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Technical Feasibility and Research & Development Needs for ± 1000 kV and above HVDC System

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Summary

There is considerable experience on 500/600 kV dc system available world wide and lot of learning's are also available now during development and recent operation of 800kV dc system. During 1970's and 80's, anticipating the next stage of high power HVDC transmission, considerable studies and field tests pertaining to Corona Studies, Insulation System Insulator Pollution Tests etc was taken up by EPRI/ other international institutions up to ±1200kV dc system. However, due to saturation of load growth, further Research and Development in Ultra High Voltage (UHV) area were slowed down or virtually stopped. With high surge of Energy requirement of geographically large countries coupled with large population and steep economic development in countries like China, India, Brazil and Africa etc, the situation has changed and these developing countries have shown high interest for harnessing remote hydro resources. This necessitates large transmission systems with UHV dc and ac to transmit large block of power to a distant load centre. It is a fact that dc phenomena is complex and different than UHV ac in regard to it's pollution performance, reliability of converter transformers, harmonics, ground return mode operation etc. The existing knowledge of electrical withstand in air, oil and other materials for voltages 2000-3000 kV is not enough neither for AC, DC, lightning or switching impulse, particularly not at high altitudes(2000-4000m) where some of the future potential transmissions are going to be built However, thanks to the ongoing development of better insulating materials for pollution, super thermal upgraded papers for transformer insulation, better quality transformer oils, split air core reactors, high energy capability surge arrestors and technology up gradation in civil engineering for cheaper in door switch yard etc which may facilitate 1000kV development.

This paper elaborates in a feasibility study for a transmission at 1000 kV dc or above and identification areas of R&D:

- Increased use of renewable hydro power resources of about 20,000-40,0000 MW in an area located 2000-4000 km from load centers calls for power transmissions capable of carrying 6000 -10000 MW of power. Such need clearly makes the use of 1000-1200 kV interesting to consider.

- HVDC terminal configuration or large modern networks need to be suitably designed to sustain a loss of power carried by such high capacity transmission.
- The stresses on the environment from the overhead line like external insulation, audible noise, electric and magnetic field need to be properly considered though effect of electric & magnetic field.
- The major challenge in converter station design is insulation co-ordination, clearances and reliability of converter transformer.
- The requirements on increased insulation clearance on equipment results in increased dimensions which in turn makes the mechanical design of the equipment more difficult and transportation of converter transformers becomes a huge challenge though it can be partly handled through configuration and also indoor switch yard etc.

KEYWORDS: DC transmission, long distance, bulk power, R & D works, HVDC station design, HVDC line design

Introduction

HVDC systems have been operating satisfactorily for several decades to transfer bulk power over long distances at 500 kV except Itaipu transmission, which is operating at 600 kV with a power rating of 3150 MW. This system entered commercial operation in 1985. However, 800 kV dc system was successfully commissioned in December 2009 which enfolds a new era in HVDC systems.

Due to the concerns over climatic changes and the search for clean power, the thrust is now by Governments /Environmentalists to tap large Hydro power at remote locations and transmit this to distant load centres. This problem has become more complex with strong public resistance, narrow transmission corridor, limited availability of Right Of Way (ROW), minimum transmission line route through forest and protection of flora and fauna for such large block of power and long length of the transmission corridor. It has been observed that the quantum of power being considered for transmission over 2000-4000 km are in the range of 10,000-40,000 MW in one large basin or near-by basins particularly in large countries like China (Yunnan and Sichuan provinces), India (Noth Eastern Region), Africa (Grand Inga etc), Russia (Siberia etc) where hydro potential has yet to be tapped. This calls for high intensity power transmission corridor i. e. MW per meter of ROW. Keeping in mind, utilities in China and India have already gone ahead with implementation of 800 kV dc and 1000/1200 kV ac systems The 5000 MW, 800 kV Yunnan-Guangdong HVDC project in China has been successfully commissioned in December 2009 and 6400 MW Xiangjiaba-Shanghai transmission is scheduled to enter commercial operation in 2010. In India, the first 800 kV, 6000 MW, multi-terminal dc transmission from the hydro generation sites in North-Eastern Region of India to Agra, close to the capital Delhi is likely to enter commercial operation in 2013/2014. Similarly 1000 kV ac system in China has already been commissioned in 2008 and charging of a prototype station at 1200 kV ac in India is envisaged in 2010 and 1200 kV ac transmission system is likely to be commercialized by 2013/2014.

