A review of dynamic models and stability analysis for a hydro-turbine governing system

Beibei Xu[1,2,#,*], Jingjing Zhang[1,2,#], Mònica Egusquiza[3], Diyi Chen[1,2,*], Paul Behrens[4,5], Eduard Egusquiza[3]

[1] Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, Shaanxi Yangling 712100, P. R. China
[2] Institute of Water Resources and Hydropower Research, Northwest A&F University, Shaanxi Yangling 712100, P. R. China
[3] Center for Industrial Diagnostics and Fluid Dynamics (CDIF), Polytechnic University of Catalonia (UPC), Av. Diagonal, 647, ETSEIB, 08028 Barcelona, Spain
[4] Leiden University College the Hague, Anna van Buerenplein 301, 2595 DG, The Hague, the Netherlands
[5] Institute of Environmental Sciences (CML), Leiden University, PO Box 9518, 2300 RA Leiden, the Netherlands

[#]These authors contributed equally to this paper.
***Corresponding author: Diyi Chen, Beibei Xu.**
Mailing Address: Institute of Water Resources and Hydropower Research, Northwest A&F University, Shaanxi Yangling 712100, China
Telephones: 086-181-6198-0277
E-mail: diyichen@nwsuaf.edu.cn; xubeibei0413@163.com

Abstract: Hydropower offers highly flexible, low-carbon generation which can be used to balance electricity grids with high levels of wind and solar penetration. This will become increasingly important as the energy transition unfolds. However, hydropower generation faces several problems when used in a flexible, fast response manner (on the order of seconds) when in part-load, over-load or transient conditions. Some of these issues may be addressed by an improved understanding of how load is measured and controlled in a hydro-turbine governing system (HTGS). Here we review different subsystem models and stability analysis approaches for HTGS along with their applicability in different operating conditions and design layouts. We find three main challenges facing the increasing flexible use of HTGS on the grid: 1) Combining the HTGS and shaft model, 2) control methods of HTGS with intermittent renewable energies, and 3) uncertain nature of load on the overall performance and stability of the hydropower system. We hope that this review stimulates further research on HTGS models and control methods with the view to improved grid management.
Keywords: Hydro-turbine governing system; dynamic models; stability analysis; control method; intermittent renewable energies
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Contents

1. Introduction

Wind-solar-hydro is already a complementary, low-carbon electricity generating mix in several regions and offers considerable unexploited potential in many others [1]. As of 2018, total renewable electricity comprised 25.6% globally, where wind-solar-hydro accounted for 88% of this total renewable electricity (Hydropower comprised 15.9% of total global electricity generation and wind-solar 6.7%) [2]. Since wind and solar power is variable, they present challenges for the electricity grid when load matching [3-4]. Hydropower generation is very well suited to load matching under fast variations, being able to rapidly ramp generation in a fast response mode. The combination of wind and solar with fast response hydropower generation offers a synergistic approach for managing the energy transition [5]. HTGS is the key component of hydropower generation, and a better understanding of HTGS under fast load matching offers the opportunity to improve the stability of grid.

