# 2.4 Mechanical and electrical design of the Three Gorges Project

[D. Yuan, Z. Tian, S. Wang]

## 2.4.1 Introduction of the Three Gorges Project

The Three Gorges Project (TGP) is world-famous. On December 14, 1994, Li Peng, the former premier, declared the start of the TGP construction. From then on, the Project is going on wheels, it is forecasted that the permanent ship lock will be open to navigate in June 2003, and the first group of units will be put into operation in October 2003. The Project includes the existing Gezhouba Project which is the counter-adjusting cascade project located 40 km downstream. Benefits from the construction of the TGP are

- controlling floods in the Yangtze River and gaining much electrical energy at one time,
- developing rich water power resource in Yangtze River.

The Three Gorges Hydropower Station, which is under construction, will have a capacity of 18200 MW, including an adjusted peak capacity varying from 6000 MW to 12000 MW, and an average annual power generation of 84.7 TWh. Adding up the capacity of the right bank underground power plant which is under schedule, the total capacity is 22400 MW, equaling to about 50 million tons of raw coal burnt annually, and it shall be the largest hydraulic power station in the world. By using the cleaning water resource to institute thermal power generation, the Project can improve environmental conditions, provide a strong power for the national economy, and at the same time improve the ability of navigation to strengthen the economy link of the West and East in China and, as a result, promote the economy development in the Yangtze River area. Therefore, the contribution of the project does not only contain the controlling of floods, power generation, navigation and improvement of environment.

The total TGP reservoir surface area is 1084 $km^2$, and a land area of 632 $km^2$ was submerged which required the relocation of 846200 inhabitants of the area to be submerged. The mean annual runoff at the site is $275 \cdot 10^9$ $m^3$ and the storage capacity is $39.3 \cdot km^3$, out of which $22 \cdot km^3$ are for flood control. The total earth rock excavation is $132.8 \cdot 10^6$ $m^3$, the total earth rock embankment is $43.4 \cdot 10^6$ $m^3$. $28.7 \cdot 10^6$ $m^3$ of concrete, 518600 tons of steel enforcement bars and 252000 tons of metal work were used during the construction of the TGP. The main buildings of the Three Gorges Project include the dam, the powerhouse and navigation facilities. The dam is of a concrete gravity type. The total length of the dam axis is 2309.5 m, with the top elevation at 185 m and a maximum height of 181 m. The powerhouses will be placed at the toe of the dam, on both sides of the spillway dam section. There are 26 units with a rated power of 700 MW. Among them, 14 units will be installed in the left and 12 in the right bank powerhouse. At the right bank, enough space has been reserved for the future underground powerhouse of 6 units with rated power of 700 MW. The permanent navigation structures consist of a permanent ship lock and a ship lift. The ship lock is schemed as a double-way five-step flight lock with a transporting capacity of 50 million tons one-way. Each lock is capable of passing 10000 tons of barge fleet. The ship lift is designed as a one step vertical hoisting type and is capable to carry one 3000 ton passenger or cargo boat each time. The power station will be integrated into the power system via 15 outgoing lines of 500 kV, 8 from the left, 7 from the right powerhouse. It will supply electricity to Eastern China, Central China, the Guangdong Province and Chongqing City. For the general layout of the TGP, see Fig. 2.4.1.

Each of the individual projects of the TGP is a large project. As one part of the TGP, the mechanical and electrical engineering is the largest-size and most complicated technical engineering in the world.

**Fig. 2.4.1.** General layout of the Three Gorge Project.

## 2.4.2 Content and characteristics of the mechanical and electrical design

### 2.4.2.1 The design content of the mechanic and electric engineering

The design content of the mechanic and electric engineering is to integrate the mechanical and electrical equipment of TGP and that of Gezhouba Project to realize supervision, communication, safety and reliable operation, then to take a maximum advantage of the composition. The main design contents are:

- Power plant connection into the electrical power system;
- Turbine/generator units and auxiliary equipment;
- Main single diagram;
- Electrical general arrangement;
- Terminal 500 kV AC step up substation;
- Main electrical equipment;
- Power supply service for power plant and dam area;
- Multi-purpose automation, communication of inside and outside;
- Electrical drive and control for the project such as spillway gate, ship lock, ship lift;
- Lighting, lightning proof earthing, fire extinguishers, air-condition, sanitation, etc.

### 2.4.2.2 Characteristics and principles of the mechanical and electrical design

The characteristics of the mechanical and electrical design for TGP are as follows:

1) The Three Gorges Project is a multi-purpose project with benefits for flood control, power generation and navigation. Mechanical and electrical design must guarantee a realization of the above functions. For example, the water level of the reservoir can be adjusted by opening or closing 23 bottom discharge gates and 22 sluice gates of the dam. During flood seasons, opening or closing the bottom discharge holes and sluice gates of the dam shall be operated according to the needs of flood control. Hence, the reliability of control of the gates, especially the gate of the spillway structure, not only involves the safety of the downstream dike of the Yangtze River, which involves not only 15 million people's life and property but also expensive industrial and urban infrastructure and 2.3 to 2.72 million hectares of farmland, but also relates to the safety of the dam itself. The capacity of the TGP Hydropower Station is huge and the station is located in the hinterland of China. Undertaking basic-load, waist-load and peak-load in the electrical power system to which it is connected, is a big task: The TGP power station is the connecting point of the local electrical networks of East and Central China, the Chongqing Municipality, Guangdong Province, etc. The TGP will play an important role in the country's electrical power system and will help accelerating the unification of the national electrical network.
2) The TGP is a large-scale project. According to the Yangtze valley planning, the Gezhouba Project located 40 km downstream is part of the Three Gorges Project. Flood control, power generation and navigation have to be unified through an optimized control of the two projects. Therefore, the integrative automatic system must include the following objects:

   - 53 units with a total installed capacity of 25115 MW, among them 32 units with a rated capacity of 700 MW (TGP), and 2 units with a rated capacity 170 MW (Gezhouba), 19 units with rated capacity of 125 MW (Gezhouba);
   - 72 spillway gates, among them 27 spillway gates in Gezhouba, 23 bottom discharge gates and 22 sluice gates in TGP;
   - Navigation structure including a three first-step ship lock in the Gezhouba Project, a double-way five-step ship lock and a ship lift in TGP.

In addition, it also includes

- a survey of information about rain, water and weather and flood control related projects located both up- and downstream,
- automatic monitoring the environment around reservoir area,
- an automatic fire alarming and control center for fire extinguishing, etc.

3) The technology of mechanical and electrical equipment typically has shorter renewal periods and a rapid technology development. In general, the renewal cycle of the mechanical and electrical equipment is 8-10 years, but the progress is accelerated due to the continuous application of computer technology, new materials and techniques. From 1992, in which the National People Congress formally approved the "Preliminary Design Report of Three Gorges Project on the Yangtze River", to 2003, when the first group of units was put into operation, it will take more than ten years. So, in order to ensure advanced world standards of the mechanical and electrical design at the time of their operation, the designers must know the latest developments of the mechanical and electrical technology in the world, use mature technology in the design of TGP and be able to modify the design at any moment.
4) Integrate design shall be applied in the mechanical and electrical design. The integrate design aims to complete the interface between the TGP and the related operation department. The following interfaces are concerned:

- Interface with the National Flood Control Office, National Electric Power Company and the control center of National Traffic and Navigation;
- Interface between the power station and the automatic control, remote control, relay protection, communication, etc. of the electrical power network;
- Interfaces among the mechanical and electrical equipment of each unit;
- Interface with the hoisting device of gates.

5) With the development of the national economy, the characteristics of the power network load have been changed in China and have become more and more consistent with power network load characteristics in developed countries. The ratio of minimum load to peak load has obviously decreased, and the difference between peak load to minimum load has become larger and larger. Compared with thermal power generation, hydropower generation not only provides clean energy, but also has the advantage of an easy and quick opening and shut-down. In cooperation with the reservoir control, the hydropower station can generate an economical and reliable peak capacity. In China, though, during the flood season adjusting hydropower stations only to peak load leads to a big surplus of water. How power stations can cover a larger load with no or just a little surplus of water is one of the problems that need to be settled. If yet, it not only takes full advantage of water resource, but also shows the advantage of hydropower. Mechanical and electrical design must adapt such need of adjusting peak load.
6) Nowadays, a project construction must reflect mankind's creativity to change nature without destroying it. In addition, the magnificent TGP shall certainly become a new hot spot of tourism. Based on the design of main building, special design features such as architecture, environment protection and landscaping were carried out in dam area.

## 2.4.3 Hydro-turbine generator units with a rated power of 700 MW

### 2.4.3.1 Basic conditions for the selection of units

Considering the large power per single unit and the large number of units to be installed in the TGP station, basic considerations as well as general principles have to be taken into account:

1) The TGP construction will be finished in one time, and an exorbitant amount of work will be accomplished continuously. The reservoir will store water in three stages. The first stage will last about six years, where the cofferdam holds up water for power generating. During the first stage, the pool water level will stay at 135 m to ensure the power generation of the first groups of units and the navigation of ships in the double-way five-step ship lock. The second stage will last more than three years when the normal pool level is 156 m during dry seasons and the flood control level is 135 m during flood seasons. The third stage is the final stage operation when the normal pool level is 175 m during dry seasons and the flood control level is 145 m during flood seasons. From above we can deduce that the head range in the TGP Station will be increased by about 40 m from the beginning of the first stage when units are put into operation to the design pool level for the final operation. The maximum head is 113 m. The minimum head is 61 m when the flood control level is at 135 m and 71 m when the flood control level is at 145 m. A debate had lasted for a long time about the choice of the rated head of the turbines, because the head is lower than 78 m during most of the flood seasons and the inflow at the dam site is abundant, so a lot of electrical energy can be gotten at this period. From the point of power generation, it is better for the rated head to be lower than 78 m. From the point of convenience for the manufacture of the units and the stability of operation, it is better for the rated head to vary between 83 and 85 m. After analyzing and comparing, 80.6 m was determined as the rated head. The ratio of maximum to minimum head is 1.85 and the ratio of maximum to rated head is 1.4, which are both in the range of existing power stations with a capacity of single units greater than 500 MW all over the world. Therefore, a wide head range is a basic condition for the selection of turbines in the TGP Station. A series of measures taken to assure the stability of the units when the turbines operate in high head regions are all related to the required characteristics (For more information on turbines see Sect. 2.7).
2) The reservoir regulation procedures are as follows. The normal pool level will be 175 m after the TGP construction is finished, during flood seasons, from June to September, the pool level in front of the dam will stay at the flood control level 145 m in order to be flexible enough to regulate a flood that may possibly come from upstream. The reservoir will begin to store water in October. In a normal year, the reservoir will store water up to the normal pool water level of 175 m at the end of October. Dry seasons are from November to the end of April of the next year. At the end of April of a normal hydrological year, the reservoir level will be above the dry season drawdown level of 155 m. Only in a dry hydrological year will the reservoir level be drawn down to 155 m. Then it will gradually decrease to flood control level 145 m at the end of May of the next year according to the flow coming from upstream.
   It is indicated by hydrological documents recorded in the past one hundred and more years that the period from June to September is the main flood season in the Yangtze River. At that time, the average flow passing across the dam of the Three Gorges is about 60% of the total annual amount. The inflow is about 275.1 billion $m^3$ and is greater than the total discharge of all 26 units with a gross head below 80 m. The power generation in the flood season is 40% of the total annual amount. Though the flow heavily decreases in dry seasons, hydro-energy is nevertheless valuable because the head is high. Based on the characteristics mentioned above, the requirements for turbines are:

   - When the head is less than or equal to 80.6 m, turbines should have a large expected output to fully utilize the flow during the flood season and generate more electrical power.
   - When the head is greater than 80.6 m, turbines should have a maximum efficiency and the high efficiency region should be as wide as possible to obtain a high weighted average efficiency, i.e. to make optimum utilization of the energy of the water.

3) Although the sediment content in the water of the Yangtze River is far lower than that of the Yellow River, the river still contains sediments. After the formation of the reservoir, most of the suspended sediments will deposit in the reservoir during the initial stage of operation. The annual average sediment content is expected to be 0.379 kg/m$^3$ in the first ten years of the reservoir operation. The content of sediments passing through the turbines will decrease continuously. After operating for about eighty years, it is expected that the sediment carried down from the upper reaches to the Three Gorges reservoir will be equal to those released through the bottom outlets of the dam.

Summing up, the basic operation conditions for the selection of turbines of the TGP are a large wide head range, the requirement for high efficiency at high head, the requirement for large expected output to produce more electrical energy at low head, and abrasion problems caused by sediments passing through the turbines. Turbine units with a rated power of 700 MW are not only one of the largest turbine units in the world, but also the key equipments to generate electrical energy in the Three Gorges Powerstation. In order to satisfy the operation conditions above, more than twenty subjects are studied, such as

- main parameters of turbines,
- operation stability of unit,
- abrasion caused by sediments,
- embedment of spiral case with water pressure,
- temporary runners,
- installation schedule of units and
- anti-vibration of the powerhouse and hydro turbine generating unit.

### 2.4.3.2 Measures for main technical problems

#### 2.4.3.2.1 Study on stability of Francis turbines

It is well known that there is only a small zone with rubbing free and small amplitude of pressure pulsation when a Francis turbine operates near the optimal efficiency point. When it operates outside of this zone, problems of stability and cavitation damage may occur. Whether, from a hydraulic point of view, a Francis turbine can operate in a stable and safe way or not mainly depends on the four factors

- vortex in the draft tube,
- channel vortex between the blades,
- cavitation and
- pressure pulsation in the vane-less space between wicket gate and runner.

The following measures are taken to overcome an unstable operation caused by the above factors:

- Optimize the hydraulic design of the runner and pay attention to the test of stability;
- Choose the design head of turbines properly;
- Blade with a negative leaning angle;
- Add the height of draft tube properly;
- Set up maximum capacity for generators;
- Other measures such as air admission and controlling the operation mode.

#### 2.4.3.2.2 Alternatives of temporary runners

The Three Gorges reservoir will store water by stage. The operation head will vary from 61 to 94 m during the initial stage which will last for about six years and vary from 71 to 113 m during the final stage. Considering the maximum head in the final stage and minimum head in the initial stage, the ratio of maximum to minimum head is 1.85. In order to better adapt the head range from the initial stage to the final stage and to gain a more economic benefit, a lot of research such as one runner for initial and final stage, a generator with two speeds, an alternating excitation generator and temporary runners for initial the stage only, etc. has been performed in the past years. One of the reasons not to adopt the idea of a generator with two speeds and an alternating excitation generator is that it is very difficult both technologically and manufacture-wise, plus there is no practical experience with such large units. Thus, research focused on the feasibility and necessity of a temporary runner for the initial stage, which is designed to optimize the operation at low head in order to fully make use of the abundant inflow resources in the initial stage. It concluded that due to the temporary runner, the turbine could operate at low head with a large expected output and generate much more electric power, and it estimated that the energy generation during construction of the power station would add up to 7 billion kWh if six units were equipped with the temporary runner according to the schedule of the TGP construction. In addition, the temporary runners can be substituted with final runners in a period of overhaul of the unit, which is reasonable by primary economic analysis.

After technological interchange with the world-leading manufacturers including domestic manufacturers, the alternatives of temporary runners were further investigated in detail as follows:

- Alternative 1:
  A part of the units is equipped with temporary runners in the initial stage and replaced with final runners in the final stage.
- Alternative 2:
  The hydraulic design of the temporary runner is based on a head between 61 and 94 m. However, the strength of the runner shall be designed according to the maximum head of 113 m in order to put it into operation in the final stage as well.
- Alternative 3:
  The runner is designed according to the head in the initial stage, but it will be modified in order to match the operation conditions in the final stage.

The alternative of temporary runner was finally dismissed by a final economic evaluation in consideration of the following factors:

- Indefinability of the operation time in the initial stage and difficulty of quantitative evaluation of the cost of the temporary runner;
- Heavy work at the site caused by the substitution of the temporary runners or the modification of the blades;
- Difficulties in manufacture and project construction.

#### 2.4.3.2.3 Time limit for the installation of units

The time limit for the installation of units not only has an impact on the planning of the TGP units put into operation, but also relates to the coordination with the schedule of the construction of the powerhouse. Based on the analysis and study of the typical time limit for the installation of large-type units in domestic powerplants as well as on advice from domestic installation specialists, the time limit for the installation of one unit of TGP and a typical installation schedule are given: It will take about 18 months from the beginning of drafting the tube elbow to the end of installing embedded parts of the draft tube cone, the discharging ring, spiral case and liner pit, including concreting to a turbine elevation of 67.0 m. Furthermore, it will take 11 months from the machining of the stay ring to the completion of the installation of the unit, and another two months for the commissioning of the unit. Thus, the total time for the installation of one TGP unit is about 31 months.

The time limit for the installation of a unit mentioned above is based on the alternative of an embedment of the spiral case with elastic outpacking layers. During the erection of the spiral case, it is embedded with pressure under constant water temperature, which prolonged the total time for the installation of a unit by 4 to 5 months. According to the time limit for the installation of a unit together with the schedule of the powerhouse construction, it is possible to install 4 units in one year.

#### 2.4.3.2.4 Study on anti-vibration of the powerhouse

Vibration of large-type hydro turbine generating units will be caused by hydraulic, mechanic and electromagnetic factors during operation; it may even induce a local vibration of the civil structure in the powerhouse. The phenomenon once occurred in the Yantan Hydropower Station in China, which was equipped with 4 Francis units of a rated power of 300 MW and put into operation in 1993. Its main parameters are

- maximum head 68.5 m,
- rated head 59.4 m,
- minimum head 37.0 m,
- speed 75 rpm and
- diameter of the runner 8.0 m.

When the units operated at a head range between 59.4 and 66 m with an output varying from 240 to 270 MW, strong pressure fluctuation at vane-less space between the runner and the wicket gate induced serious vibrations of the generator level floor and the central control room downstream. The frequency of the vibration is 24-35 Hz. This phenomenon also occurred in a few turbines with similar conditions to the TGP turbines in recent years. Therefore, we paid much attention to the safe and stable operation of the TGP units. A special study on anti-vibration of the units and the powerhouse was performed in the past years, focusing on

- self-safety of the units and induced source of vibration,
- dynamical response of the civil structure of the powerhouse induced by a vibration of the unit and relevant anti-vibration measures.

#### 2.4.3.2.5 Cooling method of the generator

The selection of the cooling method for a large-type turbine generator is a very important technical issue concerning design, manufacture and operation. At present, there are two kinds of cooling methods for a generator: full air cooling and combined air/liquid cooling, which includes water cooling or vaporizing cooling according to the cooling medium. Among them, the technique of vaporizing cooling is still developing and it is too immature in technology to be used for a large scale generator such as the TGP generator. Therefore, the selection of the cooling method was focused on full-air cooling or combined air and water cooling. Great progress has been made on both methods in recent years and both are feasible for TGP generators. After several years of comparison and argument, the method of water cooling was chosen for the stator bars and air cooling for the rotor during the bid evaluation. For more details, see Sect. 2.4.3.4.5.

#### 2.4.3.2.6 Arrangement of the thrust bearing

The thrust bearing of large-type semi-umbrella units can be mounted on a lower bracket or on the head cover of the turbine using a support cone. The arrangement of the thrust bearing and the relevant shaft system not only affects the size and weight of the unit as well as the size of the main powerhouse, but also the safe and stable operation of the units.

Considering the arrangement of the thrust bearing for large-type semi-umbrella units with a rated capacity above 500 MVA in the world, some were mounted on a lower bracket (ITAIPU, GRAND COULEE and GURI generators), others were mounted on the head cover (Sayangsusensik and CHURCHILL Fall generators). During the stage of technological interchange, manufacturers from China and oversea offered different solutions for the arrangement of the thrust bearing of the TGP which were based on their own traditional design and experience.

In order to decide on the arrangement, the structure of the shaft system must be studied first. Calculations indicated that the ratio of the first critical speed to the maximum runaway speed is 2.0 when using a three bearing arrangement and 1.4 when using a two bearing arrangement. If short circuits occur on half of the rotor poles (with maximum exciting voltage), the maximum offset of the shaft line near the rotor is 0.38 mm (2.73 mm) when using a three (two) bearing arrangement. In the three bearing arrangement, the thrust bearing and the guide bearing are combined together requiring only one oil reservoir, so the height of the bearing can be decreased which makes it convenient for installation and maintenance. Also from the point of operational safety and stability of the units, the three bearings arrangement has more advantages which is why the three bearing arrangement is adopted in many of the large-type units.

The alternative of a thrust bearing on a lower generator bracket offered better access to the turbine pit and facilitated general maintenance. The major advantage of the head cover mounted design –a reduction of the length of the shaft – could not be exploited because of civil considerations. In addition, it was considered that the arrangement with a bottom bracket would give a more natural break in the contractor design and supply responsibility, should – for commercial or technical reasons – the generator and turbine ever be supplied by separate manufacturers rather than a consortium. Thus, a three bearing arrangement with the bearing mounted on the lower bracket was finally adopted (for details see Sect. 2.4.3.4.2.3).

### 2.4.3.3 The turbine

#### 2.4.3.3.1 Basic characteristics of the power station

##### 2.4.3.3.1.1 Water levels and discharges of the power station

For a schematic diagram of the annual variation of the reservoir storage level see Fig. 2.4.3.

