高压直流

HVDC superhighways for China

Leif Englund, Mats Lagerkvist, Rebati Dass

When completed in 2009, the Three Gorges hydroelectric power plant being built on the middle reaches of the Yangtze river will be the largest of its kind anywhere in the world. With 26 turbine-generators, each rated at 700 MW, the total generating capacity will be a staggering 18.2 gigawatts.

No less challenging was the development of a technically and economically viable transmission system to carry this power to China's coastal regions, where it is urgently needed. After carrying out feasibility studies, the State Power Grid of China decided to build a hybrid AC-DC transmission system with over 10,000 km of HVAC and HVDC lines and about 2475 MVA of transformation capacity. The HVDC systems leaving the power plant site include bipolar transmission superhighways with ratings totaling more than 10,000 MW.

Two of the world's most powerful and longest high-voltage direct current (HVDC) power transmission highways, each with a nominal rating of 3000 MW, are currently being installed in China. Being built by ABB in cooperation with the State Power Grid of China (SPG), they will eventually carry clean hydroelectric power from the Three Gorges power plant, situated on the middle reaches of the Yangtze river, to major load centers near Shanghai and Shenzheng on the Chinese coast.

High availability and a low forced outage rate were key goals from the start of the transmission projects. Advanced technologies, backed up by solid field experience and featuring built-in operational flexibility and low maintenance, are therefore being used in all the crucial areas.

To promote and ensure the success of the projects at all stages, close cooperation among ABB, the client, the client's design and inspection representatives, and local equipment manufacturers, was enshrined in the project contracts in the form of training and transfer of technology (see panel).

1 Location of the Three Gorges power plant on the Yangtze river

Three Gorges power plant

The Three Gorges dam across the Yangtze river 1 is the largest of its kind in the world. Approximately 1.5 kilometers long and 185 meters (590 feet) high, its reservoir, with a normal water level of 175 meters (560 feet), will stretch over 560 kilometers (350 miles) upstream. The hydroelectric plant, with 26 turbine-generators rated at 700 MW, will have a total capacity of 18.2 gigawatts (the next-largest hydropower plant, Itaipu in Brazil, has a capacity of 12 GW). It is planned to later install a further six units in an underground powerhouse, taking the total capacity to 22.4 GW. This figure represents a more than six percent increase in China's current total installed capacity of 350 GW. The average yearly production of the Three Gorges plant will be 84.7 TWh [1,2].

> Close cooperation among ABB, the client, the client's representatives, and local equipment manufacturers, was enshrined in the project contracts in the form of training and transfer of technology.

Power evacuation system

The power generated by the Three Gorges plant will be transmitted to grids in central China, east China, Sichuan and Guangdong via the Three Gorges transmission system. With over 10,000 kilometers of HVAC and HVDC lines, this system will form the basis for a new national transmission grid, as the present seven regional power networks and five independent provincial networks will be

Transfer of technology (ToT) and local manufacturing

The contracts for both projects (3GC and 3GG) included extensive co-design, training and ToT programs.

The *co-design program* calls for the detailed design to be carried out jointly by design engineers and experts representing SPG and ABB.

Training of SPG's representatives covers maintenance and operation. Its goal is to ensure proper operation and maintenance of the projects by local personnel.

The *ToT programs* include know-how transfer in HVDC system design, control design and apparatus manufacturing to different organizations, ABB as well as non-ABB, in China. These programs will serve China's long-term objective of increased self-reliance in the design and production of high-tech HVDC equipment.