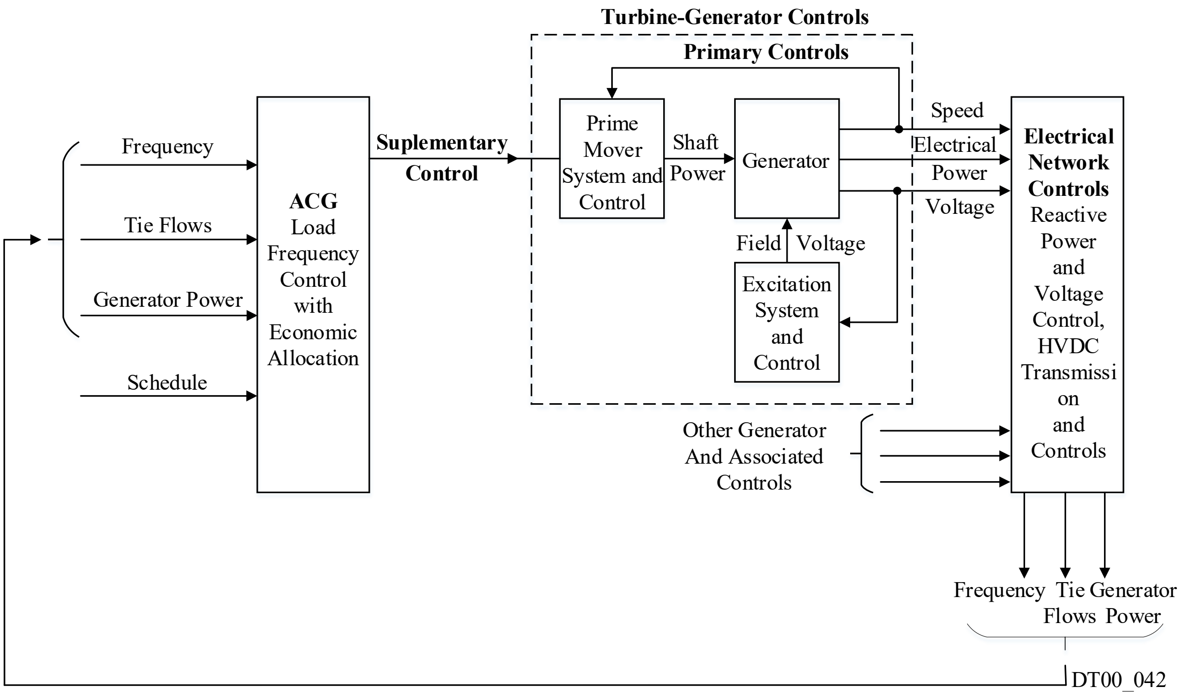


Fig. 1 Function of HTGS in a typical power system. Main elements along with associated controls and functional relationships within power system are shown [6].

HTGS is a complex system which integrates the hydraulic, mechanical, and electrical subsystems [7]. It is responsible for (1) performing the stable operation of units, as well as the mutual switching of various conditions; (2) ensuring the safe operation of the units and emergency shutdown in case of accident; (3) optimizing economic operation of the units, for example, distributing the electric load between units [8]. In other words, the performance of HTGS is a matter of hydropower security, even power quality. Hence, researches on HTGS inevitably attracts scholars' attention.

1.1 Research status

Recently, lots of researches have been done on HTGS. Most of these researches focus on three main aspects:
(1) *Modeling:* Modeling methods have been developed from modular modeling to unified modeling. The theories and methods for modular modeling are reasonably mature due to the rapid development of dynamic stability for each component. Unified modeling, where interactions between modules are characterized, has seen significant progress in recent years [9].
(2) *Stability analysis:* Stability analysis of HTGS is mainly carried out from the perspective of low-frequency oscillation [10], stability margin region [11], etc. The adopted theories from nonlinear dynamics, such as Lyapunov theory [12] and bifurcation theory [13], are common-used to achieve this analysis.
(3) *Control Methods:* Control methods are being improved from traditional control methods to artificial intelligence control methods to achieve a better power supply quality when HTGS subjects to external disturbance. Traditional control methods, such as Proportional-Integral-Differential (PID) [14], have been widely used in HTGS. However, lack of adaptability in dealing with time-delay of guide vane and multiple conditions of HTGS promotes the development of artificial intelligence control methods such as fuzzy control (FC) [15] and fault tolerant control (FTC) [16].

1.2 Research gap

The research gaps of modelling, stability analysis and control methods are listed as:

(1) *Modeling:* Most scholars pay attention to study single modular model or simplified unified model, which is unable to effectively evaluate the potential flexibility of HTGS in mitigating power variations from intermittent renewable energies. Specifically, modular or simplified model as summarized in Table 1, which may hide important dynamic phenomena, is unable to obtain the same qualitative conclusion as a more complex model, resulting in unacceptable accidents. It is often difficult to reproduce accident characteristics because models generally lack sufficient accuracy in representing this complex system, such as the 2003 "8.14" accident in the United States and Canada [17], and the 2006 "9.23" accident in Italy [18].

Table 1 Critical review summary of the modular model or simplified unified model in published literatures.

Ref.	Penstock		Hydro-turbine		Generator (Model order)				Surge tank	Tail water	Shaft vibration
	Elastic	Rigid	Linear	Nonlinear	1	2	3	5			
[19]	√	×	×	×	×	×	×	×	√	×	×
[20]	√	×	×	√	√	×	×	×	√	×	×
[21]	×	√	×	√	×	×	×	×	×	×	×
[22]	×	×	×	×	×	×	×	×	√	×	×
[23]	×	√	×	√	×	×	×	×	√	√	×
[24]	×	×	×	×	×	√	√	√	×	×	×
[25]	×	×	×	×	×	×	×	√	×	×	×
[26]	×	×	×	×	√	×	×	×	×	×	×
[27]	√	×	√	×	×	×	×	√	×	×	×
[28]	√	×	×	√	√	×	×	×	×	×	×
[29]	√	×	×	√	×	√	×	×	×	×	×
[30]	√	×	×	√	×	×	×	√	×	×	√
[31]	√	×	√	×	×	√	×	×	×	×	×
[32]	×	×	×	√	×	×	×	√	×	×	×

(2) *Stability analysis*: The step power disturbance is generally used in theoretical analysis and numerical simulation to assess the stability of HTGS. However, the combination of continuous power variation of intermittent renewable energies and dead zone of HTGS makes a big difference of stability analysis compared with the step power

disturbance, leading to difficulties for the potential flexibility evaluation of HTGS. This gap is summarized in Table 2.

