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HVDC Power Transmission for Remote Hydroelectric Plants

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Synopsis

India, China and Brazil are well advanced in the development of remote hydroelectric power plants. Brazil is now considering ever longer transmission distances, with the planning of hydroelectric development in the Amazon region. In Africa we also see plans to develop large hydroelectric projects with very long transmission distances. This increase in transmission distances has led to the consideration of higher voltages for HVDC transmission, with ± 800 kV already being proposed for several projects in China and India.

In Brazil development of hydroelectric power in the Amazon region includes active study of the Belo Monte and Rio Madeira projects. Both have planned ultimate capacities in the order of 10 000 MW. In China, Xiluodu and Xiangjiaba hydroelectric power stations on Jingsha river are already under development with a combined capacity of 18 600 MW. With distances of more than 2000 km to the country's main load centres, the use of ± 800 kV transmissions is being studied.

This paper addresses the advantages of using HVDC for bulk power transmission at voltage levels including ± 800 kV and discusses optimum line and converter ratings taking into account the relative size of the receiving network and staged development of the plant. Brazil already has a good history of the use of HVDC to connect remote hydroelectric plants with the Itaipu, 6 300 MW transmission, now in operation for more than 20 years with the worlds highest operating voltage of ± 600 kV.

Keywords: Belo Monte, Rio Madeira, Bulk power transmission, HVDC, UHVDC, Interconnection, Power control, Three Gorges, Jingsha River

1. INTRODUCTION

Brazil is now planning development of remote hydroelectric power plants in the Amazon region. The Belo Monte and Rio Madeira projects are under active study and have planned ultimate capacities in the order of 10 000 MW, with a distances of more than 2000 km to the country's main load centres.

This paper addresses the advantages of using HVDC for bulk power transmission, not only for connection to remote generating sites, but also within existing systems where large power flows are often present on a seasonal basis due to the natural characteristics of hydroelectric power plants. Brazil already has a good history of the use of HVDC to connect remote hydroelectric plants with the Itaipu ± 600 kV, 6300 MW transmission, now in operation for over 20 years and still the highest voltage in operation.

In China, where, of course, state-of-the art HVDC technology is used, the philosophy of asynchronous interconnection of regions is of particular interest, in the wake of cascading power outages. This paper will address this Chinese approach and it will also describe the most recently awarded 3000 MW Three Gorges to Shanghai ± 500 kV HVDC Transmission Project as well as the overall transmission system related to the 18 200 MW Three Gorges Power Project and planned transmission from Xiluodu and Xiangjiaba hydroelectric power stations.

2. SYSTEM CHARACTERISTICS IN CHINA

We can look at China with its very fast developing power demand and see that there is a trend towards maintaining several synchronous areas, interconnected by HVDC. At present long HVDC interconnections are used to transmit power from regions with ample hydroelectric capacity, with back to back connections being proposed for future trade purposes. China seems to have settled for three synchronous super-grid structures, North Power Grid, Central Power Grid and South Power Grid. Within each of these super-grids, two or three synchronous grids, interconnected with HVDC, are planned. For example Central China Power Grid and East China Power Grids within the Central Power Grid is interconnected with several long distance Bipole HVDC links. This is illustrated in Figure 1 below.

