



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION



Technical Guidelines for the
Development of Small Hydropower Plants
DESIGN

**Part 6-1: Hydraulic Machinery
and Turbine Generator**

SHP/TG 002-6-1: 2019



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ACKNOWLEDGEMENTS

The technical guidelines (TGs) are the result of a collaborative effort between the United Nations Industrial Development Organization (UNIDO) and the International Network on Small Hydro Power (INSHP). About 80 international experts and 40 international agencies were involved in the document's preparation and peer review, and they provided concrete comments and suggestions to make the TGs professional and applicable.

UNIDO and the INSHP highly appreciate the contributions provided during the development of these guidelines and in particular those delivered by the following international organizations:

- The Common Market for Eastern and Southern Africa (COMESA)
- The Global Network of Regional Sustainable Energy Centres (GN-SEC), particularly the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE), the East African Centre for Renewable Energy and Energy Efficiency (EACREEE), the Pacific Centre for Renewable Energy and Energy Efficiency (PCREEE) and the Caribbean Centre for Renewable Energy and Energy Efficiency (CCREEE).

The Chinese government has facilitated the finalization of these guidelines and was of great importance to its completion.

The development of these guidelines benefited greatly from the valuable inputs, review and constructive comments as well as contributions received from Mr. Adnan Ahmed Shawky Atwa, Mr. Adoyi John Ochigbo, Mr. Arun Kumar, Mr. Atul Sarthak, Mr. Bassey Edet Nkposong, Mr. Bernardo Calzadilla-Sarmiento, Ms. Chang Fangyuan, Mr. Chen Changjun, Ms. Chen Hongying, Mr. Chen Xiaodong, Ms. Chen Yan, Ms. Chen Yueqing, Ms. Cheng Xialei, Ms. Chileshe Kapaya Matantilo, Ms. Chileshe Mpundu Kapwepwe, Mr. Deogratias Kamweya, Mr. Dolwin Khan, Mr. Dong Guofeng, Mr. Ejaz Hussain Butt, Ms. Eva Kremere, Ms. Fang Lin, Mr. Fu Liangliang, Mr. Garaio Donald Gafiye, Mr. Guei Guillaume Fulbert Kouhie, Mr. Guo Chenguang, Mr. Guo Hongyou, Mr. Harold John Annegam, Ms. Hou ling, Mr. Hu Jianwei, Ms. Hu Xiaobo, Mr. Hu Yunchu, Mr. Huang Haiyang, Mr. Huang Zhengmin, Ms. Januka Gyawali, Mr. Jiang Songkun, Mr. K. M. Dhareesan Unnithan, Mr. Kipyego Cheluget, Mr. Kolade Esan, Mr. Lamyser Castellanos Rigoberto, Mr. Li Zhiwu, Ms. Li Hui, Mr. Li Xiaoyong, Ms. Li Jingjing, Ms. Li Sa, Mr. Li Zhenggui, Ms. Liang Hong, Mr. Liang Yong, Mr. Lin Xuxin, Mr. Liu Deyou, Mr. Liu Heng, Mr. Louis Philippe Jacques Tavernier, Ms. Lu Xiaoyan, Mr. Lv Jianping, Mr. Manuel Mattiat, Mr. Martin Lugmayr, Mr. Mohamedain SeifElnasr, Mr. Mundia Simainga, Mr. Mukayi Musarurwa, Mr. Olumide TaiwoAlade, Mr. Ou Chuanqi, Ms. Pan Meiting, Mr. Pan Weiping, Mr. Ralf Steffen Kaeser, Mr. Rudolf Hüpfel, Mr. Rui Jun, Mr. Rao Dayi, Mr. Sandeep Kher, Mr. Sergio Armando Trelles Jasso, Mr. Sindiso Ngwenga, Mr. Sidney Kilmete, Ms. Sitraka Zarasoa Rakotomahefa, Mr. Shang Zhihong, Mr. Shen Cunke, Mr. Shi Rongqing, Ms. Sanja Komadina, Mr. Tareqemtairah, Mr. Tokihiko Fujimoto, Mr. Tovoniaina Ramanantsoa Andriampaniry, Mr. Tan Xiangqing, Mr. Tong Leyi, Mr. Wang Xinliang, Mr. Wang Fuyun, Mr. Wang Baolu, Mr. Wei Jianghui, Mr. Wu Cong, Ms. Xie Lihua, Mr. Xiong Jie, Ms. Xu Jie, Ms. Xu Xiaoyan, Mr. Xu Wei, Mr. Yohane Mukabe, Mr. Yan Wenjiao, Mr. Yang Weijun, Ms. Yan Li, Mr. Yao Shenghong, Mr. Zeng Jingnian, Mr. Zhao Guojun, Mr. Zhang Min, Mr. Zhang Liansheng, Mr. Zhang Zhenzhong, Mr. Zhang Xiaowen, Ms. Zhang Yingnan, Mr. Zheng Liang, Mr. Mr. Zheng Yu, Mr. Zhou Shuhua, Ms. Zhu Mingjuan.

Further recommendations and suggestions for application for the update would be highly welcome.

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Foreword

The United Nations Industrial Development Organization (UNIDO) is a specialized agency under the United Nations system to promote globally inclusive and sustainable industrial development (ISID). The relevance of ISID as an integrated approach to all three pillars of sustainable development is recognized by the 2030 Agenda for Sustainable Development and the related Sustainable Development Goals (SDGs), which will frame United Nations and country efforts towards sustainable development in the next fifteen years. UNIDO's mandate for ISID covers the need to support the creation of sustainable energy systems as energy is essential to economic and social development and to improving quality of life. International concern and debate over energy have grown increasingly over the past two decades, with the issues of poverty alleviation, environmental risks and climate change now taking centre stage.

INSHP (International Network on Small Hydro Power) is an international coordinating and promoting organization for the global development of small hydropower (SHP), which is established on the basis of voluntary participation of regional, subregional and national focal points, relevant institutions, utilities and companies, and has social benefit as its major objective. INSHP aims at the promotion of global SHP development through triangle technical and economic cooperation among developing countries, developed countries and international organizations, in order to supply rural areas in developing countries with environmentally sound, affordable and adequate energy, which will lead to the increase of employment opportunities, improvement of ecological environments, poverty alleviation, improvement of local living and cultural standards and economic development.

UNIDO and INSHP have been cooperating on the World Small Hydropower Development Report since year 2010. From the reports, SHP demand and development worldwide were not matched. One of the development barriers in most countries is lack of technologies. UNIDO, in cooperation with INSHP, through global expert cooperation, and based on successful development experiences, decided to develop the SHP TGs to meet demand from Member States.

These TGs were drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of these TGs may be subject to patent rights. UNIDO and INSHP shall not be held responsible for identifying any such patent rights.

Introduction

Small Hydropower (SHP) is increasingly recognized as an important renewable energy solution to the challenge of electrifying remote rural areas. However, while most countries in Europe, North and South America, and China have high degrees of installed capacity, the potential of SHP in many developing countries remains untapped and is hindered by a number of factors including the lack of globally agreed good practices or standards for SHP development.

These Technical Guidelines for the Development of Small Hydropower Plants (TGs) will address the current limitations of the regulations applied to technical guidelines for SHP Plants by applying the expertise and best practices that exist across the globe. It is intended for countries to utilize these agreed upon Guidelines to support their current policy, technology and ecosystems. Countries that have limited institutional and technical capacities, will be able to enhance their knowledge base in developing SHP plants, thereby attracting more investment in SHP projects, encouraging favourable policies and subsequently assisting in economic development at a national level. These TGs will be valuable for all countries, but especially allow for the sharing of experience and best practices between countries that have limited technical know-how.

The TGs can be used as the principles and basis for the planning, design, construction and management of SHP plants up to 30 MW.

- The Terms and Definitions in the TGs specify the professional technical terms and definitions commonly used for SHP Plants.
- The Design Guidelines provide guidelines for basic requirements, methodology and procedure in terms of site selection, hydrology, geology, project layout, configurations, energy calculations, hydraulics, electromechanical equipment selection, construction, project cost estimates, economic appraisal, financing, social and environmental assessments—with the ultimate goal of achieving the best design solutions.
- The Units Guidelines specify the technical requirements on SHP turbines, generators, hydro turbine governing systems, excitation systems, main valves as well as monitoring, control, protection and DC power supply systems.
- The Construction Guidelines can be used as the guiding technical documents for the construction of SHP projects.
- The Management Guidelines provide technical guidance for the management, operation and maintenance, technical renovation and project acceptance of SHP projects.

Technical Guidelines for the Development of Small Hydropower Plants-Design

Part 6-1: Hydraulic Machinery and Turbine Generator

1 Scope

This Part of Design Guidelines specifies the type selection and arrangement of the main and auxiliary hydraulic machinery, the type selection and arrangement of the turbine as well as the selection of the heating, ventilation and fire protection systems of an small hydropower (SHP) station.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

SHP/TG 001, *Technical guidelines for the development of small hydropower plants—Terms and definitions*.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TR 61364 and SHP/TG 001 apply.

4 Turbine

4.1 General requirements for turbine type selection

4.1.1 The type and basic parameters of the turbine shall be selected on the basis of technical and economic comparison in accordance with the hydraulic energy parameters, the layout and operating characteristics of the hydropower station, the technical features, economic indexes, operation reliability, technical level of the design and manufacture, the transportation and in combination with the site conditions.

4.1.2 The turbine type selection shall include the following contents:

- a) Selection of the type and installation mode;
- b) Selection of the number of installed units and the unit capacity;
- c) Selection of the rated head of the turbine;
- d) Selection of the basic parameters of the turbine, including the shaft power, runner diameter, rated speed, rated discharge, efficiency, static suction head and the setting elevation. For the impulse turbine, the jet diameter, number of nozzles and the static discharge head shall be selected;
- e) Selection of the appropriate model runner and the plotting of the turbine operating characteristic curve;
- f) Estimation of the overall dimensions, weight and cost of the main components of the turbine.

4.1.3 Basic information for turbine selection shall include:

- a) Turbine net head (including the maximum head, the minimum head and the weighted average head);
- b) The operating discharge of the hydropower plant (the sum of the discharges enter into each turbine in a hydropower plant);
- c) Installed capacity of the hydropower station;
- d) Upstream/downstream water level;
- e) Parameters of the power generation and water conductor systems (including the arrangement, length, pipe diameter and head losses of all water conductor systems from the water inlet for the generation to the tailwater outlet of the hydropower station);
- f) Tailwater level-discharge relation curve;
- g) Firm output of the hydropower station, the power weighting factor can be provided when necessary;
- h) Operation mode of the hydropower station in the power system, and reservoir operation and regulation modes;

- i) Quality of the water passing through the turbine (including the sediment concentration through the turbine, the particle size grading, Moh's hardness, mineral composition, pH value and water temperature);
- j) Meteorological conditions of the hydropower station (including the air temperature, water temperature and relative humidity);
- k) Geographic position of the hydropower station (including the sea level elevation, atmospheric pressure and gravitational acceleration of powerhouse).