Table 2 Critical review summary of the stability analysis in published literatures.

Ref.	Step power disturbance	Coupling with intermittent renewable energies
[6]	√	×
[7]	√	×
[33]	√	×
[1]	√	√
[3]	×	√
[5]	×	√

(3) *Control methods*: Control methods are developed based on traditional simplified models, while these models do not consider the effect of shaft vibration on HTGS. Therefore, these methods are incapable to tracking all the operation conditions, resulting to risks of power supply reliability. The illustration of this gap is summarized in Table 3.

Table 3 Critical review summary of the control methods in published literatures. FOPID denotes fractional-order PID control. SMC and PC are sliding mode control and predictive control, respectively.

System	Ref.	Traditional PID	Modern control method				
			FOPID	SMC	FC	FTC	PC
HTGS	[1]	√	√	×	×	×	×
	[2]	√	√	×	×	×	×
	[12]	×	×	√	×	√	×
	[33]	×	×	√	×	×	√
	[35]	√	√	×	×	×	×
	[36]	×	×	√	√	×	×
	[37]	√	×	×	√	×	×
HTGS+Shaft system	[3]	√	×	×	×	×	×
	[4]	√	×	×	×	×	×
	[5]	√	×	×	×	×	×
	[6]	√	×	×	×	×	×

1.3 Novel contributions

As we all know, it is necessary and urgent to evaluate the potential flexibility of Hydroelectric Generating Units (HGUs) with the rapid promotion of energy structure reformation. The dynamic models and stability analysis of HTGS is an effective tool to assess the potential flexibility of HGUs to balance electricity grids with high levels of wind and solar penetration. Motivated by this reason, this review is conducted to provide an insight into possible solutions and development directions. The novel contributions of this review include 1) The main achievements in the aspects of modelling, stability analysis and control methods are summarized, and 2) Two challenges and possible development directions for HTGS in mitigating power variations from intermittent renewable energies in future have been identified.

The rest of this paper is organized as follows. Section 2 provides an overview of system configuration and stability analysis methods are embedded in different subsections. Section 3 provides an overview of the dynamic models used for different system components, where characteristics and applicability for these models are also compared in detail. Stability analysis in published papers are presented in section 4. Section 5 introduces several control methods and discusses the advantages and disadvantages of these methods. Section 6 overviews new challenges in integrating with renewable energies. Conclusions close this paper in section 7.

2. System configuration and stability analysis methods

2.1. System configuration

A HTGS is composed of the controlled and control system. The regulating object contains the hydraulic system, HGU and power grid. The control system includes measuring, actuating, amplifying and feedback elements, etc. The operational elements of a typical HTGS is shown in Fig. 2. The governor adjusts the distributor of the hydro-turbine according to the speed deviation of HGU to balance the power between HGU and the power grid [38]. In general, the subsystem configuration of a HTGS depends on the location of the water source and geography of the hydropower station. An example of a hydropower plant with an upstream surge tank is given in Fig. 3 [39].