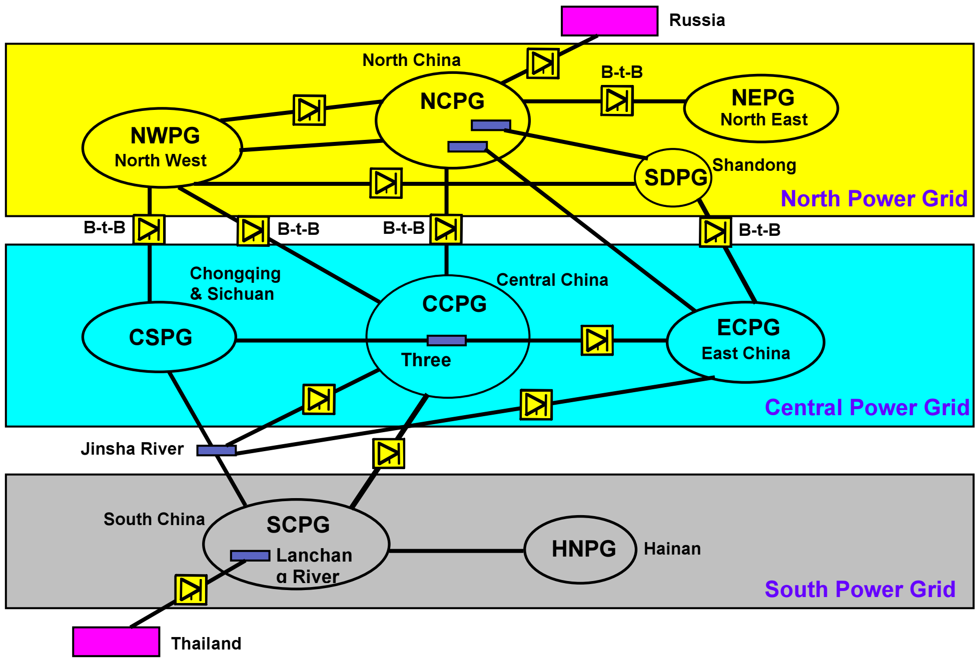

Fig.1 Conceptual Overview of China National Grid Interconnection by 2015

3. SYSTEM CHARACTERISTICS IN BRAZIL

The Brazilian system is around 95% hydroelectric and has developed over the years expanding to more remote locations. The main load centres are located in the coastal regions, especially in the southeastern state of São Paulo. By now the most parts of the country are connected in a single synchronous grid, with Manaus, the capital of Amazônia, being the only major exception.

The major part of the interconnected national grid system employs 500 kVac, with widespread use of series compensation. There is a strong backbone connecting the North to the Central Southeast, which at time considered in this study has three parallel 500 kV lines with a high level of series compensation. The major exception in the grid system is the Itaipu transmission, which employs both 765 kVac and ± 600 kV and forms the strongest single infeed, accounting for roughly 17% of the generation capacity.

Figure 2 illustrates the existing Brazilian system, plus areas of future development of hydroelectric generation. Complementary thermal generation, based on offshore natural gas, is also expected to be developed mainly close to São Paulo and Rio de Janeiro. The installed generation prior to these new developments is of the order of 70 000 MW, with the SE region accounting for about 65% of consumption, which leads us to consider configuration of new interconnections with respect to contingencies.