**Table 2.4.1.** Levels and discharges.

| Item | Initial stage | Final stage |
|---|---|---|
| Normal pool level [m] | 156 | 175 |
| Flood control limit level [m] | 135 | 145 |
| Dry season drawdown level [m] | 140 | 155 |
| Regulated average flow in dry season [$m^3/s$] | 5130 | 5860 |

##### 2.4.3.3.1.2 Operating parameters of the power station

**Table 2.4.2.** Operating parameters of the power station.

| Item | Initial stage | Final stage |
|---|---|---|
| Installed gen. capacity of power station [MW] | 18200 | 18200 |
| Number of units | 26 | 26 |
| Unit rated capacity [MW] | 700 | 700 |
| Plant guaranteed output [MW] [1]) | 3600 | 4990 |
| Unit utilization time [h] | - | 4650 |
| Max. head (gross) [m] | 94 | 113 |
| Rated net head [m] | 80.6 | 80.6 |
| Min. head (gross) [m] | 61 | 71 |

[1]) The plant guaranteed output is defined as the monthly average output of the plant during design dry season.

#### 2.4.3.3.1.3 Probability occurrence of the various heads

The control pool level of the Three Gorges Hydroelectric Power Station (TGHP) will be at an elevation of 135 m when the first group of generating units is put into operation by the year of 2003. The control pool level will then be raised to 156 m in the initial stage in 2007 and to the normal pool level of 175 m in the final stage after 2009, respectively.

In the initial stage, with a control pool level of 135 m, the probability of the various gross heads is shown in Table 2.4.3. In the second stage, the control pool level will be at 156 m and the upstream water level will vary from 135 to 156 m. The probability of the various gross heads with a control pool level of 156 m is shown in Table 2.4.4. In the final stage, the normal pool level will be at 175 m and the upstream water level will vary from 145 to 175 m. The probability of occurrence of the various gross heads with a normal pool level of 175 m is shown in Table 2.4.5.

**Table 2.4.3.** Heads during the initial stage with a pool level of 135 m.

| Head [m] | 61-65 | 65-69 | 69-71 | 71-72 |
|---|---|---|---|---|
| Probability [%] | 2.8 | 47.8 | 48.3 | 1.0 |

**Table 2.4.4.** Heads during the second stage with a pool level of 156 m.

| Head [m] | <65 | 65-70 | 70-75 | 75-80 | 80-85 | 85-90 | 90-94 |
|---|---|---|---|---|---|---|---|
| Probability [%] | 1.7 | 28.6 | 5.8 | 4.2 | 12.5 | 14.2 | 33.0 |

**Table 2.4.5.** Head during the final stage with a pool level of 175 m.

| Head [m] | <72.5 | 72.5-75 | 75-80 | 80-85 | 85-90 | 90-95 | 95-100 | 100-105 | 105-110 | >110 |
|---|---|---|---|---|---|---|---|---|---|---|
| Probab. [%] | 0.2 | 1.8 | 28.4 | 4.8 | 1.2 | 5.3 | 10.4 | 9.7 | 30.4 | 7.8 |

#### 2.4.3.3.1.4 Power station operation modes

The TGHP is a part of the Three Gorges Project (TGP). The TGP has tremendous comprehensive benefits in terms of flood control, power generation and navigation. The reservoir regulation procedures are as follows:

- In the final stage with a normal pool level of 175 m, during the flood season from June to September, the reservoir level will be kept at the flood control limit of 145 m in order to provide sufficient margin to regulate the flood water that may possibly come from upstream. The reservoir will discharge flood water downstream as long as the sum of the flood water inflow at the dam site and the flood water inflow coming from the region between the Three Gorges and ZhiCheng (downstream of Three Gorges) is less than 56700 $m^3/s$. Otherwise, the reservoir level will be raised temporarily.
- The reservoir will begin to store water in October. In a normal year, the reservoir will store water up to a normal pool level of 175 m. From November until the end of the following April, during the dry season, the reservoir level will be kept as high as possible in order to keep the tail water high enough for navigation and to maximize the head for power generation purposes. This is in accordance with its rule to generate a higher average output than the plant's guaranteed output. If the inflow is less than the flow needed to keep up the Plant Guaranteed Output, the water stored in the reservoir will be used and the reservoir level will be drawn down progressively. At the end of April of a normal hydrological year, the reservoir level will be above the dry season drawdown level of 155 m. Only in a dry hydrological year will the reservoir level be drawn down to 155 m. The reservoir regulating mode in the initial stage will be the same as that for the final stage, except that the controlling water levels will be different.

During the flood season, the tail water levels will be high as the reservoir will be normally kept at its flood control limit level, and the dam discharges will be generous. Therefore, the heads will be low, usually less than 80 m. Otherwise, during the dry season, the tail water levels will be low and the reservoir water level will normally be high. Thus, the head will be higher, usually greater than 90 m. During the flood season, from June to September, the heads will be low. The turbines will usually operate at their maximum expected output corresponding to the available head. The power plant will supply base load and waist load. During this period, the flow passing through the turbines will contain certain amounts of sediment particles. Therefore, provisions shall be made in the design to avoid – or to reduce – the sediment wear on the turbines.

During the dry season, from November to the following April, the head will be high, and the flow passing through the turbines will contain little sediment. Thus the turbines will operate at high head and a partial to maximum output because of smaller inflow in the reservoir. During this period, special attentions should be paid to the stability of the turbine operation.

A period of the TGHP reservoir with surplus water occurs when the natural inflow at the dam site is greater than the total discharge of all 26 units. The opposite is the period without surplus water. Generally, the period of surplus water will occur in the between June and September, the rest obviously is the period without surplus water.

#### 2.4.3.3.1.5 Tail water levels

The tail water levels of the TGHP are influenced by the backwater effect of the reservoir of the Gezhouba Hydroelectric Powerstation (GHP) downstream and the combined discharge in the Yangtze River. The TGHP will be regulated by the GHP reservoir. The minimum tail water level at TGHP will be 62 m by irrigation requirement. The TGHP water levels will vary from 62 to 66 m. The tail water level at TGHP versus the discharge at the dam and the levels at GHP are listed in Table 2.4.6.

**Table 2.4.6.** Tail water levels.

| Discharge [$m^3/s$] | Water level of the upper pond of the Gezhouba dam | | |
|---|---|---|---|
| | Tail water 62 m | Tail water 64 m | Tail water 66 m |
| 5000 | 62.28 | 64.15 | 66.13 |
| 10000 | 62.50 | 64.40 | 66.35 |
| 15000 | 63.09 | 64.90 | 66.80 |
| 20000 | 63.86 | 65.51 | 67.30 |
| 30000 | 65.85 | 67.18 | 68.72 |
| 40000 | 68.01 | 69.14 | 70.51 |
| 50000 | 70.19 | 71.28 | 72.45 |
| 60000 | 72.46 | 73.40 | 74.50 |
| 70000 | 74.83 | 75.61 | 76.48 |
| 80000 | 77.03 | 77.68 | 78.43 |
| 90000 | 79.24 | 79.82 | 80.45 |
| 100000 | 81.24 | 81.80 | 82.40 |
| 110000 | 83.22 | 83.73 | 84.30 |

#### 2.4.3.3.1.6 Special requirements for the TGP turbine operation

As mentioned above, the TGP is a multipurpose project having benefits in flood control, power generation and navigation. During the flood season, the reservoir inflow from the upstream reaches is greater, and the head is low as the reservoir level is kept at flood control level. During the dry season, in order to keep the tail water high enough for navigation and to maximize the head for power generation purposes, the reservoir level will be kept as high as possible in accordance with the rules of reservoir dispatch. This results in the following special operation conditions for TGP turbines:

a) *Wide head range for the turbine:*
The TGP turbine will operate in two stages: initial and final stage. In the final stage, the head will vary from 71 to 113 m, the ratio between maximum and minimum head is 1.59. However, in the initial stage, the head will vary from 61 to 94 m. Taking both stages into account, the ratio between maximum and minimum head is up to 1.85, which is just less than the one for the Tarbela hydropower station in Pakistan ($H_{max}/H_{min} = 2.74$), equipped with units of 440 MW. So the head range for the TGP turbine is the widest of all turbines with power higher than 500 MW in the world.
b) *Long periods for the turbine to operate in a high and a low head range:*
Since the TGPH Station needs to meet the requirements of flood control and sediment flushing, the reservoir water level will be lowered down to the flood control limit level of 145 m from the normal level of 175 m before floods are coming, i.e. in later May or early June every year, and will be gradually raised from 145 m to 175 m at the end of the flood periods, i.e., in later September or early October. Therefore, the time of operation for the TGP turbine in a low head range ($H \leq 78.5$ m) and a high head range (100 m $\leq H \leq$ 113 m) will respectively account for 30 percent of the annual total operating time. Thus, the TGP turbine will have to operate in high and low head ranges, i.e. away from the optimum operating conditions, for a long time. This is quite different from ordinary hydropower stations where turbines operate at a rated head which is close to the optimum efficiency point.
c) *Frequent load variation:*
The TGPH Station will undertake frequency regulation, peak load and serve as a standby in case of an accident in the electric network, resulting in frequent load variations, starting and stopping of the units. Therefore, the TGP units are required to operate in a stable and safe way not only at high load but also at low load.

According to the special operation conditions mentioned above, it is a severe challenge for the designers of the TGP turbines to ensure the stability and safety of the turbine operation in the whole specified operation range, and furthermore ensure good energy provision and minimal cavitation.

### 2.4.3.3.2 Basic characteristics and main parameters of the turbine

#### 2.4.3.3.2.1 Type of the turbine

The type of the turbines used in TGP is a Francis turbine with a vertical shaft.

#### 2.4.3.3.2.2 Specific rating

The specified rating is 710 MW at a rated head of 80.6 m. The maximum capacity of the generator is 840 MVA and the rated power factor is 0.9. It was also initially specified that the turbine would normally be wicket gate limited to 767 MW, and an operation above this level is only permitted for limited periods.

#### 2.4.3.3.2.3 Optional speed

The optional speed of the turbine at the rated turbine output of 710 MW and the rated head of 80.6 m is 71.4 rpm or 75 rpm, corresponding to a specific speed of 249 m-kW and 261.7 m-kW, respectively. The studies for the two optional speeds mentioned above are

- parameters of the turbine,
- performances, especially hydraulic stability,
- size, weight and cost of unit,
- generator design.

Analyzing all the above mentioned factors, the final speed of the TGP turbine was determined to be 75 rpm.

#### 2.4.3.3.2.4 Cavitation coefficient and setting

The cavitation characteristics of the turbine directly influence the safety of the unit operation and the economics of the power station. Usually, they are evaluated with a cavitation coefficient: the smaller the value of the coefficient, the better the cavitation characteristics of the turbine and the higher the setting of the turbine; thus, it can lower the cost of civil construction.

Due to the requirements of the TGP construction schedule, the setting of the turbine had to be determined before the bidding for it. Using the Thomas cavitation coefficient versus the specific speed and taking into account the values for cavitation coefficients that were recommended by domestic and overseas manufacturers for the TGP turbine, the minimum plant cavitation coefficient at the runner outlet was decided to be 0.186. The minimum downstream tail water level of the TGP is 62.0 m, thus it derives the setting of the turbine at the centerline elevation of the distributor at 57.0 m. The results of the model test of the TGP turbines show that the safety factor of the initial cavitation coefficient $K_i$, which is the ratio of the plant cavitation coefficient and the initial cavitation coefficient, varies between 1.0 and 1.82 in the specified operation range. This implies that the TGP turbine will operate without cavitation in the whole specified range.

#### 2.4.3.3.2.5 Operational range

According to the characteristics of the TGHP station, the specified field of operation of the TGP turbines is given in Fig. 2.4.2, where the various regions of operation are:

I. *Normal operation:*
The turbine shall be capable of a stable and safe long-term operation in the following ranges:
   A. For net heads less than the rated net head $H_r$ = 80.6 m and for outputs from 70 to 100% of the maximum expected output at that head.
   B. For net heads from 80.6 m to the minimum net head $H_{767}$ required for producing an expected output of 767 MW, and for outputs from 497 MW to 100% of the maximum expected output at that net head.
   C. For net heads from $H_{767}$ to $H_{max}$ = 113 m and for outputs from 497 MW to 767 MW.

II. *Overload operation:*
This range was specified to be at a turbine output higher than 767 MW. Operation in this region has a time restriction. According to the contract, the operating time of the turbines in the overload region shall not exceed 100 hours within the guarantee period of 8000 hours.

III. *No load and other operational region:*
It is specified that the operating time for the output range between no-load and the minimum output for continuous operation at the corresponding net head shall be not more than 800 hours.

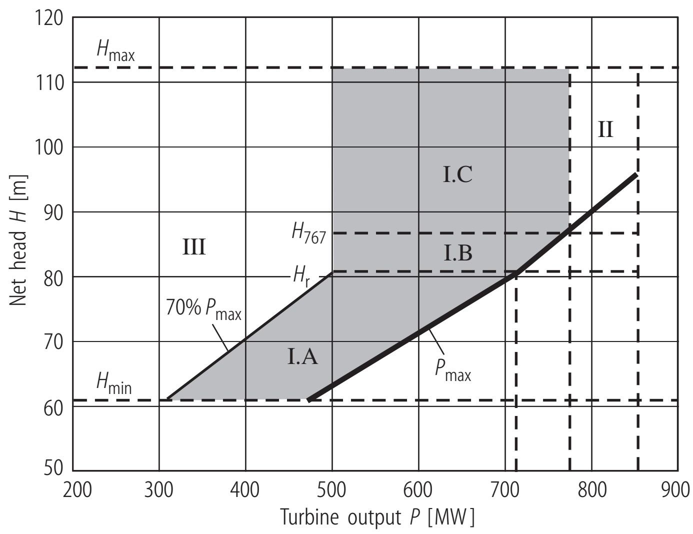


**Fig. 2.4.2.** Sketch of the various regions of operation of the TGP turbine.

### 2.4.3.3.2.6 Turbine efficiency and energy production

The efficiency is an important index to evaluate the energy performance of the turbine and it directly influences the results of power generation of a hydropower station. Especially for the TGP with its large units, a total capacity of 18200 MW and a total annual energy production of 84.7 TWh, the loss of annual energy production will be up to 0.423 TWh if the weighted average efficiency is reduced by only 0.5%. So the efficiency of the TGP turbine is worth to be concerned about.

To ensure the overall efficiency of the unit, the part of the penstock downstream of the expansion joint from the spiral inlet to 13.2 m upstream of the centerline of the units was made part of the turbine contract and was included in the turbine efficiency guarantee. The turbine efficiency was investigated using characteristic curves of turbines of the same specified speed as the TGP turbines. According to the TGP unit operation mode, these studies resulted in requirements for the maximum efficiency and the rated efficiency of the turbine:

- As the turbine operates in the high and low head during 70% of the year and operates in the near rated head of 80.6 m very shortly (about 7 days a year), the rated efficiency of the turbine at a net head of 80.6 m and 710 MW was not specified.
- The weighted average efficiency and the maximum efficiency of the model and prototype of the TGP turbine shall be greater than 93.1% and 95.3%, respectively.

According to the model test, the efficiency of the turbine prototype was calculated by the formula in accordance with the IEC Publication 995 (1991). The results are compared with the guarantee values as shown in Table 2.4.7.

**Table 2.4.7.** Guarantee, measured and predicted efficiency for the turbine prototype.

| | Weighted av. efficiency [%] | | Rated efficiency [%] | | Maximum efficiency [%] | |
|---|---|---|---|---|---|---|
| | predicted | guarantee | predicted | guarantee | predicted | guarantee |
| ALSTOM | 93.96 | 93.89 | 91.15 | - | 96.27 | 96.26 |
| VGS | 94.39 | 94.10 | 90.47 | - | 96.80 | 96.26 |

The weighted average efficiency $\eta_{cp}$ was calculated by the formula

$$\eta_{cp} = \sum_i W_i \, \eta_i / 100 \, ,$$

with $\eta_i$ the average efficiencies at the operation point that corresponds to the weighted efficiency factor $W_i$, as shown in Table 2.4.8. According to the characteristics of the TGP power station (see Fig. 2.4.3), the formula for evaluating the annual energy production of the turbine is:

- Energy production $E_1$ during the period of reservoir without surplus water is

$$E_1 = \mathrm{k} \cdot \eta_{cp} \, ,$$

where k = 2.648 TWh.

- The annual average energy production $E_2$ during the period with surplus water is

$$E_2 = \sum_i t_i P_i \, ;$$

$t_i$ is a time factor and $P_i$ is the turbine maximum output at a net head greater than 78.5 m.

- The formula for calculating the total annual energy production $E$ of the turbine is

$$E = E_1 + E_2 \, .$$

**Table 2.4.8.** Weighted efficiency factors $W_i$ for different power rates.

| Head $H$ [m] | 60% Power | 70% Power | 80% Power | 90% Power | 100% Power | 108% Power (767 MW) |
|---|---|---|---|---|---|---|
| 110 | 0.15 | 0.60 | 2.92 | 5.36 | 9.08 | 1.78 |
| 105 | 0.25 | 0.77 | 3.14 | 6.11 | 9.95 | 2.08 |
| 98 | 0.10 | 0.28 | 1.36 | 3.08 | 6.68 | 1.22 |
| 89.4 | 0.08 | 0.20 | 1.10 | 2.85 | 7.32 | 1.45 |
| 80.6 | 0.05 | 0.82 | 2.62 | 6.43 | 3.30 | - |
| 78.5 | - | 1.50 | 3.57 | 13.80 | - | - |

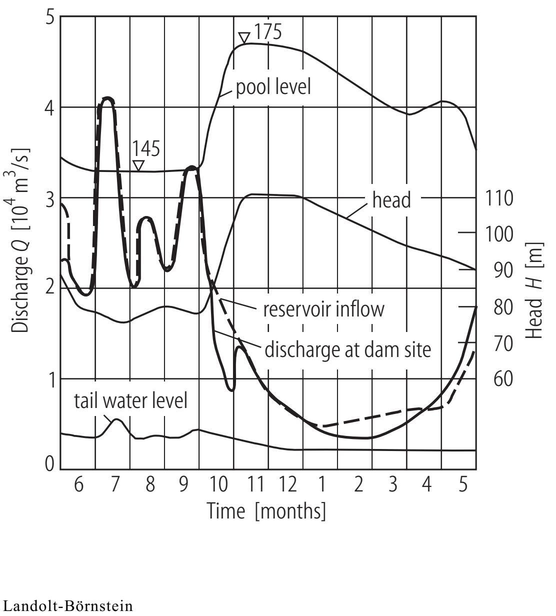


**Fig. 2.4.3.** Pool and tail water level, head vs. discharge for the Three Gorge Hydro Power Station.

#### 2.4.3.3.2.7 Cavitation damage

The allowable loss of metal of the runner, stay ring, wicket gate, bottom ring, discharge ring and draft tube, resulting from cavitation over the first 8000 hours from the date the turbine is placed in commercial operation (or two years, whichever occurs first), was specified to be smaller than 52 kg. The depth of pitting shall not exceed 10 mm and any continuously damaged area shall not to be larger than 0.5 $m^2$. Within the guarantee period, the operating time for the output range between no-load and minimum output for continuous operation at the corresponding net head shall be not more than 800 hours, while the operating time for the output greater than 767.0 MW shall be not more than 100 hours.

#### 2.4.3.3.2.8 Cracking guarantee of the runner

Because of the fact that cracks occurred in the turbine runners in domestic and overseas power stations due to turbine design and/or manufacture quality, it was specified in the contract that no cracks were to occur for a guaranteed period. In addition, it was also specified that potential cracks will be detected by ultrasonic, magnetic particle and/or dye penetrant testing, and the acceptance standard shall be the same as used for the manufacture of the runner. In case of cracks in the runner within the guarantee period, the manufacturer shall repair the damaged area in site free of charge and the guarantee period will recommence after completion of the repair work. If cracks requiring repair are still found in the runner within 24000 operating hours, the owner has the right to reject the runner and the manufacturer shall supply a new runner free of charge.

#### 2.4.3.3.3 Model tests

Fourteen Francis turbines for the TGP left bank power station were purchased in an international bidding. Eight turbines were awarded to the French company ALSTOM HYDRO, the hydraulic design and turbine model test was undertaken by the Norwegian company Kvaerner Energy Company. The other six turbines were awarded to the VGS Consortium, comprising Voith, GE Canada and Siemens. According to the specification in the contract, the model tests witnessed by the owner were conducted in the manufacturer’s laboratory, the Kvaerner Energy Hydraulic Laboratory in Trondheim and Voith Hydraulic Laboratory in Heidenheim/Germany in July 1998 and August 1998, respectively. In order to further improve the hydraulic stability of the turbine, supplementary research and tests were done by the two suppliers and also witnessed by the owner. The following parameters had to be verified by model tests according to the contract specifications:

- *Optimum efficiency:* Ten tests were conducted for the optimum efficiency point to obtain an optimum efficiency of the model turbine as the mean value of ten measurements;
- *Weighted average efficiency:* Every one of the specified thirty-six points (including the rated point) with weighted factor $W_i$ was tested three times each and the mean value was regarded as the turbine efficiency at this condition point;
- *Cavitation characteristics:* In order to fully check the cavitation characteristics of the TGP turbine, another nine test conditions were added to the model witness test besides the test conditions specified in the contract. These conditions cover the whole operating range with a head from 67 m to high head of 110 m and an output from 300 to 852 MW;
- *Hydraulic stability:* Including incipient channel vortex and developed channel vortex line, pressure fluctuations of the draft tube, the spiral case and the vane-less space between wicket gate and runner. The tests put an emphasis on the pressure fluctuation at high part load;
- Hydraulic thrust;
- Air admission test;

- *Output guarantees:* The guaranteed turbine output at 63, 67, 78.5 and 80.6 m specified in the contract had to be verified;
- Energy converted from model test.