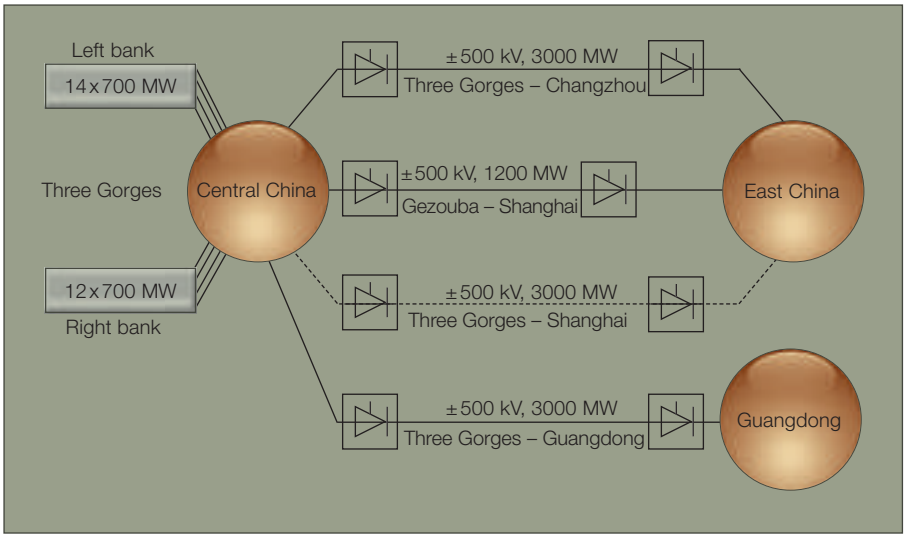
combined to create two new regional networks. A national integrated grid is planned for 2015.

A major portion of the power will be carried to China's industrialized coastal areas in Shanghai and Shenzheng by means of four HVDC links 2:

- Gezhouba-Shanghai 1200-MW HVDC bipole, in operation since 1991.
- Three Gorges – Changzhou 3000-MW bipole (3GC), commissioned in May 2003.
- Three Gorges – Guangdong 3000-MW bipole (3GG), currently being commissioned.
- Three Gorges – Shanghai, 3000 MW, scheduled to be operating by 2007.

HVDC was chosen to transmit power from the Three Gorges plant for several reasons. Since the central and east China/Guangdong AC networks are not synchronized an AC transmission scheme would have required coordination, and it would have been very difficult to ensure adequate stability margins. HVDC allows controlled transmission of power between the networks, which also retain their independence. DC is also more economic in terms of construction costs and losses. Five series-compensated 500-kV AC lines would be necessary to transmit the same amount of power, and each line would require a larger right-of-way than one HVDC transmission line for 3000 MW.

2 Four HVDC links will carry hydroelectricity from the Three Gorges power plant to China's coastal area and the industrial region of Guandong



Unmatched experience with HVDC bulk power

ABB's record of large bipolar HVDC installations is unmatched. Prior to winning the Three Gorges contract, ABB had successfully built a whole series of large bipolar installations worldwide, for example:

- Itaipu (Brazil): two bipoles, each rated 3150 MW
- Intermountain Power Project (USA): one bipole, 1920 MW
- Rihand-Dadri Project (India): one bipole, 1500 MW
- Chandrapur–Padghe Project (India): one bipole, 1500 MW
- Quebec-New England Multiterminal (Canada/USA): three bipolar stations rated 2250/2250/2000 MW

> HVDC allows controlled transmission of power between the central and east China/Guangdong AC networks, which remain independent.

Highway construction on schedule

ABB was awarded the first contract, to supply equipment for two converter stations for the 3000-MW HVDC bipolar link between Three Gorges and east China, in April 1999. This entrusted ABB with overall project responsibility, including the supervision of site work undertaken by the client. The contract also included ToT, covering HVDC system design, control design and equipment manufacturing. Approximately 85% of the total contract value was for equipment or services provided by the ABB Group. The installation was commissioned on time in May 2003.

In October 2001 ABB won a second order, this time for the 3000-MW HVDC link between Three Gorges and Guangdong province. This fast-track project cuts 30 percent off the normal lead-time, enabling the first pole to be commissioned 28 months after signing of the contract. Similar in scope to the 3GC, it provides for more local content. The ToT covers HVDC system design as well as the design of the control and protection system. This project is well advanced and on schedule.

