

DESIGN CONSIDERATIONS OF ULTRA HIGH VOLTAGE DC SYSTEM

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INTRODUCTION

Large HVDC transmission schemes having power transmission capacities of 4000-6000 MW and distance up to 2000 km are currently under planning for various large hydropower stations in China, India and other regions. Ultra high dc voltage (UHVDC) in the range of 750 and 800 kV is the preferred dc voltage level for these applications.

In the last decades the HVDC developed into a mature and proven technology for bulk power transmissions. Many HVDC projects have been realized for power rating in the range of 2000 – 3000 MW at 500 kV voltage levels. The first HVDC project with voltage above 500 kV is the Cahora-Bassa between Mosambique and South Africa (533 kV, 1920 MW), which was built almost 30 years ago. The second HVDC project with voltage over 500 kV is the Itaipu HVDC project (600 kV, 3150 MW) constructed about 20 year ago.

HVDC system for UHVDC range (750 – 800 kV) has been often identified as advantageous for transmitting large power over extremely long distances. In the past there were already study reports on the feasibility of UHVDC up to 800 kV conducted by the international organizations such as IEEE and Cigre [1, 2] . All these working groups reported that the UHVDC system is technically feasible with some research and development efforts in few key areas.

This paper summarized some basic design aspects of an UHVDC scheme at UHV level ($\pm 750 - 800$ kV). This paper offers a general discussions on the basic design considerations for UHVDC projects with power ratings upto 6000 MW and also includes an example parameters of two alternatives for a UHVDC project of 2000 km, 5000 MW operating at ± 750 kV. Two basic alternatives of this project viz., one series group per pole and two series groups per pole are discussed.

It is expected that the design for UHVDC projects would follow several practices established for the existing HVDC projects of rating 3000 MW. However, as the power and voltage level increase and as the systems are expanding or have their own specifics the UHVDC projects would certainly demand to have a fresh and detailed look at many aspects. Some of these are discussed in this paper.

1.0 SELECTION OF BASIC CONCEPT OF AN UHVDC SYSTEM

1.1 Selection of rated voltage, current and project configuration

The motivation to increase the voltage level for transmission of power over long distances is there as it would reduce the overall cost of transmission of large quantities of power. Upto a power of about 3000-3500 MW, a single bipole operating at ± 500 kV might be sufficient. But for higher power levels there are likely to be sufficient reasons to either increase the operating voltage or number of bipoles or both. The reasons may be due to the cost of transmission line, cost of losses, transportation limitations of converter transformers, approaching current limits of thyristor valves etc.

While the losses of the overhead lines reduce with increased operating voltage at a given power, the converter losses of the converter station will remain within in the same range (approximately 1.5% of both stations) due to voltage dependent portion of load losses. With increased line length and the power rating the optimal operating voltage will be higher. However, the finally selected rated voltage shall base on the optimization results taking overall capitalized cost of losses into account together with cost of equipment and materials.

As power level increases various options should be evaluated to arrive at the final configuration of the transmission system. The first impact of increase in power transmission requirements of *more than* 3000-3500 MW (say 3500-4500 MW) may be reflected in the increase in the size of converter transformers beyond the transportation limits of certain locations. The solution may be to adopt single phase two winding converter transformers which would result in smaller but increased number of converter transformers. However, keeping in view the increasing losses of the system there would be high motivation to increase the operating voltage of the project above ± 500 kV.

The size of equipment, notably that of converter transformer in the present context is affected both by the power level and the operating voltage level. Therefore, with still higher power levels, approaching 5000 MW, there may be a need to further

split the converter transformers from transportation point of view with consequent emergence of multiple valve groups per pole; either in series or parallel form.