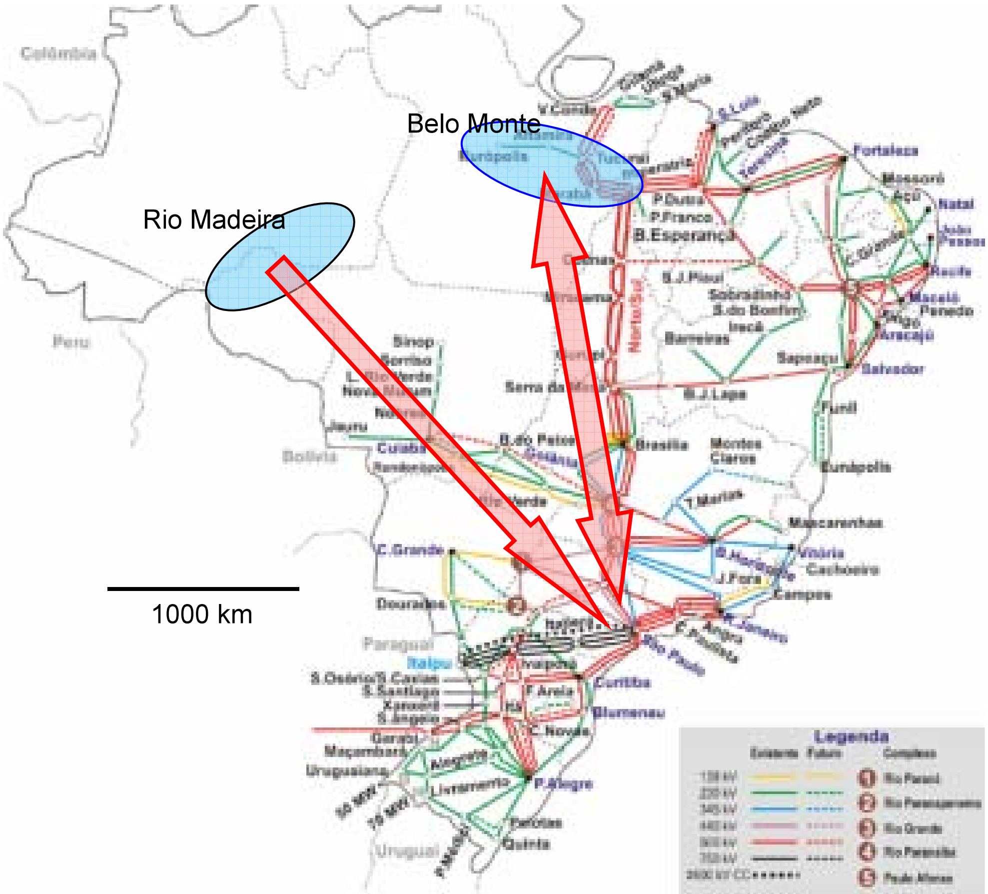

Fig.2 Brazilian Integrated System

4. REFERENCE PROJECTS

As a basis for the studies given here, two projects were used as references for the development of the parameters for the optimised transmission proposals. These two projects are the Itaipu 6 300 MW, ± 600 kV transmission, which having been in operation for more than 20 years forms a good basis for performance data, and the Three Gorges transmission, which demonstrates the most modern technology in use for classical HVDC systems.

4.1 The Itaipu HVDC Transmission

The Itaipu 6 300 MW, ± 600 kV transmission [1] has been in operation since 1984 and is still the highest voltage HVDC system in operation in the world.

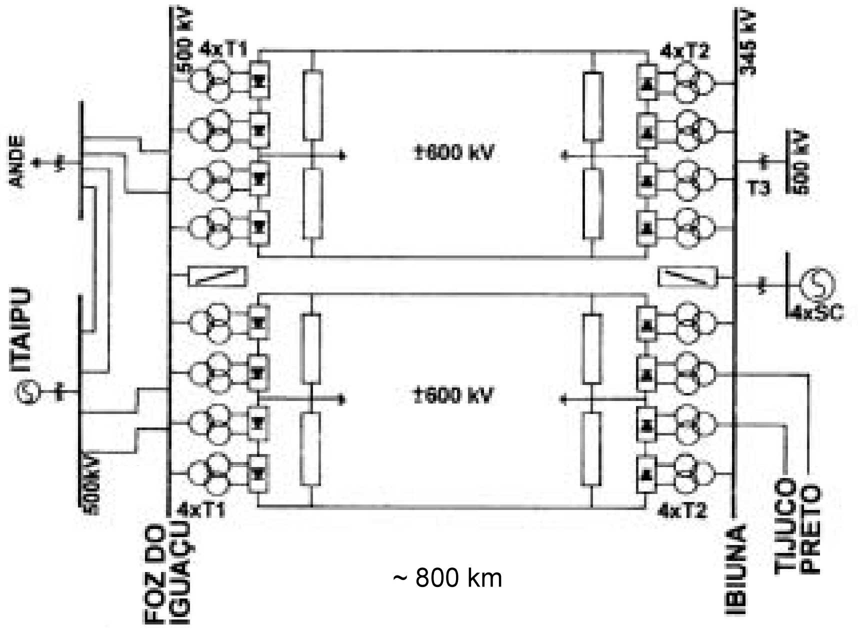

Fig.3 The Itaipu HVDC Transmission

It can be seen in figure 3 that Itaipu HVDC has two parallel bipoles with a rating of 3 150 MW and has two converters per pole. This gives a converter rating close to the Itaipu power plant generator rating of 700 MW and allows coordination of maintenance outages. The HVDC converters have a current overload rating of 12% for two hours at rated ambient temperature of 40°C or continuous if below 30°C, which permits transmission of close to full power for a converter outage. There is also a five second overload rating of 30%, which ramps down to 12% according to thyristor junction temperature. This assists dynamic stability of the interconnected system. The two bipoles were put into operation over a period from 1984 to 1989, with each converter roughly corresponding to the operation of an Iaipu generator.