The test head was specified to be 30.0 m except in the runaway speed test. The main findings of the model tests are listed in the following sections.

### 2.4.3.3.3.1 Efficiency and output

The values of the model efficiency evaluated from the head, flow and torque measurements are given in Table 2.4.7. The conversion of the model to the prototype efficiency was calculated in two steps in accordance with the IEC Publication 995 (1991):

- Transferring the model efficiencies $\eta_{\mathrm{hMi}}$ (measured at different test points with Reynolds numbers $Re_{\mathrm{uMi}}$) into a constant Reynolds Number $Re_{\mathrm{uM*}}$ of the model:

$$\Delta\eta_{\mathrm{hMi}\to\mathrm{M*}} = \delta_{\mathrm{ref}}\left[\left(\frac{Re_{\mathrm{uref}}}{Re_{\mathrm{uMi}}}\right)^{0.16} - \left(\frac{Re_{\mathrm{uref}}}{Re_{\mathrm{uM*}}}\right)^{0.16}\right],$$

$$\delta_{ref} = \left(1-\eta_{\mathrm{hoptM}}\right) / \left[\left(\frac{Re_{\mathrm{uref}}}{Re_{\mathrm{uoptM}}}\right)^{0.16} + \frac{1-V_{\mathrm{ref}}}{V_{\mathrm{ref}}}\right].$$

- Scaling-up the transferred model efficiencies to prototype conditions: To scale up the model efficiencies $\eta_{\mathrm{hM*}}$ already referring to the constant Reynolds number $Re_{\mathrm{uM*}}$ to a prototype Reynolds number $Re_{\mathrm{up}}$, the following formula applies:

$$\Delta\eta_{\mathrm{hM*}\to\mathrm{p}} = \delta_{\mathrm{ref}}\left[\left(\frac{Re_{\mathrm{uref}}}{Re_{\mathrm{uM*}}}\right)^{0.16} - \left(\frac{Re_{\mathrm{uref}}}{Re_{\mathrm{up}}}\right)^{0.16}\right].$$

The efficiency of the prototype turbine is then given as

$$\eta_{\mathrm{p}} = \eta_{\mathrm{hMi}} + \Delta\eta_{\mathrm{hMi}\to\mathrm{M*}} + \Delta\eta_{\mathrm{hM*}\to\mathrm{p}},$$

where

| | |
|---|---|
| $\delta_{\mathrm{ref}}$ | convertible loss rate; |
| $Re_{\mathrm{u}} = \frac{\pi}{60}\frac{n \cdot D^2}{\nu}$ | Reynolds number; |
| $\nu$ | kinematic viscosity; |
| $Re_{\mathrm{uref}} = 7 \cdot 10^6$ | reference Reynolds number; |
| $\eta_{\mathrm{hoptM}}$ | optimal hydraulic efficiency of the model; |
| $V_{\mathrm{ref}} = 0.7$ | distribution factor of loss corresponding to $Re_{\mathrm{uref}}$; |
| $D$ | runner nominal diameter,<br>subscript P refers to prototype;<br>subscript M refers to model; |
| $n$ | shaft speed in [rpm]. |

The predicted prototype efficiency calculated by this formula is shown in Table 2.4.7. The model results also demonstrated that the guaranteed values of the output at the specified heads could be met.

#### 2.4.3.3.3.2 Cavitation

The results of model tests for the initial cavitation coefficient $\sigma_i$ and the plant cavitation coefficient $\sigma_p$ at the main operating condition points are shown in Table 2.4.9. Generally speaking, a margin factor $K_i = \sigma_p/\sigma_i$ greater than 1.0 basically allows an operation of the turbine without cavitation. As seen in Table 2.4.9, the factor $K_i$ is acceptable, so it can be predicted that the TGP turbines will operate without cavitation in the whole specified operation range.

#### 2.4.3.3.3.3 Operating stability

The factors affecting the operating stability of the turbine are complicated, including electromagnetic, mechanic and hydraulic factors of which the hydraulic factors are the key factors. Draft tube pressure fluctuations are experienced in all Francis turbines operating other than at the optimum efficiency point. In the past, the main concern had been at partial loads, but in recent turbines, problems have occurred at high outputs close to the optimum efficiency point, exhibiting high amplitude and frequency of the pressure fluctuation, and it may lead to resonance with the structure of powerhouse. Therefore, detailed test were done to find special pressure fluctuations in the model witness test of the TGP turbine. The main findings are as follows:

1) *Stable operating range of the turbine, channel vortex and cavitation limit*
The stable operating range, the incipient channel vortex line, the developed channel vortex, the incipient cavitation line for the inflow edge in the pressure side and the incipient cavitation line for the inflow edge in the suction side observed in the model tests are shown in Fig. 2.4.4 and Fig. 2.4.5. It is clearly specified in the contract that the incipient channel vortex does not lie in the specified normal operating range. The incipient channel vortices are defined as visual vortices occuring simultaneously in 3 channels between the blades when operating conditions are changed. From Fig. 2.4.4 and Fig. 2.4.5, we can see:

   - The developed channel vortex line occurs beyond the specified operating range, so it can be predicted that a high frequency vibration due to the channel vortex will not occur as long as the TGP turbines operate in the normal range.
   - There is no inlet cavitation in the specified operating range, i.e. the incipient cavitation line for the inflow edge in the pressure side and the incipient cavitation line for the inflow edge in the suction side are outside of the specified operating range. It can be predicted that there will be no cavitation for the TGP turbines in the whole specified operation range.

**Table 2.4.9.** Initial cavitation coefficient $\sigma_i$ and plant cavitation coefficient $\sigma_p$; reference level of cavitation is at the centerline of the distributor.

| No. | Conditions | | | Plant $\sigma_p$ | Initial cavitation $\sigma_i$ | | $K_i = \sigma_p / \sigma_i$ | |
|---|---|---|---|---|---|---|---|---|
| | Head $H$ [m] | Power $P$ [MW] | Tail water level [m] | | ALSTOM | VGS | ALSTOM | VGS |
| 1 | 67 | 426 | 68 | 0.31 | 0.270 | 0.253 | 1.14 | 1.23 |
| 2 | 75.5 | 639 | 68 | 0.275 | 0.238 | 0.160 | 1.16 | 1.72 |
| 3 | 80.6 | 710 | 62 | 0.184 | 0.184 | 0.151 | 1.0 | 1.20 |
| 5 | 110 | 767 | 62 | 0.135 | 0.093 | 0.085 | 1.45 | 1.59 |
| 6 | 110 | 710 | 62 | 0.135 | 0.074 | 0.068 | 1.82 | 1.98 |
| 7 | 110 | 639 | 62 | 0.135 | 0.09 | 0.061 | 1.50 | 2.20 |
| 8 | 110 | 497 | 62 | 0.135 | 0.106 | 0.0689 | 1.27 | 1.96 |

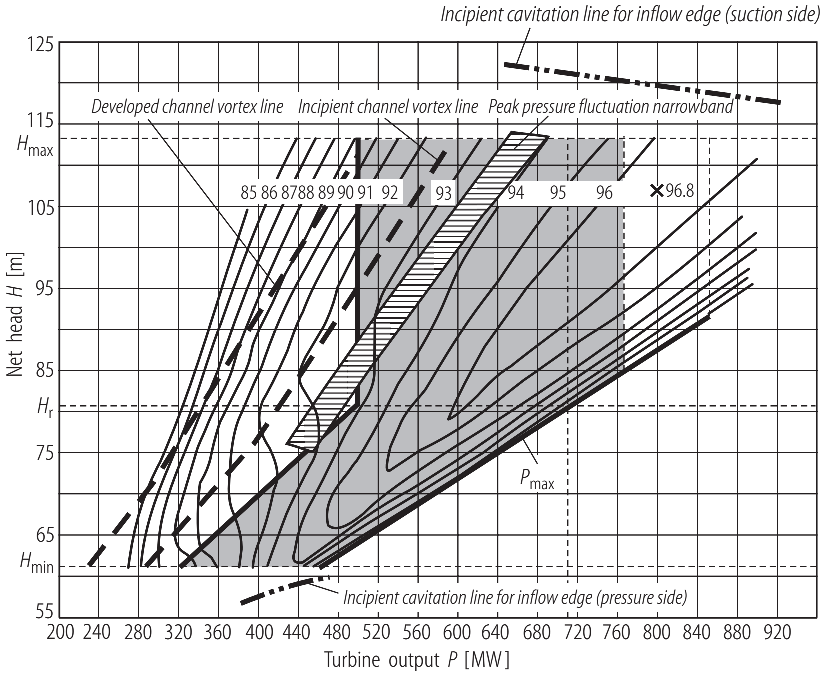


**Fig. 2.4.4.** Predicted characteristic curve of the TGP turbine for the units No. 1-3 and No. 7-9 with $H_r$ = 80.6 m, $P_r$ = 710 MW, $D_M$ = 9.4 m and $n$ = 75 rpm.

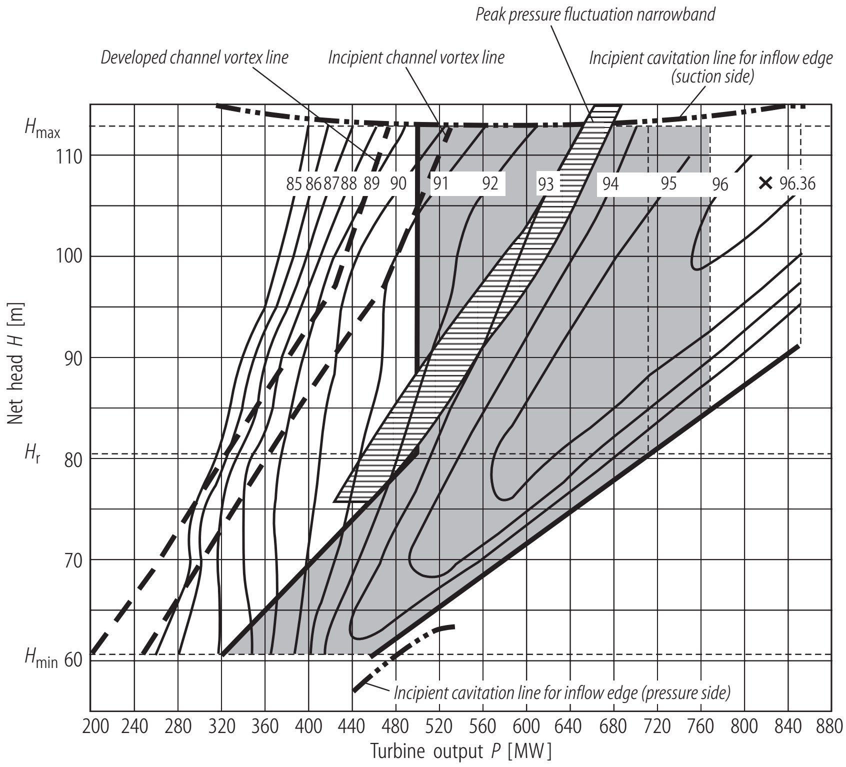


**Fig. 2.4.5.** Predicted characteristic curve of the TGP turbine for the units No. 4-6 and No. 10-14 with $H_r$ = 80.6 m, $P_r$ = 710 MW, $D_M$ = 9.8 m and $n$ = 75 rpm.

2) *Pressure fluctuations and peak pressure fluctuation narrowband*
In order to find out the pressure fluctuations along the whole water passage, the measured points were arranged from the inlet of the spiral case to the outlet of the draft tube elbow as follows:

- Spiral case inlet (casing);
- Head between wicket gates and runner (vane-less space);
- Tail and head water side of the draft tube cone located at a distance of 0.3×runner discharge diameter below the runner outlet;
- Draft tube elbow headwater side;
- Draft tube elbow tail water side.

The conditions for the pressure fluctuations cover the normal operating range. To be in accordance with the conditions of the prototype's actual operation, the cavitation reference level for pressure fluctuation tests was specified to be at the centerline of the distributor and the tests were conducted considering the plant's cavitation coefficient $\sigma_p$.
The results of the model test show that there exists a peak pressure fluctuation narrowband in the specified operating range, shown in Fig. 2.4.4 and Fig. 2.4.5. Peak pressure fluctuation means that the amplitude of the pressure fluctuations of each measured location reaches a maximum value in this narrowband which is about twice the amplitude of pressure fluctuations nearby the narrowband, and the frequency of the pressure fluctuations is higher than the rotational speed for the turbine model. In addition, the peak pressure fluctuation narrowband skews the high output with an increase of the head and is close to full load at a head of 110 m. The pressure fluctuations of other conditions except in the narrowband are at normal level, such as the peak to peak amplitude $\Delta H/H$ of pressure fluctuations at an output greater than 70% of the rated output in the whole operating range which is 5-6%.
The pressure fluctuation phenomena in the narrowband mentioned above are likely to cause resonance with the powerhouse structure. This already occurred in the Yantan hydropower station in China and resulted in serious problems in the turbines. However, up to now, research on the mechanisms of the above phenomena and the relation between the prototype and the model turbine are still on an experimental stage. Although the phenomena occurring in the model turbine do not automatically imply that they will occur in the prototype of the TGP turbine as well, it is necessary to extensively investigate the vibration problem in the narrowband and the measures to mitigate the vibration in order to avoid resonances induced by pressure fluctuations.

#### 2.4.3.3.3.4 Hydraulic thrust

The hydraulic thrust measured on the model hydrostatic bearing required corrections when transferred to the prototype values. After these corrections, the maximum hydraulic thrust measured on the model and converted to the prototype are as follows:

- ALSTOM: 1900 t (measured), 2250 t (guarantee);
- VGS: 1380.9 t (measured), 1440 t (guarantee);

### 2.4.3.3.4 Structure of main parts

#### 2.4.3.3.4.1 General arrangement

The TGP turbine is of a vertical-shaft Francis type. The shaft of the turbine is connected to the shaft of the semi-umbrella generator. The unit is equipped with three guide bearings, i.e. an upper guide bearing above the generator rotor, a combined thrust bearing and a lower guide bearing below the rotor as well as guide bearing of the turbine. The thrust bearing is supported on the lower bracket of the generator. The general arrangement layout of unit is shown in Fig. 2.4.6 and Fig. 2.4.7.

#### 2.4.3.3.4.2 Stay ring

The stay ring consists of top and bottom ring-shaped members, rigidly connected with 24 stay vanes. The members are made of good-grape tear-resistant steel plates and welded together. The stay ring is split in 6 sections which will be welded together at site. The main parameters and dimensions of the stay ring are listed in Table 2.4.10.

#### 2.4.3.3.4.3 Spiral case

The spiral case is constructed of welded plate steel. Segments of the spiral case are rolled and welded at the factory. The segments are required to be welded to form sections before delivery. The inlet diameter of the spiral case is 12.4 m and the wrap of the spiral case is 345°. According to a proposal of the specialist's review, the spiral case is not necessary for the conduction of a field hydrostatic pressure test; however, it shall be embedded under pressure. The water pressure for embedding the spiral case shall be 70 m $H_2O$ and its temperature between 16 and 22°C. The main parameters and dimensions of the spiral case are listed in Table 2.4.11.

**Table 2.4.10.** Main parameters and dimensions of the stay-ring.

| Supplier | Outer diameter [mm] | Height [mm] | Weight [t] | Material of top and bottom ring-shaped members | Thickness of top and bottom ring-shaped members [mm] | Number of stay vane |
|---|---|---|---|---|---|---|
| ALSTOM | 15670 | 4640 | 390 | S355J2G3/Z35 | 230 | 24 |
| VGS | 14492 | 4755 | 382 | A516M Gr.485 | 190 | 24 |

**Table 2.4.11.** Main parameters and dimensions of the spiral case.

| Supplier | Material | Inlet diameter [mm] | Max. thickness of plate [mm] | Number of sections | Trimming joints | Total weight [t] |
|---|---|---|---|---|---|---|
| ALSTOM | 610U2 | 12400 | 53 | 29 | 4 | 755 |
| VGS | 610U2 | 12400 | 56 | 29 | 2 | 739.7 |

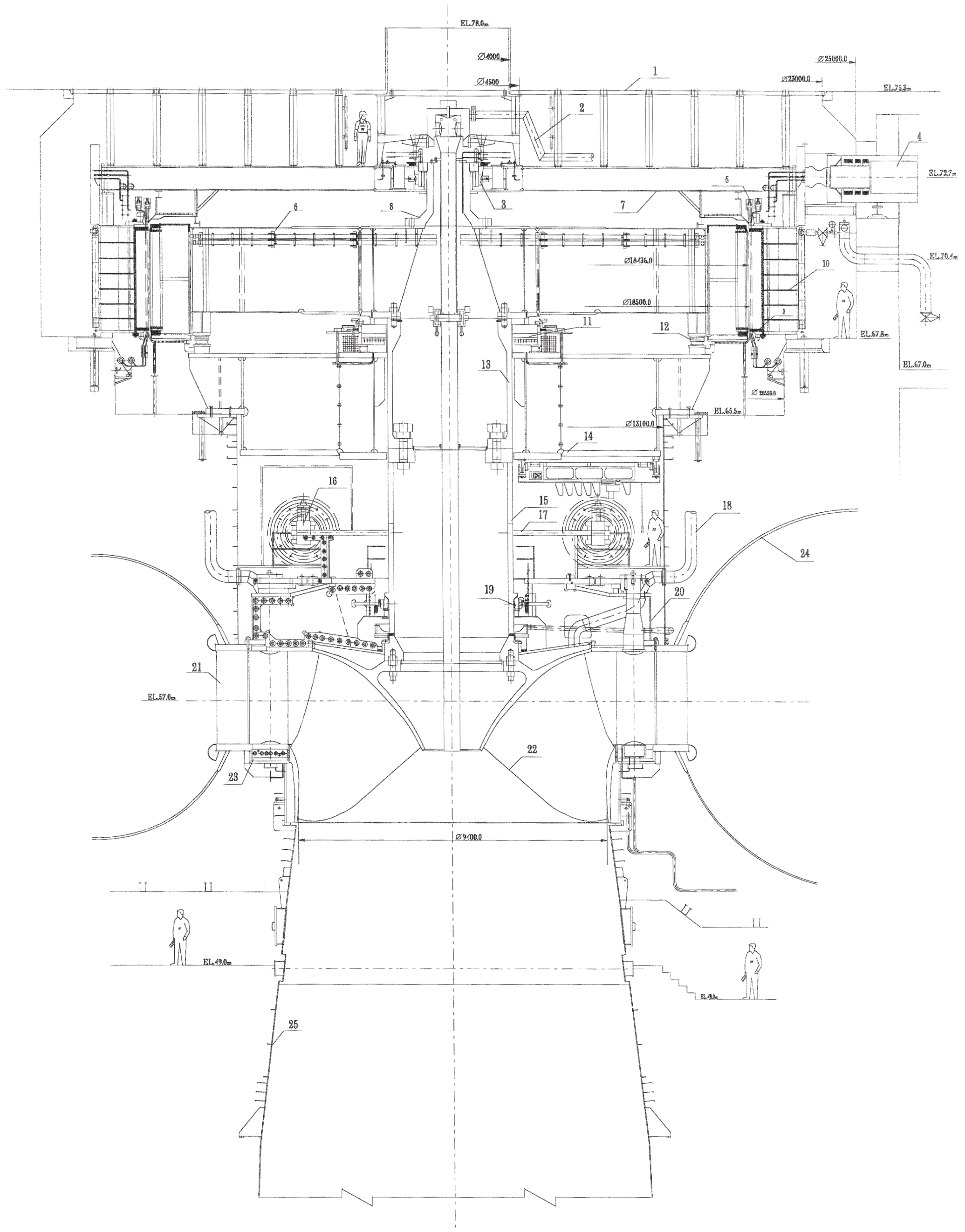

**Fig. 2.4.6.** General structure and cross section of the TGP units No. 1-3 and No. 7-9.

1. Generator top cover
2. Air admission pipe
3. Upper guide bearing
4. Main leads
5. Stator winding
6. Rotor arm
7. Upper bracket
8. Generator upper shaft
9. Stator core
10. Stator frame
11. Combined thrust and lower guide bearing
12. Braking cylinder
13. Generator lower shaft
14. Lower bracket
15. Turbine shaft
16. Server motor
17. Operating ring
18. Head cover relief pipe
19. Turbine guide bearing
20. Head cover
21. Stay ring
22. Runner
23. Bottom ring
24. Spiral case
25. Draft tube

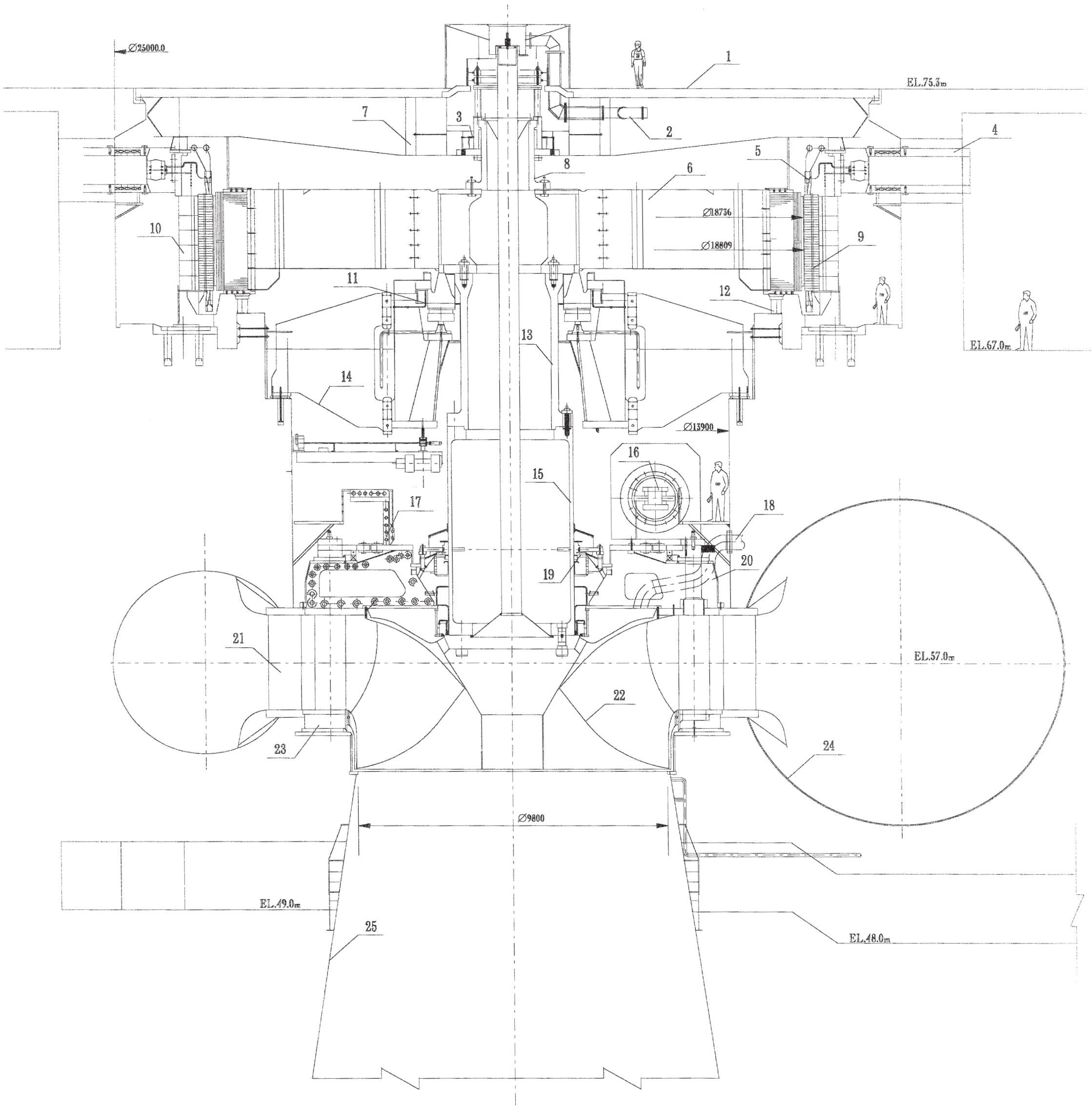


**Fig. 2.4.7.** General structure and cross section of unit No. 4-6 and No. 10-14. Designation of the numbers same as in Fig. 2.4.6.

