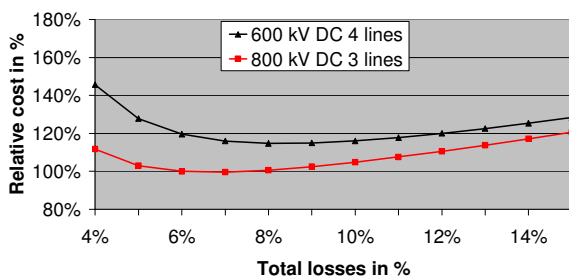


Fig x. Total cost comparison for transmission of 19200 MW 1800 km at 600 kV DC and 800 kV DC

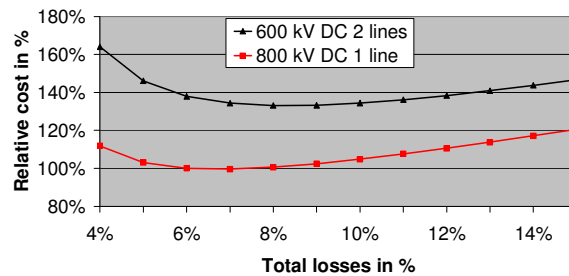


Fig x. Total cost comparison for transmission of 6400 MW 1800 km at 600 kV DC and 800 kV DC

From the graphs it can be observed that:

- 800 kV DC is more cost effective than 600 kV DC because of the higher transmission capacity per line, and lower line losses.
- The 800 kV DC alternative needs fewer lines due to the higher capacity per line.
- The total losses are 50 % higher for the 600 kV DC alternative compared to the 800 kV DC alternative

Availability and reliability

Transmission of 3000 – 6000 MW bulk power into heavy load-centers like Shanghai or Delhi 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 faults are single pole to ground, and they are cleared easily within some periods by retarding and restarting the pole. During the retard time the healthy pole compensates the power loss on the failing pole.

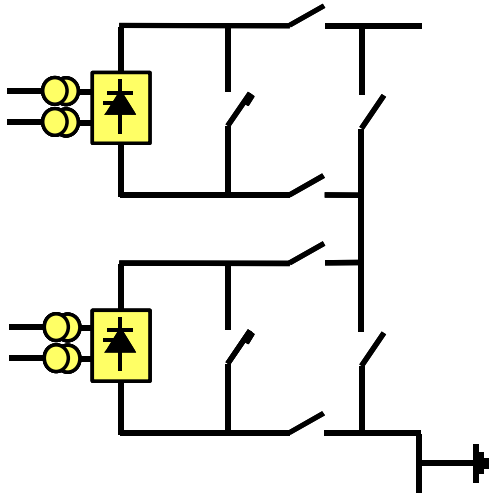
B. Converter stations

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.

Each twelve pulse group will have a separate valve hall with three quadruple valves and six single phase two winding transformers penetrating into the hall. The bypass breaker will be installed inside the valve hall in order to reduce the number of outdoor insulators.

Converter configuration

The rating of the foreseen transmissions, 6000~6400 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 series 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.

The arrangement in 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

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

Insulation coordination

A. General

For 800kVDC stations, the basic ideas for insulation coordination are the same as those applied for lower voltages. The difference for 800kVDC is that it is economically beneficial to control the expected stresses to an even higher degree, and to keep insulation margins tight.

Controlling the overvoltages aims 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, the savings in engineering are far outweighed by the savings in equipment and more detailed studies and control are justified.

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, with regard to preliminary design of the equipment expected for such an installation. Further, the study showed that splitting the smoothing reactor function in two equal inductances, one at the neutral, and one at the pole yields significant advantages

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 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)

One important advantage from the mentioned splitting of the smoothing reactor is that 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.

Another result of the study 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. This leads to more arresters, even at the same bus, and for the same protective levels, but results in savings in equipment.

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 or 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, 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. Then, depending on the materials, and the internal configuration, 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.

In some HVDC transmissions, for thyristor valves, by extension, the same insulation margins used for conventional equipment have been required. There are a couple of important points why the same margins need not be used. One point is the extremely well known voltage grading along the valve, transiently, dynamically, and also 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 margins advocated by the authors are thus:

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 resulting stresses, or more accurately, the resulting protective levels, for the most important equipment are listed to the right

With the results found, as given in the table at right, the margins advocated, and with the rules given in standards for other tests, test voltage levels are proposed for the main components, as shown in the table below.

Protective levels (kV)		
Location	Switching	Lightning
Converter transf. Valve side	1410	1442
Smoothing reactor. Across	NA	1800
Smoothing reactor. To earth	1382	1522
Thyristor valve. Across	405	386
Thyristor valve. Top to ground	1381	1412
DC bus Line side	1382	1592

Test levels (kV)					
Equipment	SI	LI	AC _{rms}	DC	DC Polarity reversal
Transformer Valve side	1622	1731	900	1250	970
Transformer bushing Valve side	1622	1731	900	1250	970
Multiple thyristor valve, top to ground	1589	1692	NA	1040 (3 hs)	NA
Wall bushing	1589	1692	1000 (one minute)	1235	1030
Smoothing reactor: Across To earth	NA	2160/n	NA	NA	NA
	1590	1827	NA	NA	NA
Nono-porcelain, dc bus connected equipment	1590	1911	1000 (one minute)	NA	NA
Porcelain-only, dc buss connected equipment	1590	1911	NA	NA	NA