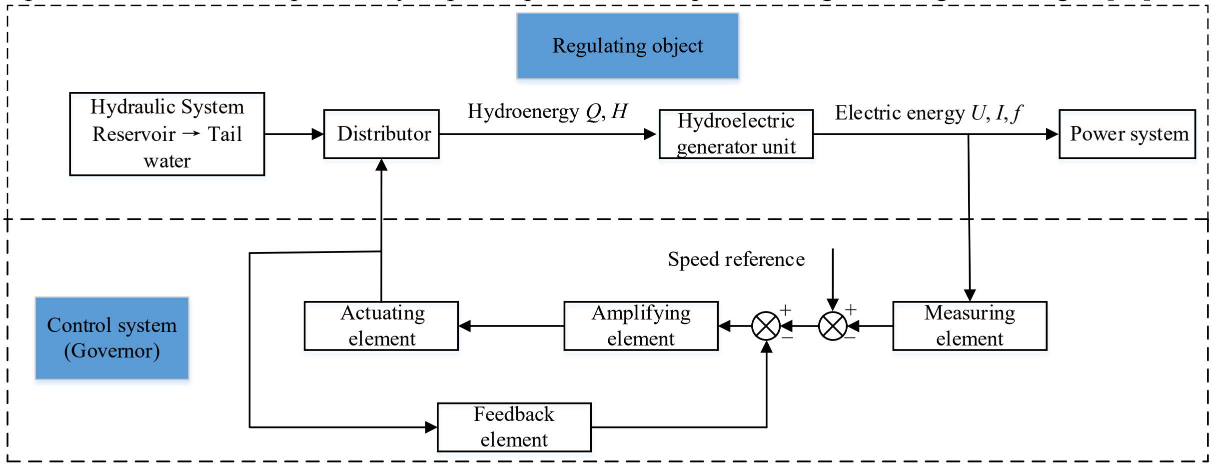


Fig. 2 Operational elements of a HTGS [39]. Q and H are the turbine flow and water head, respectively. U, I and f are the voltage, current and frequency of HGU, respectively.

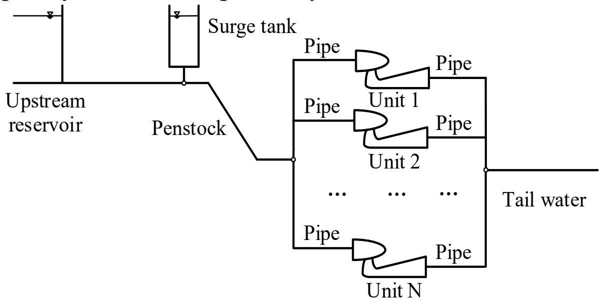


Fig. 3 Layout of a hydropower station with an upstream surge tank [33].

2.2. Stability analysis methods

The stability of HTGS refers to the ability that it remains in an equilibrium state under normal conditions and regains an acceptable equilibrium state after being disturbed. Methods on stability analysis of HTGS are divided into theoretical analysis [40], numerical simulation [38] and field experiment [41]. For the theoretical analysis, works are carried out using Lyapunov theory, bifurcation theory etc. In terms of the numerical simulation, various simulation models were established to cope with the dynamic characteristics. Regarding the field experiment, it is conducted based on the prototype model of HTGS, while field experiment on this issue is relatively rare. This is due to that HGU is a large-scale and important equipment of the hydropower plant. It is difficult to guarantee its safety, and some commissioning projects are very destructive during the field experiment process [42]. Table 4 shows the research status of stability analysis in published papers. Based on the above considerations, common-used stability analysis methods are mainly concentrated on theoretical analysis and numerical simulation as shown in Table 5. The processing flow chart of these methods are presented in Fig. 4.

Table 4 Research status of stability analysis methods.

Ref.	Theoretical analysis	Numerical simulation	Field experiment	Lab experiment
[43]	√	×	×	×
[44]	×	√	×	×
[45]	×	×	√	×
[46]	×	√	×	×
[47]	√	×	×	×
[41]	√	×	×	√
[13]	√	×	×	×
[19]	√	√	×	×

Table 5 Characteristics review of common-used methods for stability analysis.

Approaches	Characteristics	Ref.

Bifurcation theory	**Advantages**: Reflects the characteristic oscillation of the system **Disadvantages**: The calculation is complex with higher equation order	[48]
Lyapunov theory	**Advantages**: Suitable for both linear and nonlinear systems **Disadvantages**: No generalized functional form for Lyapunov functions	[49]
Numerical simulation method	**Advantages**: The results are reproducible **Disadvantages**: Different algorithmic approaches might result in different characterizations. The calculation time increases non-linearly for high-order systems	[50]

- Bifurcation is a specific phenomenon of the nonlinear system, where the system changes from one behavior to another very different one [51]. In HTGS, bifurcation usually results in a continuous oscillation phenomenon of HGU [52]. The theoretical basis for this approach is pioneered in a set of papers. Guo and Yang [53] studied the HTGS's performances using Hopf bifurcation and found that the bifurcation solutions' stability is altered by changing the nonlinear term. Liang et al. [54] proposed the HTGS model, where surge tank is considered and then investigated unstable oscillation using bifurcation theory. Chen et al. [55] applied the bifurcation theory to a HTGS to visualize bifurcation diagrams, phase orbits, etc.
- Lyapunov theory uses the Lyapunov exponent to analyze and identify the local stability in the field of potential operational states, also known as small range stability [56]. The positive and negative exponents indicate the system are in the chaotic and stability state, respectively [57]. An example framework for calculating the largest Lyapunov exponent is shown in Fig. 4(*b*). Foundational literature includes: Deng et al. [58] utilized the maximal Lyapunov exponent to analyze stochastic global stability of HGU. Yi et al. [34] demonstrated that global asymptotic stability of the HTGS with the state feedback predictive controller is achieved using the Schur complements and discrete Lyapunov function. Su et al. [59] found chaotic attractors when maximum Lyapunov exponents were greater than zero.
- Numerical simulation assesses system's stability by analyzing the fluctuation state of the system output (i.e. convergence, divergence or continuous oscillation). Common-used visualization forms include time domain diagram, phase trajectory diagram etc. Here, Guo et al. [60] studied the influence of PI parameters on the oscillation characteristics of HTGS using time domain diagrams. Li et al. [61] used numerical simulation to investigate the operational characteristics of the HGTS form the viewpoint of multi-time-scale. Zhang et al. [62] established a multi-time-scale HTGS model and HTGS's stability under different time-scale were presented using time domain simulation. Xu et al. [63] proposed a novel fractional-order HTGS model and gave the stable region law of the novel system based on time domain simulation analysis.