4.2 Selection of the rated head

4.2.1 The rated head of turbine shall be selected through technical and economic comparison in accordance with the head variation of the hydropower station, the regulating characteristic of the reservoir, the stable operation requirements of the unit, the operation mode of the hydropower station in the power system and the characteristics of the power generation and water conductor systems.

4.2.2 As for the hydropower station with the medium/high head, the rated head should be selected within the range of 0.85 to 0.95 times the weighted average head.

4.2.3 As for the run-of-river hydropower station, the rated head shall guarantee that the installed capacity of the hydropower station is fully used for generating power.

4.2.4 As for the hydropower station in the muddy river with the operation mode of "storing clear water and discharging muddy water", the rated head should be selected within the range between the weighted average head and the lower limit productive head in the storage period of the reservoir.

4.2.5 When the rated head is close to the minimum head, it is necessary to demonstrate its rationality and economical efficiency. With regard to the impulse turbine with high head and small variation of the reservoir water level, the minimum head may be used as the rated head of the turbine.

4.3 Turbine type selection

4.3.1 The turbine type selection shall meet the following requirements:

- a) The turbine type shall be selected within the operation head range in accordance with the basic principles in 4.1. The common turbine types and the applicable head range shall meet the requirements in Table 1.

Table 1 Turbine types and the applicable head range

Turbine type			Applicable head range (m)
Classified as per the energy conversion mode	Classified as per the flow direction	Classified as per the structural feature	
Reaction turbine	Tubular turbine	Bulb turbine	2~30
		S-type turbine	
		Pit turbine	
		Rim-generator turbine	
	Axial flow turbine	Propeller turbine	2~60
		Kaplan turbine	
Diagonal turbine		40~120	
Francis turbine		25~450	
Impulse-type turbine	Pelton turbine		60~1 300
	Inclined-jet turbine		50~250
	Crossflow turbine		5~200
<p>NOTE The applicable head range is the parameter under normal conditions. The selection of small turbine may be determined through comprehensive comparison according to the specific situation and the special requirements of the different projects. The applicable head range for the various types of units in the same head section may be appropriately broadened.</p>			

- b) As for the run-of-river hydropower station with a maximum head of 20 m or lower and a unit capacity of more than 10 MW, the tubular turbine should be selected by preference.
- c) When there are two applicable turbine types under the same head, the selection shall be made by technical and economical comparison in the respect of the technical characteristic parameters, the economic indicators, operational reliability and the design and manufacturing difficulty.

4.3.2 The selection of model runner shall meet the following requirements:

- a) The model runner should be selected in combination with the selected turbine type and the comparison should be carried out according to the operation head of the hydropower station, and a reliable model runner with mature technology should be used after appropriate technical and economical comparison of the basic parameters of the turbine.
- b) The model runner shall have relatively higher energy and cavitation performance, and its performance shall be free from any obvious pressure pulsation or cavitation erosion under all operating conditions.
- c) For the hydropower station in the muddy river, it is necessary to select the model runner with a

relatively lower rotational speed; for the hydropower station with big head variation, it is necessary to select the model runner with wider stable operating range; for the hydropower station in high altitude localities, it is necessary to select the model runner with the appropriate cavitation performance in combination with the setting elevation factors.

4.3.3 The layout of the vertical shaft and horizontal shaft Francis turbines and impulse turbines shall be combined with the single unit capacity, the diameter of the runner, and the appropriate speed and plant layout for a comprehensive comparison. The horizontal shaft should be preferred for SHPs.

4.4 Selection of the basic parameters of the reaction turbine

4.4.1 The basic parameters of the reaction turbine shall be selected after the primary selection of the unit capacity, rated head and model runner; the main parameters include runner diameter, rated speed, rated discharge, rated efficiency, rated power, static suction head, maximum runaway speed, maximum head, minimum head, design head and the weighted average efficiency.

4.4.2 A reasonable scheme of the basic parameters of turbine shall be selected from a number of different combinations of the parameters by technical and economic comparison combined with the power station layout, the actual topography and geological conditions, the operating water head range and the reservoir regulation characteristics, as well as the technical characteristics, economic indicators, operational reliability, and design and manufacturing technology level.

4.4.3 After determining the main parameters of the turbine, the turbine operating performance curve including the equal efficiency curve, equal cavitation curve and output limitation curve should be drawn.

4.4.4 The axial hydraulic thrust and the weight of main components should be estimated.

4.4.5 The turbine shall have higher weighted average efficiency and the operating range shall include the high efficiency area. In the working head range, the turbine shall have a good overall operating condition and no obvious vibration area.

4.4.6 The static suction head and setting elevation of the turbine shall be determined according to the following requirements:

- a) The static suction head of the reaction turbine shall be respectively calculated in accordance with the operating conditions under the different characteristic heads and their corresponding initial cavitation coefficients σ_i . If no initial cavitation coefficient σ_i is available, it may be calculated by multiplying the critical cavitation coefficient by the ratio coefficient $K\sigma$.
- b) Under the condition that the power plant units share the tail water pool, when 1 or 2 units are installed, the requirements of the static suction head and the tailwater level of a unit at 50% maximum output operation under various water heads should be satisfied; when more than

2 units are installed, the requirements of the static suction head and the tailwater level of one unit at maximum output operation under various water heads should be satisfied.

- c) To determine the design tailwater level of the setting elevation, factors such as the relationship between tailwater level and discharge, initial generation requirements, flood control requirements and operational water level of the downstream cascade power stations shall be considered comprehensively.
- d) The setting elevation of the turbine shall meet the requirements for the static suction head and the corresponding tailwater level under various operating conditions, and shall comply with the requirements that the minimum submerged depth of the upper edge of the draft tube (or the tailrace tunnel, excluding the tailrace tunnel with sloping ceiling) outlet shall not be less than 0.3 m to 0.5 m.
- e) The installation elevation shall be determined by technical and economic comparison on the basis of the actual topographic and geological conditions of the project, the layout of the plant and other factors.

4.4.7 The maximum runaway speed of the Francis or propeller turbine shall be determined by the maximum net water head and the maximum unit runaway speed. The maximum runaway speed of the Kaplan turbine shall be calculated according to the combined relationship. When there are special requirements, it may be calculated according to the damage from the combined relationship.

4.4.8 The turbine runner diameter shall be calculated by the Formula (1).

$$D_1 = \sqrt{\frac{N_f}{9.81 Q'_1 H_{sj}^{1.5} \eta_T \eta_f}} \dots\dots\dots (1)$$

where

D_1 is the nominal diameter of runner, in m;

N_f is the rated power of generator, in kW;

Q'_1 is the unit discharge under design conditions, in m³/s;

H_{sj} is the rated head, in m;

η_T is the prototype turbine efficiency;

η_f is the rated efficiency of generator.

4.4.9 The rated speed shall be calculated by the Formula (2):

$$n_r = \frac{n'_1 \sqrt{H_{pj}}}{D_1} \dots\dots\dots (2)$$

where

n_r is the rated speed, in r/min;

n'_1 is the unit speed, in r/min; $(1 - 1.05) n'_{10}$ is taken for Francis turbine; $1.1 n'_{10}$ is taken for high specific speed axial-flow turbine;

H_{pj} is the weighted average head, in m.

4.4.10 See Appendix A for reference formulas for the rated discharge Q_r , static suction head H_s , setting elevation ∇ of the turbine and the correction calculation of the reaction turbine efficiency.

4.5 Selection of basic parameters of the Pelton turbine

4.5.1 The basic parameters of the Pelton turbine shall be selected after the primary selection of the unit capacity, rated head and model runner; the main parameters include the rated head, rated speed, rated discharge, rated power, pitch diameter, jet diameter, ratio of runner diameter to jet diameter (m -value), bucket numbers, rated efficiency, maximum head, minimum head, design head, runaway speed and static discharge head. The selection of the basic parameters of the turbine shall be determined through technical and economic comparison.

4.5.2 After the main parameters of the turbine are determined, the turbine operating performance curves including the turbine output limitation curve and the equal efficiency curve shall be drawn.

4.5.3 The basic parameters of the Pelton turbine may be calculated with the fixed specific speed method, and converted by the combined model characteristic curve, or calculated with the variable specific speed method.

4.5.4 The number of nozzles of the Pelton turbine is usually 1, 2 or 4; the number of nozzles shall be selected with consideration given to the arrangement of the nozzles to avoid the mutual interference of the jet flow.

4.5.5 When selecting the number of buckets, it is necessary to avoid the jet flow funnel phenomenon, meanwhile the arrangement and processing of the buckets shall be taken into account.

4.5.6 As for the multi-nozzle turbines, the jet flow intersection angle shall not be a multiple integer of the intersection angle between the adjacent buckets.

4.5.7 For ensuring the relatively high efficiency of the turbine, m -value should be selected in the range of 10 to 20; when selecting the m -value, the manufacturing mode of the runner and the

strength of the bucket shall be considered; usually, the large value should be taken for the high head and the small value should be for the low head.

4.5.8 When calculating the unit discharge of the turbine, the difference of the m -value between the real turbine and the model turbine shall be considered; its unit discharge may be converted by the Formula (3):

$$Q''_1 = (m/m_M)^2 \times Q'_1 \quad \dots\dots\dots(3)$$

where

Q''_1 is the unit discharge of the model turbine, in m^3/s ;

Q'_1 is the unit discharge of the real turbine, in m^3/s ;

m is the m -value of the real turbine;

m_M is the m -value of the model turbine.

4.5.9 The efficiency of the Pelton turbine may not be corrected. When the m -value of the turbine exceeds the range of 10 to 20, about 0.5% negative correction may be considered.

4.5.10 The operation range of the turbine shall include the high efficiency area.

4.5.11 The maximum unit runaway speed of the Pelton turbine may be 70 r/min. the maximum runaway speed should be determined according to the maximum water head conditions.

4.5.12 The static discharge head of the Pelton turbine shall be selected to ensure the safe and stable operation of the turbine, avoid the influence of the tailwater surge and keep sufficient ventilation height for the tailrace at the maximum tailwater level and under any power generating condition of the hydropower station.

4.5.13 The static discharge head shall be the diameter(1 to 1.5) D_1 of the runner pitch circle. The horizontal shaft unit should take a small value, and the vertical shaft unit should take a large value. When determining the static discharge head, the necessary ventilation height shall be ensured, and the ventilation height should be no less than 300 mm.