Experience with the two ± 600 kV transmission lines has been extremely good. This can be seen from table 1 below, where an average failure rate of less than 1 fault per 100 km/year is given and also that only 20% of these faults required operator action to restore the pole. Of particular note is the fact that line faults are not only cleared very rapidly, but involve only one pole. The only cases of bipolar outages have been when a line tower has failed mechanically.

	Bipole 1						Bipole 2					
	P1 -			P2 +			P3 -			P4 +		
	Trans	Red.V	Perm	Trans	Red.V	Perm	Trans	Red.V	Perm	Trans	Red.V	Perm
1993	0	1	0	8	1	2	2	0	3	2	0	0
1994	3	0	3	3	0	1	1	2	3	3	0	1
1995	4	0	0	3	0	1	0	0	0	3	1	0
1996	3	0	0	5	0	0	0	0	0	5	0	0
1997	5	2	5	0	0	1	0	0	1*	2	0	1*
1998	2	1	0	4	2	2	0	0	1*	1	0	1*
1999	2	0	0	3	0	0	2	0	1	2	0	1
2000	5	0	1	7	0	1	2	0	0	3	0	0
8 year	24	4	9	33	3	8	7	2	7	21	1	2
Ave.	3	0,5	1,13	4,13	0,38	1	0,88	0,25	0,88	2,63	0,13	0,25

Trans = 0,659 pole faults / 100km / year
RedV = 0,078 pole faults / 100km / year
Perm = 0,202 pole faults / 100km / year

*Line Tower Failures total two events

Isokeraunic Level 90 (Foz) to 50 (SP)

Table 1 Performance of Itaipu Transmission Lines

± 600 kV dc Transmission Line

Bipole 1 792 km 1984
Bipole 2 820 km 1987

About 80% Guyed Mast
Average weight 5000 kg, guyed
Self supporting, weight 9000 kg
Conductor 4xBittern 644 mm² 45/7ACSR
450 mm subconductor spacing
32 Insulators 510 mm creep, 27 mm/kV
16,40 m pole spacing
72 m RoW per circuit

Fig.4 Itaipu HVDC Transmission Line

Each bipole has one earth electrode and corresponding electrode line. The electrodes are a conventional type, basically a ring of silicon iron rods buried to about three meters, embedded in a layer of coke. The experience with ground return, which was used extensively during the construction period, has been very good. Nowadays ground return is used only during period of maintenance involving a pole outage.

4.2 The Three Gorges Transmission

The Three Gorges hydroelectric power project has a planned ultimate power capacity of 18200 MW. Ten units, each 700 MW, are already in operation and completion of the whole Three Gorges hydroelectric power project is scheduled for 2009. Through four HVDC transmissions (3x3000 MW and 1x1200 MW), this power will be made available to the load centres in East respectively South China, some 800-1100 km away, together with other 500 kV ac lines. Three of these projects are now commissioned successfully and the fourth one, Three Gorges - Shanghai is under construction with completion scheduled for 2007.

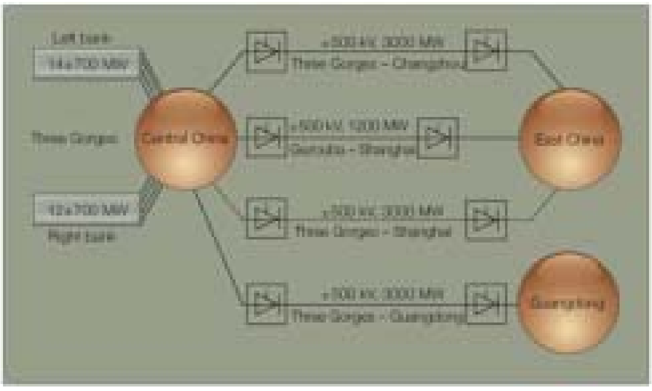

Fig.5 Four HVDC links will carry hydroelectricity from the Three Gorges power plant to the industrial regions of Shanghai and Guangdong

Three Gorges – Shanghai

Normal sending (rectifier) converter station of Three Gorges ~ Shanghai ± 500 kV HVDC Transmission Project will be located at Yidu, close to city of Yichang in Hubei Province and will be connected to Three Gorges Power station by three 58 km long 500 kV AC lines. Normal receiving (inverter) converter station is located at Huaxin in Qingpu close to city of Shanghai and will be connected by two 5 km long 500 kV AC lines to station Huangdu, which is part of the 500 kV AC ring around Shanghai city.