### 2.4.3.3.4.4 Gate operating mechanism

The gate operating mechanism consists of 24 guide vanes made of stainless steel. Each gate shall be supported in 3 self-lubricated guide bearings of proven design, one located in the bottom ring and two in the head cover. Operating the gate is realized by two oil pressure operated, double-acting hydraulic cylinder type servomotors, which are located inside the turbine pit. Oil for operating the servomotors is supplied from the governor hydraulic pressure oil system with a rated operating pressure of 6.3 MPa.

In order to prevent the wicket gates from swinging when shear pins are sheared, friction devices are set between the wicket gates and the connecting rods. When the gate operating mechanism is working well, the operating force of the servomotor will be transferred to the wicket gates by shear pins together with the friction devices and make the wicket gates synchronously run. When the shear pins are sheared, the connecting rods and the guide-blade arms will slide against each other to guarantee that the force acting on the connecting mechanism does not increase and thus protect the connecting mechanism.

#### 2.4.3.3.4.5 Runner and connection between runner and main shaft

The runner is made of welded stainless steel cast, i.e. the crown, the blades and the band are manufactured individually, welded together to form a runner and then transported to the site. The complete runner is made of very well weldable ASTM A743 Gr.CA-6NM stainless steel to protect it against cavitation erosion and wear. The crown is made of welded steel cast. The blades are manufactured with a 5-axis numerically controlled machine tool to guarantee the quality and precision of the blade shape and the flow-passing parts. The band is made of steel cast or rolled from steel plate. The main parameters and dimensions of the runner are listed in Table 2.4.12.

The blade shape of the runner determines the main performances of the runner to some extent. The two suppliers both take the X-shaped blades whose inlet edge has a negative blade leaning angle and whose outlet edge is a skewed outlet. Looking from the runner inlet, the blades look like X-shaped. Compared to an ordinary blade shape, X-shaped blades can better adapt to the characteristics of a wide head and a wide load range. The runner cone and the wearing ring are manufactured in a different way by the suppliers according to their techniques and practice. On the VGS runner, the cone is concealed due to the long crown when the X-shaped blades are adopted. ALSTOM uses a long semi-cone runner cone with a diameter of 2.044 m. It is about 2.5 m long and good for improving the turbine's stability.

In order to guarantee the interchange of the runner, the turbine shaft is connected to the runner provided through 28 bolts of M160 and a shear sleeve with a diameter of 280 mm in the case of VGS. The tightening force of the bolts is 8500 kN. The runner and the shear sleeve can be interchanged among different units. ALSTOM chose the way of bolts and pins. The tightening force here is 180 MPa and the length of tension is about 0.7 mm. The bolt holes in the flanges of the main shaft and the runner do not necessarily have to be manufactured at site, they were made by high precision templates in the factory.

#### 2.4.3.3.4.6 Bottom ring and head cover

The head cover and the bottom ring are made of welded plate steel with an adequate rigidity. In accordance with the shipping limitations, they are divided into four parts when transported to the site and connected by bolts. In order to decrease the water pressure in the space between the runner and the head cover as well as the downwards water thrust force acting on the runner, 4 (ALSTOM), respectively 8 (VGS), large-caliber relief pipes are installed from the head cover extend to the draft tube diffuser. The main parameters and dimensions of the head cover are listed in Table 2.4.13.

Stationary wearing rings on the head cover and the bottom ring are fixed on the sectional head cover and the bottom ring by radial bolts in the shop. After the wearing rings are assembled at the site, welding will be performed on the parting of wearing rings. The head cover and the bottom ring are separately attached to the flange faces of the upper and lower rings of the stay ring. Assembled at the site, independent pads arranged on the flange faces of the upper and lower rings of stay ring are used to adjust the elevation of the head cover. The sealing face of the stay ring is required to be cut and grinded at site.

**Table 2.4.12.** Main parameters and dimensions of the runner.

| Supplier | Nominal diameter $D_2$ [mm] | Throat diameter [mm] | Number of blades | Height [mm] | Material | Total weight [t] |
|---|---|---|---|---|---|---|
| ALSTOM | 9800 | 9800 | 15 | 5062 | A743 Gr.CA-6NM | 445 |
| VGS | 9525 | 9400 | 13 | 5401 | A743 Gr.CA-6NM | 434 |

**Table 2.4.13.** Main parameters and dimensions of the head cover.

| Supplier | Material | Outer diameter [mm] | Height [mm] | Number of parts | Total weight [t] |
|---|---|---|---|---|---|
| ALSTOM | GB Q235C | 13670 | 3100 | 4 | 380 |
| VGS | GB Q235C | 12720 | 2267 | 4 | 300 |

#### 2.4.3.3.4.7 Turbine shaft and shaft seal

The main shaft consists of two shafts, the turbine and the generator shaft. The turbine shaft is hollow with inside flange connections and a support for the guide bearing. It is made of carbon or alloy steel suitable for heat treatment and shall be fabricated from weldments of forging steel. The turbine shaft is connected to the generator shaft at the top and connected to the runner at the bottom. The shaft seal consists of a service and a maintenance seal. In the design of the shaft service seal by ALSTOM, the seal set connects with a horizontal supporting plate in order to seal by friction. The supporting plate, made of stainless steel, is divided into 6 sections and fixed on the upper flange surface of the runner. A spring allows the supporting plate of the shaft seal to move up or down, balancing out the dynamic water pressure acting on the shaft seal. The structure of the shaft service seal designed by VGS is of radial type, lubricated and cooled by water. The main water resource is the clean water system in the power station with a water pressure varying from 0.2 to 0.5 MPa. Whenever the shaft seal needs a higher pressure, 2 booster pumps (one service and one standby) are installed in order to provide sufficient pressure. To check, adjust and change the service seal set, one does not need to dismantle the main shaft, the guide bearing of the turbine, the gate operating mechanism, the piping system and the drainage measure in the pit. Below the service seal, an air inflatable rubber seal ring is installed to prevent the water from entering the head cover while the unit is at standstill. The compressed air with a pressure varying from 0.5 to 0.8 MPa for maintaining the seal is supplied by the ventilation system in the power station.

#### 2.4.3.3.4.8 Air admission system

An air admission system was equipped by both suppliers to allow atmosphere air to go through the connection at the top of the upper generator shaft to the space below the runner as required for smoothing a part-load or overload operation. While the pressure at the runner is below setting value, the air admission valve installed on the upper shaft of the generator will open automatically and let air in. In case of a failure of the air admission valve and the tail water level gets above the seal surface of the air admission valve, the labyrinth and the drain pipe will conduct water to the gallery at 44.0 m in order to prevent water from entering into generator. In addition, the head cover, bottom ring and discharge ring were provided with an admission piping in order to allow compressed air to come through, but only if it becomes absolutely necessary. These pipes were all extended to the downstream auxiliary station at elevation 61.24 m. Additionally, ALSTOM equipped the draft tube cone with admission piping.

### 2.4.3.4 Generator

#### 2.4.3.4.1 Main parameters and performance of the generator

Parameters of the generator represent the level of technology in terms of generator design and manufacture. They directly influence the safe and economic operation of the electric power system, the price of the generator and the selection of electric equipment connected with the generator main circuit. When determining generator parameters, it should first be emphasized that the parameters are optimized comprehensively because they are interrelated with each other. It should be avoided to try to optimize individual parameters. Secondly, a balance of advanced technical parameters and reasonable cost of the generator should be achieved, which means determining the parameters based on the present technical possibilities in design and manufacture. One-sided stressing of good parameters will lead to increasing difficulties in manufacture and cost of the generator. Parameters of the TGP generators are determined based on the principles mentioned above and are specified in bidding documents of the generator including parameters such as generator capacity, rated voltage, power factor, efficiency, direct-axis transient reactance, direct-axis subtransient reactance, short-circuit ratio, generator flywheel effect etc. The main parameters and performance of ALSTOM and VGS generators are listed in Table 2.4.14.

**Table 2.4.14.** Main parameters and performance of the TGP turbines.

| | ALSTOM | VGS |
|---|---|---|
| Rated capacity [MVA] / rated power [MW] | 777.8 / 700 | 777.8 / 700 |
| Maximum capacity [MVA] /maximum power [MW] | 840 / 756 | 840 / 756 |
| Phase-leading capacity with rated output [Mvar] | 339 | 339 |
| Phase-leading capacity with maximum output [Mvar] | 366 | 366 |
| Rated voltage [kV] | 20 | 20 |
| Rated current [A] | 22453 | 22453 |
| Maximum current [A] | 24249 | 24249 |
| Rated power factor (lagging) | 0.9 | 0.9 |
| Power factor at maximum capacity (lagging) | 0.9 | 0.9 |
| Rated frequency [Hz] | 50 | 50 |
| Rated speed [rpm] | 75 | 75 |
| Runaway speed [rpm] | 150 | 150 |
| Generator flywheel effect $GD^2$ [t-$m^2$] | 450000 | 450000 |
| Temperature of stator winding [°C] | 65 | 65 |
| Temperature rise of field winding [°C] | 75 | 75 |
| Temperature rise of stator core [°C] | 60 | 60 |
| Guaranteed efficiency at rated capacity[%] (with copper loss reference temperature of 90°C) | 98.77 | 98.75 |
| Guaranteed efficiency at maximum capacity [%] (with copper loss reference temperature of 90°C) | 98.76 | 98.75 |
| Guaranteed weighted average efficiency [%] (with copper loss reference temperature of 90°C) | 98.76 | 98.74 |
| Rated field voltage [V] | 475.9 | 390 |
| Maximum field voltage [V] | 497.1 | 404 |
| Rated field current [A] | 4158 | 3779 |
| Maximum field current [A] | 4345 | 3940 |
| Direct-axis synchronous reactance Xd at rated capacity (unsaturated/saturated per unit values) | 0.939/0.835 | 0.97/0.88 |
| Direct-axis synchronous reactance Xd at maximum capacity (unsaturated/saturated per unit values) | 1.014/0.902 | 1.05/0.95 |
| Quadrature-axis synchronous reactance Xq at rated capacity (unsaturated/saturated per unit values) | 0.690/0.648 | 0.74/N.A. |
| Quadrature-axis synchronous reactance Xq at maximum capacity (unsaturated/saturated per unit values) | 0.745/0.700 | 0.80/N.A. |
| Direct-axis transient reactance Xd′ at rated capacity (unsaturated/saturated per unit values) | 0.315/0.295 | 0.32/0.30 |
| Direct-axis transient reactance Xd′ at maximum capacity (unsaturated/saturated per unit values) | 0.340/0.319 | 0.35/0.32 |

| | ALSTOM | VGS |
|---|---|---|
| Quadrature-axis transient reactance Xq′ at maximum capacity (unsaturated/saturated per unit values) | 0.745/0.700 | N.A. |
| Direct-axis subtransient reactance Xd″ at rated capacity (unsaturated/saturated per unit values) | 0.240/0.200 | 0.22/0.20 |
| Direct-axis subtransient reactance Xd″ at maximum capacity (unsaturated/saturated per unit values) | 0.259/0.216 | 0.23/0.21 |
| Quadrature-axis subtransient reactance Xq″ at rated capacity (unsaturated/saturated per unit values) | 0.277/0.260 | 0.28/N.A. |
| Quadrature-axis subtransient reactance Xq″ at maximum capacity (unsaturated/saturated per unit values) | 0.299/0.280 | 0.29/N.A. |
| Stator leakage reactance at rated capacity (per unit values) | 0.163 | 0.14 |
| Stator leakage reactance at maximum capacity (per unit values) | 0.176 | 0.15 |
| Negative sequence reactance X2 at rated capacity (unsaturated/saturated per unit values) | 0.258/0.230 | 0.30/N.A. |
| Negative sequence reactance X2 at maximum capacity (unsaturated/saturated per unit values) | 0.279/0.248 | 0.32/N.A. |
| Zero sequence reactance X0 at rated capacity(per unit values) | 0.20 | 0.14 |
| Zero sequence reactance X0 at maximum capacity (per unit values) | 0.216 | 0.15 |
| Short-circuit ratio at rated capacity | 1.2 | 1.2 |
| Short-circuit ratio at maximum capacity | 1.1 | 1.1 |
| Direct-axis transient open-circuit time constant $T'_{d0}$ [s] | 10.1 | 11.1 |
| Quadrature-axis transient open-circuit time constant $T'_{q0}$ [s] | 1.5 | N.A. |
| Direct-axis subtransient open-circuit time constant $T''_{d0}$ [s] | 0.075 | 0.1 |
| Quadrature-axis subtransient open-circuit time constant $T''_{q0}$ [s] | 0.15 | 0.2 |
| Stator winding short-circuit time constant Ta [s] | 0.28 | 0.32 |
| Number of stator slots | 540 | 510 |
| Number of parallel branches of stator winding | 5 | 5 |
| Connecting mode of stator winding | Wave-wound | Wave-wound |
| Positive sequence resistance R1 of stator winding [Ω] | 0.0021 (90°C) | 0.0025 (90°C) |
| Field resistance [Ω] | 0.1029 (90°C) | 0.09643 (90°C) |
| Stator winding to earth capacitance per phase [μF] | 2.03 | 1.35 |

#### 2.4.3.4.2 Structures, dimensions and weights of the generator main components

The TGP generator features low speed, large capacity and heavy thrust load. Its dimension and weight are the biggest in the world. The total weight of ALSTOM and VGS generators are up to 3333.5 t and 3143 t, respectively. Due to the large capacity and dimension, all kinds of mechanical forces in the generator, such as unbalanced magnetic force, thermal expansion force, short circuit force, are very large. So, countermeasures in the design of the structure should be taken to withstand these forces. In their designs of the TGP generators, ALSTOM and VGS make full use of modern advanced technology and the experiences from design and manufacture of large-scale hydro generators such as ITAIPU, GRAND COULEE and GURI hydro generators which were successfully operated. The general arrangement layout of a TGP unit is shown in Fig. 2.4.6 and Fig. 2.4.7.

#### 2.4.3.4.2.1 Stator

The stator consists of a stator frame, a stator core and a stator winding. The outer diameter of the stator frame, the inner diameter of the stator core, the height of the stator frame, the height of the stator core and the weight of the complete stator of the ALSTOM generator are 22.03 m, 18.8 m, 6.04 m, 2.95 m and 804 t. The values of the VGS generator are 21.45 m, 18.5 m, 4.27 m, 3.13 m and 707 t. Due to the big dimensions of the stator, the frames of ALSTOM (VGS) generators are constructed in 5 (8) sections consistent with transportation limitations. The stator frame sections will be assembled at the site to form a solid, round continuous frame, the stator core laminations will also be stacked at the site in order to improve the quality of the core lamination stacking and to ensure the roundness of the stator core. The stator frame can withstand the following forces without deformation:

- Tangential forces caused by a short circuit of the stator windings;
- Tangential forces under rated operating conditions;
- Radial unbalanced magnetic force caused by a short circuit of half of the field windings;
- Forces caused by thermal expansion under all operating conditions;
- Vertical forces transmitted via the upper bracket, etc.

The stator core is attached to the stator frame through dovetail key bars. Because of the size of the stator, thermal expansion of the stator core and frame is a very important problem when designing the generator. The temperature of the stator core is always higher than the one of the stator frame. Although the stator frame is bigger than the core, the thermal expansion of the stator core is far greater than the one of the stator frame. As a consequence, the force between core and frame caused by the difference in thermal expansion is very large. To accommodate the thermal expansion and to minimize a buckling of the stator core, ALSTOM and VGS used different design schemes.

ALSTOM introduced an oblique element concept for the design of the stator. These oblique elements are made of hot rolled high quality steel plate and arranged in an angular position with respect to the radial direction and equidistantly placed around the stator frame, crossing through the stator frame ring plates and welded to them. The oblique elements are supported and rigidly connected to the foundation; the stator top is rigidly connected to the upper bracket arms. The oblique elements of the stator frame are dimensioned so that a thermal expansion is absorbed and, up to an acceptable value, the forces caused by thermal expansion differences between the frame and the core, are minimized. This kind of design has been successfully applied in the ITAIPU generators as well.

VGS adopted a floating type stator frame. The connection between the stator frame and the sole-plates is of “radial freedom”. This is done by a radial key that allows a necessary radial movement of the stator frame but, at the same time, limits any tangential movement in order to prevent large counteraction forces on the stator core. To reduce the heat loss and thus reduce the temperature and expansion of the stator core, the latter is made from high-quality, low loss, 0.5 mm thick, cold-rolled silicon-steel laminations. Specific losses of the material are 2.5 W/kg (2.7 W/kg) at 1.5 T for ALSTOM (VGS) generators.

In the design of the generator ventilation system, the number of ventilation ducts is increased, while the height of the single ventilation ducts is reduced to 6 mm. The total area of ventilation circuits remains unchanged, but the cooling area of the stator core is increased, and thus the temperature difference between the stator core and frame is reduced effectively. Certainly, when the stator winding is directly cooled by water, a part of the heat in the stator core is indirectly taken away by the cooling water and thus the temperature of the stator core is reduced.

The stator core may become loose during operation, especially at the top and bottom tooth of the stator core. The ground wall insulation of the stator bar may tear apart as long term vibrations and a grounding short circuit fault may occur. In order to avoid this kind of fault, both ALSTOM and VGS take countermeasures in the structural design of the stator core.

For ALSTOM generators, the stator core clamping is made by 270 studs with spring nuts and washers that distribute the pressure in the whole core sheets area homogeneously. The final clamping pressure of the core is approximately 1.5 MPa. The clamping studs are installed through the core and are electrically insulated from the core. There are no connections between the top clamping plate of the stator core and the top ring plate of the stator frame. For VGS generators, the stator core clamping is made by studs between the outer circle of the stator core and frame. The core clamping studs are made of high yield point steel to provide extra elasticity which maintains the required pressure on the core laminations. An axial expansion is allowed by the proper elongation of the clamping studs and by the use of additional springs. Consequently the pressure in the core is, under all operation conditions, sufficient to avoid dangerous vibrations of the core laminations. The final clamping pressure of the core is approximately 1.0 MPa. At the site, the laminations are alternatively stacked, sheet by sheet with an overlap of 1/3 sheet, to form a continuous integral core. After cold pressing, heat pressing for the stator core will be performed to maintain sufficient and equal clamping forces. After testing the core loss, the clamping studs of the stator core will be re-tightened according to recommended values.