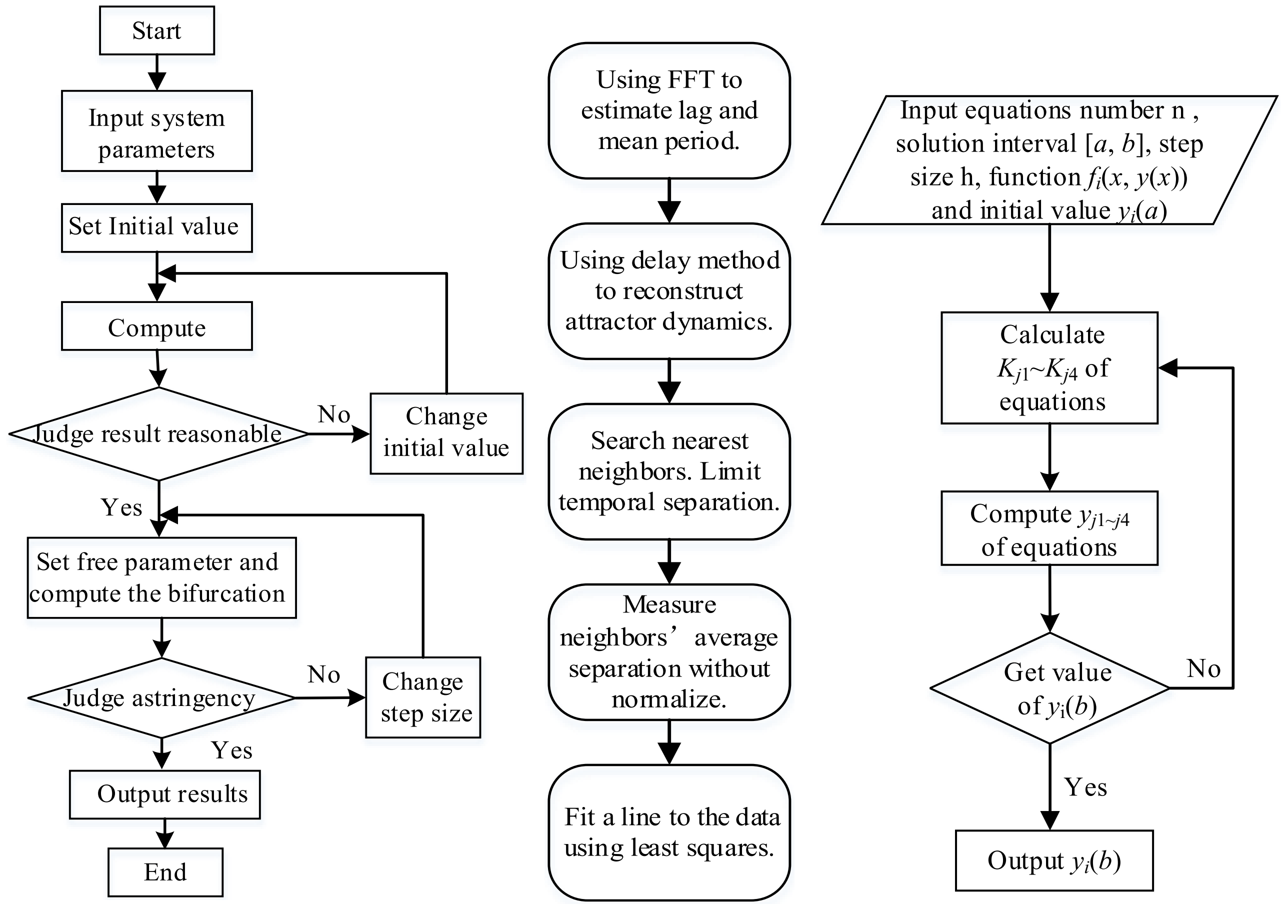


Fig. 4 Flow charts of the three stability analysis approaches. (*a*) Bifurcation theory [64]; (*b*) Lyapunov theory [57]; (*c*) Numerical simulation [65].