When the need for multiple groups arises, generally the series group may tend to be adopted mainly because the series groups maintain balance in the two pole currents even during outages of a series groups and hence there are potentially no ground currents even when one of the series groups is out. In case of parallel groups there would be ground currents whenever one of the groups has suffered outage. However, in case the requirements of high power transmission forces the thyristors to reach their current limitations parallel groups (or additional bipoles) may be the choice. The parallel groups also have lower losses as compared to series group when there is an outage of a valve group. Further, the parallel groups are highly adaptable to stage wise development of a project as parallel groups can easily be added to an existing pole with minimum of disturbance. This advantage of parallel groups may be attractive whenever staging is required even when power rating of a project is low in spite of the fact that certain equipment like smoothing reactor and valves may increase in number. The parallel group option is like a multi-terminal project and thus the parallel groups can easily be located at different places and may be used to reduce the cost of ac transmission system by collecting and delivering power at different locations in the grid. This may have several system related advantages.

In case the requirements of power transmission are not above the capabilities of valves alternative solutions may be considered for evaluation whereby the converter transformers may be kept out in the switchyard where valve side wye and delta connections can be formed and final connections taken inside the valve hall. Perhaps a small reservation with this alternative is due to a complicated bus works that contains combined ac and dc voltages in the ac switchyard that is exposed to environment.

In view of above it is clear that the operating voltage and configuration of project, i.e. the number and type of converter transformers and adoption of series and parallel groups will be strongly influenced by the amount of power that has to be transmitted. With increasing power level a likely transition may be

A bipole with single valve group and single phase three winding transformer



A bipole with single valve group and single phase two winding transformer



A bipole with series valve group and single phase two winding transformer



A bipole with parallel valve groups and single phase two winding transformer

The above, by no means, is a complete list of possible options. For example, due to some requirements of reliability for HVDC line a decision may be taken to go for an additional bipole. Such alternatives may interleave in the above list.

1.2 Further Comments on the Selection of Rated Current

For UHVDC projects, depending upon the rating of the project, the continuous current rating may approach 3500-4000 Amps. Over and above the rated current, the project would also require overload ratings. Important considerations with regard to the current rating of the project would be with respect to

- losses on dc line,
- overload capability of thyristors and the project
- cooling equipment
- tap changer range due to higher voltage drop on the line
- ground currents during pole outages

For long distance bulk power transmission projects, the losses are highly dependent upon the operating current level especially as these are related to the square of current. The losses can be reduced by either reducing the resistance i.e. increasing the size or number of conductors or by reducing the current i.e. increasing the voltage. The reduction of losses beyond a certain level by reducing resistance or current becomes counterproductive due to increased cost of equipment and transmission line.

The long term (from minutes to several hours) and short term (generally for few seconds) overload capability of the project are critical to take care of outages in the DC as well as AC system and to maintain ac system stability following faults and disturbances. Further, since the operating voltage in a long distance project is more or less fixed the variations in power over the link have to be adopted by varying the current which means margins in the capability to go for higher current must be available in the equipment. Any restriction on the overload capability of the project as required by the system, for example, due to current limitations is therefore not desirable. Therefore, the project must have transient overload current requirements over the continuous current requirements. The usual values for long term overload may be 10-30% and for short term these may be upto 50% of the normal range.

At the levels of currents of 3500-4000 Amps, with the present day technology, the limiting component in the design of an HVDC projects from current point of view is likely to be the thyristor. Therefore, the choice of thyristor has to be such that sufficient margins are left after meeting the system requirements. The modern 5" thyristors (both ETT and LTT) have a voltage capability of 8 kV and a continuous current capability up to 4 kA depending on the transient current requirements and cooling conditions. Higher currents can be managed by the thyristors with lower voltage capability (for example 4.5 kA / 5.5 kV). However, this will increase the number of thyristors and the valve tower sizes significantly. The rated dc currents in the range of 3-3.5 kA can fit better into the current capability of the 8kV thyristors.