The stator winding consists of single-turn coils, wye-connected with 5 parallel circuits. The connecting mode between the coils is wave wound. The windings are insulated with Class F insulation as defined in IEC 34.1. The ground wall insulation of the stator winding is impregnated by a vacuum-pressure method with epoxy resin. The ALSTOM generator stator winding consists of 1020 stator bars with 42 solid copper strands and 6 hollow stainless steel strands each. The ground wall insulation of the stator bar with a thickness of 4.75 mm can withstand an AC voltage of 80 kV for 1 minute. The insulation breakdown voltage is not less than 130 kV. The VGS generator stator winding consists of 1080 stator bars with 24 solid copper strands and 6 hollow copper strands each. The ground wall insulation of the stator bar with a thickness of 4.6 mm can withstand an AC voltage of 61.5 kV for 1 minute. The insulation breakdown voltage is not less than 110 kV. The stator bar is transposed by the Roebel method for reducing additional losses and temperature differences between the conductor strands which are caused by a circulating current in strands due to unbalanced leakage flux.

#### 2.4.3.4.2.2 Rotor

The rotor consists of a disk type rotor spider, a rotor rim and rotor poles. The ALSTOM rotor spider consists of one rotor hub and 16 oblique arms. The VGS rotor spider consists of one rotor hub and 20 arms. The outer diameter, height and weight of the ALSTOM generator rotor are 18.74 m, 3.42 m and 1780 t, the values of the VGS generator rotor are 18.44 m, 3.44 m and 1710 t, respectively. The welding of the rotor spider, the stacking of the rotor rim laminations and the assembly of the rotor poles are carried out at the TGP site.

The rotor rim consists of laminations stacked at the site. The laminations are made of high-grade strength, 3 mm thick, cold-rolled steel sheets with passivation treatment. The rotor rim is fixed on the rotor spider by a rim key. The connecting method between rotor rim and spider (i.e. rotor rim key) is very important to guarantee the concentricity of the rotor rim with the rotor spider during an over speed operation. A floating type rim with only a tangential rim key or a rim with a combined radial and tangential rim key may be used. The GRAND COULEE generator with a rated power of 700 MW is designed with a floating type rim. An accident of the stator hitting the rotor occurred during operation, though. The main reason is that the radial rim key is not firmly fitted during the rotor rim assembly, which results in a congenital eccentricity of the rotor rim. Afterwards the radial rim key was shrunken up. In the design of the ITAIPU generator rotor, a floating type rim scheme was considered but not adopted. Finally a shrinkage rim key scheme was adopted. The rim was heated to 60°C and radial keys were then fitted. While the rim was cooling down it griped the spider and was induced with the calculated stress. The pre-tightening force of the radial keys ensured that the rotor rim was in contact with the rotor spider at 1.1 times the rated speed and less. For TGP generators, the rotor rim and spider are connected through combined radial and tangential keys. During the assembly of the rotor, the rim is heated until it has expanded to the predetermined size. Shrinkage radial keys are then fitted. Then the tangential keys are fitted. The pre-tightening force of radial keys ensures that the rotor rim is in contact with the rotor spider at 1.4 times the rated speed and less. In doing so, the rotor rim rotates concentrically with the rotor spider at all operating conditions, and thus no vibration occurs. The complete rotor will withstand the centrifugal force at runaway speed without deformation.

The rotor of the TGP generator has 80 poles (40 pairs). Each pole consists of a pole body stacked with pole laminations and field windings around it. The number of turns of the field winding is 13.5 with F class insulation. The rotor poles are designed with damper windings at the surface of the pole. The single rotor pole is assembled in the factory, shipped to the TGP site and then attached to the rotor rim with pole keys. The field windings of all poles are connected together to form a complete field winding. The insulation of the field windings can withstand an AC voltage of twice the maximum field voltage plus 4 kV for 1 minute.

#### 2.4.3.4.2.3 Bearings of the generator

The generator is equipped with two guide bearings and one thrust bearing. The upper guide bearing is located above the rotor; the lower one and the thrust bearing are located below the rotor. The thrust bearing and lower guide bearing are supported on the lower bracket. The guide bearings are self-lubricated, segmental, adjustable, oil immersed and babbitted. The upper guide bearing is equipped with a complete, independent lubricating oil system which is installed on the upper bracket. The lower thrust and guide bearing are equipped with a common oil reservoir which is installed on the lower bracket. The temperature of the upper and lower guide bearings is less than 70°C.

The thrust bearing is a key component of hydro generating units. It supports the weights of the rotating parts of the generator and the turbine plus the hydraulic thrust of the turbine runner. A large weight of the unit and a large hydraulic thrust of the turbine runner lead to a heavy thrust load and a big size of the TGP thrust bearing. If the unit resists the maximum load with twice the turbine guide bearing seal gap, the hydraulic thrust of the turbine runner is maximized up to 2920 t (2200 t), and correspondingly the total thrust load of the thrust bearing is up to 5520 t (4850 t) for ALSTOM (VGS) generators. At normal operating conditions, the hydraulic thrust of the turbine runner is 2250 t (1440 t), and correspondingly the total thrust load of the thrust bearing is 4850 t (4050 t) The outer diameter is 5.2 m (5.4 m), and the inner diameter is 3.5 m (4.04 m) for ALSTOM (VGS) thrust bearings. So considering its thrust load and dimension, the TGP generator thrust bearing will be the largest in the world. So far, the heaviest thrust load and biggest outer diameter of thrust bearing put into operation are 4700 t and 5.36 m in the GRAND COULEE hydro power station in the USA.

The supporting method of the thrust bearing is very important to reduce the surface deformation of the thrust bearing pads and to make the distribution of both surface load and temperature even. The thrust bearing pad is a double-layer pad, developed and patented by ALSTOM. It consists of a thin running pad with a thickness of 50-60 mm, supported by a thick load-bearing pad through a number of vertical pins with various diameter and thus different elasticity. This makes the pad surface load evenly distributed. The thick load-bearing pads rest on compression columns, which themselves are supported by the segment carriers fixed on the lower bracket. The compression columns can be adjusted in order to evenly distribute the vertical forces between the 24 pads. The running pad surface is coated with a cast babbitt metal layer. The thrust bearing of the VGS generator consists of 28 babbitt-lined bearing pads with a thickness of 55 mm, which are supported on pre-compressed springs. The load distribution on both the pad surface and among the pads is even and the load per unit area, mean velocity of sliding surface, minimum oil film of ALSTOM thrust bearing pads are 5.7 MPa, 17.1 m/s and 40 μm. The values of the VGS thrust bearing pads are 4.18 MPa, 18.7 m/s and 30 μm. The temperature of the thrust bearing pads is less than 80°C. The thrust bearings can safely be operated at runaway speed for 5 minutes.

Concerning the arrangement of the thrust bearing, two schemes have been studied. One of them is an arrangement on the lower bracket, the other one is on the turbine head cover. The main merits and demerits are as follows:

1) Arrangement on the lower bracket
   - The thrust bearing is located in the generator pit. The maintenance space for the thrust bearing is larger, and thus maintenance is more convenient.
   - There are no common components between generator and turbine except for the connections between generator main shaft and turbine shaft, which is more convenient for the coordination between generator and turbine suppliers. This additionally allows a bid division between generator and turbine.
   - The turbine room is spacious, so maintenance for the turbine guide bearing is convenient.

- The thrust bearing is not influenced by the vibration and deformation of the turbine head cover induced by a hydraulic impulsive force.
- The total height and weight of the hydro generating unit is increased, and thus the height of power house is also increased.

2) Arrangement on the turbine head cover
   - The total height and weight of the hydro generating unit is reduced, and thus the civil work of the power house is also reduced.
   - The water pressure force upward and thrust load downward simultaneously act on the turbine head cover, which improves the conditions for turbine head cover forces.
   - There is more equipment in the turbine room. The maintenance space for the thrust bearing and the turbine guide bearing is reduced. But this problem is not obvious for TGP generators due to a big diameter of the turbine pit of approx. 14 m.
   - The stability of the generator is influenced by the vibrations of the turbine head cover coming from hydraulic vibrations.
   - There is more need to coordinate both design and manufacture of the generator and the turbine.

These two arrangement schemes are both technically feasible and good experiences have been achieved both in China and abroad. Because of the heavy thrust load of the thrust bearing, its safe and stable operation, the convenience of maintenance and the bid division, the arrangement scheme of the thrust bearing on the lower bracket was finally adopted.

In order to reduce the temperature of the thrust bearing pads and increase the operational reliability, the thrust bearing of the ALSTOM generator is equipped with 8 external oil-water coolers mounted on the lower bracket. The oil is circulated by an external self-circulation cooling system with a thrust runner pumping function. The thrust bearing of the VGS generator is equipped with 6 external oil-water coolers, where the oil is circulated by an external circulation cooling system with oil pump equipment. The oil-water coolers and the oil pump equipment are mounted at the lower bracket area. The thrust bearing can operate at normal speed and a rated/maximum load without cooling water in the bearing oil cooling system for 15 minutes.

The thrust bearing is equipped with a high-pressure oil lift system to provide oil to the thrust bearing surface while starting and stopping the generator. Under normal conditions, the high-pressure oil lift system will automatically operate in the starting and stopping sequences. Under fault conditions, the thrust bearing will operate safely in the stopping sequence of the generator even when the high-pressure lift system is out of service. For each generator, the high-pressure oil lift system is equipped with two independent oil pumps – one main pump and one in standby – driven by AC motors to constantly maintain the pressure required by the oil film on the bearing surfaces.

#### 2.4.3.4.2.4 Generator shafts

The shafts (including the upper and the generator main shaft) are hollow. The upper shaft is located above the rotor and connected with the rotor hub. The generator main shaft is located below the rotor and connected with the rotor hub at its upper end and with the turbine shaft at its lower end. The length, outer diameter, inner diameter and weight of the ALSTOM (VGS) generator main shaft are 4.94 m (4 m), 3.1 m (3.8 m), 2.65 m (3.5 m) and 106 t (88 t). The length, outer diameter and weight of the ALSTOM (VGS) upper shaft are 2.22 m (2.98 m), 2.7 m (2.7 m) and 37 t (26.42 t).

#### 2.4.3.4.2.5 Upper and lower brackets

The ALSTOM (VGS) generator lower bracket consists of one hub and 16 (6) oblique arms with an outer diameter of 15.1 m (16.1 m) and a total weight of 364 t (283.5 t). The lower bracket shall be designed to withstand the following basic forces:

- Axial thrust load;
- Radial unbalanced magnetic force due to a short-circuit of half of the rotor poles;
- Radial expansion force.

The maximum thrust load is 5520 t (4850 t) and the total unbalanced magnetic force due to a short-circuit of half of the rotor poles is 9000 kN (8024 kN) for ALSTOM (VGS) generators. Of the total unbalanced magnetic force, the lower bracket withstands 5744 kN (5235 kN). An axial deflection exits downwards in the lower bracket due to the heavy thrust load and size. In order to distribute the thrust load evenly on the thrust bearing pads and to avoid unduely influence between the lower guide bearing pad and the thrust block not influenced, sufficient rigidity is required for the lower bracket. It is specified that the axial deflection is less than 3.5 mm under the worst operating conditions. The design of both ALSTOM and VGS meet these requirements.

The ALSTOM generator upper bracket consists of one hub and 20 oblique arms. Its outer diameter is 23.2 m and total weight is 118.5 t. All the arms are supported on the generator pit wall in radial direction and on the stator frame in axial direction. The VGS generator upper bracket consists of one hub and 16 radial arms with a circumferential connecting plate at the outer side between two arms. Its outer diameter is 21.35 m and total weight is 83.5 t. Of the 16 radial arms, 8 are supported on the generator pit wall in radial direction and all of them are supported on the stator frame in axial direction. Between the axial supporting components and the arms, measures are taken for the limitation of radial thermal expansion of the stator frame. Adopting the above structure of the upper bracket, the radial force acting on the generator pit wall is reduced and the influence on the upper bracket hub and the gap between the upper guide bearing collar and the guide bearing pads is minimized. The upper bracket is designed to withstand the following basic forces:

- Axial load from top cover;
- Radial unbalanced magnetic force due to a short-circuit of half of the rotor poles;
- Tangential force transmitted via the stator frame due to a short circuit of the stator windings.

The top cover is designed for a load of 500 kg/m$^2$. With a diameter of approx. 22 m, the total axial load on the top cover is approx. 200 t. The radial unbalanced magnetic force due to a short-circuit of half of the rotor poles is 3256 kN (2333 kN) to withstand by the ALSTOM (VGS) generator upper brackets.

#### 2.4.3.4.3 Stability of the generator

Vibration and shaft system stability are two important indexes to evaluate the stability of generator. For generators with low rotating speed, it is normally required that the dual-amplitude horizontal vibration of the upper bracket is less than 0.1 mm and the dual-amplitude vertical vibration of the lower bracket is less than 0.1 mm. The guaranteed values of 0.08 mm for the upper and 0.04 mm for the lower bracket by ALSTOM and VGS for TGP generators is far lower than required.

The shaft system consists of an upper shaft, a rotor hub, a main shaft and all the other components for a complete shaft system. The main shaft is a two-piece shaft, including the generator shaft and the turbine shaft coupled by a flange. TGP generators have a low rotating speed, a large capacity and a heavy thrust load. The generators are of semi-umbrella type with a vertical shaft and one upper guide bearing, one lower guide bearing and one turbine guide bearing to ensure a safe and stable operation of the TGP hydro generating units. To ensure shaft system stability, it is required that the first critical speed of the combined rotating parts of turbine and generator is at least 125% of the maximum runway speed under all conditions. From stability calculations of the shaft system, the values 286 rpm (190% percent of the runaway speed) and 205 rpm (137% percent of the runaway speed), respectively, were found for ALSTOM and VGS generators, which shows that the shaft system of the TGP generators is stable.

#### 2.4.3.4.4 Rigidity and strength

For large-scale generators, the problem of rigidity and strength is obvious and especially the rigidity issue should be taken seriously. It is required that the maximum stress of the rotor rim should not exceed two-thirds of the yield strength of the materials at runaway speed in order to guarantee a safe operation of the rotor. To meet this requirement, ALSTOM (VGS) selects 3 mm thick steel plate for the rotor rim with a yield strength of 600 MPa (520 MPa), while the calculated stress is 398 MPa (297 MPa).

The stator frame has to be adequately rigid to withstand the maximum unbalanced magnetic force. On the other hand, it has to have a certain elasticity to accommodate thermal expansion resulting from a temperature rise between stator core and stator frame. To meet these contradictory requirements, ALSTOM and VGS adopt an oblique and floating type stator frame, respectively. The structure of the rotor is of disc type with a high rigidity, low weight and high stability. The axial deflection is a very important index for the rotor spider. It is required that the maximum axial deflection of the rotor spider is 1 mm for TGP generators. The design has to equilibrate a series of conditions:

- For a minimal axial deflection of the rotor spider, the rotor has to be adequately rigid in axial direction. Nevertheless, if the rotor spider is too rigid, the shrinkage force has to be taken over by the rim and would destroy it through the stress induced by the heating shrinkage.
- The shrinkage force should not influence the rotor hub. The rotor arms are welded to the rotor hub and the welding seams cannot withstand too high stress. If the hub itself is stressed too much, the coupling flanges between rotor hub and shafts would be deformed, which would influence the flange flatness and roundness.
- The axial eigenfrequency should not be excited under any circumstances. When the axial rigidity is increased, the axial eigenfrequency increases as well, so there is a danger of hitting the excitation frequency of the turbine.

The thrust bearing is supported on the lower bracket. The lower bracket should have adequate rigidity to guarantee the safe operation of the thrust bearing. It is required that the axial deflection is less than 3.5 mm under the worst operating conditions. The calculated value is approx. 3.47 mm.

To guarantee the stability of the shaft system, the upper, lower and turbine guide bearings have to be adequately rigid. The rigidity of these three guide bearings is 833 kN/mm (900 kN/mm), 1250 kN/mm (2400 kN/mm) and 1428 kN/mm (3436 kN/mm) for ALSTOM (VGS) generators.

#### 2.4.3.4.5 Generator cooling method and cooling system

The cooling method is a very important technical issue concerning design, manufacture and operation of the TGP generators. For a long time, the experts at home and abroad had two different opinions on the issue. One of them is full air cooling, i.e. air cooling for the stator core, stator winding and field winding, the other is a combined air and water cooling, i.e. air cooling for the stator core and field winding, water cooling for the stator winding. The technology for both generator air cooling and water cooling are progressing. It is difficult to make a decision, as both kinds of cooling methods are feasible for the TGP generators. They have the following merits and demerits:

1) Air cooling
   - Simple structure, convenient maintenance, high level parameters and high accessibility without hydraulic connections in the stator winding.
   - More material is required than for combined cooling, but the installation and maintenance is convenient without a pure water system.

- Thermal expansion of the stator core is higher due to a comparatively high temperature rise of the stator winding. As a consequence, measures have to be taken in the generator structure design to prevent the stator core from bucking.

2) Combined air and water cooling
   - One of the main technical problems of large hydro generators is mechanical deformation such as bucking due to thermal expansion. Water cooling for the stator winding can effectively solve this problem. The heating in the stator winding is carried out directly by water. The temperature difference between the maximum and average values is small, which implies an even distribution of the temperature in the stator winding. As a consequence, the displacement between stator winding and stator core is minimized.
   - Unless there are special $GD^2$ requirements, the material consumption is lower, and the dimensions and weights are smaller than that for full air cooling. Although some auxiliaries such as a pure water system are required, the total price of the generator is lower. So this method is more economical for the generator.
   - Due to the lower temperature rise of the stator winding, the life span of the stator winding insulation is expanded and the comprehensive thermal stress performance is improved. The thrust load is reduced because of the smaller dimension and weight of the generator rotor.
   - A pure water system is required for the generator. Thus, the failure frequency is increased, and with it the working amount for maintenance.
   - It is hard to avoid water leakage because of the high amount of hydraulic connections in the stator winding.

The capacity of 840 MVA of the TGP generator does not yet represent the maximum capacity of a fully air cooled generator. For those, the temperature of the stator winding is higher and the thermal stress is greater than that for a combined air and water cooled generator. But these problems do not influence the safe and stable operation of the generator, because the technology for full air cooling is being improved and measures on the generator structure can be taken to accommodate the thermal expansion. For example, oblique or floating type stator frames are adopted to accommodate a radial expansion of the stator core and the end of the stator winding is supported to accommodate an axial expansion of the stator winding. Experiences with fully air cooled generators in the GURI II and GRAND COULEE II hydro power stations can be used for reference.

The outstanding merit of combined air and water cooled generators is the low temperature (the stator winding temperature less than 65°C) and the small thermal stress, and consequently the risk coming from a thermal expansion is eliminated. Due to improved technology on water cooling, water cooling systems become more and more reliable. Although the working amount for maintenance is unavoidably increased, the operation with combined air and water cooled generator is, generally speaking, satisfactory. For example, sediment in the water pipes can be avoided effectively with hollow stainless steel conductors in both the stator bar and hydraulic connections. It is also possible to eliminate the need for chemical and mechanical cleaning. Hydraulic connections are the rigid ones formed in the factory, and a water leakage due to vibrations of the stator bar is avoided. Pure water systems have been improved from big dimension, low cooling efficiency and separate arrangement to small dimension, high cooling efficiency and compact arrangement. Experiences with combined air and water cooled generators in the ITAIPU and GRAND COULEE II hydro power stations can be used for reference.

Concerning the availability of generators, it is difficult to evaluate the advantages of the two cooling methods due to a limited statistical scope. The performance and parameters of the generator are basically the same for both cooling methods, so it is feasible for the TGP generators to adopt both methods. As the technical and commercial indexes are basically the same, the choice of the cooling method depended on the technology superiority of the selected bidder. The technology superiority and main references of ALSTOM, having won the bid of 8 TGP generators, are on combined air and water cooled generators. The technology superiority and main references of VGS, having won the bid of 6 TGP generators, are on both fully air cooled and combined air and water cooled generators. So it is feasible for VGS to adopt both kinds of cooling methods. As it is beneficial, in terms of generator installation, operation, maintenance and management, to adopt only one cooling method in the TGHP station, the combined air and water cooling method was chosen for TGP generators.

The pure water system supplying water for the cooling of the stator winding consists of

- 2 motor-driven water pumps,
- 2 water-to-water heat exchangers,
- 2 mechanical filters,
- 2 ion exchangers,
- 1 expansion tank and pipes, etc.

One pump, exchanger and filter are in service, the other ones are in standby in order to guarantee a reliable operation of the pure water system. The devices are assembled on one skid. The pure water system with a dimension of 5800×2300×2300 mm has a small volume and high cooling efficiency. The conductivity of the pure water must be kept low because the pure water gets in direct contact with both the conductors of the high voltage stator winding and the grounded pipe system. The permitted maximum value for the conductivity is 5 µS/cm. In case it is above this value, a breakdown failure may take place between the high voltage and the grounded parts. On the other hand, the conductivity must not be too low either. The pure water flows in the hollow conductors with a velocity of approx. 2 m/s. If the conductor is made from copper, the water will corrode the conductor. Experiments show that the corrosion will be increased rapidly if the water conductivity is less than 1 µS/cm. So it should normally be kept between 1 and 5 µS/cm for copper conductors. For stainless steel hollow conductors, the value should be kept as low as possible. For ALSTOM generators, stainless steel hollow conductors are used in the stator bar and the water conductivity is 0.1 µS/cm. For VGS generators, copper hollow conductors are used and the value is less than 2.5 µS/cm. The $p_H$ value of pure water is 6-8 (8.5-9) for ALSTOM (VGS) generators. Particles with a diameter up to 5 mm can be mechanically removed.