4.5.14 The runner diameter and the m -value shall be calculated by the Formula (4) and the Formula (5):

$$D_1 = \frac{(39 \sim 40) \sqrt{H_{sj}}}{n_r} \quad \dots\dots\dots(4)$$

$$m = \frac{D_1}{d_0} \dots\dots\dots (5)$$

where

D_1 is the pitch diameter of the bucket, in m;

m is the ratio of the runner diameter to the jet diameter.

The m -value should be in the range of 10 to 20. Small value should be taken for the low head and large value should be taken for the high head.

4.5.15 See Appendix B for the reference formulas for the estimation of the jet diameter d_0 , rated speed n_r , nozzle diameter d_p and the number of buckets Z_1 of the Pelton turbine and the calculation of the static discharge head h_p and setting elevation ∇ .

4.5.16 The basic parameters of the inclined-jet turbine may be selected with reference to the requirements in this section.

4.6 Unit transient performance analysis

4.6.1 Calculation of turbine transient performance shall be conducted according to the main electrical connection mode of the hydropower station, the power grid requirements, type and parameters of the water conductor system of the hydropower station, the characteristics and parameters of the turbine generator units as well as the operating conditions.

4.6.2 As for the hydropower station with bifurcated/trifurcated penstocks, the maximum speed increase rate of the units and the maximum pressure increase rate at the end of the spiral casing shall be calculated according to the number of units connected to the main penstock and the main electrical connection mode, as well as the number of units that may be simultaneously perform load rejection.

4.6.3 As for the hydropower station with a relatively simpler power generation and water conductor system, the calculation of the turbine transient performance may be conducted by the empirical formula, and with the numerical method or analytical method; as for the hydropower station with a complex water conductor system, the calculation shall be made by computer simulation.

4.6.4 Axial-flow and tubular turbine units may be equipped with a two-stage closing device.

4.6.5 The water flow inertia time constant T_w of the water conductor system without a pressure regulating facility shall not be greater than 4 s; the inertia time constant T_a of the reaction turbine unit shall not be less than 4 s and the inertia time constant T_a for the impulse turbine unit shall not be less than 2 s. The T_w/T_a ratio should not be greater than 0.4; if T_w/T_a ratio is greater than 0.4, the stability of the water diversion system and unit may be calculated in case of small fluctuations.

4.6.6 When calculating the rising ratio of the rotational speed of the axial-flow and tubular turbine units, it is necessary to include the influence of the inertia moment of the water flow; the calculation of turbine transient performance shall include the pressure of the reverse water hammer.

4.6.7 The guaranteed value of the maximum speed increase rate of the unit during the load rejection shall be selected according to the following different circumstances:

- a) The guaranteed value should be less than 50% when the unit capacity accounts for a large proportion of the total capacity of the power system or the unit is responsible for frequency modulation.
- b) The guaranteed value should be less than 60% to 65% when the proportion of the unit capacity to the total capacity of the power system is not large, or the unit is not responsible for frequency modulation.
- c) The maximum speed increase rate of the tubular turbine unit should be less than 65%.
- d) The maximum speed increase rate of the impulse turbine unit should be less than 30%.

4.6.8 In case of load rejection, the guaranteed value of the maximum pressure increase rate at the end of the spiral case (in front of the movable guide vane of the tubular turbine unit) shall be selected as per the following circumstances:

- a) The guaranteed value should be 70% to 100% if the rated head is less than 20 m.
- b) The guaranteed value should be 70% to 50% if the rated head is 20 m to 40 m.
- c) The guaranteed value should be 50% to 30% if the rated head is 40 m to 100 m.
- d) The guaranteed value should be 30% to 25% if the rated head is 100 m to 300 m.
- e) The guaranteed value should be less than 25% if the rated head is more than 300 m.

4.6.9 When the unit load suddenly increases or decreases, the minimum pressure at the highest point of all sections of the pressure conveyance system shall not be less than 0.02 MPa, and the negative pressure flow separation phenomenon shall not occur.

4.6.10 In case of load rejection, the maximum vacuum guaranteed value at the entrance section of the draft tube shall not be greater than 0.08 MPa.

5 Generator

5.1 General requirements for generator type selection

5.1.1 The generator shall be selected through technical and economic comparison mainly in accordance with the type and the parameters of the turbine and the requirements of the power system, and in combination with the parameters such as the unit output, rotational speed, unit configuration and layout determined during turbine selection.

5.1.2 The type selection for the generator shall include the following consideration:

- a) Rated power/apparent power of the generator (P_r/S_r);
- b) Rated voltage of the generator (U_r);
- c) Rated speed (n_r);
- d) Rated frequency (f_r);
- e) Rated power factor ($\cos\Phi$);
- f) Insulation grade;
- g) Exciting mode;
- h) Ventilation-cooling type of the generator;
- i) Moment of inertia of the generator (GD^2);
- j) Estimation of the dimensions, weight and cost of the main components of the generator.

5.1.3 The selection of generator shall be based on the following factors:

- a) Determine the power and rotational speed according to the turbine characteristics;
- b) Determine the voltage and power factor according to the requirements of the electrical power system;
- c) Determine the moment of inertia of the generator according to the calculation of the turbine transient performance of the hydropower station and the requirements of the power system;
- d) Determine the structural style of the generator according to the general situation.

5.2 Selection of rated data and main parameters

5.2.1 The generator power shall meet the following requirements:

- a) Relationship between the generator power and turbine output:
 - 1) Directly coupled unit: the rated power of the generator shall be equal to the rated output of the turbine multiplied by the generator efficiency;
 - 2) Booster unit: the rated power of the generator shall be equal to the rated output of the turbine multiplied by the booster efficiency and by the generator efficiency.

b) Priority selection series (MW) of generator rated power:

0.5, 0.63, 0.8, 1.0, 1.25, 1.6, 2.0, 2.5, 3.2, 4.0, 5.0, 6.3, 8.0, 10.0

5.2.2 The generator voltage shall meet the following requirements:

- a) The requirements of the national power grid.
- b) The selection of rated voltage shall consider the value range of the rated current. The rated current shall be calculated by the Formula (6):

$$I_r = \frac{1\,000P_r}{\sqrt{3}U_r\cos\varphi} \dots\dots\dots(6)$$

where

I_r is the rated current, in A;

P_r is the rated power, in MW;

U_r is the rated voltage, in V;

$\cos\varphi$ is the power factor.

5.2.3 The generator power factors shall meet the following requirements:

- a) The rated power factor may lag 0.8 or 0.92 under the premise of meeting the requirements of the power grid;
- b) The generator is allowed to operate in leading phase at rated power;

- c) It is preferable to select a higher power factor value when the system permits, select a lower value when the hydropower station is close to the load centre and select a higher value when the transmission distance is long.

5.2.4 The synchronous speed of the generator shall meet the following requirements:

- a) The rated synchronous speed of the generator shall be determined by the turbine type. It shall be calculated by the Formula (7):

$$n_r = \frac{60 f_r}{p} \dots\dots\dots (7)$$

where

n_r is the rotational speed, in r/min;

f_r is the grid frequency, in Hz;

p is the number of pole pairs, 2p refers to the number of poles.

- b) The synchronous speed of conventional generator is shown in Table 2.

Table 2 Optional rotational speed for the synchronous generator

Number of poles 2p	4	6	8	10	12	14	16	(18)	20	(22)	24
n_r (50 Hz)	1 500	1 000	750	600	500	428.6	375	(333.3)	300	(272.7)	250
n_r (60 Hz)	1 800	1 200	900	720	600	514.3	450	(400)	360	(327.3)	300
Number of poles 2p	(26)	28	30	32	(34)	(36)	40	42	(44)	48	(50)
n_r (50 Hz)	(230.8)	214.3	200	187.5	(176.5)	(166.7)	150	142.9	(136.4)	125	(120)
n_r (60 Hz)	(276.9)	257.1	240	225.0	(211.8)	(200)	180	171.4	(163.6)	150	(144)
Number of poles 2p	(52)	56	60	64	(66)	(68)	70	(72)	(78)	80	...
n_r (50 Hz)	(115.4)	107.1	100	93.8	(90.9)	(88.2)	85.7	(83.3)	(76.9)	75	...
n_r (60 Hz)	(138.5)	128.6	120	112.5	(109.1)	(105.9)	102.9	(100)	(92.3)	90	...
NOTE The values without brackets are the recommended speeds; the value within brackets may be selected when necessary.											

- c) The coefficient for determination of the unit rotational speed shall be calculated by the Formula (8); the coefficient for determination of the rotational speed shall meet the provisions of Table 3:

$$K_n = P_r (10^{-3} n_r)^3 \dots\dots\dots (8)$$

where

K_n is the coefficient for determination of the rotational speed;

P_r is the rated power, in MW;

n_r is the rated rotational speed, in r/min.

Table 3 Coefficient for determination of the rotational speed

K_n	$K_n \leq 0.01$	$0.01 < K_n \leq 0.15$	$0.15 < K_n \leq 2$	$2 < K_n \leq 4$ For the vertical type $n_r \geq 1\ 000$ For the horizontal type $n_r \geq 1\ 500$	$K_n > 4$
Rotational speed type	Ultra-low speed	Low speed	Medium speed	High speed	Ultra-high speed
NOTE Neither the ultra-low speed nor the ultra-high rotational speed is preferable for the units. It is necessary to perform the detailed technical assessment when the ultra-high rotational speed has to be selected.					

5.2.5 The relationship between generator power and efficiency shall meet the requirements in Table 4.

Table 4 Relationship between output and efficiency

P (MW)	$0.5 < P \leq 1.0$	$1.0 < P \leq 2.0$	$2.0 < P \leq 5.0$	$5.0 < P \leq 10$
Efficiency (%)	90~94.5	90~95.5	92~96	93~96.5

5.2.6 The insulation grade of the generator shall be Grade F. In the high altitude region or under special ambient air temperature, the temperature rise shall be corrected.

5.2.7 The moment of inertia shall meet the following requirements:

- a) The mechanical time constant shall be calculated by the Formula (9); the value range shall meet the provisions of Table 5.

$$T_{mec} = 2.74GD^2 (10^{-3} n_r)^2 / P_r \dots\dots\dots (9)$$

where

T_{mec} is the mechanical time constant;

GD^2 is the moment of inertia, in $t \cdot m^2$;

n_r is the rated speed, in r/min;

P_r is the rated power, in MW.