Having a greater amount of rated current may also have impact on the design and location of the ground electrode as during the outage of a dc line the pole connected to the other line has to be operated in the ground return mode. This may, depending on the selected power and voltage level, require currents higher than 3 kA through the ground for long durations. Experience has shown that impacts of injecting high amount of DC current through ground are not always entirely predictable. Thus, relatively speaking, the ground return mode operation is more demanding in the configuration wherein the current through the ground is over 3000 A.

Wherever multiple HVDC projects are located close to each other several other considerations and studies may be necessary for their mutual effects including the effect of simultaneous operation in ground return mode.

Due to the practical limits on the operating current, required developments on the maximum operating voltage and system requirements, it seems that the maximum continuous power with present day technology of a single bipolar UHVDC projects with two series converters is about 6000 MW.

2.0 AN EXAMPLE – 5000 MW, ± 750 KV, 2000 KM BIPOLAR UHVDC PROJECT

To further discuss the basic design concepts of an UHVDC project an example of a 5000 MW UHVDC project is chosen with two alternatives: with one and two twelve pulse groups per pole.

2.1 AC System Requirements

This example assumes that a)The AC system are with adequate strength (SCR >> 2.5) for UHVDC system. b)In case of the bipolar trip of HVDC system the AC system will not suffer from stability risk or can be kept in stable condition by coordinated interlock and load shedding. c)The fundamental frequency overvoltage at load rejection shall not exceed 1.3 pu. Specially coordinated control functions of integrated ac / dc system need to be investigated in detail in system studies in order to fully utilize the potential benefits of modern HVDC systems.

2.2 BASIC DESIGN

2.2.1 Single Line Diagram

A simplified schematics of the two series twelve pulse groups per pole and one twelve pulse group alternatives per pole is shown below at Figure-1 and Figure-2. These figures indicate the requirement of dc side series group bypass switches and large number of converter transformers.