3 Indoor DC yard at Zhengping converter station (3GC)

3GG benefits from 3GC

The 3GC project has established a world record by transmitting 1650 MW on a single pole. Since the Zhengping converter station is exposed to very heavy industrial pollution, the DC pole insulators had to be longer than those the manufacturers could provide. This and the difficulty of coordinating the external and internal insulation of extra-long bushings led to the decision to build indoor DC switchyards 3. All high-potential DC equipment is installed indoors and all the DC neutral equipment is outdoors. There are four separate halls for each pole: one for switches, two for the DC filter capacitor banks, and one for the DC PLC capacitor bank.

The 3GG project is in a class of its own with regard to the very short 28 months to commissioning for monopolar and 32 months for bipolar operation. Here the knowledge and experience base provided by the 3GC project proved to be a huge asset. Areas that profited included the project engineering phase and the equipment design and delivery times, all of which could be significantly reduced. The cost benefit to the client was also considerable.

To keep the AC yard of the 3GG Jingzhou converter station as small as possible, outdoor gas-insulated switchgear (GIS) is used for all of the ten 500-kV bays 4.

4 500-kV yard with SF_6 gas-insulated switchgear, at Jingzhou converter station (3GG)

The transmission systems

The 3GC and 3GG projects are both bipolar transmission schemes [3] with identical main primary and secondary equipment and operating strategies.

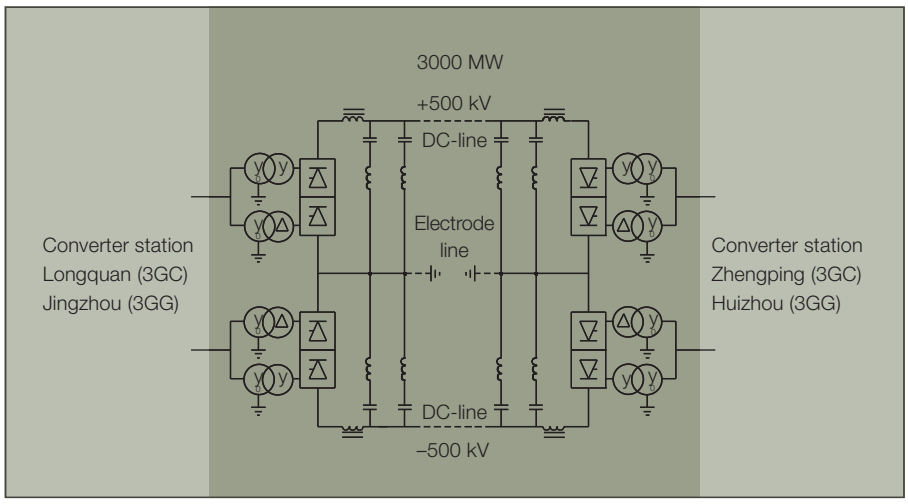
The two 3GC converter stations are at Longquan (Hubei province) and Zhengping (in Changzhou, Jiangsu province), about 890 km apart. Longquan converter station is situated some 50 km from the Three Gorges Dam. The receiving station at Zhengping is approximately 200 km from Shanghai. Power will be transmitted eastward during the peak generation period and toward the central power grid whenever reservoir water needs to be conserved.

The converter station at the transmitting end of the 3GG project is located 16 km from Jingzhou city, about 135 km from the Three Gorges power plant. The receiving station is at Huizhou, in Guangdong province. Power will be transmitted over a distance of 940 km.

Power ratings

The links are designed for a normal rating of 2 x 1500 MW under the (relatively conservative) specified conditions. They have been designed for a continu-

5 Power circuit arrangement used for the 3GC and 3GG projects



ous overload capability of 3480 MW, and a 5-second overload capability of 4500 MW.

To minimize bipole outage the HVDC system can be operated with balanced bipolar currents, using the ground mats of the converter stations as temporary grounding, should the ground electrodes or their lines be out of service.

The nominal reverse power transfer capability is 90% of the rated power. The HVDC links are designed to operate continuously down to 70% of the rated DC voltage. The main technical data are given in the table.