The theoretical analysis and numerical simulation have the advantages of clear principles and concise physical meanings. However, some specific assumptions or simplifications (e.g., ignoring nonlinear factors and high-order components) needs to be made using theoretical analysis and numerical simulation, which may hide some dangerous phenomena posing an unpredicted threaten to the stable and safe operation of HTGS.

With the rapid implementation of energy-structure reformation, the requirements of the flexibility of HTGS change from optimal operating region to overall operating region. Therefore, it is an urgent and burning issue to combine field experiment and numerical simulation/theoretical analysis to keep the safe and stability of HTGS.

3. Dynamic models of HTGS components

3.1. Models of the diversion system

3.1.1 Models of the surge tank

Hydropower plant with long conduits may subject to water hammer, which may threaten the system's stability. The classic solution is introducing upstream or/and downstream surge tank to minimize water hammer effects [19]. The surge tank, as a critical component of diversion-type hydropower plants [66], has an important function in reducing the amplitude of pressure fluctuations through reflecting the incoming pressure waves, and to both store and provide water [20, 21].

(*a*) Layouts of surge tank

The surge tank is arranged in various forms, such as upstream or/and downstream side of the powerhouse. Fig. 5 displays four typical layouts of surge tank.

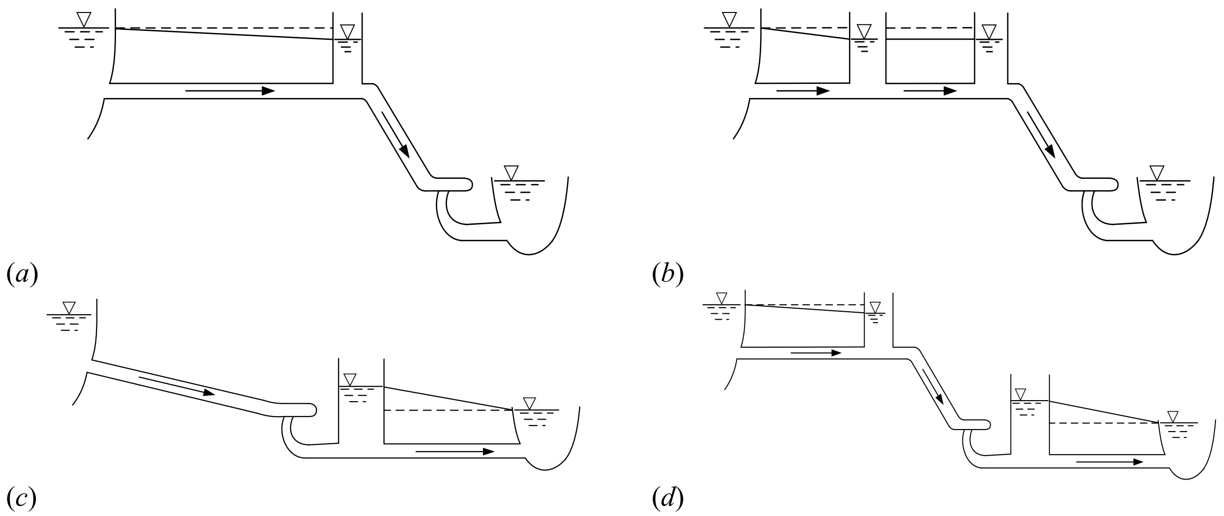


Fig. 5 Typical layouts of a HTGS with surge tanks [67]. (*a*) Upstream surge tank; (*b*) Upstream double surge tank; (*c*) Downstream surge tank; (*d*) Upstream and downstream double surge tanks.

(*b*) Models of surge tank

The mathematical equation of a surge tank is [47]

$$\frac{dQ_t}{dt} = \frac{gA_t}{L}(H - z + fQ_t|Q_t|) \tag{1}$$

where Q_t is the flow. A_t is the constant proportionality factor. L is the length of the conduit. f is the Darcy-Weisbach friction factor. g is the gravitational acceleration.

The equation of continuity for the junction of the tunnel and the surge tank is

$$Q_t = Q_s + Q_{tur} \tag{2}$$

where Q_s is the flow into the surge tank, and Q_s=A_s(dz/dt). Q_{tur} is the turbine flow. A_s is the surge tank cross-sectional area. This gives

$$\frac{dz}{dt} = \frac{1}{A_s}(Q_t - Q_{tur}) \tag{3}$$

Eq. (1) and Eq. (3) are the basic expressions which are suitable for both the upstream and downstream surge tanks. If neglect the hydraulic losses of the surge tank orifice then normalizing Eq. (3), the transfer function between the flow and head is written as [55]

$$\frac{h_s}{q_s} = T_j s \tag{4}$$

where h_s and q_s represent head and the flow of surge tank. T_j is the time constant of surge tank.