Table 5 Value range of T_{mec}

n_r (r/min)	$1\ 500 \leq n_r \leq 1\ 000$	$750 \leq n_r \leq 428.6$	$375 \leq n_r \leq 200$	$n_r < 200$
T_{mec} (s)	2~3.5	2.5~5	3~6	3.5~6.5

NOTE For the low-speed generator and the high-power generator, it is allowed to select the higher value in Table 5; for the high-speed generator and low-power generator, it is necessary to select the lower value.

b) The method of increasing the moment of inertia shall meet the following requirements:

- 1) A small increase may be realized by increasing the weight of the rotor section with larger rotary diameter;
- 2) A relatively greater increase may be realized by increasing the external diameter of the stator iron core;
- 3) For the horizontal unit, the moment of inertia may be increased by installing additional flywheel according to the provisions in Table 6.

Table 6 Moment of inertia increased by additional flywheel

n_r (r/min)	1 500	1 000	750	600,500	≤ 428.6
GD^2 (tm^2)	0.2~0.7	0.3~1.4	0.5~3	0.75~4.5	1~6

NOTE Take the higher value for high-power generator and the smaller value for low-power generator.

d) Determination of the moment of inertia of the unit shall meet the following requirements:

- 1) The moment of inertia for the unit shall be determined through calculation of the regulation guarantee of the hydraulic system of the hydropower station;
- 2) The value for the moment of inertia shall be reasonable; when the relatively higher moment of inertia is required, it is necessary to comprehensively consider the influences on generator dimension, appearance, efficiency, stability and weight.

5.2.8 The value for the generator short-circuit ratio shall be in the range provided in Table 7. Higher value is for the unit operating in the small power grid and for the low-speed unit, and the lower value is for the high-speed unit.

Table 7 Value for the power factor and the short-circuit ratio

Power factor (lag)	0.8	0.85	0.9
Short-circuit ratio	0.9~1.0	0.95~1.05	1.0~1.1

5.3 Selection of the generator mechanical structure

5.3.1 The external diameter of the stator iron core shall be selected as follows:

- a) Common external diameters of the stator core include (mm): 740, 850, 990, 1 180, 1 430, 1 730, 2 150, 2 600, 2 860, 3 250, 3 300, 3 600, 3 850, 4 250, 4 650, 5 000, 5 500 and 6 000;
- b) The conventional external diameter of the stator core may be estimated by the Formula (10):

$$D \approx 1\,500 \left(\frac{P_r^{1.25}}{n_r^{kd}} \right)^{0.25} \dots\dots\dots (10)$$

where

D is the preliminarily-calculated diameter of the stator core external diameter, in mm;

P_r is the rated power, in MW;

n_r is the rated speed, in r/min;

K_d is the value coefficient: 1.3 for ultralow speed, 1.4 for low speed and 1.5 for other speeds.

- c) The external diameter of the stator core of the vertical reaction turbine unit may be calculated by the Formula (11):

$$D \approx K_s D_1 \left(1 + \frac{2.7}{2P} \right) \dots\dots\dots (11)$$

where

D_1 is the runner diameter, in mm;

K_s is the value coefficient, take 1.35 for the axial-flow turbine and 1.45 for the Francis turbine;

$2P$ is the number of poles of the generator.

- d) The value D for the generator shall be estimated by the Formula (10), another value D for the

vertical reaction generator shall be estimated by the Formula (11) as if the head cover is lifted out in its entirety from the inner circle of the core; the higher value shall be selected after comparison, and then a similar size is selected;

- e) A smaller external diameter of the stator core should be selected to reduce the centre height of the horizontal unit.

5.3.2 The bearings shall meet the following requirements:

- a) Each turbine-generator shall be equipped with at least two bearings, which shall be selected by the manufacturer according to the load conditions.
- b) Rolling bearing applies to the series of the horizontal generator with a core external diameter of 990 mm or smaller and the unit has two or three or four fulcrums, as well as the vertical generator with a core external diameter of 1 180 mm or smaller which does not sustain the weight of the rotary part and the axial hydraulic thrust of the turbine.
- c) Sliding bearing applies to all the generators.
- d) Except that the horizontal impulse unit is fitted with only two transverse bearings, the other generators shall be fitted with at least one thrust bearing.

5.4 Selection of generator auxiliary equipment

5.4.1 The cooling mode of the generator shall be air cooling, and the ventilation modes mainly include closed recirculation, duct ventilation and open-type ventilation.

- a) Closed recirculation: the hot air generated from the cooling of the generator is cooled by the air cooler, and then returned to the generator in a closed loop which applies to all types of generators. The closed-recirculation air cooler of the horizontal generator may be arranged in the turbine pit by the side or on the top of the generator.
- b) Duct ventilation: includes the ordinary duct ventilation structure with direct axial air inlet and the closed duct ventilation structure absorbing air from the turbine pit.
- c) Open-type ventilation: take air from the powerhouse to cool down the generator and then discharge the hot air directly into the powerhouse.
- d) The applicable range of the different ventilation modes may be referred to Table 8. Generators within the power overlap range shall be selected according to different ambient temperatures.

Table 8 Applicable range of the different ventilation modes

Ventilation mode	Open-type ventilation	Ordinary duct ventilation	Closed duct ventilation	Closed recirculation ventilation
Power (MW)	~1.0	0.8~3.2	2.5~6.3	3.2~

5.4.2 The unit with the sliding bearing should be equipped with mechanical braking devices, while the impulse turbine unit with reverse jet braking may not be equipped with mechanical braking device. The braking device shall meet the following requirements:

- a) The braking medium of the mechanical braking device should be 0.7 MPa compressed air, or the pressure oil of the governor with reduced pressure may be used as the braking medium.
- b) The brake shoes shall be made of asbestos-free environmentally-friendly material.
- c) In the mechanical braking device for the vertical generator, the pressure oil shall be able to jack up the rotating part of the unit and the lock safely on any position, and the brake with a piston diameter greater than 100 mm shall employ the oil-gas separation structure.

5.4.3 The fire extinguishing method of hydropower stations and generators shall be selected according to the national fire control regulations.

5.4.4 The dehumidifier shall be installed according to different environmental humidity and unit capacity. The dehumidifier may be electric heater and dehumidifier. In case of the electric heater, the air temperature in the turbine pit shall be 5 K higher than the ambient temperature, and the insulation shall not be damaged by local high temperature.

6 Turbine governing system

6.1 Basic principles of governing system selection

6.1.1 The turbine governing system shall be able to reliably control the unit under all operating conditions and start/stop the machine in the time required by the calculation of the regulation guarantee.

6.1.2 In order to ensure the safety of power station equipment and users when disconnecting with the system, the automatic microcomputer-based turbine governing system shall be equipped for the unit with the possibility that operating within an isolated grid.

6.1.3 As for the small and micro units without the frequency regulation task and with no need to guarantee the auxiliary power when the unit breaks down, the electric actuator or hydraulic actuator may be used, but it shall ensure that the unit could stop safely and reliably when it breaks down. As

for the hydropower station without the DC operating power supply, the actuator shall be equipped with the emergency shutdown device for power failure.

6.1.4 As for the governor with the pressure regulating valve control function, the control of its pressure regulating valve shall employ the hydraulic-coordinated mechanism.

6.1.5 The high oil pressure (10 MPa and above) bladder-type energy accumulator and the external servomotor should be adopted.

6.1.6 The governor shall satisfy all requirements of automatic regulation and remote control. It could be operated manually and meet the demands in the process of starting, stopping, emergency stopping, and the overhaul process of the unit.

6.2 Operating capacity of the governor

6.2.1 The operating capacity of the governor shall be selected so that the unit could be reliably controlled under the maximum head and the maximum discharge and be started and stopped as per the time required by the calculation of the regulation guarantee. The operating capacity of the governor shall have sufficient reserve allowance.

6.2.2 The operating capacity of the governor for the medium and small sized Francis and axial-flow fixed blade propeller turbine may be calculated by the Formula (12) :

$$A = KQ \sqrt{H_{\max} D_1} \dots\dots\dots (12)$$

where

A is the operating capacity of servomotor, in N·m;

K is the coefficient, value range: 250 to 300;

Q is the rated discharge of unit, in m³/s;

H_{max} is the maximum head, in m;

D₁ is the diameter of the turbine runner, in m.

6.2.3 See Appendix C for the reference formulas for the calculation of the operating capacity of the governing systems of the impulse turbine, Kaplan turbine, S-type turbine and bulb turbine.

6.3 Control system of the governor

6.3.1 The control system of the governor should employ the single microcomputer system and be

connected with the PID structure in parallel.

6.3.2 Advanced and mature hardware and supporting electronic components should be adopted, and the hardware should be the programmable logic controller (PLC) or the single chip, and the interface communicating with the monitoring system shall be equipped.

6.3.3 The control system of the governor shall have the following basic auxiliary functions: frequency tracking (or fast synchronization), fault detection and treatment, artificial dead band, non-disturbance manual and automatic switchover, auxiliary test and partial fault-tolerance.

7 Main valve of the turbine

7.1 Principles of the main valve installation

7.1.1 For the hydropower stations where several turbines are supplied by one single penstock, the main valve shall be set in front of each turbine.

7.1.2 For the unit water conductor system of the dam toe hydropower station with the short penstock, or the low head unit water conductor system of the runoff hydropower station or the riverbed hydropower station, the main valve may not be equipped in front of the turbine.

7.2 Selection of the main valve

7.2.1 The main valve shall be selected based on the comprehensive analysis of the technical, economic and operational safety and reliability, according to the water head, the maximum transient pressure, the rated discharge of turbine, the diameter of the spiral case inlet and the sediment characteristics.

7.2.2 The selection of main valve shall include the following contents:

- a) Main valve type;
- b) Design pressure and nominal diameter of the main valve;
- c) Operation mode of the main valve;
- d) Sealing type of the main valve;
- e) Type and diameter of the bypass valve;
- f) Opening and closing time of the main valve.

7.2.3 The following basic data shall be required for main valve selection:

- a) The maximum static head and the maximum transient pressure at the main valve of the power station;
- b) Rated flow rate of the turbine;
- c) Spiral case inlet diameter;
- d) The content and characteristics of the sediment passing through the machine;
- e) Length of the diversion system and the emptying time.

7.2.4 Selection of the main valve type:

- a) The butterfly valve, spherical valve and gate valve are often used as the main valve of the turbine. When the maximum head is lower than 250 m, the butterfly valve should be selected. When the maximum head is higher than 250 m (inclusive), the spherical valve or the gate valve should be selected. The butterfly valve used as the main valve of the turbine shall be of the eccentric structure, and the valve body shall be marked with arrows indicating the water flow direction. Full size fixed spherical valve shall be used and should be arranged horizontally. The gate valve shall be of full size structure and the valve shaft shall be installed vertically.
- b) The main valve shall be able to be closed in flowing water, and the closing time shall not exceed the time allowable for the continuous operation of the unit under the maximum runaway speed. The main valve shall be able to be opened normally and not produce harmful vibration when the pressure difference between both sides is not greater than 30% of the maximum static water pressure.