Power circuit arrangement

The main circuit arrangement of the two links 5 is identical except for the reactive power compensation equipment. Stable steady-state and dynamic operation of the AC-DC systems is ensured by optimizing use of the reactive power capacity of the generators in the Three Gorges power plant and the AC networks at each end of the links. One-and-a-half breaker configurations are used on the AC side at both stations.

In addition to the bipolar transmission scheme, the links can be connected for monopolar transmission with either a ground or metallic return. The main circuit connection on the DC side is typical for an HVDC bipole with overhead transmission line. Metallic return transfer breakers and ground return transfer switches have been installed to meet the requirements of monopolar metallic return operation, and provide capability for uninterrupted transfer. Neutral bus grounding switches are also installed at the neutral buses of both stations to meet temporary grounding requirements.

Main parameters	3GC (3GG)
Nominal power rating, MW	3000
Nominal dc voltage, kV	±500
Transmission distance, km	890 (940)
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	290/270 (290)
Thyristor type	YST-90
DC filter type	Passive
AC filter type	Passive
AC system voltage, kV	525/500
AC system frequency, Hz	50

6 Thyristor valve structures

> The links have been designed for a rating of 2x1500 MW, a continuous overload capability of 3480 MW, and a 5-second overload capability of 4500 MW.

Thyristor valves

A double valve scheme 6 was chosen to take account of the converter transformers being single-phase, two-winding units. Longquan and Jingzhou converter stations have 90 thyristors (3 kA, 7.2 kV) per valve, while at the receiving stations Zhengping and Huizhou each valve has 84 thyristors (same rating). Dry-type damping capacitors and film DC resistors are used. Comprehensive fire detection and protection is incorporated in the valve hall design.

AC filtering

Four types of filter are used: double tuned 11th and 13th, double tuned 24th and 36th, double tuned 12th and 24th, and C-type 3rd harmonic. Shunt capacitor banks, with and without damping

reactors, balance the reactive power requirement at Jingzhou, Zhengping and Huizhou converter stations.

DC filtering

Robust passive DC filtering ensures a performance level of 500 mAp (bipole)/1000 mAp (monopole) for both projects. Each terminal pole has two filter arms designed as double tuned filters, one tuned to the 12th and 24th harmonics and the other to the 12th and 36th harmonics.

Control and protection

The projects' control and protection strategies are realized with ABB's state-of-the-art MACH2 system. MACH2 features high-level performance, low maintenance, a very powerful programming environment and good integration with SCADA systems. The SCADA systems enable information about the operating status of each converter station to be accessed remotely by dispatch centers. These centers have full remote control capability and can regulate power transmission on the link. Terminal-to-terminal communication is via optical fiber ground wire. Capacity not needed for communication is used for dispatch and for data transfer on the networks, but could also be used for commercial purposes.

> Power will be transmitted eastward during the peak generation period and toward the central power grid whenever reservoir water needs to be conserved.

Control functions such as power ramping, frequency control and damping modulation, are also integrated. The station engineer can adjust the interface and parameters as required by the system.

Converter transformers and smoothing reactors

The single-phase converter transformers 7 in the Longquan and Jingzhou stations are rated 297.5 MVA, 525/√3:210.4/√3 (210.4 for Y-D) kV, 16% reactance, with an OLTC tap range of +25/-5 (1.25% per step). The Zhengping transformers are rated 283.7 MVA, 500/√3:200.4/√3 (200.4 for Y-D) kV, 16% reactance. Here, the OLTC tap range is +26/-2. In the Huizhou station the transformers are rated 283.7 MVA, 525/√3:200.6/√3 (200.6 for Y-D) kV, 16% reactance, also with an OLTC tap range of +28/−4 (1.193% per step). Dry-type bushings are used for the valve hall penetration. The converter transformers at Longquan, Jingzhou and Huizhou are also equipped with electronic control, allowing analysis and reporting, plus intelligent fan control to minimize losses.

The smoothing reactors are connected to the valves via the bushing penetrating the valve hall wall. An electronic control system for the reactors at Longquan, Jingzhou and Huizhou features the same capability as that provided for the transformers.