The transfer functions of the upstream and downstream surge tanks are described as Eq. (5) and Eq. (6), respectively [68].

$$\frac{h_{s1}}{q_1 - q_t} = \frac{1}{T_{j1}s} \tag{5}$$

$$\frac{h_{s2}}{q_t - q_2} = \frac{1}{T_{j2}s} \tag{6}$$

where h_{s1} and h_{s2} are the head of upstream and downstream surge tanks, respectively. q_t is the flow of hydro-turbine. T_{j1} and T_{j2} represent the time constant of upstream/downstream surge tanks, respectively. q_1 and q_2 are the flow of upstream and tail race tunnel, respectively.

(*c*) Appropriate configuration of surge tanks

Surge tanks must be sized and placed thoughtfully in the larger hydropower system if excessive pressure or over speed problems are to be avoided. In hydropower plant with long conduit, the surge tank is generally larger in size and higher in cost. There is a vigorous academic debate about how this is best done. Here, we show some international regulations for the configuration of surge tanks in Table 6.

Table 6 Regulations for the configuration of surge tanks.

Country	Upstream surge tank	Ref.	Downstream surge tank	Ref.

Former Soviet Union	$\frac{\sum LV}{H_0} > K$ ICP: >50% SCP or ISO, K: 16~20 ICP: 10-20% SCP, K: ≥50	[66]	There is no water column separation in the draft tube	[22]
USA	$T_w = \frac{LV}{gH_0} > [T_w]$	[69]	$\sum LV > 1800 m^2/s$	[66]
China	$T_w = \frac{\sum L_i V_i}{gH_p} \ge [T_w], [T_w] \in [2,4]$	[70]	$L_w > \frac{5T_s}{v_{w0}}(8 - \frac{\nabla}{900} - \frac{v_{wj}^2}{2g} - H_s)$	[70]
Japan	$\sum LV / H_0 > 45$	[71]	$T_{ws} = \frac{LV}{g(-H_s)} > 6$	[72]

When $T_w = \frac{LV}{gH_0} \ge 1.8 \sim 6.0s$ or $\beta_m = \sqrt{1 + \frac{365 N_0 T_s' f}{GD^2 n_0^2}} - 1$ is established, surge tank should be set up.

Country	β_m	Ref.
France	0.60	[73]
Austria	0.45	
Canada	0.70	

Note: K is the critical value. L and V represent the length of the pressure draft tube and flow velocity in the penstock, respectively. H_0 is initial working head of unit. T_w is the water inertia time constant. $[T_w]$ stands for the allowable value of T_w. T_s is the effective closing time of guide vane. L_i is the length of each segment of penstock and tail tunnel. V_i is the corresponding velocity of flow in each segment. ∇ is the installation elevation of hydro-turbine. v_{w0} and v_{wj} are the steady-state flow velocity in the pressurized draft tube and at the inlet of the draft tube. H_p is the design head. L_w is the length of pressure tail channel. β_m is elevated value of unit speed. N_0 and n_0 represents the rated output and rated speed of unit. T_s' is the shutdown time from full start to full shutdown of the unit. f stands for the water hammer influence coefficient. GD^2 is the flywheel torque. ISO stands for the isolated operation. ICP represents installed capacity. SCP is the system capacity. H_s is the minimum inundation depth. T_{ws} is the time constant of draft tube.

(*e*) Applications of surge tank model

There have been several applications of a surge tank model. For example, France [74-77] focused on finite difference and finite element methods to study surge tank problems. Bao et al. [66] summarized the conditions for the configuration of surge tanks from the viewpoint of operation stability, regulation assurance and regulation quality, which provides a guidance for surge tank setting. Fang et al. [78] established HTGS model with high water-head and a long-distance penstock and then investigated the influence of surge tank parameters on the dynamic performances of HTGS. Vereide et al. [79] investigated the influence of surge tank throttle on hydraulic transient and results showed that the throttle enhances water hammer.

3.1.2 Model of penstocks

The penstock is subject to water hammer during the water fluctuating, which brings undesirable threat to the penstock (e.g. pipe-broken accident). Hence, transient modeling of the penstock to analyze the water hammer effect to eliminate hidden dangers is an indispensable task. Main calculation method of water hammer include analytic method, graphic method, characteristic method, etcetera as shown in Table 7. At present, analytic method and characteristic method are most widely used and verified.