The question right away arises whether there is a need to consider HVDC at voltages higher than 800 kV to transfer more power with more MW per meter of line corridor. There is no doubt that there is now interest in HVDC at 1000 kV. Such interest is driven by strong growth in load and demand for electrical energy and the potential of developing even more remotely located hydro resources, 10,000-40,000 MW located 2000-4000 km from load centres.

In order to assess the research and development requirements to meet the challenges of increasing the transmission voltage to 1000 kV and above, one has to look at:

- The current performance concerns about HVDC
- Is it economically possible to build transmission systems for UHVDC ±1000 kV?
- The type and nature the of equipment in the converter station
- HVDC overhead line
- Environmental effects caused by UHVDC stations and lines
- New challenges introduced by increasing the dc voltage to 1000 kV and above

Costs

In the following scenario it is assumed that 8000 MW of power has to be transmitted point to point over 2000 km. Alternative voltages, 600, 800, 1000 and 1200 kV are studied. For 600 kV, two lines will be needed, while for 800, 1000 and 1200 kV only one line is needed. The total cost includes cost for converter substations, overhead lines and capitalized cost of losses. The result is indicative as specific conditions like cost of overhead lines, cost of power etc will influence the result. However it is obvious that, for the power rating 8000 MW, moving to higher voltages leads to reduced costs.

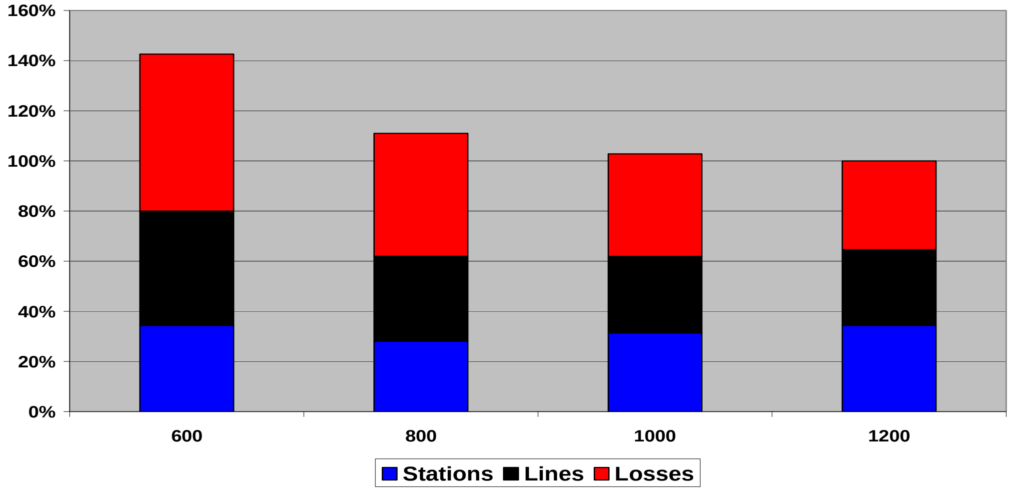

Fig 1 Optimization of voltage when transmitting 8000 MW over 2000 km

The table below gives an approximate optimized voltage rating depending upon the power rating including the cost of losses:

Power rating, MW	Voltage rating, kV
500	250-350
1000	350-400
2000	400-500
3000	500-600
5000	800-1000
8000 or more	1000-1200

Table 1. Economical optimum voltage rating at different power ratings when Transmitting power over large distances, more than 1000 km

Optimization of the voltage of the overhead line itself results in the higher figures in the range shown above. When considering also the HVDC substation, the optimum voltage is reduced as the substation cost increases with voltage.

A power rating of 8000 MW at 1000 kV results in a current rating of 4000 A. The short circuit current capability of the thyristor normally determines the maximum possible current rating. Today six inch thyristors with a current rating of approximately 5000 Ampere are available. However, most equipment is designed for maximum 4000 Ampere being the maximum current rating in operation in any scheme today primarily in back-to-back schemes. Therefore, a current rating substantially above 4 kA would in itself mean that a significant quantum of equipment development is needed.

Converter stations

Although every one is already familiar with what equipment is in a converter station, it is important to review what equipment is impacted by the increase in dc voltage.