Equipment considerations

A. General

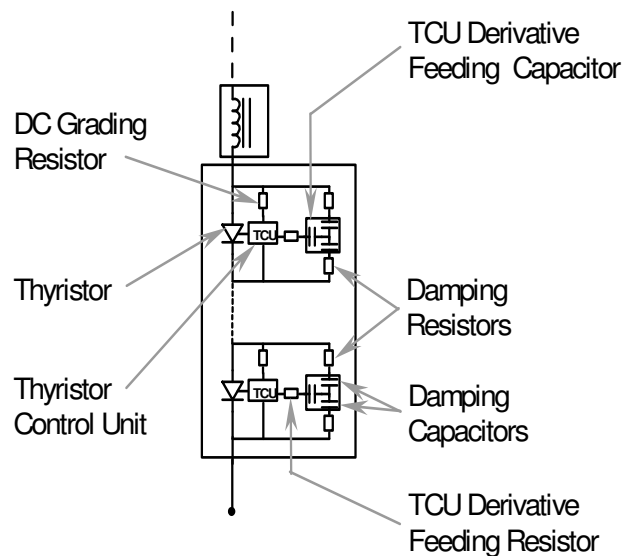
The equipment affected by the increased voltage level is of course limited to apparatus connected to the pole bus, such as converter transformers, wall bushings, thyristor valves, DC-voltage divider etc. The main part of the equipment within the converter station is not exposed by DC, such as AC yard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

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, see 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 subjected to equal stresses as in a 500 kV valve or 600 kV valve.

The experience from more than 14000 electrically triggered thyristor positions in commercial operation using the 5" thyristor is excellent: just one single thyristor failure has been reported as of this writing.

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Fig. 3. The components of a thyristor valve.

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 higher DC voltage is easily handled by adding more capacitor units in series.

D. RI filter capacitors

Although the RI filter capacitors are enclosed in a hollow 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 enclosed in an insulator containing the capacitive elements and the grading resistors instead of in a metal can. Also RI-capacitors can easily be extrapolated to higher DC voltage.

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 smaller 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.

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. The necessary 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.

H. Pole bus disconnecter

Requirements on high specific creepage distance for post insulators in combination with 800 kV DC will result in very long insulators. With conventional design, an insulator length of up to 12 m is feasible, corresponding to a specific creepage distance of 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 be considered, such as using parallel porcelains or pantograph disconnectors. The use of composite support insulators for the pole disconnector makes it possible to reduce the length of the insulators to ~10 m, still meeting the requirements on creepage distance.

I. Smoothing reactor

At present, the idea is to use air core smoothing reactors. The higher DC voltage has no influence on the 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.

J. Wall bushing

The wall bushing design 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.

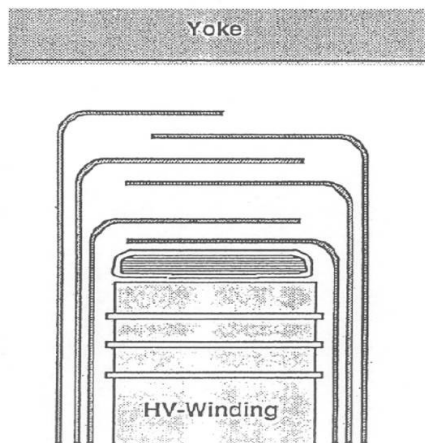


Fig. 4. Transformer main insulation

L. Converter transformers

As has been described above, for most equipment the DC grading is done by using real resistors. 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, 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, and the stress in each point should be well within the acceptable criteria.

Since resistivity of oil and paper vary with temperature and aging, the voltage distribution must be calculated for several different conditions. 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. 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].

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 number of experiments were performed in STRI's laboratory with pollution test ability up to 1200 kV DC [5]-[8]. As a result, design rules for HVDC insulators has been established up to 800 kV.

B. Operation experience

The authors' group has performed reviews on the operational experience of the existing HVDC stations worldwide. Some of the outcomes of these studies were published successively, e.g. [9],[10]. 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 been 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 flashovers per pole per year has been achieved in a total of 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 [11]. The effect of hydrophobic coating and booster sheds have proved to be very effective. The well known uneven wetting flashovers on, mostly, wall bushings have been prevented with insulators with hydrophobic surface.

C. Site conditions

The most important factor for insulator selection is the site conditions. One should be aware that insulators under DC voltage may collect more pollution than insulators under AC voltage at the same site. In order to make long-term measurement on site, the authors group can provide a portable test station that measures pollution, collects weather data like wind, rain, humidity and temperature. DC voltage (100 kV) is generated to energize insulators. Also the leakage current on insulators is continuously measured.

D. Laboratory tests

Laboratory tests with pollution and with uneven rain have been performed on different types of insulators [5]-[9]. It is clear from laboratory studies that for a SDD level equal to or higher than $0.05\text{mg}/\text{cm}^2$, a linear relationship holds between the required creepage distance and the applied voltage for the same type of insulator. Insulators of different shed profiles have also been compared in laboratory tests. The result shows that a relative large shed spacing is of importance for the good pollution performance. This conclusion is applicable for insulators of hydrophilic surface. For insulators with hydrophobic surface, limited results exist. However, a relative large shed spacing even for this type of insulator is considered to be advantageous in pollution and heavy rain conditions.

E. Means of improving pollution performance

Instead of using extremely long creepage distance for the very heavy inland industrial pollution, the use of composite insulators with good ability to retain a hydrophobic surface is a good solution. Today, composite insulators are used on almost all the apparatus insulators, e.g. bushings in DC yard. Only station post insulators are still of porcelain material. Hydrophobic coating of some types is often applied afterwards in operation. Station post insulators of composite material are now under intensive development.

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 design 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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