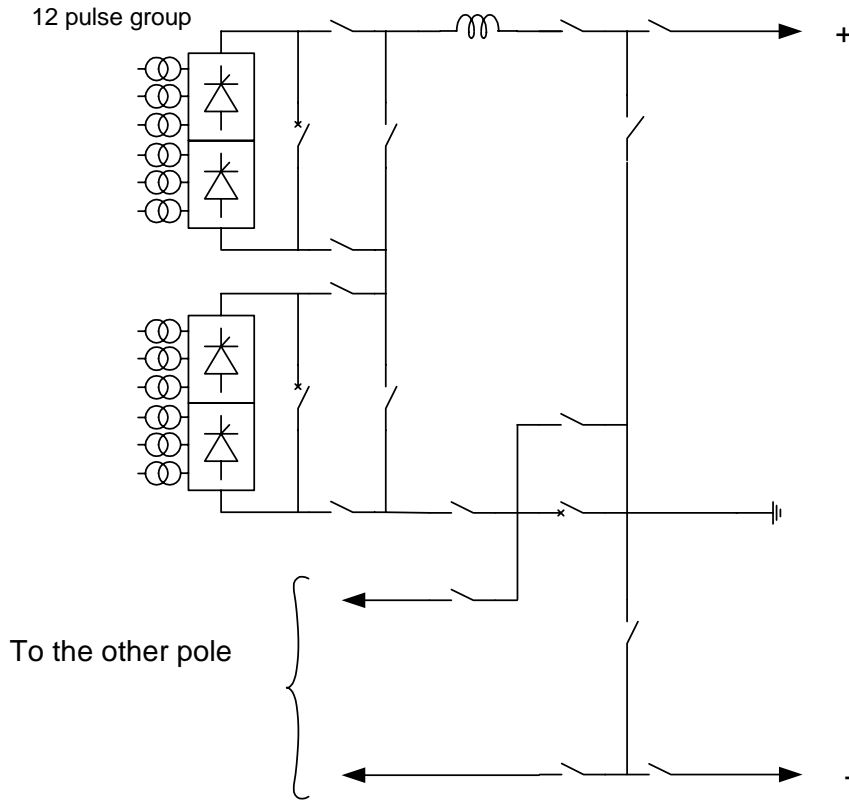


Figure-1: Simple Schematic of Two Twelve Pulse Groups Per Pole

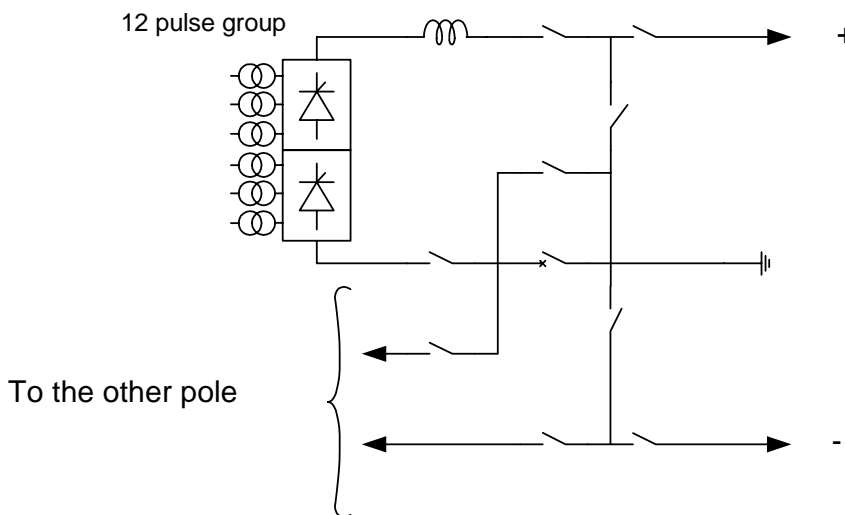


Figure-2: One Twelve Pulse Group Per Pole

2.2.2 Main Circuit Parameters

The basic design parameters for the two alternatives; with one and two twelve pulse groups per pole of a 5000 MW HVDC project operating at 750 kV dc are given at Table-1, Table-2, Table-3 and Table-4 below:

Table-1: Overall Scheme

Bipole Capacity	MW	5000	
Voltage Level	kV	± 750	
No. of 12 Pulse Groups per Pole	No.	1	2
Power Per Pole	MW	2500	2500
Power Per Twelve Pulse Group	MW	2500	1250
Converter Transformers per Station per bipole, without spares	No.	12	24
Valve Halls per Pole	No.	1	2
Converter Bypass Switches and Sequences		No	Yes
Power Change on loss of one twelve pulse group.	MW	2500	1250
Power Change on permanent DC Line Faults (Loss of a pole)	MW	2500	2500
Power Change on Bipole Loss	MW	5000	5000
Reduced Voltage Operation(Normal values) (possibility to shut down a 12 pulse group)	kV	525 -	525 375

Table-2: Main Parameters

The following nominal main data are given for a 5000 MW scheme assuming the dc line resistance of 18 Ω:

			One 12 pulse group		Two 12 pulse group	
			Rectifier	Inverter	Rectifier	Inverter
DC power	P _{dn}	MW	5000		5000	
DC current	I _{dn}	A	3333		3333	
DC voltage	U _{dn}	kV	± 750	± 696	± 750	± 696
No. of 12p bridges / pole			1	1	2	2
Firing angle	alfa	deg	15	----	15	----
Extinction angle	gamma	deg	---	17	---	17
Overlap	u	deg	25	24	25	24
Transformer impedance	uk	pu	0.20	0.20	0.20	0.20
Rel. ind. voltage drop	dxn	pu	0.10	0.10	0.10	0.10
Rel. resistive voltage drop	drn	pu	0.004	0.004	0.004	0.004
Transformer sec. voltage	U _{secn}	kV	322	297	161	148
Transformer prim. voltage	U _{ac}	kV	525	525	525	525
Converter reactive power	Q _{dc}	MVA _r	2800	2700	2800	2700