Equipment	Voltage impact	Reasons
HVDC disconnects and switches	yes	Subjected to 1000 kV
DC filters	yes	Subjected to 1000 kV
Smoothing reactors	yes	Subjected to 1000 kV
Bus-bar insulation	yes	Subjected to 1000 kV
HVDC measuring equipment	yes	Subjected to 1000 kV
Thyristor valves	yes	Subjected to 1000 kV
Wall bushings	yes	Subjected to 1000 kV
Converter transformers	yes	Subjected to 1000 kV
Surge arrestors	yes	Subjected to 1000 kV
Neutral bus equipment	no	Not subjected to 1000kV
AC filters	no	Not subjected to 1000kV

HV circuit breakers	no	Not subjected to 1000kV
Buildings & structures	yes	Larger physical size of the equipment
Control and protection	no	Not subjected to 1000kV

As HVDC converter substations have been built up entirely by 12-pulse converters ever since the introduction of the thyristor valve, it is expected that 12-pulse converters will be used also for a potential 1000 kV system.

For 800 kV, the Yunnan-Guangdong 5000 MW transmission and the Xiangjiaba-Shanghai transmission, utilizes series connection of two 12-pulse converters. For the Northeast-Agra, 6000 MW, 800 kV transmissions, there are three converter substations utilizing parallel converters each rated 1500 MW, 800 kV. Such configuration is particularly convenient in a multi-terminal network in order to be able to continue operation at rated voltage even at disconnection of a converter in one of the stations.

The receiving ac network where an 8000 MW, 1000 kV HVDC system terminates has to be strong. The short circuit level has to be in the range 20,000-30,000 MVA. Such short-circuit capacity normally requires a voltage in the receiving ac network of 400 or 500 or 800 kV. Lower system voltage in the receiving network will mean that the HVDC transmission and the receiving ac network will have too low short-circuit capacity and thereby not having sufficient dynamic stability to operate safely.

A lot of works are being carried out in the area of wide area monitoring through phase angle measurement and possibility of providing advance information regarding likely disturbance in the connected ac network to the control system of HVDC to minimise the disturbances due to commutation failure.

New challenges due to the increase in voltage to 1000 kV

Obviously just by increasing the transmission voltage to 1000kV which may imply the increase in the transmitted power although it may not be necessary true in all cases, there will be challenges such as:

- Converter station appearance
- Audible noise
- Availability of testing facilities
- Mechanical design of the equipment because of size
- The loss of power in the event of an outage
- Air clearances with regard to stress by dc voltage and switching surges
- Creepage distances particularly in areas with high pollution
- Thermal design of equipment in case of rated current above 4000 Ampere

We need now to pose back and examine how we channelise the research and development effort to achieve the intended goals. It is expected that the R&D should be concentrated into the following areas:

- Thyristor valve design with regard to air clearances to walls, ceiling and floor in the valve hall considering ac and dc voltage, lightning and switching surges
- Converter transformer internal design with the oil/paper insulation barrier system around the windings as well as conductors from windings to bushings, considering a combination of ac, dc voltage and switching surges
- Bushing design internal as well as external with regard to simultaneous thermal, mechanical and electrical stress also considering influence of light or heavy pollution
- Switchgear equipment with due consideration to simultaneous design of internal and external insulation to achieve same voltage grading externally and internally
- Support insulators sustainability to wind and seismic stresses eliminating flashovers because of pollution
- External insulating system for transmission lines to minimize flashovers, limiting Electric & Magnetic field and minimum right of way (ROW)

Thyristor valves

Six inch thyristors are today available with a blocking capability of 8.5 kV, 5000 A current rating and 50kA short circuit capability. These thyristors meet the requirement for potential high power transmissions at 1000 kV, as thyristor valves are built up by modules and the voltage increase to 1000 kV means 25% additional modules compared with 800 kV

The step to 1000 kV will require further studies in valve voltage withstand to walls, ceiling and floor.Large electrodes should be used and thereby the stress of the gap increases. Voltage breakdown may occur even by a very small disturbance in the gap. It is interesting to verify whether or not the dielectric strength of an air gap will increase linearly with the distance of the gap under dc voltage. The electrical field stress has to be limited to such extent that abnormal flashovers cannot occur.