7.2.5 Selection of the basic parameters of the main valve:

- a) The design pressure of the main valve is the maximum transient pressure, in MPa.
- b) The nominal diameter of the butterfly valve may be calculated by the Formulas (13) and (14):

$$D_f = \frac{D_0}{\sqrt{\alpha}} \dots\dots\dots (13)$$

$$\alpha = 1 - 0.068 7 \sqrt[3]{H_{\max}} \dots\dots\dots (14)$$

where

D_f is the diameter of the butterfly valve, in m;

D_0 is the diameter of section of the spiral casing inlet, in m;

α is the coefficient related to the head;

H_{max} is the maximum static head of the hydropower station, in m.

- c) The operating mode of the main valve shall meet the following requirements:
 - 1) The main valve may be operated manually, hydraulically or electrically. For the hydropower station designed no personnel on duty, the main valve shall be electrically or hydraulically driven.
 - 2) The hydraulically-driven main valve has mainly two types namely the counterweight and the accumulator type. The counterweight hydraulic control device opens the valve with the oil pressure supplied by the oil pump and closes the valve with the counterweight. The accumulator type control device opens or closes the valve with the oil pressure supplied by the accumulator and the oil pump is equipped to maintain the oil pressure in the accumulator. The hydraulically-driven main valve shall be equipped with the manual mechanical locking device for overhaul.
 - 3) The manual valve shall be fitted with a legible arrow indicating the closing direction.
- d) The type selection and diameter of the bypass valve shall meet the following requirements:
 - 1) The bypass valve may employ the straight-through valve or the angle valve. As for the medium and low heads, the straight-through valve is usually used and, as for the high head, the angle valve is used.
 - 2) The discharge capacity of the bypass valve shall be greater than the water leakage of the guide vane, and its nominal diameter shall not be less than 10% of the nominal diameter of the main valve.
 - 3) As for the high sediment concentration and high water head, the diameter of the bypass valve may be preliminarily calculated by the Formula (15):

$$D_p = (0.29 \sim 0.33) \sqrt{\frac{Q_{sj}}{\sqrt{H_{sj}}}} \dots\dots\dots (15)$$

where

Q_{sj} is the design discharge of the turbine, in m^3/s ;

H_{sj} is the design head of the turbine, in m.

- e) The adjustable range of the opening and closing time of the main valve should be 60 s to 120 s. The closing time of the main valve in flowing water shall not exceed the allowable operating time of the unit at maximum runaway speed.

7.3 Selection of sealing type of the main valve

For the high sediment concentration and low or medium water head, the rubber soft seal should be used; when the head is high and the sediment concentration is low, the metal hard seal should be used. The shaft end seal may employ the entire-loop solid rubber seal.

8 Auxiliary system

8.1 Cooling water and drainage system

8.1.1 The water supply source for cooling and sealing shall reasonably be selected according to the requirements of the water volume, water pressure, water temperature and water quality, and the specific conditions of the power station. Water may be taken from reservoirs, penstock, power station tail water or other water sources and then passed through a filtration system before feeding to bearing and generator coolers or shaft sealing arrangement.

8.1.2 The water supply mode shall be determined according to the range of water head of the power station:

- a) When the minimum head is lower than 15 m, the water should be supplied by pump;
- b) When the net head is 15 m to 100 m, the water should be supplied by gravity flowing or gravity flowing with pressure reduction;
- c) When the net head is higher than 100 m, the water should be supplied by gravity flowing with pressure reduction and others.

8.1.3 The water supply system shall be able to be operated automatically.

8.1.4 The main shaft sealing water of the turbine should be provided with standby water supply which could be put into use automatically.

8.1.5 When water is supplied by pump, the standby water pump shall be equipped.

8.1.6 The water supply system shall be equipped with the water filter. When the water filter is working, water supply system shall not be interrupted. Water quality of bearing lubrication water and main shaft sealing water shall meet the requirements of the unit.

8.1.7 The water drainage system shall be set up respectively for unit maintenance drainage and plant leakage drainage, and the following requirements shall be met:

- a) Two drainage pumps shall be installed for the unit maintenance, and the total displacement shall be guaranteed to exclude the total displacement of one unit for maintenance within 4 hours to 6 hours.
- b) There shall be no less than two drainage pumps for the leakage drainage sump in the plant, one of which shall be set aside. The drainage pumps shall be automatically controlled with the change of water level of the drainage sump.

8.1.8 The outdoor drainage system within the plant area shall be an independent system, which shall not feed water into the drainage sump or the drainage gallery in the plant.

8.1.9 The leakage drainage from the power station should not be directly discharged into the river without treatment.

8.2 Oil system

8.2.1 A turbine oil system may be set up according to the needs of the hydropower station, and oil treatment and storage equipment shall be equipped. Insulation oil system may not be set.

8.2.2 The volume of the turbine oil tank shall meet the requirements of oil storage, oil replacement during overhaul and oil purification. The volume of the turbine oil tank should be 110% of the oil consumption of the unit with the largest capacity.

8.2.3 The oil treatment equipment shall include the oil pump and oil purification equipment, and the types, capacity and quantity of which may be determined according to the oil consumption of the hydropower station.

8.2.4 A central oil service system should be established for the cascade hydropower stations or a group of hydropower stations. The central oil service system shall be equipped with the oil storage, oil treatment and oil purification equipment. The configuration of the oil system for the hydropower station equipped with central oil service system shall be simplified.

8.3 Compressed air system

8.3.1 The medium pressure and low pressure compressed air system may be set up in the powerhouse according to the needs of the hydropower station.

8.3.2 The pressure of the medium pressure compressed air system for the inflation of the oil pressure device shall be determined according to the rated operating pressure of the oil pressure device; two air compressors shall be equipped, one for use and one for standby and air tank shall be

equipped. The volume of the air tank may be determined according to the air compensation for the pressure oil tank. The rated operating pressure of the air tank should be 0.2 MPa to 0.3 MPa higher than the rated operating pressure of the pressure oil tank. The air tank shall be fitted with the safety valve, pressure gauge and blow-down valve.

8.3.3 The pressure of the low pressure compressed air system used for unit braking, overhaul and maintenance, and sealing of the circular band of the turbine main shafts shall be from 0.7 MPa to 0.8 MPa; the braking air for the unit shall meet the following requirements:

- a) The braking air of the unit should be equipped with exclusive air tank and exclusive air supply pipe.
- b) The total volume of the air tank for unit braking shall be determined according to the total air consumption of the units to be braked simultaneously;
- c) The capacity of the air compressor shall be determined as per the air consumption of the units to be braked simultaneously and the time of restoring working pressure of the compressed air tank. The time of restoring working pressure of the compressed air tank may be from 10 min to 15 min;
- d) The braking air of the unit should be supplied with the standby air compressor or other standby air source.

8.3.4 The rated working pressure of the air compressor should be 0.1 MPa to 0.3 MPa higher than the rated working pressure of air tank.

8.4 Hydraulic monitoring system

8.4.1 The hydraulic monitoring system shall meet the requirements for safe, reliable and economical operation and automatic control of the turbine generator unit.

8.4.2 The hydropower station should be equipped with the conventional instrumentation for measurements parameters viz the upstream water level, downstream water level, surge-chamber water level, hydropower station head, pressure difference between the front and back of the trash rack as well as the reservoir water temperature. The unit should be provided with routine measurement instruments such as pressure at the intake of the spiral case, head cover pressure, pressure at the intake of the draft tube as well as the cooling water pressure of the unit, while the selective measurement items may be provided as well, such as the flow passing through the unit, the pressure fluctuation of the turbine, the unit efficiency, unit vibration, runout of the unit and the pressure (vacuum) in the draft tube.

8.4.3 The hydraulic monitoring system shall be designed and arranged in combination with the automatic monitoring system of the hydropower station.

8.5 Selection of the lifting equipment

8.5.1 Cranes or other hoisting equipment shall be installed in the powerhouse of the hydropower station. Single-trolley or double-trolley bridge cranes may be used. The rated lifting weight shall be determined according to the total weight of the heaviest object to be lifted plus any hoisting tools and with reference to the standard lifting capacity of the crane series. The crane span may be selected according to the standard crane span. The lifting height and speed of the crane shall meet the requirements of installation and overhaul of units.

8.5.2 For the hydropower station with a Gas Insulated Switchgear (GIS) room, a crane shall be installed for the installation and overhaul of GIS room.

8.6 Heating and ventilation

8.6.1 The heating and ventilation patterns of the hydropower station shall be determined according to the local meteorological conditions, the powerhouse type and the requirements for air parameters in production sites.

8.6.2 Natural ventilation should be adopted for the generator hall, erection bay and auxiliary rooms of the surface powerhouse. When the natural ventilation could not meet the requirements of indoor air parameter, the natural-mechanical mixed ventilation, mechanical ventilation and partial air conditioning may be adopted.

8.6.3 If the pipeline ventilation is adopted for the generator, the hot air shall be directed outside the powerhouse.

8.6.4 The oil tank room and the oil treatment room shall be equipped with separate ventilation system. The air outlets of the ventilation system shall be 1.5 m higher than the roof.

8.6.5 The ventilation rate of the GIS room shall be 8 times/hr., and the air inlet shall be set in the lower part of the room.

8.6.6 The heating device shall be equipped when the indoor temperature of the main and auxiliary powerhouses is lower than 5 °C.

8.6.7 Necessary ventilation facilities shall be installed in the gallery at the bottom of the dam.

8.7 Repair and maintenance equipment

8.7.1 The mechanical repair and maintenance may be configured according to the overhaul content of electro-mechanical equipment, external transportation and outsourcing fabrication conditions, etc.

8.7.2 A central repair and maintenance workshop should be set up for cascade hydropower stations and a group of hydropower stations.

9 Fire protection system

9.1 General requirements for the fire protection system

9.1.1 Fire protection system of the power station and unit equipment shall follow the national fire protection specifications.

9.1.2 The fire hazards and fire resistance rating shall be classified for the buildings and structures in the hydropower station.

9.2 Technical requirements

9.2.1 The fire lane in the plant area should not be less than 4.0 m in width and should be used as the access road as well. The dead-end of the fire lane shall be designed with a turnaround.

9.2.2 There shall be at least two evacuation exits for the main and auxiliary powerhouse of the hydropower station. On the generator floor and the floors below, the distance between the furthest indoor workplace to the nearest safe evacuation exit on this floor shall not exceed 60 m.