Basic design parameters of Three Gorges ~ Shanghai ± 500 kV Transmission Project is quite similar to the other two 3 000 MW projects from Three Gorges [2]. Main parameters are summarised in Table 2 below.

Main parameters	Yidu/Huaxin
Nominal power rating, MW	3000
Nominal dc voltage, kV	±500
Transmission distance, km	1060
Power overloads at max ambient temperatures with redundant cooling in service, MW:	
Continuous	3150
2 hour	3390
10 seconds	4230
5 seconds	4500
Converter transformers:	
Type	1-phase, 2-winding
Power rating, MVA	297.5/283.7
Smoothing reactors:	
Type	Oil-insulated
Value, mH	290
Thyristor Valves:	
Type of thyristor	YST-90
Arrangement	Double valve, suspended from ceiling
No of thyristors per valve	90/84
DC filter type	Passive, DT6/12 and DT24/36
AC filter:	
Type	Passive
Yidu, no x type; MVar	3xHP11/13, 3xHP24/36, 2xHP3, 1xSC; 1371
Huaxin, no x type; MVar	5xHP12/24, 4xSC; 1890
AC system voltage, kV	535/500
AC system frequency, Hz	50
Losses:	
Converter Station, %	1.3
DC Line, %	5.8

Table 2 Basic parameters of Three Gorges ~ Shanghai ± 500 kV Transmission

5. CHOICE OF VOLTAGE LEVEL

Figure 2 shows that transmission distances of more than 2 000 km are involved in the development of the new hydroelectric projects. This section discusses the choice of optimum HVDC configuration, taking 2000 km as the distance from hydro plant to load centre. A range of bipolar power ratings is considered, given that total power available at the locations considered varies from 6000 MW to 12 000 MW.

The Itaipu design has been used as a base to develop the transmission line costs for optimisation, maintaining 27 mm/kV creepage distance at all voltage levels. The calculations were carried out using costs applicable for implementation in Brazil. A fixed distance of 2000 km was used, with various economic values set for losses, ranging from 20 \$/MWh to 100 \$/MWh. The optimum line conductor was calculated for each loss value and voltage level. As can be expected, the optimum conductor total cross section increases with loss value and decreases with voltage. Figure 6 below shows the total transmission cost for each bipole rating as a function of value of losses.