All equipment in the valve hall has to be supported or suspended by insulators. The introduction of an insulator “damages” the uniform electrical field between large electrodes. Such “damage” cause significant reduction of the dielectric strength of the gap and makes the mechanical attachment of the insulator into the electrode crucial for the voltage withstand.

Converter transformers

The challenges we face when considering 1000 kVdc converter transformers can be subdivided into two general areas: the direct challenges arising from the increase in voltage stress on the valve side of the transformers and the indirect impact of integrating the increased requirements into high power transformer units.

Increased voltage stress experienced in service at 1000 kV dc is directly reflected in the testing requirements of IEC 61378-2. It means an increase in test requirements for DC-related testing such as DC withstand and DC polarity reversal. However, the transformer is exposed to combined ac/dc stress and therefore requirements for design to withstand the most extreme requirements for AC voltage stress that is seen in the industry arises. Both these physically very different voltage stress requirements, DC and AC, have to be incorporated into the same design simultaneously. This statement is relevant to all parts connected to the valve side of the transformer, including the transformer DC bushing.

Once a reliable design for the valve side of the transformer is achieved, this design has to be incorporated into a full transformer design. As the main usage of 1000 kV dc is to enable utilization of distant energy resources, it naturally leads to remote sites for converter stations. Remote sites are intimately connected to the transport challenges of the largest and heaviest pieces of equipment, foremost the converter transformers. In order to enable transportation of the converter transformers a balance of the design risk often have to be maintained. This balance must take into account the need for reliable solutions for the increased voltage level of the valve side, while integrating the requirements posed from the DC-transmission on the converter transformer such as rated power, impedance and tapping range. This design also have to be handled carefully in order to be correctly manufactured, transported and installed on site. In the light of the most recent review of HVDC converter transformer failures performed by Cigré the design, manufacturing, transportation and installation must be stressed. One interpretation of the review of converter transformer failures in service points that such failures are caused by tap changers and bushings, poor installation and in some cases issues related to design areas which are unrelated to the increased voltage on the valve side of the converter transformers. These modes of failures should be and can be controlled for all converter transformers, both for existing and future DC voltage levels.

Transformer bushings and wall bushings

The challenge for design of bushings to be used for 1000kVdc, and perhaps combined with operation at high altitude, involves dielectric, thermal and mechanical issues.

Thermal and mechanical issues may be dealt with using general knowledge and experience as available today, which by no means indicates the task is simple. The full air side insulation distances needed for 1000kVdc insulation, with the associated test levels, are deemed to give rise to mechanical challenges.

The dielectric issues involves design of internal field control components, external shields and screens, etc, that are to be handling surge and continuous voltage levels of higher magnitude than previously used.

It is foreseen that after establishing and agreed on target levels to aim for during design and development, early engineering should yield proposed mechanical solutions that can fulfil the dielectric requirements. When this proposal also is verified against thermal and mechanical demands, planning for obtaining material and building prototypes should be the next step.

One of the most challenging issues to resolve involves design and testing of electrodes to be used for the increased test voltage levels, and also aimed at applications at high altitude. The size and properties of electrodes and their interaction with ambient air is one of the key issues for successful operation.

The new applications at the higher voltage levels call for full size long-term testing before the solutions are finalized. Such tests require facilities with sufficient capability, and the tests should be carried out well in advance to final delivery and installation at an HVDC converter station.

Switchgear equipment and support insulators

A general requirement on all switchgear at application for ultra high dc voltage is that internal and external voltage grading needs to be coordinated in order to avoid excessive radial stress and subsequent flashover through the insulator. In order to control the external voltage grading it is preferable to have only one insulator particularly for the dc voltage divider.

The development of equipment for 1000 kV poses many challenges in the combined design considering mechanical and electrical design. For the first two 800 kV projects to enter into operation in China most equipment were provided with composite insulators and their field experience shall provide inputs for 1000 kV insulation system development.

It is expected that also support insulators for UHV will be made of composite insulators. There exist various types of composite support insulators:

- Insulators filled with foam
- Insulators filled with gas
- Insulators with porcelain core

The experience of extremely long (10-14 meters) composite support insulators is today very limited both considering their ability to withstand electrical and mechanical stress.