The stator core, stator frame, rotor rim, rotor poles and field windings are cooled with air in a closed, self-circulating cooling system. The air circulation is realized by the radial air flow of the generator rotor. The air flow will pass through the ventilation ducts into the rotor rim and the poles, the air gap between stator and rotor, the ventilation ducts in the stator core. It circulates out of the opening in the stator frame, goes through the air-to-water coolers and back to the top and bottom of the rotor through air passages. Additional fans on the rotor are not necessary. The total ventilation amount is approx. 170 $m^3/s$. With this cooling method, the cooling effect is even better than with additional fans on the rotor. 20 (16) air-to-water coolers are placed symmetrically around the periphery of the stator frame for the ALSTOM (VGS) generators. The air coolers provide sufficient heat dissipation. The generator can safely operate under maximum capacity operating conditions with two of the air coolers out of order, and the rise of temperature is within the specified range. The air coolers are designed for an inlet water temperature of 28°C and an outlet cold air temperature of less than 40°C. The total cooling capacity of the air coolers is 6000 kW (5520 kW) for ALSTOM (VGS) generators.

#### 2.4.3.4.6 The generator neutral point grounding system

The generator neutral point is set up inside the generator pit. Each phase of the stator winding consists of 5 parallel paths which are divided into two groups: One group consists of three parallel paths No.1, 2 and 3, the other one consists of two parallel paths No. 4 and 5. There are two neutral points inside the generator pit: One of them is set up by connecting the three parallel paths No.1, 2 and 3 of three phases, the other one by connecting two parallel paths No.4 and 5 of three phases. The final neutral point is set up by connecting the two neutral points and is connected via a cable with a neutral point grounding device outside of the generator pit. For the VGS generators, all neutral leads, connecting busbars and neutral point current transformers are supported on the stator frame. For ALSTOM generators, they are supported by insulators on a metal frame which is attached to the inside of the generator pit wall with expansion bolts. Due to the small clearance of less than 0.5 m between the neutral point busbar and the pit wall, and due to the large current of 14550 A and 9700 A, respectively, for the two neutral points with three and two parallel paths in the busbar, a magnetically induced heating in the reinforcing steel bars of the generator pit wall has to be considered. Calculations have been done by ALSTOM to determine the losses and the temperature rise of the reinforcing steel bars: Without shielding, the temperature rise is more than 90 K in some individual reinforcing bars, which is not acceptable. So shielding is mandatory. The following alternatives have been investigated for the neutral point with three parallel paths (14550 A):

- Shielding with a single steel plate;
- Shielding with a single aluminum plate;
- Shielding with a combination of aluminum and steel plate.

When shielding with a single steel plate, the maximum temperature rise in the reinforcing bars is 13.5 K, but the maximum temperature rise in the steel plate is up to 170 K, which is not acceptable. As a consequence, this kind of shielding cannot be applied. When shielding with a single aluminum plate, the maximum temperature rise in the reinforcing bars is 27.2 K, which is worse than with a single steel plate, but in exchange, no problems considering losses and a temperature rise in the aluminum plate occur. The most favorable results considering a temperature rise in the reinforcing steel bars as well as in the shielding system can be achieved by the combination of aluminum and steel plate (steel plate covered by an aluminum plate with the same dimensions): The maximum temperature rise in the reinforcing bars is 18.8 K, and the maximum temperature rise in the steel plate is 30 K. For the neutral point with two parallel paths (9700 A) losses and a temperature rise are reduced by a factor $(2/3)^2 = 0.444$. As a consequence, shielding by a single aluminum plate can be applied.

The neutral point is grounded through a grounding transformer with a resistor that is connected on its secondary side. If a single-phase grounding fault occurs, the neutral point is grounded through the primary coil of the transformer with a favorable resistor on its secondary coil circuit. By selecting a suitable voltage and current signal at the secondary side, sending the signal to the relay protection system and initiating tripping the circuit breaker and stopping the generator, the generator can be protected from damage. Applying this kind of grounding method, the total grounding current is the sum of the capacitance current and the resistance current. The stator winding to earth capacitance per phase is 2.03 μF (1.35 μF) for ALSTOM (VGS) generators. Taking into consideration the capacitance of other equipment connected with the generator main circuit, such as the isolated phase bus, the main step-up transformer and the station service transformer, the total capacitance per phase is 2.06 μF (1.4 μF), which is quite a strong capacitance current. In case of a single phase grounding fault, a transient over voltage will occur on the two other phases of the generator. By selecting a suitable resistance, the transient voltage can be limited to an acceptable value for the generator stator winding insulation. According to the ANSI/IEEE C37.101 standard "IEEE Guide for Generator Ground Protection" this value is 2.6 times the generator phase voltage (i.e. 1.5 times the generator line voltage). In order to meet this requirement, the primary resistance is approximately equal to the three-phase capacitance, and as a consequence, the primary resistance current is approximately equal to the three-phase capacitance current. Through calculation, the resistance of the secondary resistor was determined to be 0.85 Ω (1.42 Ω) and the total grounding current to be 30.6 A (25 A) for ALSTOM (VGS) generators, which is very large. According to ALSTOM experiences, a current of 20 A for 10 s or 30.6 A for 4.5 s will not damage the stator core. Normally the relay protection tripping time is 0.5 s. So, the TGP generator stator core is safe in case of a single phase grounding fault. The voltage of the generator neutral point to earth is as high as the phase voltage in case of a single-phase grounding fault, so the primary rated voltage of the grounding transformer is selected to be $20/\sqrt{3}$ kV, and the secondary rated voltage is selected to be 480 V or 500 V in order to limit the secondary current to a manageable level. The grounding transformer is of cast resin dry type and is magnetically designed for a primary rated voltage of 20 kV without saturation. For the ALSTOM generator, the capacity of the grounding transformer is 51 kVA in continuous rating and 240 kVA for a duty time of 60 s (over load factor of 4.7). The value for the VGS generator is 26 kVA in continuous rating and 176 kVA for a duty time of 30 s (over load factor of 6.8). For maintenance, a disconnecting switch is installed between the generator neutral point and the grounding transformer. Disconnecting switch, grounding transformer, resistor, and the other elements are all housed in a cubicle which is fixed outside of the generator pit wall.

## 2.4.4 Electrical design

The electrical design mainly deals with the

- integration of the power station into the power system,
- main single diagram,
- single diagram of the station service power supply,
- inlet and outgoing line mode,
- selection of the high-voltage switchgear,
- general layout of the project,
- selection of electric equipment,
- over voltage protection,
- earthing engineering,
- service illumination.

### 2.4.4.1 Integration of the power station into the power system

Because of the large size of the TGP power station with its installed generating capacity of 18200 MW, the design of the integration of the power station into power system is of utmost importance. It will impact the safe transmission of energy out of the station, the allocation of future power supply and the design of the power system covering various areas. Since 1986, a special work group has done a lot of research and demonstration work for the TGP power station in terms of power supply, power transmission mode, the amount of outgoing lines, further requirements to connect the station to the power system etc.

The TGP power station is located in the hinterland of China, and all the area within a radius of 1000 km can be reasonably supplied with power. Considering the distribution of energy resources as well as the economic development in different areas, the study shows that it will be reasonable to send energy mainly to Eastern China with a capacity of 6000-8000 MW, to Central China with 10000-12000 MW, to the Guangdong province with 3000 MW and to Chongqing City with a capacity of 1500-2000 MW.

As the transmission distance from the TGP power station to the load center of Central China or Chongqing city is within 600 km, and as in these areas a transmission network of 500 kV has been formed, it will be reasonable to adopt an AC 500 kV transmission line. Due to the long transmission distance of about 1000 km from the TGP power station to Eastern China and the high transmission capacity of 6000-8000 MW, a great deal of calculation and research has been made on transmission mode and voltage in the last 25 years. The research fields include AC 500 kV, AC 750 kV, pure DC, AC 500 kV combined with a DC ±500 kV line, etc. as well as the possibility of an EHV AC line of 1000 kV. The improvement of the socialist market economy and of the DC transmission technology, and the enriching experiences in AC and DC transmission engineering cause the following three aspects to be considered:

1) Pure DC transmission can easily be integrated into the network and is beneficial to the long-term plan of interconnecting large electric networks.
2) The liability of DC transmission is being constantly enhanced along with the development of new technology. Since the scale of the electric network is generally increasing, the influence of a potential fault on the network, if it occurs on a DC transmission line, will become less and less.
3) Foreign manufacture technology for DC transmission will be imported through cooperation with the manufacturers, and more and more domestic products will generally be adopted. As a result, the cost of DC transmission will decrease.

In conclusion, a pure DC mode will be adopted for the transmission to Eastern China (two lines of DC ±500 kV, each with a 3000 MW transmission capacity, one from the left and one from the right bank power station). Taking the existing DC ±500 kV line with a capacity of 1200 MW from Gezhouba to Shanghai into account, the total transmission capacity to Eastern China will be up to 7200 MW. Also, a DC ±500 kV line with a capacity of 3000 MW will be constructed for the transmission to Guangzhou.

For the convenience of the network management, the converter stations for the transmission to Shanghai and Guangzhou are located at the left and right bank, not far from the TGP. So the outgoing lines from the TGP power station are all of AC 500 kV and the arrangement of the step-up substation of the TPG can be simplified. As for the number of outgoing lines, several factors have to be considered:

- The total transmission capacity of all outgoing lines should match the installed capacity of the station. Based on the design experience of our national hydropower stations, it will be relatively reasonable that the ratio of the transmission capacity to the installed capacity of the hydropower station be between 1.2 and 1.35. The design principle “N-1” should also be taken into account, i.e. all the generated energy should be sent out safely even if one outgoing line fails.
- In order to cut down the short circuit current, there will be no direct connection inside the project area between the left and the right bank power station.
- For the stability of the power system, especially in times of full generation and large output of the TGP station, sectional circuit breakers will be installed for the right and left bank power station. So, the overall power plant could be divided into four sub-plants.
- The 500 kV outgoing lines should be allocated properly according to the busbar sections. The power energy should be sent out smoothly under normal and emergency current flow (“N-1” operation mode). The routes of the outgoing lines should not cross each other.

Eventually, 15 circuits of 500 kV AC outgoing lines were recommended, 8 circuits from the left bank power station and 7 circuits from the right one. The ratio of the transmission capacity and the installed capacity of the station will be 1.24.

For the No.1 left bank power plant, there will be 8 units of generators and 5 circuits of outgoing lines. Of the 5 circuits, 2 circuits will be connected to the Wanxian district and Chongqing City; the other 3 circuits are connected to the DC converter at the left bank sending power to Eastern China.

For the No.2 left bank power plant, there will be 6 units of generators and 3 circuits of outgoing lines sending power to Jinzhou. A DC converter will be built up to transfer the power to Guangzhou city. For the No.1 right bank power plant, there will be 6 units of generators and 4 circuits of outgoing lines. Of the 4 circuits, 2 circuits will be connected to the Gezhouba-Shanghai DC converter at Songjiaba, the other 2 circuits to Jinzhou. For the No.2 right bank power plant, there will be 6 units of generators and 3 circuits of outgoing lines all connected to the DC converter at the right bank sending power to Eastern China.

### 2.4.4.2 Electric main single line diagram

To send the generated power smoothly out of the TGP station and to meet the requirements of the electric power system, an electric connection grid including all the electric equipment and based on the operation peculiarity of the station has to be formed. It should have the flexibility for adjustment and allocation as it will be influenced by the type selection and arrangement of the electric equipment, the cost of the project and whether the power can be sent out or not, and shall contribute to a safe delivery of the power. In a word, it is of great importance to the overall electrical design of the project. When designing the main single diagram, the following principles, besides the ordinary ones, should be abided by:

- In order to limit the short circuit current (below 63 kA at the 500 kV side) and render it advantageous to the operational stability of the system, both the left and the right bank power station should adapt to independent operation. There will be no direct electric connection through the 500 kV busbar between the two stations. On the other hand, sectional circuit breakers will be installed on the 500 kV busbars for both stations, so each of the left and the right power station can be separated into two power plants for operation.
- Regarding the safety of the system operation, the set of generator units or the lines to be shut down under serious fault should be limited to a minimum. Under double faults, no more than two combined units of generator-transformer or two lines shall be shut down.
- In case one set of circuit breakers or one busbar is under maintenance, the continuous power supply should not be affected. Outage all over the plant will not be allowed in any case.

- It should enable the station to provide only peak load to the system, especially in the dry season. In any case, the station service power supply should be reliable.

Based on the design principles mentioned above, several schemes for the combination mode between transformer and generator and for the 500 kV side connection have been studied.

#### 2.4.4.2.1 Combination between generator and transformer

Several aspects were considered for the study of all the possible combination modes:

- Reliability of the power supply;
- Good match with the line transmission capacity;
- Least inlet lines into the 500 kV switchgear and the least current though the busbar;
- Maximum set of generators to be shut-down by the system in case of fault;
- Least split windings of the transformer LV side;
- Least short circuit current as it occurs at the generator terminal.

It was considered to either adopt a one generator/one transformer combined unit or an enlarged unit. Based on these ideas, four main important modes were studied:

1) Three-phase assembled transformer of 1680 MVA with double split LV windings as well as a generator circuit breaker (GCB);
2) Single-phase transformer group of 2×840 MVA with double split LV windings as well as GCB;
3) Three-phase transformer of 2×840 MVA as well as GCB;
4) Three-phase transformer of 2×840 MVA as well as HV circuit breaker at HV side (Fig. 2.4.8).

Mode 1) is the most expensive, while the cost of the others is similar. From the point of reliability, two sets of generators will be shut down in case of a transformer fault for the modes 1) and 2), but only one set for the modes 3) and 4). Therefore one of the first two modes will result in an outage loss of 84616,200 Yuan RMB/a more than that from one of the latter two modes. Additionally, the reliability calculation has showed that the outage frequency of mode 1) or 2) is higher than the one of mode 3) or 4). Although the manufacture of the transformer in mode 2) will be easier, the three single phase buses of the generator voltage should be fed into a delta connection, so the arrangement will be complicated and the occupied space in the power house will be considerable. On the other hand, mode 3) or 4), with three-phase transformer, will make the arrangement and protection more simple and the operation and maintenance more convenient. For mode 3), the GCB with a rated current of 26 kA, a rated breaking current of 160 kA is needed. In the early 1990s, it was only possible to select air circuit breakers of a KYN middle air insulated circuit breaker type. The experiences from the first channel works of the Gezhouba power station show that this type of GCB is heavy, clumsy and complex. Since it needs an air compressing system with a high level technical performance, its operation and maintenance are complicated and the noise due to switching is heavy, which is not appreciated by customers. However, the circuit breaker placed at the 500 kV side is a technically mature product and can meet the requirement of the station under all kinds of operation conditions. Considering all these reasons, the generator-transformer mode with circuit breaker at the HV side, i.e. mode 4), is recommended for the combination of generator and transformer.

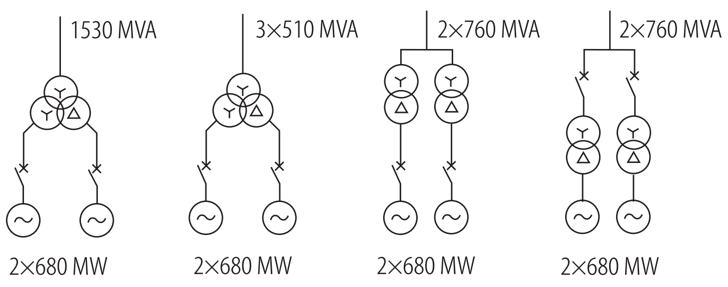


**Fig. 2.4.8.** Connection mode of the generator and the transformer.

#### 2.4.4.2.2 Diagram of the 500 kV switchgear

As an example, there are 7 circuits of inlet lines and 8 circuits of outgoing lines in the left bank power station. Calculations of reliability and a comprehensive comparison were made for more than 20 possible diagram schemes of 500 kV, such as double-busbar for each double section, double-busbar-double-breaker, breaker-and-a-third, breaker-and-a-half, breaker-and-a-half combined with double-breaker for outgoing lines and many other simplified schemes based on the connection group of the generator-transformer-outgoing line. Based on the requirements of high safety and reliability, good flexibility for regulation, compact arrangement, convenience for operation, advanced and available equipment, reasonable cost, a breaker-and-a-half connection with busbar sectionalizing breakers was recommended. The single line diagram for the left bank power station is shown in Fig. 2.4.9.The diagram of the right bank power station is similar to the left one.

### 2.4.4.3 Selection of the main electric equipment

There are various types and large quantities of electric equipment in the TGP with voltages of 0.4, 10, 20, 35 and 500 kV. Only several ones will be discussed here:

- 15 sets of three-phase transformers (one for standby) supplied by Siemens, Germany;
- 39 breaker bays of 500 kV GIS supplied by ALSTOM, Switzerland;
- 1176 m (single phase) of phase isolated busbar with a rated current of 26 kA, used for the generator circuit, supplied by Changjiang Electrical Corporation, Jiangsu, China.

The main technical parameters are listed in the Tables 2.4.15 to 2.4.17.

**Table 2.4.15.** Main technical parameters of the transformer.

| | | |
|---|---|---|
| Rated capacity [MVA] (at each tapping and with the voltage at the LV side decrease for 5%) | | 840 |
| Number of phases | | 3 |
| Rated frequency [Hz] | | 50 |
| Rated voltage [kV] | HV side | 550 – 2×2.5% |
| | LV side | 20 |
| Connection symbol | | Yndn |
| Impedance voltage [%] | | 16 |
| Neutral point grounding | | via small reactor |

**Table 2.4.16.** Main technical parameters of the GIS.

| | | |
|---|---|---|
| Rated voltage [kV] | | 550 |
| Rated frequency [Hz] | | 50 |
| Number of phases | | 3 |
| Rated current [A] | circuit of combined units | 2000 |
| | circuit of breaker-and-a-half and outgoing lines | 3150 |
| | main busbars and sectionalizing equipments | 4000 |
| Rated breaking current [kA] | | 63 |
| Rated short time withstand current [kA] | | 63 |
| Rated short circuit duration [s] | | 2 |
| Rated peak withstand current [kA] | | 171 |

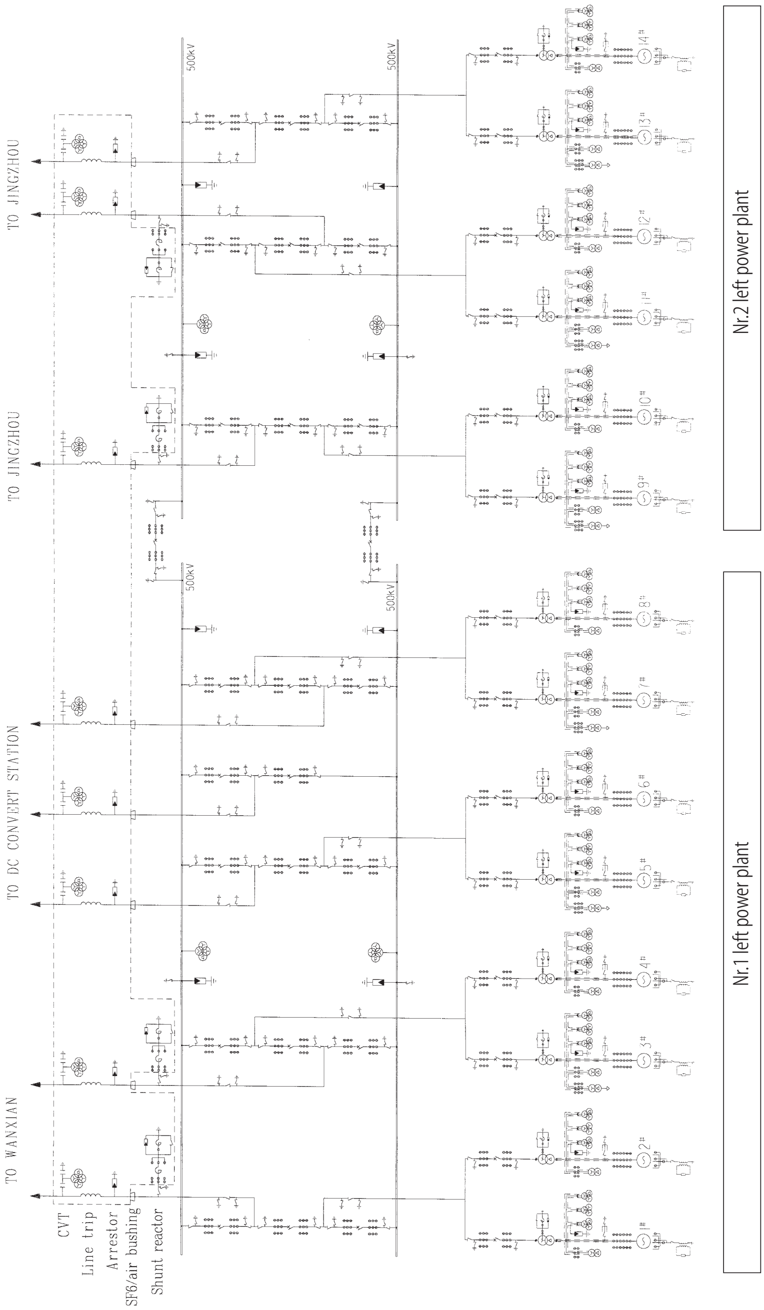


**Fig 2.4.9.** Single line diagram of the left bank power station of the TGP.

**Table 2.4.17.** Main technical parameters of the phase-isolated busbar.

| | Main circuit | Branch circuit |
|---|---|---|
| Rated voltage [kV] | 20 | 20 |
| Max. voltage [kV] | 24 | 24 |
| Rated current [kA] | 26 | 0.5 |
| Rated frequency [Hz] | 50 | 50 |
| Three-phase short circuit current [kA] | 160 | 300 |
| Rated peak withstand current [kA] | 440 | 820 |
| Rated short time withstand current [kA] | 160 | 300 |
| Rated short circuit duration [s] | 2 | 2 |

### 2.4.4.4 Explanation of the main technical issues

#### 2.4.4.4.1 Partial discharge level

The partial discharge is an important factor for measuring the manufacture quality and to guarantee the operation safety. Requirements are strictly specified for each component in terms of the measurement method and the voltage applying procedure.