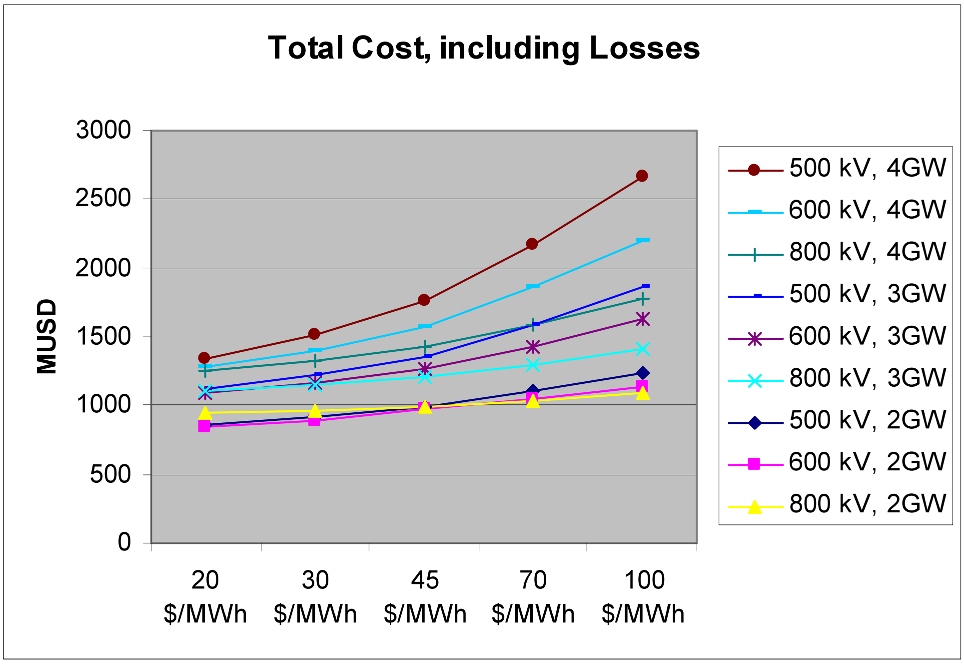

Fig.6 Total cost as a function of Value of Losses

It can be seen that even for power transmission as low as 2000 MW the use of ± 800 kV could be economically advantageous at high loss evaluations. In fact the conductor surface gradient limits the use of smaller conductors and the economy comes from reduced losses, with a higher initial capital cost. In this study only four conductor bundles were considered and perhaps a more economical solution could be obtained at ± 800 kV with the use of a higher bundle number and a lower total cross section. Nevertheless, ± 600 kV would seem to be more appropriate for 2000 MW over 2000 km. However at higher power ratings, 3000 MW and above, the four-bundle solution gives satisfactory performance at ± 800 kV with the optimum conductor at low loss values and lower initial capital cost is obtained. For higher loss values very large conductors result if the four-bundle solution is kept. As we have limited the maximum conductor diameter to 50 mm, the optimum solution is not always obtained and perhaps we should look to higher bundle numbers for high loss values.

The converter station costs used are based on one converter per pole, including 4000 MW, ± 800 kV. A conventional bipolar system is assumed, with ground electrodes used for monopolar outages.

6. PROJECTS UNDER DEVELOPMENT

This section describes new projects being developed in China and in Brazil

6.1 Projects in China

Xiluodu and Xiangjiaba are the two hydropower stations located in lowest reach of Jingsha river in China. Xiluodu power installation will be 12 600 MW (18x700). Its lower reach power plant is Xiangjiaba hydropower station with a capacity of total 6 000 MW (8x750) [3].

After the great success of Three Gorges Project, CTGPC has started construction of Xiluodu and Xiangjiaba, in Jinsha River which is the upper stream of Yangtze River. For Xiluodu project, the work was started February 2004, while for the Xiangjiaba project work started on October 28, 2004.

The total capacity of these two stations under Jiangsha River Phase 1 is to be 18 600 MW. During high water level seasons, all power generated will be transmitted out, 10 500 MW to East China and, 8 100 MW to Central China. Considering the operation need within the power stations and some power transmission for local networks during low water level seasons, the power stations shall be connected through 500 kV lines, to Sichuan & Yunnan.

In the study for transmission systems, because it is huge power and extremely long transmission distance from these two power stations, thus several alternatives were considered: 1 000 kVac, 1 150 kVac, ± 600 kVdc and ±800 kVdc. For transmission to Sichuan/Chongqing and Yunnan, as it is low power and short distance, adopting 500 kV ac transmission has been considered.

The below map of China shows several future potential HVDC projects, in addition to Xiluodu and Xiangjiaba transmissions where 800 kVdc is one of the most favourable transmission alternative [4]. From Xiangjiaba to Shanghai (2 100 km) one 6 300 MW and from Xiluodu to Hunan (1 100 km) and Hanzhou (1 900 km), one Bipole each of 6 300 MW is under consideration, together with around 4 000 km of 500 kVac transmission lines.