Table-3: Converter Transformer Data

			One 12 pulse group		Two 12 pulse group	
			Rectifier	Inverter	Rectifier	Inverter
Type			Single phase two winding		Single phase two winding	
Rated power	S	MVA	506	467	253	233
No. of units w/o spares			12	12	24	24
Transformer impedance	uk	pu	0.20	0.20	0.20	0.20
Transformer sec. voltage	U _{secn}	kV	322	297	161.1	148.5
Transformer prim. voltage	U _{ac}	kV	525	525	525	525

Table-4: AC Filters and Reactive Power Compensation

		Rectifier	Inverter
No. of banks		3	3
No. of subbanks incl. harmonic filters		11 6	13 6
shunt capacitors		5	7
Rating of subbanks	MVA _r	185	220

2.2.3 Converter Transformer Data

The converter transformer data at both converter stations is given in Table-3.

2.2.4 AC Filters and Reactive Power Compensation

The data for AC filters is given at Table-4.

Rectifier Station : Considering reactive power supply capability of the generators, usually available at rectifier side, the reactive power band is assumed to be : +200 -1000 MVar (“-“ indicates reactive power supplied by ac system). Inverter Station (Inverter): Reactive power band is assumed to be : +350 -350 MVar.

2.2.5 DC Filters

Two triple tuned passive filters TT 12/24/36 are assumed to be needed at each pole and each station.

2.2.6 Smoothing Reactor

A smoothing reactor in the range of 250 – 300 mH is installed in each pole at each station. The final size of the smoothing reactor will be selected based on the dc filter performance requirements and the overhead line parameters. Air core type smoothing reactors are likely the preferred solution for such UHVDC applications, particularly in case of a configuration with two series group per pole or a distributed smoothing reactor concept with reactors coils in high voltage and neutral side.

2.2.7 Thyristor Valves

Valves will be of modular design and consisting of modern light triggered thyristors as today’s 500 kV thyristor valves. Individual thyristor modules will be arranged in valve towers. Double valve tower or quadruple valve tower are possible solutions depending on the valve hall and transformer arrangement. For UHVDC application double valve towers seem to be more adequate due to large clearance requirements inside the valve halls.

2.3 Comments on the two schemes

2.3.1 Choosing the option

The choice of opting two series twelve pulse groups is mainly due to the limitation of manufacturing / transportation of the converter transformers. The capacity of converter transformers is about 500 MVA with one twelve pulse group per pole, which may require careful examination of the transportation possibilities. With two series groups per pole the transport weight of the transformers (appr. 250 MVA) will be in the range of 260 Tons and transport dimensions will be within the railway transport limits in China, India and the like (such as used for Anshun Converter Station in Gui-Guang I and East-South HVDC Projects). It may be noted that the dimensions of the converter transformer are also influenced by the voltage level and therefore the size of the converter transformer in the upper bridge may not be greatly different from the one in twelve pulse configuration.

The two series 12 pulse group alternative requires 24 converter transformers as compared to 12 converter transformers per station for one twelve pulse group. In addition to the dc side bypass switches and isolators, the two series groups also requires ac side breakers and other related equipment to isolate each of the twelve pulse groups. The requirements of isolating a twelve pulse group may arise due to planned actions or due to protective actions such as faults on the dc line or converter transformer etc.

2.3.2 Complexity of option

In any HVDC project a major emphasis is on a design to achieve

- long continuous operations without fault
- ability to recover from faults quickly
- only partial and acceptable loss on major faults, and
- well integration in the AC system.

The long continuous operation of the project is basically achieved by proper design, strict quality control, adequate redundancy, efficient operator interface and proper installation to mention a few things. One additional thing that

has the potential to affect long continuous operation is the inherent complexity of a project. In spite of paying full attention to all the above aspects it is still desirable to keep the number of equipment installed as low as possible. With respect to the present application having two twelve pulse groups in series adds more equipment in the ac switchyard, valve halls and dc switchyard and at least theoretically is somewhat less reliable as compared to a much more common and utilized one twelve pulse configuration per pole.