9.2.3 A 100% oil storage pit or a 20% oil storage pit and a common oil storage tank shall be provided for the main oil-immersed transformer with single oil capacity over 1 000 kg and the other oil filling equipment.

9.2.4 Power cables and control cables shall be laid in layers. The cables laid in layers shall be separated by clapboards with fire endurance not less than 0.5 hour.

9.2.5 Every 100 m of cable tunnel and ditches shall be equipped with a fire-proof partition. Closure and partition measures shall be implemented for the through-wall.

9.2.6 Automatic fire extinguishing system such as water spray or CO₂ spray shall be equipped for the turbine generator unit with a unit capacity not less than 12.5 MVA and water spray system for the indoor main oil-immersed transformer with a unit capacity not less than 12.5 MVA.

9.2.7 The powerhouse shall be equipped with smoke exhaust facilities and shall be integrated with the ventilation system.

9.2.8 Natural water source, specific fire water ponds or fire water pumps may be used as the water supply sources for in-plant fire protection. The water supply for fire protection may be incorporated with the living and production water supply system. The quality, pressure and volume of supplied

water shall meet the requirements of fire protection purposes.

9.2.9 Firefighting apparatuses shall be powered as per the Grade 2 load with an independent power supply circuit. The control equipment for the firefighting apparatuses shall be installed in the central control room. When the water is supplied with the fire water pump, the starting device for the fire-water pump should be set in the fire cabinet.

9.2.10 The emergency lighting and evacuation signs shall be provided in the evacuation exit, stair-cases, exits and fire pump house of the powerhouse.

9.2.11 The automatic fire alarm device shall be installed in the hydropower station.

10 Layout of the powerhouse

10.1 Basic principles

Hydraulic machinery and electrical equipment should be arranged separately. The length and width of the unit section of the main powerhouse shall be determined according to the size of the unit as well as the passageway, governor, oil pressure device, main valve and electrical panel/cabinet, and in combination with the requirements for installation, overhaul, operation, transportation and civil engineering design. The width of the main powerhouse shall also meet the requirement of the size of the crane lifting components and the main valve. The layout of the powerhouse shall be designed with full consideration given to the comprehensive requirements of ecology and environmental protection.

10.2 Technical requirements

10.2.1 The lifting height in the main powerhouse shall meet the following requirements:

- a) Requirements for the integral lifting of the generator rotor with the shaft;
- b) Requirements for assembling the turbine with the shaft sleeve for integral lifting;
- c) Requirements for in-plant maintenance of the main transformer if necessary;
- d) Requirements to turn over the guide vane and other parts of the bulb tubular unit;
- e) The distance between parts to be lifted by the crane and fixed objects shall be neither less than 0.3 m in the vertical direction nor less than 0.4 m in the horizontal direction.

10.2.2 The area of the erection bay shall be determined according to the needs of the extended overhaul of one unit. The main parts of the unit shall be arranged within the working range of the

crane hook and shall meet the following requirements:

- a) Requirements for hoisting order of lifting parts during installation and overhaul;
- b) The net distance between the large parts of the unit and between the large parts of the unit and the walls (columns) and the fixed equipment shall be from 0.8 m to 1.0 m;
- c) Requirements for in-plant loading and unloading by vehicles;
- d) Turbine oil room may be located in the powerhouse; insulation oil tank should be located outside the powerhouse; oil treatment room shall be arranged near the tank room;
- e) Other auxiliary machinery shall be arranged to facilitate the installation, operation and maintenance of the equipment.

10.2.3 See Figures D.1 to Figure D.7 for typical layout of units and schematic diagrams of oil, air and water systems.

Appendix A
(Normative)

Reference formulas for the basic parameter calculation of the reaction turbine

A.1 Calculation of the rated discharge

$$Q_r = Q'_{1r} D_1^2 \sqrt{H_r} \dots\dots\dots (A.1)$$

where

Q_r is the rated discharge, in m³/s;

Q'_{1r} is the unit discharge under the rated working condition, in m³/s ;

H_r is the rated head, in m;

D_1 is the nominal diameter of the runner, in m.

A.2 Calculation of the static suction head and determination for setting the elevation of the turbine

A.2.1 See the Formula (A.2) for calculation of the static suction head

$$H_s \leq 10 - \frac{\nabla}{900} - K_\sigma \sigma_m H \dots\dots\dots (A.2)$$

where

H_s is the static suction head, in m;

K_σ is the ratio of device cavitation coefficient to model cavitation coefficient;

σ_m is the cavitation coefficient of the turbine model;

H is the turbine head, in m.

Usually it may be calculated as per rated head; for the minimum head of the axial-flow turbine as well as the maximum head and corresponding σ_m of the Francis turbine shall be verified.

A.2.2 See the Formula (A.3) for setting the elevation of the vertical-shaft Francis turbine.

$$\nabla = \nabla_w + H_s + \frac{b_0}{2} \dots\dots\dots (A.3)$$

where

∇ is the setting elevation, in m;

∇_w is the tailwater level, in m;

b_0 is the guide vane height, in m.

A.2.3 See the Formula (A.4) for setting the elevation of the vertical-shaft axial-flow turbine.

$$\nabla = \nabla_w + H_s + xD_1 \dots\dots\dots (A.4)$$

where

x is the height efficiency of the axial-flow turbine.

A.2.4 See the Formula (A.5) for setting the elevation of the horizontal-shaft reaction turbine.

$$\nabla = \nabla_w + H_s - \frac{D_1}{2} \dots\dots\dots (A.5)$$

A.3 Reaction turbine efficiency and correction calculation

A.3.1 See the Formulas (A.6) and (A.7) for the calculation of the prototype turbine efficiency

$$\eta_T = \eta_M + \Delta \eta \dots\dots\dots (A.6)$$

$$\Delta \eta = \eta_{T \max} - \eta_{M \max} \dots\dots\dots (A.7)$$

where

η_M is the model turbine efficiency;

$\Delta \eta$ is the corrected value for turbine efficiency;

$\eta_{T \max}$ is the maximum efficiency of the prototype turbine;

$\eta_{M \max}$ is the maximum efficiency of the model turbine.

In addition to the calculation according to the reference formulas listed in A.3.2 to A.3.4 below, the efficiency correction of the turbine should also take into account the correction caused by the abnormal components and the process deviation between the prototype and the model turbines. When the diameter of the runner is less than 1 m, it should be negatively corrected.

A.3.2 For the first method for the turbine efficiency correction, see the Formulas (A.8) and (A.9).

Francis:

$$\Delta \eta = K(1 - \eta_{M \max}) \left[1 - \left(\frac{D_{1M}}{D_1} \right)^{0.2} \right] \dots\dots\dots (A.8)$$

Axial-flow:

$$\Delta \eta = K(1 - \eta_{M \max}) \left[0.7 - 0.7 \left(\frac{D_{1M}}{D_1} \right)^{0.2} \left(\frac{H_M}{H_P} \right)^{0.1} \right] \dots\dots\dots (A.9)$$

where

K is the coefficient, $K = 0.5-0.7$ (low value is for the retrofitted unit and the high value is for the new unit);

D_{1M} is the runner diameter of the model turbine, in m;

H_M is the test head of the model turbine, in m;

H_P is the head of the prototype turbine, in m.

A.3.3 For the second method for the turbine efficiency correction, see the Formulas (A.10) and (A.11).

Calculation formula for the efficiency correction of the reaction turbine recommended in IEC 60193:

$$\Delta \eta_b = \delta_{ref} \left[\left(\frac{Re_{uref}}{Re_{um}} \right)^{0.16} - \left(\frac{Re_{uref}}{Re_{up}} \right)^{0.16} \right] \dots\dots\dots (A.10)$$

$$\delta_{ref} = \frac{1 - \eta_{boptm}}{\left(\frac{Re_{uref}}{Re_{uoptm}} \right)^{0.16} + \frac{1 - V_{ref}}{V_{ref}}} \dots\dots\dots (A.11)$$

where

$\Delta \eta_b$ is the corrected value converted from the model efficiency to the prototype efficiency;

δ_{ref} is the corrected value converted from the nominal value to the prototype efficiency;

Re_{uref} is the standard Reynolds number;

Re_{um} is the model Reynolds number at the calculating point;

Re_{up} is the prototype Reynolds number at the calculating point;

Re_{uoptm} is the Reynolds number at the optimum efficiency point of the model;

η_{boptm} is the optimum efficiency of the model;

V_{ref} is the standard loss distribution coefficient (0.8 for the Kaplan turbine, 0.7 for the Francis and the fixed blade propeller turbines).

A.3.4 The third method for the turbine efficiency correction

As for the existing model test curve, the model test data of the Reynolds number and the water temperature, the efficiency correction may be calculated by the Formulas (A.12 to A.14):

$$\Delta \eta_b = (1 - \eta_{boptm}) V_m \left[1 - \left(\frac{Re_{um}}{Re_{up}} \right)^{0.16} \right] \dots\dots\dots (A.12)$$

$$V_m = V_{optm} = V_{ref} \dots\dots\dots (A.13)$$

$$Re_{um} = Re_{uref} = 7 \times 10^6 \dots\dots\dots (A.14)$$

where

V_m is the loss distribution coefficient of the model;

V_{optm} is the Loss distribution coefficient at the optimum efficiency point of the model.

A.4 Calculation of the rated power

$$N_{Tr} = 9.81 Q_r H_r \eta_{Tr} \dots\dots\dots (A.15)$$

where

N_{Tr} is the rated power of the turbine, in kW;

η_{Tr} is the prototype turbine efficiency under rated condition.

A.5 Calculation of the maximum runaway speed

The maximum runaway speed of the Francis or propeller turbine shall be determined according to the maximum head and the maximum unit speed. The maximum runaway speed of the Kaplan turbine shall be calculated under the condition that the coordination relationship is maintained; in case of any special requirements, it may be calculated on the assumption that the coordination relationship is broken.

$$n_{f \max} = n'_{1f \max} \frac{\sqrt{H_{\max}}}{D_1} \dots\dots\dots (A.16)$$

where

$n_{f \max}$ is the maximum runaway speed, in r/min;

$n'_{1f \max}$ is the maximum unit runaway speed, in r/min;

H_{\max} is the maximum head, in m.

A.6 Estimation of the axial hydraulic thrust

$$P_z = K_z \frac{\pi}{4} D_1^2 H_{\max} \text{ (kN)} \dots\dots\dots (A.17)$$

where

P_z is the axial hydraulic thrust, in kN;

K_z is the axial hydraulic thrust coefficient; to be obtained as per the relevant experimental parameters.