DC-side breakers and switches

SF_6 breakers are used for all the high-

7	Converter transformer arrangement per pole

Power take-off

Electric power generation in China tends to be located in the northeast (coal-fired), and in the west and southwest (hydropower), while the main consumer areas are in the eastern coastal area and southern industrial region of Guangdong.

China's total generating capacity of more than 350,000 MW (end of 2002) needs to grow to at least 500,000 MW by the end of the decade to cope with increased demand. Due to its fast-growing economy, many areas, including Shanghai, Guangdong and Zhejiang provinces, are already today suffering from a significant power supply shortfall. Guangdong province, for example, has a deficit of over 30,000 MW, some of which is met through imports from neighboring Hong Kong.

China now plans to start adding 25,000 to 30,000 MW each year through 2005, for an annual growth of 7 % to 8 %. Both AC and DC transmission are foreseen for the extensions. Over the next ten years, the HVDC market – long-distance transmissions and back-to-back stations to interconnect the regional networks – is estimated at 40,000 MW.

speed DC switches: metallic return transfer breakers, neutral bus grounding switches, neutral bus switches and ground return transfer switches. The ground return transfer switch is the only one of these to be of conventional passive design. All the others have an active auxiliary transfer circuit consisting of a capacitor and a charger. The charger gives the DC switches extra current commutation capability, enabling them to handle even the highest overload currents.

Operating configurations

The links can be operated in many different configurations and modes. Emergency operation is provided for, as is operation without telecommunication. Through accurate measurement and control it is ensured that in the case of bipolar balanced operation with local station ground the unbalance current to ground will be zero.

HVDC, with all its advantages for long-distance transmission, is expected to play a major role in the creation of China's national grid.

The operating modes are:

- Bipolar
- Monopolar earth return and metallic return
- Reduced DC voltage (from 500 kV to 350 kV)
- Reverse power operation
- Bipole and pole power control
- Pole synchronous and emergency (separate) power control
- Pole backup synchronous control (for modulation of DC current without inter-station telecommunication)
- Pole current control

Meeting China's energy demand

China plans to substantially expand its generating capacity by 2010 in order to cope with the predicted growth in demand (see panel). At the same time, two new regional networks will be created as the basis for a new national transmission grid. HVDC, with all its advantages for long-distance transmission, is expected to play a major role in the extensions.

"A remarkable achievement in the history of ABB's HVDC technology"

The inauguration of the Three Gorges – Changzhou HVDC link in August 2003 in the presence of representatives of the Chinese government, State Council Three Gorges Office, State Power Grid Corporation and ABB, marked the successful completion of trials and the start-up of commercial operation. The 500-kV, 890-kilometer long HVDC link can operate at world record levels of up to 3,480 megawatts, and when the Three Gorges generators begin operating later this year it will transmit electricity to millions of consumers in eastern China. The largest and longest bipole DC power transmission link in China was completed on schedule in four years.

"Considering the project's technical complexity, this is a remarkable achievement in the history of ABB's HVDC technology," says Peter Smits, head of ABB's Power Technologies division. "By delivering this challenging project on time almost to the day, we have demonstrated our commitment to speed and precision, and to improving the quality of life for millions of Chinese citizens."

Leif Englund
Mats Lagerkvist
Rebati Dass
ABB Power Technologies
SE-771 80 Ludvika
Sweden
leif.englund@se.abb.com
mats.lagerkvist@se.abb.com
rebati.dass@se.abb.com

References

[1] Introduction to China's Yangtze River Three Gorges Project. The PRC State Council Three Gorges Construction Committee, Ministry of Land and Resources, State Environmental Pollution Administration, State Bureau of Cultural Relics, September, 2002.

[2] **Z. Xiaoqian, D. Gongyang, G. Ricai:** The Three Gorges power grid and its development. Cigré 1998, 37–203, Paris.

[3] **Z. Xiaoqian, et al:** Design Features of the Three Gorges – Changzhou ±500 kV HVDC Project. Cigré 2000, 14–206, Paris.