- For the transformer, the partial discharge should be tested separately. Voltage at the 550 kV terminal should be applied as 477 kV (for 5 min), 550 kV (for 5 s), 477 kV (for 1 h). During the last hour, the value of the partial discharge at the 550 kV terminal shall not exceed 100 pC.
- For the GIS, the voltage applying procedure should be 1 p.u. = 318 kV (for 1 min), $\sqrt{3}$ p.u. (for 3 min), 680 kV (for 1 min), 1.5 p.u. (for 3 min), 1.1 p.u. (for 2 min).

The partial discharge is measured in the period of 1.5 and 1.1 p.u. The two values 1.5 p.u. and 1.1 p.u. are to be submitted, the former used for reference, the later used for acceptance. The initial voltage of the partial discharge should not be less than 1.1 p.u. The partial discharge of a single element should be less than 3 pC (but partial discharge not greater than 2 pC for the insulator and not greater than 5 pC for the potential transformer). The partial discharge of an assembled bay should not be greater than 10 pC.

#### 2.4.4.4.2 Insulation level

The insulation level of the main electric equipment is listed in Table 2.4.18. The specific creepage distance is 25 mm/kV for SF6 epoxy resin bushing and 17 mm/kV for the insulator of the phase-isolated busbar.

#### 2.4.4.4.3 Very fast transient over voltage (VFTO)

When the circuit breaker at the HV side of transformer is open, VFTO due to switching off the GIS disconnector will be transferred to the HV side of the transformer through the voltage grading capacitors installed between the breaker gaps. This VFTO will damage the terminal insulation of the transformer. Based on the pre-breakdown time of 200 ms in the period of closure of the disconnector and an arc resistance of 4 Ω, ALSTOM calculated VFTO for various operation conditions. The maximum voltage factor of 1.46 as well as its waveform was submitted. It was found that an arc resistance varying between 0 and 4 Ω would turn the tolerance of the calculation result for VFTO below 5%. This conclusion has been submitted to Siemens for the design of the transformer.

**Table 2.4.18.** Insulation levels of main electric equipments.

| | | Transformer | | | | | | | GIS | | | Phase-isolated busbar |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HV | HV phase-phase | LV | Neutral point | Bushing | | | Phase-earth | Between open contacts | SF6 bushing | |
| | | | | | | HV | LV | Neutral point | | | | |
| BIL [$kV_{peak}$] | Full wave | 1550 | | 125 | 325 | 1675 | 125 | 325 | 1550 | 1550 + 450 | 1675 | 125 |
| | Chopped wave | 1675 | | 140 | | 1800 | | | | | 1800 | |
| SIL [$kV_{peak}$] | | 1175 | 1800 | | | 1175 | | | 1175 | 1050 + 450 | 1240 | |
| Power frequency, withstanding voltage [KV rms for 1 min] | | 680 | 950 | 55 | 140 | 740 | 55 | 140 | 680 | 800 | 740 | wet: 55<br>dry: 68 |

#### 2.4.4.4.4 100% breaking DC component of circuit breaker

As the capacity of the step-up transformer in the TGP station is rather large, its inductance is correspondingly large. It was calculated that a short circuit can occur from 78% of the final DC component on, and the time constant is 120 ms. The short circuit time of the circuit breaker during breaking was found to be 14 ms for both a negative and a positive loop. These results provide the circuit breaker manufacturer with strict requirements.

### 2.4.4.5 Arrangement of the electric equipment

Based on conditions such as the integration of the station into power system, the arrangement of the hydraulic engineering buildings, the natural circumstances of the project, the inlet and outgoing line connection and the convenience of operation and maintenance, an optimum overall arrangement for the electric equipment was selected from various schemes. The main factors affecting the overall arrangement are:

1) *The layout of the 500 kV outgoing lines*
Several factors such as cable, SF6 bus duct and overhead line have been studied. For the operational safety, the convenience of maintenance and economic reasons, the overhead line was recommended.
2) *500 kV switchgear*
A study and comparison was made for all types of switchgear already known in the world, such as the conventional type (including PASS), hybrid type (H-GIS) and the metal enclosed SF6 gas insulation switchgear. Regarding safety and reliability, convenience of operation, simplicity of maintenance, need of space and investment of civil work, the GIS obviously has advantages. Even though it is more costly, the importance of the reliability determines that the GIS is the optimal solution since the switchgear is the pivot joint connecting several large scale networks in Eastern and Central China, Guangzhou City and Chongqing City.

The GIS will be arranged in the upstream auxiliary powerhouse at an elevation of 93 m. It will be connected with the main transformers and the 500 kV shunt reactors through a SF6 bus duct. The transformers and shunt reactors are arranged at the platform at 82 m between dam and powerhouse, beneath the GIS room. 8 circuits of 500 kV outgoing overhead lines will get to the left bank of the ship lock via towers located at the main wall of the main powerhouse and the fix device at the dam, crossing the tail water and the forth chamber of the ship lock. The electric equipment is assembled in the upstream auxiliary powerhouse, the water supply system and water purifying devices for the stator cooling are arranged in the downstream auxiliary powerhouse. For a safe operation of the turbine units, there is leftover room in the downstream powerhouse at 75.3 m for a possible arrangement of gas refilling devices. For details of the powerhouse arrangement see Fig. 2.4.10.

It should be particularly pointed out that tests and research have been made on problems considering the safety of the 8 circuits of 500 kV overhead lines passing above chamber of the ship lock, their interference with communication systems and the influence of their electromagnetic field on personal health. The results are:

- The 500 kV overhead lines will not damage the ships, even if they carry flammable or explosive goods.
- The power frequency electromagnetic field is not harmful to people on the ships.
- There will be no shielding effect on the EHF broadcasting, GPS, navigation devices, mobile phones, bi-bi phone etc.
- In order to avoid a break up of the conductors and a collapse of the towers, a greater safety coefficient is used in the design and rigid environment conditions are supposed.

As a conclusion, the overhead line will directly pass above the chamber of the ship lock without protection mesh.

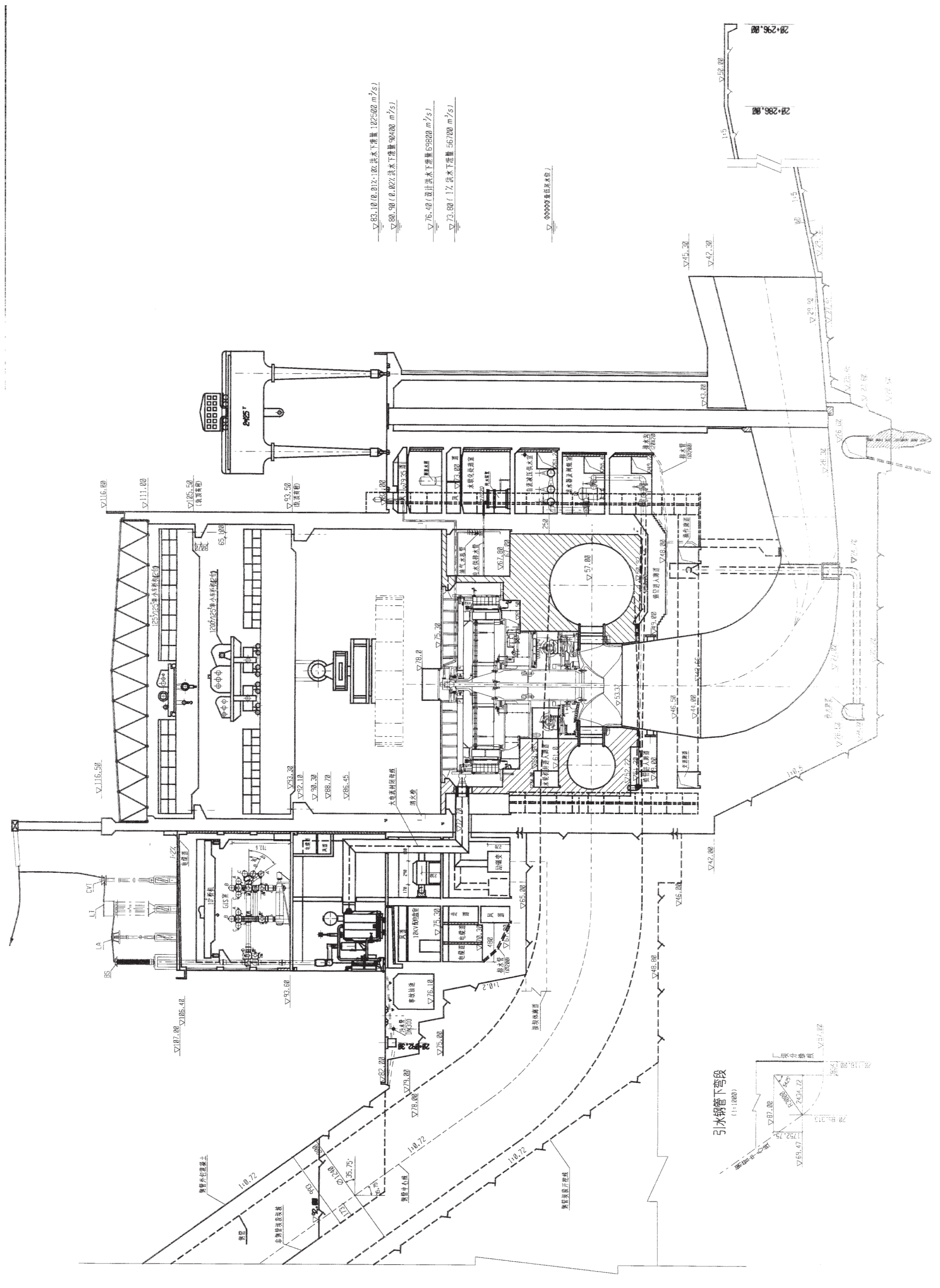

**Fig. 2.4.10.** Cross section of the power plant house.

## 2.4.5 Automation of the Three Gorges-Gezhouba cascade project

The Gezhouba Water Project is a reverse regulation reservoir and a navigation cascade of the TGP, so united management and combined dispatch must be implemented. It can be seen that the combined Three Gorges-Gezhouba Cascade automation system has special characteristics, such as a vast zone, a large scale, numerous objects to be controlled, complete function configuration etc. Modern advanced techniques of automation and communication will be used to outfit the combined automation system with advanced technology, clear structures and a reasonable management. It must be able to perform operational and managerial tasks in a safe and reliable way with easy supervisory control as well as in an unmanned mode, and it must guarantee unblocked information. For this reason, besides the engineering characteristics of the Three Gorges-Gezhouba Cascade project, many special topics about the structure, functions and main technical characteristics of the system, the transmission of information etc. have been studied. The topological network diagram of the computer supervision and control system of the Three Gorges-Gezhouba cascade dispatch, which is recommended to use, is shown in Fig. 2.4.11, and its main parts are described in the following sections.

### 2.4.5.1 Functions of the system

The integrated benefits of flood control, power generation, navigation etc. are tremendous, and these benefits influence each other through various factors. In order to maximize the integrated benefits, the factors related to dispatch and operation must be compared and selected in order to gain an optimum operating instruction. The Three Gorges-Gezhouba cascade project has an important status in the national economy and will receive dispatch instructions from superior main management agencies such as the National Flood Control General Headquarter, the Changjiang Flood Control General Headquarter, the National Power Dispatch Center, the Navigation Headquarter, etc. The cascade dispatch has to be set up in accordance with the above conditions. According to the overall arrangement of various structures, the cascade dispatch is divided into 2 levels: station subsystem level and local level. The functions of the various levels are explained as follows:

#### 2.4.5.1.1 Functions of the cascade dispatch level

The reservoir dispatch, flood dispatch, power generation dispatch, navigation dispatch etc. will be incorporated into the cascade dispatch. A computer supervisory control system of the cascade dispatch will allow a united and combined dispatch of water spill, water storage, power generation etc. for the Three Gorges and Gezhouba water projects, and it will be able to coordinate all relevant aspects in accordance with superior dispatch instructions and to supervise and manage the operation of the cascade project including emergency processes.

#### 2.4.5.1.2 Functions of the station subsystem level

According to the structures and specialties, the management range, the geographic position etc., the station subsystem level is divided: It both accepts instructions from the cascade dispatch and performs its own functions. Generally, these functions are data acquirement and processing, control and regulation, man-machine interface and manipulation, monitoring of equipment operation, system diagnosis, system communication, training, diagnosis and maintenance of the operation.

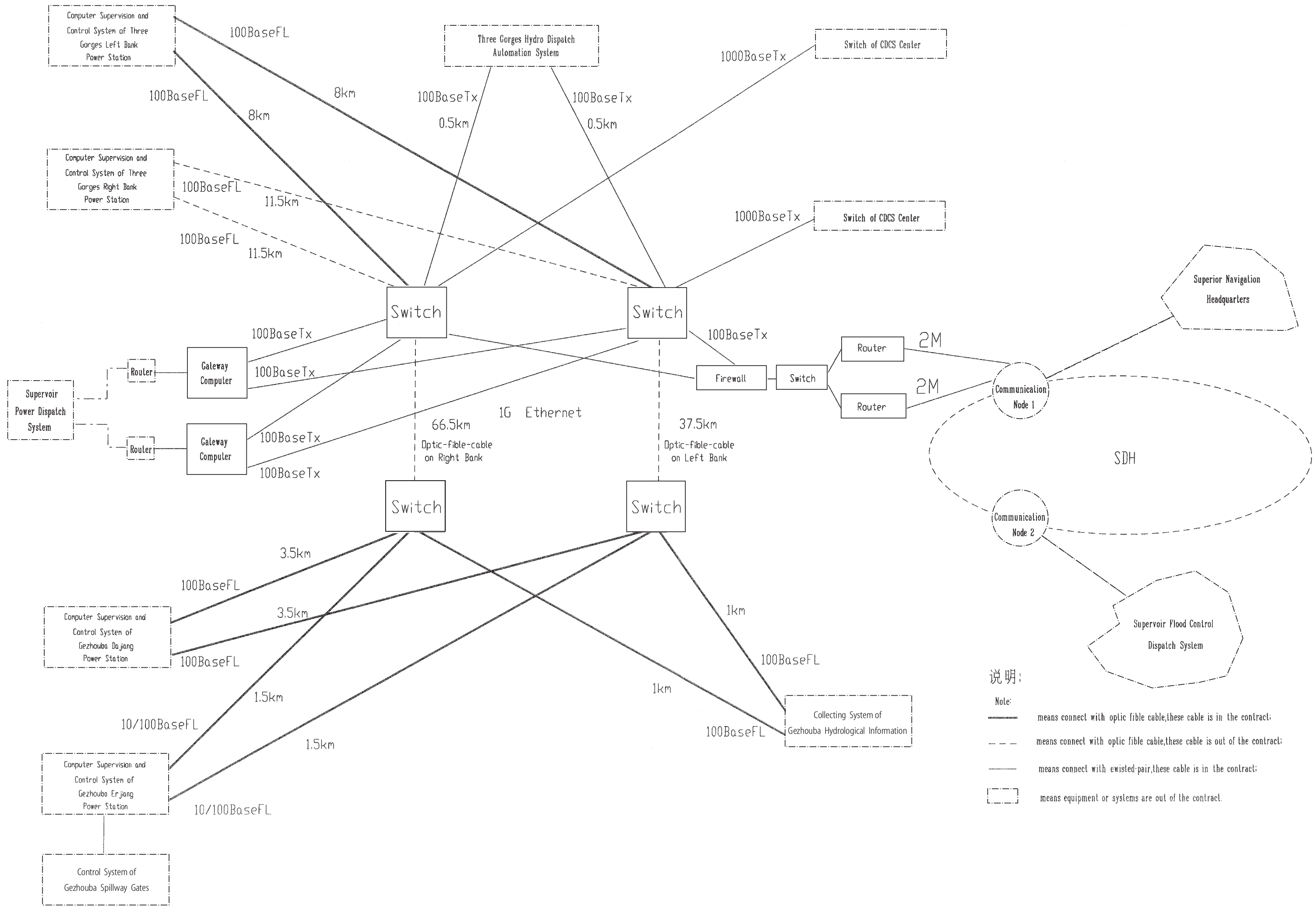


**Fig 2.4.11.** The topological network diagram of the computer supervision and control system of the Three Gorges-Gezhouba cascade dispatch.

#### 2.4.5.1.3 Functions of the local level

Below the station subsystem level, local levels are set up according to the unit functions such as the generator or the spillway. They perform various functions realized by the unit itself, and do data acquirement, data processing, control and regulation, man machine interface, communication, self diagnosis etc.

### 2.4.5.2 System structure

According to the function division and in order to raise the real time reliability, the automation system of the cascade project uses a hierarchical, distributed and open system structure. The whole system is fully computer controlled and is, as mentioned above, divided into cascade level, station subsystem level and local level. The system structure has the following characteristics:

- The overall system structure is an arrangement of distributed functional systems and a corresponding database. The real time and the history database are separated. Various functions are distributed to each node of the network, which implements the stipulated task while communicating with all the other nodes through the network.
- The cascade dispatch computer supervisory control uses a LAN supported by high speed Ether network. The transmission rate of the network is at least 100 Mpbs. The network uses a redundant structure. As transmission media, twisted-pair and optic fiber cables are used. In the computer supervisory control system of the power station, the upper local computing unit (LCU), two network layers – an optic fiber control network and an optic fiber/twisted-pair cable information network – are used. The control network has a rate greater or equal than 10 Mpbs. The information network is a double redundant hot standby self-adapted exchange mode Ether network with a transmission rate greater or equal than 100 Mpbs. In the lower LCU, a field bus is used to connect remote I/O and field intelligent monitor equipment with double redundancies. The transmission media is twisted-pair or optic fiber cable.
- The control functions of the local level are strengthened by using as many intelligent structures as possible, namely all remote I/O boards are configured with their own independent CPU. The power supplies are configured with a redundancy to raise reliability and to assure that the I/O boards can operate independently.

### 2.4.5.3 Main technical characteristics of the system

The main technical characteristics and requirements of relevant parameters are:

- *Integrality*
  The functional modules shall be relatively independent, so a fault of a certain functional module does not affect the functions of others.
- *Openness*
  For hardware, the possibility of adding functions to existing equipment and of adding new equipment to the system is given. The system software and application software can be expanded and updated easily.
- *Real time feature*
  a) The acquisition period, i.e. the time it takes from sending data from the computer supervisory control system of the station subsystem level until the main database of the cascade dispatch is refreshed, is less than 1.5 s for both analog and digital data. The refreshing period of the real time database is less than 2 s.
  b) The data of the two databases for the main and hot standby computers are kept strictly identical. The data input from a man-machine interface of the main computer is copied into the database of the hot standby computer within less than 1 s.

c) The time that it takes to send a command from the man-machine interface on the cascade dispatch control level to the local control level is less than 1 s.
d) The response time of the man-machine interface to recall new pictures is less than 1 s. The time for refreshing dynamic data on the pictures after updating the database is less or equal than 1 s. In case of any events, the time from the occurrence of the event until an alarm is sent and pictures are refreshed is less than 1 s.
e) When switching between the two redundant computers, it shall be ensured that no task is interrupted under the hot standby condition.

- *Reliability*
  For the cascade dispatch computer supervisory control system of the TGP, a fault of a single element of the interface equipment shall not affect the normal running of the system. The mean time between failures of the cascade dispatch computer supervisory control system is more than 16000 h for supervisory control equipment and more than 32000 h for single equipment.
- *Maintainability*
  Generally, the mean time to restore shall be 0.5-1 h, without consideration of the alert and transport time for technical support personnel. In case of a software fault, the fault module and the cause of the fault shall be recorded.
- *Availability*
  The availability index of the computer supervisory control system is more than 99.99%.
- *Security*
  Besides the operating system and database management system, the application software shall also have priority control for the security of the system. Different passwords are provided for maintenance personnel and operators, and the security levels shall meet the requirements of the users. In order to assure the operational security, checks and confirmations for the operation and control must be guaranteed. If the control order is not confirmed, it is allowed to cancel the control command. If the operator does not act within a certain timeframe, the control operation will automatically be cancelled. It is necessary to render the application software error tolerant, as a fault of any single hardware in the system shall not cause an improper operation of the controlled equipment. The CPU average load ratio of the computer shall not be more than 30%, and the maximum load ratio shall not be more than 70%. At any time, the usage ratio of the memory shall not be more than 50%.

#### 2.4.5.4 Communication of the computer supervisory control system

The communication of the computer supervisory control system can be divided into three parts:

1) As a water, power and navigation dispatch organization, it must accept dispatch orders from relative superior departments and make best use of them in a proper synthesis.
2) It must be able to receive the operating status, operating parameters and information of the subsystems and can perform control functions by sending down instruction information. This sort of information transfer, mainly from the power station and the spillway structures, requires strong real time features and high precision.
3) It is only supervised by the cascade dispatch system which it can obviously not control. As the amount of information exchanged between them is rather low, real time features are less important. According to the above characteristics, the communication system between the Three Gorges and Gezhouba, only 40 km apart, has been studied separately. Two schemes are selected and compared in Sect. 2.4.6. It is an independent high speed Ether network scheme of the computer supervisory control system and a SDH network scheme joint with the Three Gorges cascade dispatch communication system. In order to reduce interventions into the computer supervisory control system and to operate safely and reliably, an independent high speed Ether network is used. The navigation dispatch, meteorological information system (MIS), dam safety monitor and fire monitor systems, which have only supervision functions and whose requirements for real time are relatively low, will be merged into the Three Gorges SDH communication network.