There are several characteristics of the control systems that ensure coordinated recovery of the integrated AC and DC system. In the present discussion, however, we may mention only that the two 12 pulse groups require additional control sequences and procedures for bringing in the second group into service and for taking out a group from service. The sequences are fairly robust but a small amount of disturbance to the system is almost inevitable.

Therefore, in view of the added cost, complexity and consideration of long continuous operation the two series group option should be employed only if it is a must and as stated above this would generally arise due to restriction of transportation of converter transformer due to its weight / dimensions.

Partial outages

When there are two series 12 pulse groups per pole there shall be certain faults within the converter station that may require shut down of only one of the two 12 pulse groups. Under these circumstances the loss of power in case of two series groups per pole shall be lower as compared to the case when there is only one twelve pulse group per pole. However, it is likely that while designing the project the contingency of faults on DC line that require shutting down entire one pole of the station has to be considered, and therefore even when there are two twelve pulse series groups per pole the outage of a pole has to be considered for the design of the project.

Reduced Voltage Operation

The reduced voltage operation is mostly anticipated to ride through flashover problems on the DC line or DC switchyard. These flashovers may be caused by a reduced insulation strength or environmental conditions like fog, pollution etc. The reduced voltage operation is achieved through a combination of tap changer operation and firing angle control. In case of two twelve pulse groups per pole there is an additional flexibility to reduce the operating voltage by shutting down one twelve pulse group which shall bring down the voltage to half. However, this shall also bring down the power to half. This flexibility of shutting down one of the two twelve pulse groups, however, may be of limited use since the normal requirements of improving flashover problems by operating in a reduced voltage are met by bringing down the voltage to about 80% of the nominal voltage or at most to 70% of nominal voltage.

Spares and Maintenance

The spare inventory is directly related to the number of different types of equipment installed in the project and to the number of equipment installed. The most important equipment in the present context are the converter transformer and the DC bypass switches. Generally, when single-phase two winding transformers are employed there are two types of converter transformers; one YY and another YD type. In case of two 12 pulse groups per pole since the voltage level of the lower twelve pulse group is substantially low compared to the upper group one may opt to design different types of converter transformers for the two groups. This shall then require four types of spare converter transformers. The spares of converter bypass switches are required only when there are two 12 pulse groups per pole.

Since there are 24 converter transformers in case of two 12 pulse groups compared to 12 converter transformers for one 12 pulse option there shall be increased maintenance requirement in case of former. The two group option requires separate valve halls for the two groups so that maintenance can be carried out when one group is operating.

3.0 FEASIBILITY OF DESIGN AND MANUFACTURING OF UHV DC EQUIPMENT

The mature HVDC technology accumulated over last decades is the solid foundation for the design and manufacturing of UHVDC equipment. There were already study reports on the feasibility of UHVDC up to 800 kV by the international organization such as IEEE and Cigre. All these working groups reported that the UHVDC system is technically feasible with some research and development efforts in a few key areas.

The major concern is basically the oil-immersed equipment such as converter transformer and oil-type smoothing reactor, while other DC equipment can be well designed to withstand the UHV stresses by scaling the design from existing 500 kV equipment supported by testing. This means that the UHV DC equipment will be considerably large in length and may consist of several units in series. The decisive measure for designing UHVDC equipment is to control the voltage distribution inside and outside of the equipment to avoid overstresses. It is a proven technology to control the dc voltage distribution by a pre-defined resistive current. Such technology can be found in the design of dc voltage divider, dc filter capacitor, dc PLC-coupling capacitor and ZnO-arresters.

The need to optimize the size and insulation level of major equipment would require careful selection and placement of ZnO-arresters. This may call for use of additional arresters at UHVDC level particularly for oil filled equipment such as converter transformer.