At sites with extreme pollution, indoor switch yards have been arranged e.g at Zhengping in the Three Gorges-Changzhou, 3000 MW, 500 kV transmission. Thereby the pollution problem is eliminated and equipment can be designed with substantially lower creepage distances and instead switching surges become decisive for air clearance to ground. The indoor switchyard should be kept clean but environmental requirements are not as strict as for valve halls in regards to temperature and humidity.

The possibility to build the dc switchgear with GIS has been discussed and investigated. GIS DC busbars were installed in the Gotland, 180 kV scheme in 1983 between the transformers and the valve hall. It is not expected though; that GIS will be introduced in a large scale for UHVDC, as it requires new integrated design for all the equipment connected to the UHVDC bus i.e. busbars, support, insulators, bushings, DCCTs, disconnect switches, by-pass switches, DCVD, CVT, smoothing reactor, arrester and PLC reactor.

Alternative technologies

Currently the HVDC systems that are going in service at 800 kV are based on the LCC technology and one can be certain that the same will be true for the 1000 kV applications. For HVDC systems rated 8,000-10,000 MW, the minimum short-circuit capacity of the receiving network needs to be in the range 20,000-30,000 MVA. For networks, which cannot fulfill this requirement at low load conditions, the technology with Capacitive Commutated Converters (CCC) offers an alternative solution. At operation with CCC, the reactive power compensation is with series capacitors and the amount of ac filters and shunt capacitors is substantially reduced. An HVDC station with CCC technology can operate at much lower short circuit capacity and offer a bigger safety margin against instability compared with conventional LCC technology.

One can also look into the future and consider the VSC technology being substantially expanded to UHV. Such a step would open a new era in the world of HVDC. Not only the VSC technology would be the area for R&D but the revival of the need for a dc circuit breaker coupled with VSC applications with an overhead lines.

One can also imagine a bigger role will have to be played by fast dynamic voltage control devices such as STATCOMs and SVCs for such large HVDC systems.

Transmission line

1000 kV and above DC transmission line is another area where optimization in tower design shall have an overall impact on the cost of the entire HVDC project. HVDC transmission line design is also required to be optimized for conductor configuration, insulator type as well as string configuration like V or Y, electric & magnetic field at ground level, corona, radio & TV interference, audible noise, etc. The electric field and current density under DC transmission lines have been observed to be statistical in nature and influenced by atmospheric conditions like humidity, wind velocity, wind direction etc. and therefore assigning absolute theoretical values for exposure limits may not be appropriate and are to be selected based on feedback from operating experience of existing systems where the transmission lines designed for computed exposure limits upto 25 kV/m and Ion current density from 60 nA / sq.m to 100 nA / sq.m are in operation under fair weather conditions without any adverse public response. The measurement of audible noise, radio interference, ion current density and electric field of the operating 800 kVdc projects shall demonstrate the acceptance limits those have been considered during the design stage. Standard self supporting lattice type towers have been used for both China and India 800 kV projects and similar design may be foreseen for 1000 kV and above dc system. However, the line performance related to flashover, tower failure, transient faults during operation and behavior of insulators both porcelain disc and silicone rubber insulator type shall be assessed and suitable modification if required shall be incorporated.

Conclusions

Preliminary studies of HVDC transmissions to operate at 1000 kV have resulted in the following conclusions:

- The drive for more environmentally friendly generation calls for increased use of hydro power remotely located from load centres
- UHVDC at 1000 kV is economical for transmission of large amounts of power, more than 7000 MW for more than 1500 km
- The operating record of the two first 800 kV transmissions, Yunnan-Guangdong and Xiangjiaba-Shanghai shall be evaluated as an input for development of 1000 kV equipment and to decide upon a new project with 1000 kV rating
- The major challenges at development of 1000 kV converter substation equipment are:
    - Air insulation of thyristor valve to floor, ceiling and walls
    - Transformer oil/paper insulation
    - Bushing design considering thermal, mechanical and electrical stresses

    - Switchgear equipment and support insulators with large dimensions being able to withstand electrical stresses but also have to be well mechanically designed to withstand seismic and wind stresses.
- Design of Overhead line towers for optimizing the cost of the total dc transmission systems keeping the tower design parameters within the specified limits
- Before proceeding with 1000 kV or above HVDC systems, proto should be developed & put to testing / field trial to fine tune the design and technical parameters.