## 2.4.6 Communication of the Three Gorges-Gezhouba cascade project

### 2.4.6.1 Functions of the communication system

According to the variety of transmitted information, the functions of the communication system for Three Gorges-Gezhouba cascade project involve:

1) In order to realize the integrated dispatch of flood control, electricity generation, shipping with the biggest comprehensive benefits, commands via voice, data and image given by the higher departments from Beijing and the major cities of the Southwest must be received in time. Other information such as meteorology, hydrology and water levels are also transmitted by the communication system.
2) The Three Gorges-Gezhouba cascade power station is not only the key power station of the power system, but also the relay point of electric power from West to East. To guarantee a safe and reliable operation of the power system, the transmission of supervision information and other informations of telecontrolling, telemetering and relay protection setting must be transmitted without blocking.
3) Dispatch communication and administration communication is also provided.
4) Connection to the regional communication network for exchange of information.

Summed up, the Three Gorges-Gezhouba communication system is a multi-user and multi-purpose system covering a wide region.

### 2.4.6.2 Scheme of the communication system

When designing and creating the Three Gorges-Gezhouba communication system, the development of modern communication technology must be taken into account, such as:

- a digitalized self-healing SDH information transmission network has been adopted extensively;
- the carrier communication extensively adopted in the 1980s has now been mostly replaced by communication through optical overhead ground wire (OPGW);
- analog transmission has been replaced by digitalized transmission etc.

Our goal is to use modern communication and network technology to form the internal and external communication system of the cascade project. The communication system should be unblocked, accurate and reliable with a complete set of functions. Based on multi-scheme research, we think that the design of the communication system should comply with the following principles:

1) For safety and reliability, the communication method must be available any time.
2) An independent communication channel shall be formed by utilizing the communication facilities which are established in the Yichang area such as the microwave projects of the electric power system and water conservancy. Furthermore, a satellite communication system shall be established as a standby communication channel to connect the Three Gorges with Beijing, Wuhan and other districts.
3) A complete construction communication system has already been established. In order to avoid a repeated construction and to save investment, the design scheme of the permanent communication system must somehow incorporate the construction communication system.
4) When setting the nodes of the communication network, some peculiarities of the Three Gorges-Gezhouba cascade project must be considered. As an example, there are so many separately arranged buildings in the project that the types and quantities of the communication equipment required are various. Furthermore, operation and management of each main building are different,

so the requirements for transmitted information and the amount of exchanged information are not the same.

5) For safety and reliability, the main trunk must be equipped with standby alive. According to the requirements, equipment in the communication network such as microwave, optical fiber, electric power line carrier, satellite, mobile communication, SPC etc. is equipped.

The Three Gorges-Gezhouba cascade project communication system is composed of multiple network nodes connected by optical cables. The choice of nodes is crucial for the flexibility, life and safety of the entire communication network, therefore the regional distribution and the realization of the functions should be considered carefully when choosing the nodes. There can never be too many nodes, and they help making the network clear. From research, 7 nodes are considered reasonable in the Three Gorges-Gezhouba cascade project. They are placed in the Three Gorges left and right bank power station, the Cascade Dispatch Center, CTGPC at Yichang Xiba, the big Gezhouba river power plant, the second Gezhouba river power plant and the Gezhouba 550 kV switch station. The node in the Cascade Dispatch Center represents the communication center of the Three Gorges-Gezhouba cascade project. The communication equipment of other buildings is merged into nearby nodes. After the determination of the communication nodes and under the SDH system of the network structure, two different schemes for district self-healing rings, a big one and a small one, have been studied. The reliability of the big one is higher than that of the small one, its network structure is simpler and management and maintenance are more convenient. So the big district self-healing ring with SDH transmission was chosen. In the communication scheme of the Three Gorges and Gezhouba cascade project, an SDH optical fiber ring net is used as the main transmit channel, and an SDH microwave is used as standby channel. A digital communication network is established with the left bank junction communication center as a tandem connecting center and to combine the wired and wireless communication equipments. The network's topological diagram of the communication system of the Three Gorges cascade dispatch is shown in Fig. 2.4.12.

### 2.4.6.3 Supervision and management system of communication network

The Three Gorges-Gezhouba cascade project communication network has a great scale, a large quantity and separate arrangements of the communication equipment. To guarantee a reliable operation of the communication system and reduce the amount of personnel for communication maintenance and operation, it is necessary and reasonable to establish a high performance supervision and management system in the communication center, which contains advanced and reliable supervision equipment and easy to use software with the complete functions:

1) Raising the efficiency of operation and partially selecting the communication network under the unified management and operation;
2) Enhancing the abilities of the on-time inspection and management commander to accurately achieve the operational status of the communication network;
3) Discovering faults in time, adjusting communication circuits and removing faults in order to reduce the time of outage for inspection and the number of people for operation and maintenance;
4) Sending signals of the running status of the communication equipments to the Cascade Dispatch Center to inform them about the operation conditions of the communication channels and equipment.

To realize these functions, a layered and distributed structure is adopted in the communication supervision and management system. The main station is set up in the Three Gorges Cascade Dispatch Center. The junction supervision stations are set up in the right bank power station and the dispatch center. Furthermore, spot monitor stations are established according to the zone where the communication equipment is placed. Each monitor station sends its data to both the junction station and the main station.

## 2.4.7 Electric drive and control of the double-line continuous 5-level ship lock

The double-line continuous 5-level ship lock of the TGP comprises 6 lock heads and 5 lock chambers. The whole length is 1607 m and the effective size of the lock chamber is 280×34×5 m. The maximum rising height is 113 m; the single direction transportation capacity per year is 50 Mt. During half of the year, ship convoys of 10000 t can pass the lock. Generally, a single direction passing mode can be adopted, i.e. one line will be used for passing downstream, the other one for passing upstream. When one line is repaired, the other line will be run with in single direction batch passing mode, i.e. the passing direction will be exchanged and both lines can be passed in two directions. In order to realize automatic control of the double-line continuous 5-level ship lock to guarantee safety and continuity of the operation, the electric and mechanic design must resolve technical questions such as electric driving and control of the miter gates and the culvert valves, operating and control of the whole ship lock, ship detection and water level detection.

### 2.4.7.1 Electric drive and control of miter gates and the culvert valves

The entry and exit of ships is implemented by closing and opening the miter gates of the lock heads and the culvert valves which control the water level of the adjacent lock chambers. The electric drive and control of the miter gates and the culvert valves is the key to guarantee a smooth navigation of the ship lock. The height, width and weight of the miter gate are 38.5 m, 22.01 m and 850 t, the maximum water depth is 36 m. All miter gates use straight link type hydraulic hoists for operation. The capability curve of straight link type hydraulic hoists has the peculiarity that the two ends of the curve are low and the middle of the curve is arched upwards. In operation, a resistance moment peak of the miter gate is produced in the start phase of opening or closing. There are discussions concerning the capability curve of hydraulic hoists about how to adapt the resistance moment peak. For multi level continuous ship locks, the reverse water head should increase in front and behind the gates due to an extra discharge of the up level chamber and an extra fill of the low level chambers. Studies show that decreasing the acceleration and speed in the start phase of opening or closing the gates will significantly reduce the operating resistance moment peak and make it match the capacity curve of the hydraulic hoist. As straight link type hydraulic hoists are used to operate the miter gates, it is very important to carefully select $v$-$t$ (or $v$-$a$, with $a$ the opening degree of the miter gate) of operation process. If the selection is right, the driving force of the hydraulic hoist can be fully used both during opening and closing time, especially in the upper protrusive part. The operation curve in Fig. 2.4.13 was finally selected after studying and testing many schemes of $v$-$t$ process operation curves. A programmable logical controller (PLC), whose control program can be changed flexibly and whose performance is stable, was selected for the control. It has no direct connections, has strong control functions and is suitable for severe environment.

The culvert valves will be operated with hydraulic hoists. As the miter gate and the culvert valve at each side of the lock head are operated at different times, they will use the same hydraulic pump station to reduce equipment cost. The opening and closing time of the culvert valve directly affects the amount of extra charge and discharge water of the lock chamber, so the control of the operating time for the culvert valve is very important. In order to reduce the positive water level difference in front and behind the miter gate to an acceptable value, the culvert valve is closed earlier by a time determined by tests. The control of the culvert valve and the miter gate is incorporated.

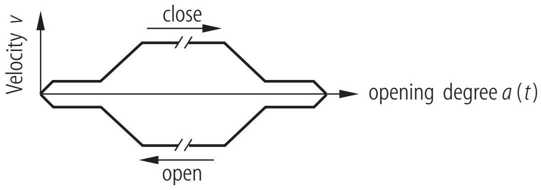


**Fig. 2.4.13.** Operation velocity of a $\lambda$-type gate.

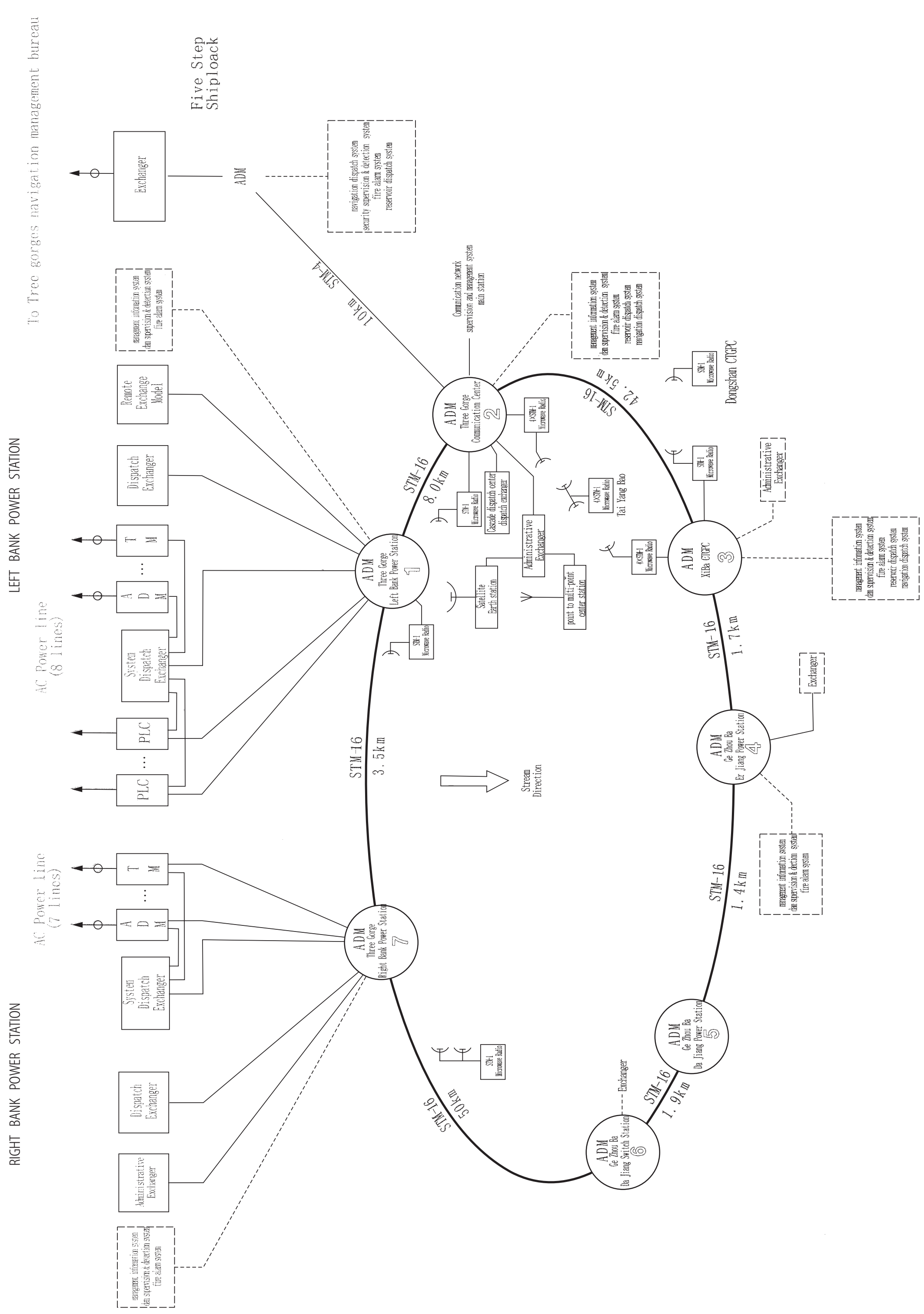


**Fig. 2.4.12.** Topological diagram of the Three Gorges-Gezhouba communication system. Circles indicate the nodes of the communication system, dotted lines indicate other systems; ADM - Add/drop multiplexer of the communication system; TM - Terminal multiplexer of the communication system.

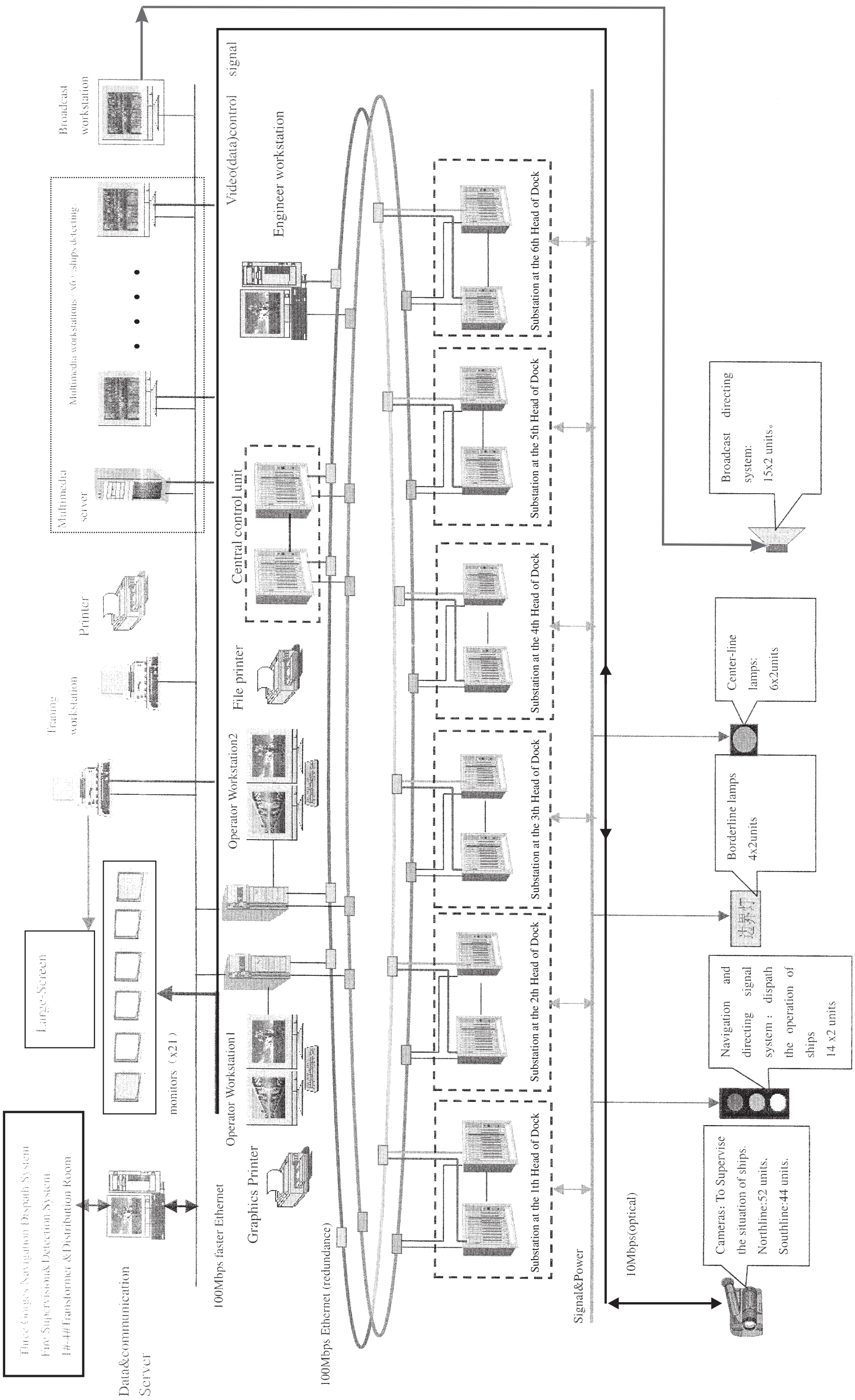


**Fig. 2.4.14.** Structure of the computer supervision and control system of the double-way five-step permanent ship lock.

#### 2.4.7.2 Central auto supervisory control of integral operation for the permanent ship lock

According to the general construction schedule of the TGP, navigation will begin as soon as the water level reaches 135 m. At that time the third phase of the project will be under construction. Once the project is completed, the normal impoundment water level is 175 m, so the temporary variation of the water level is up to 45 m. According to the main navigation conditions of double-line continuous 5-level ship locks explained above, the following characteristics shall be considered when designing and studying the central auto supervisory control system of integral operation:

- High level number of the ship lock;
- Distance up to 1.6 km;
- Complex technology of passing the lock;
- Various operating modes;
- Large quantity of equipment that is widely located;
- Severe environment conditions (large humidity and temperature differences, foggy weather).

The functions of the central supervisory control system for integral operation are:

1) A control command will be sent to the local stations to acquire operation conditions and information of the local stations. The passing process will be supervised and controlled automatically. Each level can run sequentially and continuously according to the navigation conditions, the operation mode, the technology to pass the lock and logical relations of interlock protection conditions between the one-line ship lock and the valve.
2) The operation program can be changed (including different level numbers and directions, water transportation mode, if water needs to be complemented etc.) according to variations of the upstream water level and the condition of ships waiting to pass the ship lock.
3) The local station has automatic and manual supervisory control functions and emergency functions to stop the machines in case of failure and fault. The local mechanical, electric and hydraulic equipment of this station will be controlled and protected strictly according to the interlock protection conditions between adjacent local gates and valves by the local control station.
4) The operation process and operating parameters of various equipments can be displayed both dynamically and statically. At the same time, there are functions for status test and fault diagnosis of equipment, alarm display and record archive as well as excellent database and data processing functions.
5) The system can trace and display integral pictures and pictures of locally restricted windows during operation.
6) It can emulate a real operation under various conditions, debug and check the operating programs in order to train the operation and management personnel.
7) It has protection functions in case of abnormal operation conditions.

In order to realize the above functions, the computer supervisory control system uses a hierarchically distributed control structure. The whole system is divided into a local control layer (including 24 local sending stations), a central control layer and an information management layer. The topological diagram of central supervisory control system of the continuous 5-level ship lock is shown in Fig. 2.4.14. In addition, systems such as industrial TV, ship detection, water level monitor, navigation command signal, navigating broadcast command, communication, data acquirement etc. are installed to fully monitor the operation conditions of the ship lock. In order to monitor the water levels of the adjacent lock chambers, a total of 12 water test wells are mounted for each ship lock at the upstream and downstream sides of each gate. As a pressure sensor, water level measurement sensors are used that have a measurement error within ± 1 cm in a range of 40 m.

During the operation process of the continuous 5-level ship lock, the step of opening or closing the corresponding miter gates can only be initiated after making sure that ships in the lock chamber have passed upstream or downstream into the adjacent lock chamber. So, achieving a correct judgment whether there are ships in the ship lock chamber is very important. For this reason, industrial TV imaging technology, laser detection technology, radar and microwave detection technology, and non-refrigeration hot imaging instrument detection technology etc. are tested and studied. At present, industrial TV imaging technology is adopted in the project. Under all weather conditions, the error rate is a ten thousandth, which does not match the requirements of a hundred thousandth. This question is still being studied and will be resolved.

### 2.4.8 Economical aspects of the Three Gorges Project

Here, only a short tabular survey of the investment cost of the TGP is given. The estimated total investment cost of 117.621 billion Yuan (13.5 billion US$, based on prices of 1993) can be divided into

- 50.09 billion Yuan (5.75 billion US$) for construction of the plant,
- 39.999 billion Yuan (4.59 billion US$) for resettlement,
- 27.532 billion Yuan (3.16 billion US$) for power transformation and transmission.

This total investment is leading to an investment per installed electric power of 741.8 US$/$kW_{inst}$.

### Acknowledgement

I am much honored to be invited by Prof. Dr. Klaus Heinloth to write an article about the mechanical and electrical design for the Yangtze River Three Gorges Project, China. The Project is not only huge in scale, listed as a super project in the world by the United Nations, but also plays an important role in the Chinese national economy due to tremendous synthetical benefits in flood control, power generation and navigation after completion. The TGP is a key project in controlling and harnessing the Yangtze River, which is the third largest river in the world. From the middle of 1950s to present, more than half a century of extensive efforts have been made to choose the location of the project, accumulate hydrological information, geological reconnaissance, to plan and design, and scientific research has been done for major problems to realize the aim of constructing a top-ranking project as soon as possible. The design for the main structures of the project is undertaken by Changjiang Water Resources Commission (CWRC). With the help of experts from all over the world, several generations from CWRC worked hard with their shoulders to collars and devoted their lives to the project. The project is world-famous, involving wide specific fields, rich contents and brilliant achievement. As the article is restrained, only a part of the mechanical and electrical designs, which have been adopted or are under construction, are introduced here. Hydraulic and electrical experts from all over the world are very welcome to visit the project, though.