Another aspect, which is to be considered for UHVDC equipment, is the external insulation of outdoor equipment with due considerations to environmental factors such as pollution, temperature and height of installation. The creepage and clearance requirements may result in extreme dimensions in length, which may cause mechanical and manufacturing difficulties for equipment like disconnectors and wall bushings. It may be mentioned that since the flashover performance of outdoor insulators under polluted conditions depends to a large extent on the pollutant and atmospheric conditions including orientation of installation as these may directly affect the non uniformity of depositions and voltage distribution an increase in specific creepage distance may not be the remedy against performance under such conditions. Therefore, a reasonable external insulation level should be applied for such equipment. In case of need, other measures such as booster sheds may be applied to reduce the physical dimensions of the equipment. Maximum use of composite insulators is envisaged as it promises better performance and would enable use of smaller insulators. At present, it seems likely that some porcelain insulators will remain in the DC switchyard due to e.g. mechanical strength considerations.

Air core type smoothing reactors are likely the preferred solution for such UHVDC applications, particularly in case of a configuration with two series group per pole or a distributed smoothing reactor concept with reactors coils in high voltage and neutral side.

In order to meet the anticipated time schedule of the transmission projects, considerable amount of investment in research and development in some key areas shall be conducted in advance to ensure the availability of design in time. Following areas may be included in the R&D program:

- Converter transformers
- Bushings
- HVDC Post-Insulators / Disconnectors

Additional investment in the testing facilities is necessary to accommodate the higher testing levels and large equipment dimensions. An optimized design of whole UHV dc system requires a well coordinated R&D program. All HVDC equipment except dc filter capacitors are within Siemens product portfolio, so a lot of synergy is available to ensure the success of the R&D program. From today's point of view, the core design of major UHVDC equipment is expected to be available within 12 months, partially verified by testing. Therefore the anticipated date of operation for the first UHVDC system in 2009/2010 is feasible.

4.0 SUMMARY

In order to transmit large power over extremely long distance UHV technology is regarded as beneficial for HVDC systems. In case of high amount of power per pole, two twelve pulse groups per pole is considered as necessary to reduce the size of the converter transformer to a manageable value. The project components must be selected to ensure proper availability of long and short term requirements of the project. However, the conventional and the most optimized configuration of using one 12 pulse group per pole is preferred as long as there is no constraints from transport capabilities of large equipment. The design and manufacturing of UHVDC is basically feasible based on existing experience and know-how. Research and development works are needed in few areas such as converter transformers and wall bushings to ensure the design available to the first project application within next few years.

5.0 REFERENCES

- [1] EPRI : “HVDC Converter Stations for Voltages above 600 kV”. February 1985
[2] Cigre WG 14.32 : “HVDC Converter Stations for Voltage above 600 kV”, December 2002

Biographies:



Hartmut Huang, born in 1963, received his Dipl.-Ing. degree and PhD in Electrical Engineering from University of Braunschweig, Germany, in 1986 and 1992, respectively. Since he joined Siemens AG in 1992, he has been working on HVDC system engineering for many HVDC projects world wide. Currently he is manager of HVDC system engineering department at Siemens Power Transmission and Distribution Group.



Ramaswami Velpanur, born in 1946 received his Bachelors Degree in Electrical Engineerin from the University of Bangalore in 1969. He has been working in the HVDC field since 1980, first with Brown Boveri & Cie and then with Siemens AG. Currently he is responsible for HVDC Sales and Marketing at Siemens Power Transmission and Distribution Group



Devinder Kumar, born 1958, received his B.Tech degree in Electrical Engineering from IIT Delhi, in 1980. He joined NTPC, India in 1980 and later POWERGRID, India in 1990. Since 2005 he has been working with TransGrid Solutions Inc., Canada. He has worked on various areas of HVDC projects such as planning, specification preparation, design, implementation and operation & maintenance. His present assignments concern power system studies and design of HVDC projects.