Appendix B
(Normative)

Reference formulas for the basic parameter calculation of the impulse turbine

B.1 Calculation of the jet diameter

$$d_0 = 545 \sqrt{\frac{Q_{sj}}{K_p Z_0 \sqrt{H_{sj}}}} \dots\dots\dots (B.1)$$

$$Q_{sj} = \frac{N_f}{9.81 H_{sj} \eta_T \eta_f} \dots\dots\dots (B.2)$$

where

d_0 is the jet diameter, in mm;

Q_{sj} is the turbine discharge under the design condition, in m³/s;

K_p is the number of runners;

Z_0 is the number of nozzles per runner;

η_T is the prototype turbine efficiency under the design condition;

η_f is the generator efficiency.

B.2 Calculation of the rated speed

$$n_r = \frac{n_s H_{sj}^{1.25}}{\sqrt{N_{Tr}}} = \frac{n_s H_{sj}^{1.25}}{\sqrt{K_p Z_0 N_1}} = \frac{n_{s1} H_{sj}^{1.25}}{\sqrt{N_1}} \dots\dots\dots (B.3)$$

$$n_{s1} = \frac{n_s}{\sqrt{K_p Z_0}} \dots\dots\dots (B.4)$$

$$N_1 = \frac{N_{Tr}}{K_p Z_0} \dots\dots\dots (B.5)$$

where

n_s is the specific speed of the turbine, in $m \cdot kW$;

n_{s1} is the specific speed of the single nozzle, in $m \cdot kW$;

N_1 is the output of the single nozzle, in kW.

B.3 Calculation of the runner diameter and m -value

$$D_1 = \frac{(39 \sim 40) \sqrt{H_{sj}}}{n_r} \dots\dots\dots (B.6)$$

$$m = \frac{D_1}{d_0} \dots\dots\dots (B.7)$$

where

D_1 is the pitch diameter of the bucket, in m;

m is the Ratio of the runner diameter to the jet diameter, non-dimensional.

In order to ensure the relatively higher efficiency of the turbine, the m -value should be within the range of 10 to 20. Small value applies to the low head while the large value applies to the high head.

B.4 Estimation of the nozzle diameter and the number of buckets

$$d_p = (1.15 \sim 1.25) d_0 \dots\dots\dots (B.8)$$

$$Z_1 = 6.67 \sqrt{\frac{D_1}{d_0}} \dots\dots\dots (B.9)$$

where

d_p is the nozzle diameter, in mm;

Z_1 is the number of buckets.

B.5 Calculation of the static discharge head

B.5.1 The static discharge head refers to the height that ensures the safe and stable operation of the Pelton turbine, avoiding surge in case of load variation, guaranteeing the ventilation and preventing the energy losses due to the vortex and flow splash in the tailrace.

B.5.2 When determining the static discharge head, the necessary ventilation height shall be ensured, which should not usually be less than 400 mm.

B.5.3 Calculation of the static discharge head, see the Formula (B.10)

$$h_p = (1.0 \sim 1.5) D_1 \dots\dots\dots (B.10)$$

where

h_p is the static discharge head, in m; high value is for the vertical shaft unit and the low value is for the horizontal shaft unit.

B.6 Calculation of the setting elevation

B.6.1 The setting elevation shall be determined according to the maximum tailwater level for power generation. Under any power generation conditions, sufficient static discharge head should be kept for the tailrace.

B.6.2 For the vertical shaft Pelton turbine

$$\nabla = \nabla_{wm} + h_p \dots\dots\dots (B.11)$$

where

∇_{wm} is the maximum tailwater level, in m.

B.6.3 For the horizontal shaft Pelton turbine

$$\nabla = \nabla_{wm} + h_p + \frac{D_1}{2} \dots\dots\dots (B.12)$$

B.7 Calculation of the rated specific speed

$$n_{sr} = \frac{n_r \sqrt{N_{Tr}}}{H_r^{5/4}} \dots\dots\dots (B.13)$$

where

n_{sr} is the rated specific speed, in m • kW.

B.8 Calculation of the maximum runaway speed

$$n_{fmax} = \frac{70 \sqrt{H_{max}}}{D_1} \dots\dots\dots (B.14)$$

where

n_{fmax} is the maximum runaway speed, in r/min.

B.9 Calculation of the rated power

$$N_{Tr} = 9.81 Q_r H_r \eta_{Tr} \dots\dots\dots (B.15)$$

where

N_{Tr} is the rated power of the turbine, in kW;

η_{Tr} is the prototype turbine efficiency under rated condition.

Appendix C
(Normative)

Reference formulas for the operating capacity calculation of the governing system for some turbines

C.1 Impulse turbine

For the calculation of the operating capacity of the governing system for the impulse turbine, see the Formulas (C.1) and (C.2)

$$A_{nz} = 10Z \left(d_0 + \frac{d_0^2 H_{max}}{6\,000} \right) \dots\dots\dots (C.1)$$

$$A_{de} = 11 \times 10^{-3} d_0^3 H_{max} Z \dots\dots\dots (C.2)$$

where

A_{nz} is the operating capacity of the needle servomotor, in N·m;

Z is the number of nozzles;

d_0 is the jet diameter of the dependable discharge (or output), in cm;

H_{max} is the maximum head, in m;

A_{de} is the operating capacity of the deflector servomotor, in N·m.

C.2 Kaplan turbine

For the calculation of the operating capacity of the governing system for the Kaplan turbine, see the Formulas (C.3) and (C.4)

$$A_{ga} = K_1 Q \sqrt{H_{max} D_1} \dots\dots\dots (C.3)$$

$$A_{ru} = K_2 \phi H_{max} D_1^3 \dots\dots\dots (C.4)$$

where

A_{ga} is the operating capacity of the guide vane servomotor, in N·m;

K_1 is the coefficient, value range: 250 to 300;

Q is the rated discharge of the unit, in m^3/s ;

H_{max} is the maximum head, in m;

D_1 is the turbine runner diameter, in m;

A_{ru} is the operating capacity of the blade servomotor, in $N \cdot m$;

K_2 is the coefficient;

φ is the intersection angle between two extreme positions of the blade, in radian.

When the number of blades $Z = 4$, $K_2 = 8.0$; when $Z = 5$, $K_2 = 8.5$; when $Z = 6$, $K_2 = 9.0$.

C.3 S-type turbine and bulb turbine

For calculation of the operating capacity of the governing systems for the S-type and bulb tubular turbines, see the Formula (C.5)

$$A = 400 Q \sqrt{H_{max} D_1} \dots\dots\dots (C.5)$$

where

A is the operating capacity of the servomotor, in $N \cdot m$;

Q is the rated discharge of the unit, in m^3/s ;

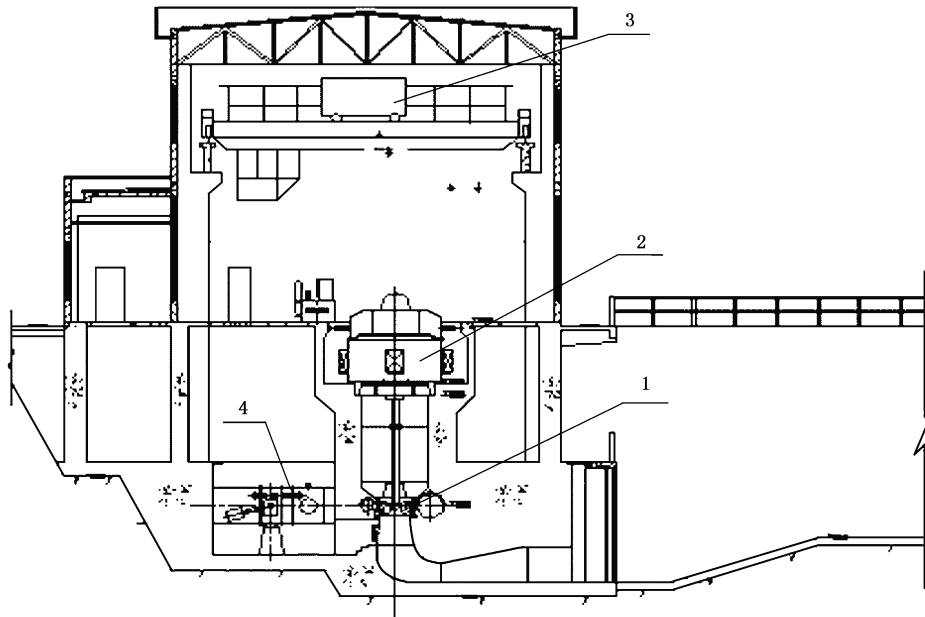
H_{max} is the maximum head, in m;

D_1 is the turbine runner diameter, in m.

Appendix D
(Informative)

Typical layout of units and schematic diagrams of oil-air-water systems

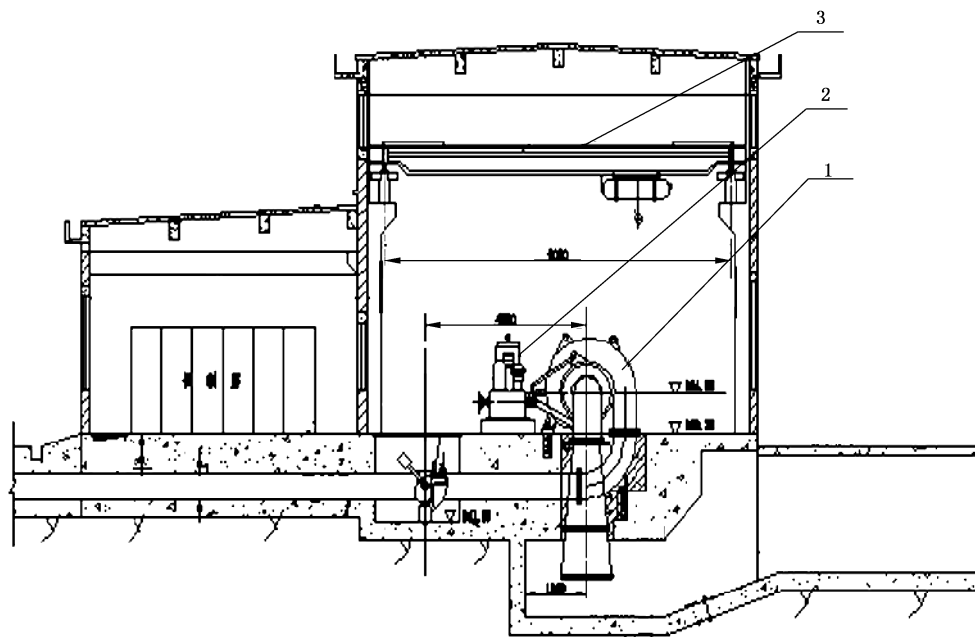
D.1 Typical layout of vertical and horizontal shaft units