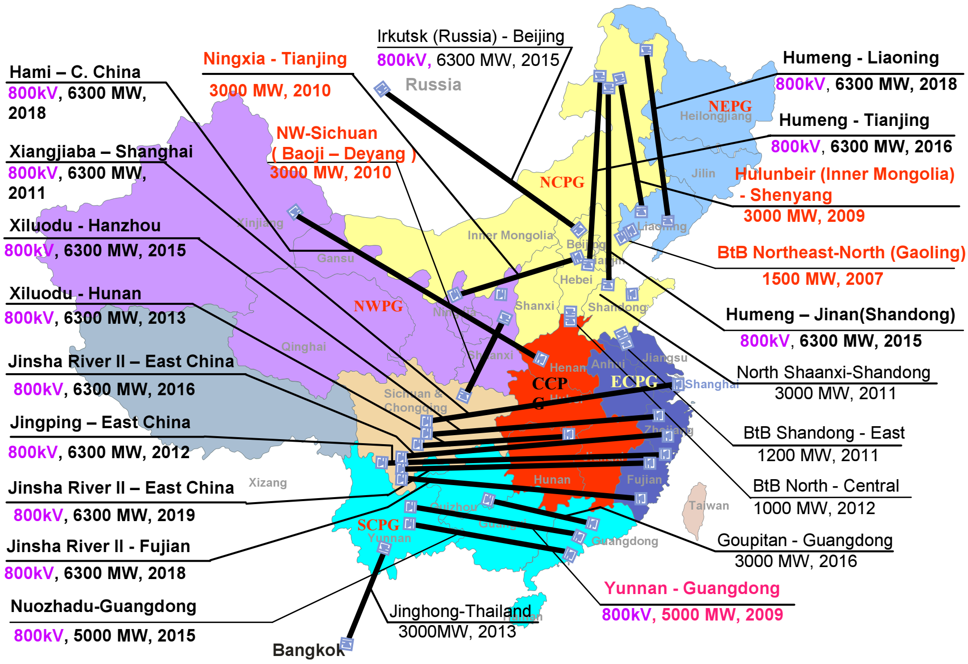

Fig.7 Potential HVDC projects in China

6.2 Projects in Brazil

As mentioned above, the Belo Monte and Rio Madeira projects are under active study and are probably to be the first large developments in the Amazon region [5]. Here we discuss possible transmission configurations for the two projects.

Belo Monte

This project is situated on the Xingu river and close to the Tucuruí hydro plant on the Tocantins river. There is a strong 500 kVac system to the southeast region, as described in item 3 above. With the configuration suggested here, good use is made of this 500 kV system, with the HVDC transmission covering outages in the EHVAC system and vice versa. For purposes of this study it is assumed that the hydro plant is to be developed in two phases each of 5 500 MW. Here we consider only the first phase, connected by two 500kVac lines to the existing station of Marabá. This is shown schematically in figure 8 below, where it can be seen that two bipoles are proposed for the HVDC transmission. Given the capacity of Belo Monte and the existence of other power plants to be developed in the region, a bipole rating of 3000 MW is proposed. With distance of 1800 km for Bipole I and 2300 km for Bipole II, section 5 shows that ± 800 kV should be used.

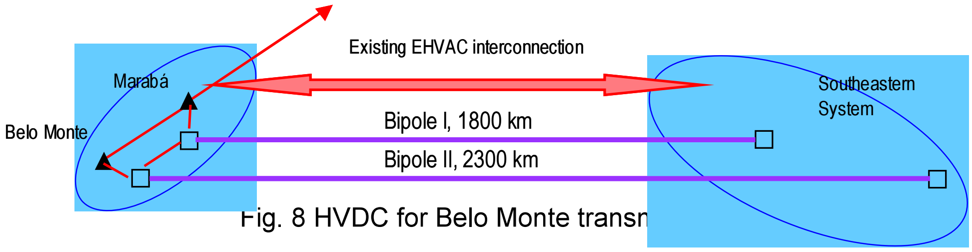

Fig. 8 HVDC for Belo Monte transn

The overload capability of the two bipoles has to be coordinated with the short time rating of the series capacitors in the 500 kVac interconnection. Bipole I is connected to the central area of the southeastern system where it can participate in seasonal power exchange to the north. Bipole II has a longer transmission distance and feeds directly into the most concentrated load area.