Key

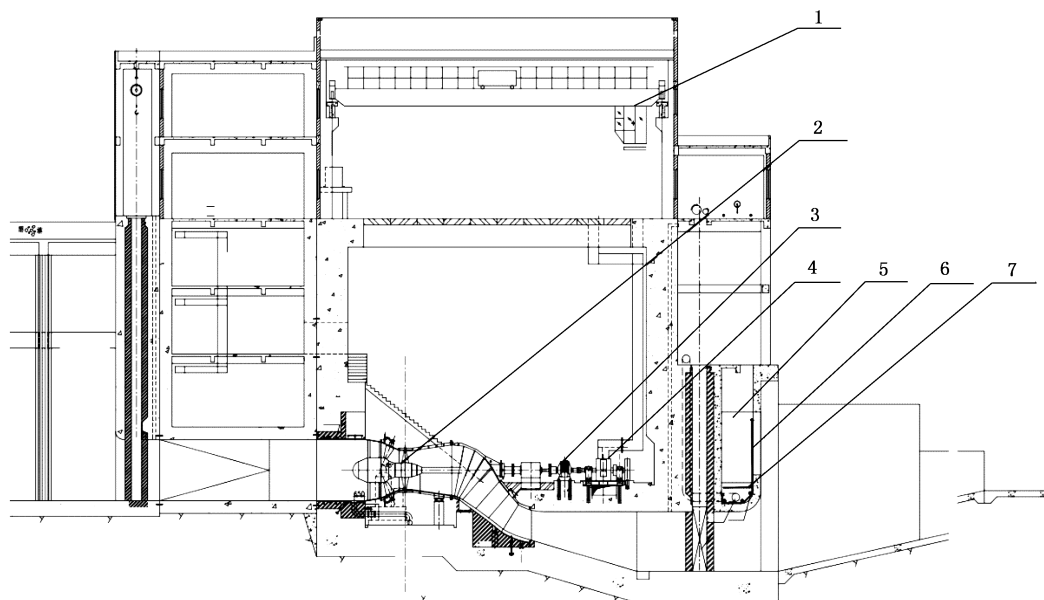
- 1 turbine
- 2 generator
- 3 bridge crane
- 4 main valve

Figure D.1 Transverse cross-section plan of the vertical unit power plant



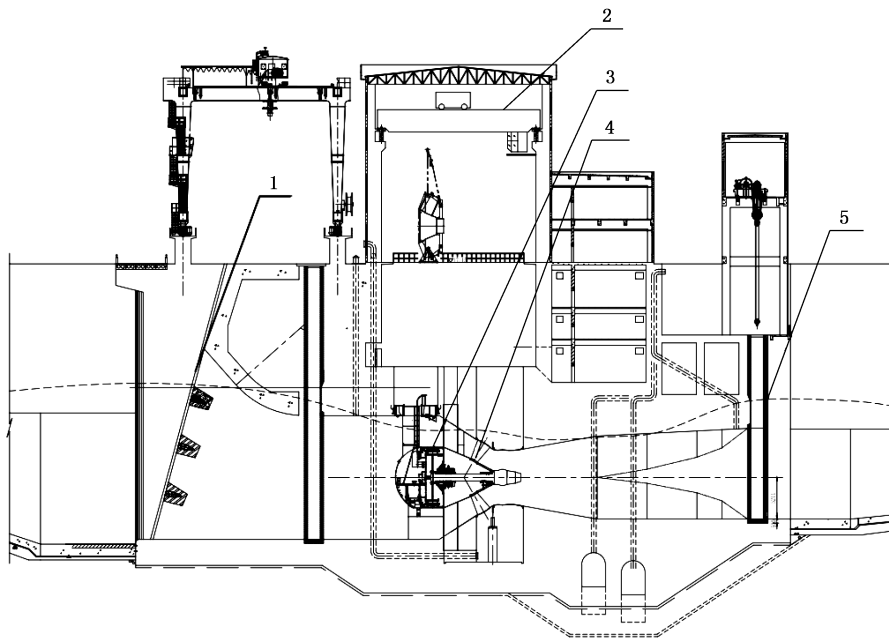
- Key
- 1 turbine
 - 2 generator
 - 3 bridge crane

Figure D.2 Transverse cross-section plan of the horizontal unit power plant



- Key
- 1 bridge crane
 - 2 turbine
 - 3 speed increaser
 - 4 generator
 - 5 fish guiding box of tailwater
 - 6 curtain type regulating weir
 - 7 energy dissipation network

Figure D.3 Layout of the shaft-extension tubular type turbine unit

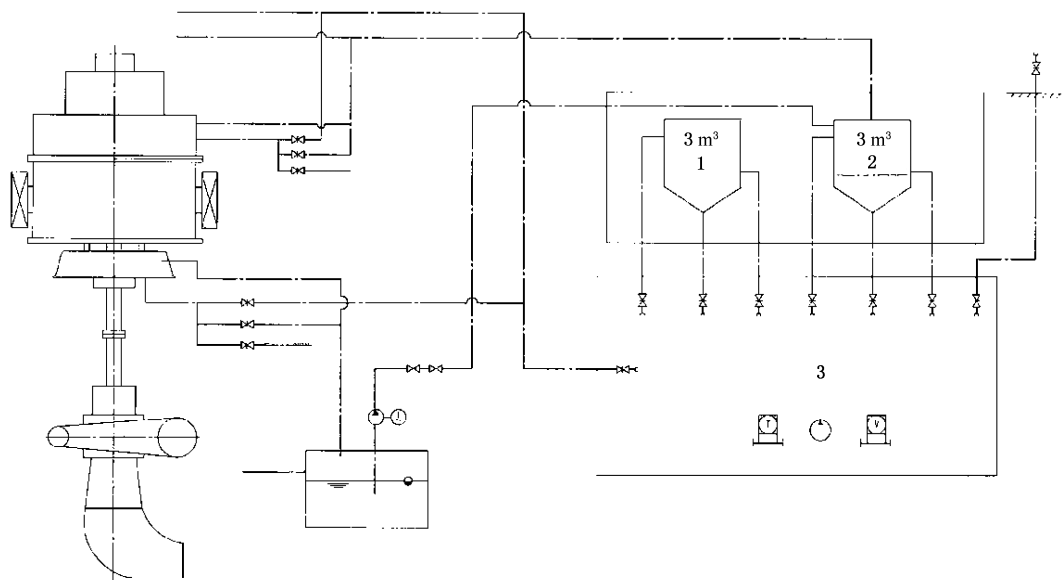


Key

- | | |
|----------------|-----------------------|
| 1 trash rack | 4 turbine |
| 2 bridge crane | 5 fast emergency gate |
| 3 generator | |

Figure D.4 Layout of the Bulb Tubular Turbine Unit

D.2 Typical schematic diagrams of oil-air-water systems



Key

- | |
|-------------------------|
| 1 net oil tank |
| 2 working tank |
| 3 oil purification room |

Figure D.5 Schematic diagram of the turbine oil system

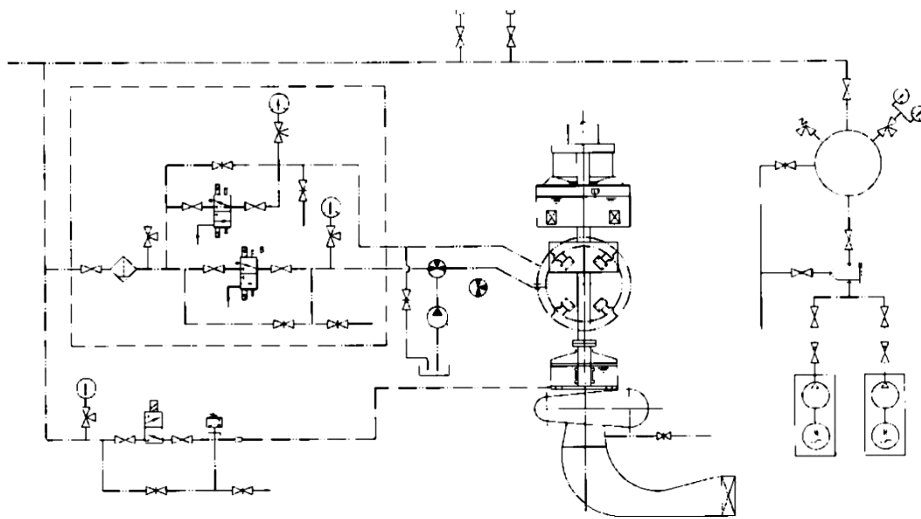


Figure D.6 Schematic diagram of the low pressure compressed air system

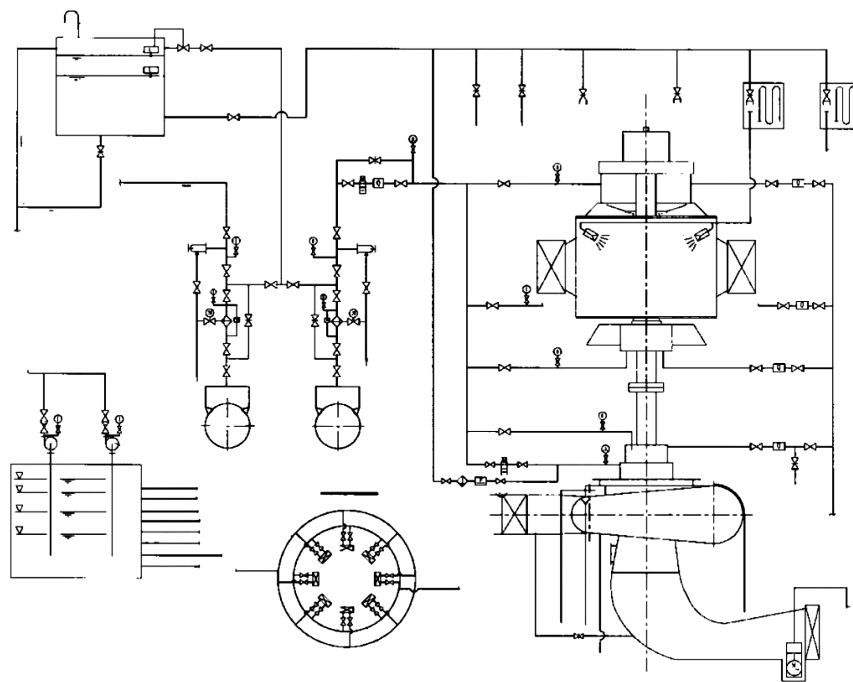


Figure D.7 Schematic diagram of the technical water supply and drainage system