Rio Madeira

The Rio Madeira development comprises two power plants in Brazil, Santo Antônio and Jirau together having a capacity of 6 500 MW. There is also the possibility of further development on the river in Bolivia, adding an estimated 3 000 MW of further capacity. There is little local load in the region of the hydro plants, but the rapidly developing area around Cuiabá about halfway to the main load centre of São Paulo may have to be taken into consideration. The distance from Santo Antônio to the load centres close to São Paulo is 2700 km, which means that ± 800 kV should be used. Given a 500 Kvac collector system to incorporate Jirau, 90 km away, two bipoles of 3250 MW are needed. In this case the overload capacity is to be defined by a pole outage, as the HVDC is the only connection. In order to maintain full power transfer for a pole outage, a 33% continuous overload would be required, but this could be smaller if generation is reduced following the short time overload action.

One particular advantage of the use of HVDC for this project is the fast control of power flow, which can be used to assist the stability of the many bulb type turbines proposed to be used in this low head hydro plant.

7. CONCLUSIONS

While this paper discusses optimum interconnection characteristics for use in the large hydropower developments foreseen in Brazil and China, it is also applicable to similar projects being studied in other countries and continents. The long term experience from the Itaipu ± 600 kV system coupled with recent advances in technology as used in China confirms the advantages of HVDC for long distance power transmission.

Given this very good experience in terms of high availability and reliability, we look to higher voltages to make longer transmission distances viable. The economic evaluations carried out make it clear that when interconnecting large hydro power plants to distant load centres by HVDC, ± 800 kV has the lowest evaluated cost, making it the most economical solution. This trend to use the highest available voltage was already confirmed in 1979 when ± 600 kV was chosen for the Itaipu system based on an economic evaluation that included firm bids for converters of ± 500 kV to ± 600 kV [6].

The implementation of the HVDC solution provides further benefits. The staged development involved in large hydro power plants is facilitated and the sizes in the sending and receiving ends can be easily optimised. The environmental impact of the smaller dc towers and narrow right of way facilitates the environmental licensing process and reduces the time involved as well the cost of right of way acquisition.

Due to the inherent features of HVDC technology, the controllability of the transmission as well as the dynamic stability of the connected ac-networks is increased and thus the use of both systems can be optimised. This can be seen to be an advantage both in the Belo Monte project, where optimised use of the parallel 500 kVac system can be used and for Rio Madeira where additional stability is an advantage due to the low inertia bulb turbines. Furthermore, at the receiving ends close to load centres HVDC does not contribute to increase the short circuit level, which may be vital for some connection points.

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9. Biographies

John Graham was born in Northampton, England, in 1942. He received his degree in Electrical Engineering from the University of Warwick, England, in 1965. His employment experience includes service with Teshmont Consultants in Canada and Brown Boveri in Switzerland. He has worked in Brazil since 1972, initially on the studies for the integration of the Itaipu Hydro Plant into the Brasilian system. He joined ASEA, now ABB, in 1982 and was involved in the commissioning of the Itaipu HVDC system. He has worked with ABB in India on the Rihand – Delhi HVDC project in and more recently back in Brasil on the Garabi 2200 MW HVDC back-to-back interconnection to Argentina, both studies and project.

Abhay Kumar was born in Delhi, India in 1961. He obtained his degree in Electrical Engineering from University of Roorkee (now IIT) in 1982. He joined National Thermal Power Corporation Ltd. (NTPC) in 1982 and worked until 1995 as Deputy Chief Design Engineer. He has been involved in the design of Vindhyachal B2B HVDC and Rihand - Delhi HVDC Projects and many other EHV substations. He has also been consulting engineer for Chandrapur – Padghe HVDC Project. From 1995 to 2000 he worked for ABB Ltd. New Delhi as Senior Manager at Power System Engineering and Business Development department. Since May 2000, he has been working for ABB Power Technologies AB in Sweden as the Technical Manager for The Three Gorges - Changzhou ±500 kV DC Transmission Project. At present he is working as the Lead Engineer cum Project Manager for The Three Gorges - Shanghai ±500 kV DC Transmission Project.

Geir Biledt was born in Moss, Norway in 1958. He obtained his degree in Mechanical Engineering from the University of Linköping, Sweden in 1980. He joined ASEA AB in 1981 and worked in various positions in HVDC projects in Brasil, USA, Zaire and Malaysia amongst others. From 2000 he joined ABB Ltd. in Brasil as T&D manager. In 2004 he took up the position as Business Development Manager Latin America a position he still maintains.