Table 7 Numerical solutions of water hammer.

Methods	Characteristics	Ref.
Analytic method	**Advantages**: Concise physical meanings; simple solving process. **Disadvantages**: Difficult to deal with the boundary conditions of complex piping system; lower calculation accuracy	[80]
Graphic method	**Advantages**: Clear concept and simple calculation procedure for simple pipe systems. **Disadvantages**: Tedious drawing process and lower calculation accuracy for complex pipe system.	[81]

Characteristic method	**Advantages**: High precision; easy to deal with complex boundary condition. **Disadvantages**: Needs to be corrected under the condition of non-constant or non-equilibrium Kurang number.	[82]

(*a*) Characteristic Method

Wylie and Streeter first proposed the water hammer equation based the characteristic method [83]. It replaces partial differential equations by ordinary differential equations by introducing a Lagrange factor, Segmentation of pipeline, and solving equations using boundary conditions.

The continuity and momentum equations used to describe the flow characteristic are given as [10, 84]

$$\begin{cases} \dfrac{\partial H}{\partial x}+\dfrac{1}{g}\dfrac{\partial v}{\partial x}+\dfrac{v}{g}\dfrac{\partial v}{\partial x}+\dfrac{fv|v|}{2gD}=0 \\ \dfrac{\partial H}{\partial t}+v\dfrac{\partial H}{\partial x}+\dfrac{a^2}{g}\dfrac{\partial v}{\partial x}+v\sin\alpha=0 \end{cases} \tag{7}$$

where H, x and v are the water head, the distance along the pipeline and the flow victory, respectively. g represents the acceleration of gravity. D, a and α represent the penstock diameter, wave speed of water hammer and angle between the penstock and horizontal, respectively.

Transforming Eq. (7) into finite difference equations, then one can get

$$\begin{cases} C^+ : \mathrm{Q_p}=C_p-C_{aR}H_p \\ C^- : \mathrm{Q_p}=C_n+C_{aS}H_p \end{cases} \tag{8}$$

where P and R represent two points of the penstock. C_P, C_n, C_{aR} and C_{aS} stand for intermediate variables. The expressions of these intermediate variables are

$$\begin{cases} C_p=Q_R+\dfrac{gF_R}{a_R}H_R-\dfrac{f_R\Delta x}{2D_RF_Ra_R}Q_R\,|Q_R\,|-\dfrac{Q_R\Delta xg}{a_R^2}\sin\alpha \\ C_n=Q_s-\dfrac{gF_S}{a_S}H_S-\dfrac{f_S\Delta x}{2D_SF_Sa_S}Q_S\,|Q_S\,|+\dfrac{Q_S\Delta xg}{a_S^2}\sin\alpha \end{cases} \tag{9}$$

where Q_R, Q_S, H_R and H_s represent the flow and head at R and S, respectively. F_R and F_S stand for the cross-sectional area at R and S, respectively.

(*b*) Analytic method

The Laplace transformation of the water hammer equation is carried out using the analytic method, and the expression of water hammer is solved in frequency domain. The analytic expression of water hammer is then obtained by inverse Laplace transformation. Common-used water hammer models are rigid and elastic model depending on the length of the penstock. Generally, rigid model are used in short-distance penstock, while elastic model is as good choice for the long-distance penstock [55]. The advantages and disadvantages of rigid and elastic models are shown in Table 8.

Table 8 Penstock models for hydro-turbine governing system.

Models	Equations	Characteristics	Ref.
Rigid model	$G_h(s)=-T_w s$	**Advantages**: Simple calculation and reasonable accuracy **Disadvantages**: Modeling inaccuracy when penstock length is above 200m	[39, 85]
First order elastic model	$G_h(s)=-2h_w\tanh 0.5T_r s$	**Advantages**: Accurate modeling of any penstock length **Disadvantages**: Ignoring the first oscillation mode between the mechanical and hydraulic systems	[86]
Second order elastic model	$G_h(s)=-T_w s/(1+0.125T_r^2s^2)$	**Advantages**: Captures second oscillation mode of hydro-mechanic-electric factors **Disadvantages**: Complex calculations	[87]
Third order elastic model	$G_h(s)=-2h_w\dfrac{T_r^3s^3/48+T_r s/2}{T_r^2s^2/8+1}$	**Advantages**: Higher oscillation modes are captured **Disadvantages**: (Even more) complex calculations	[43]

- Due to its simplicity, the rigid model is widely used when the penstock is in a short/medium length. Guo et al. [23] analyzed the dynamic behaviors of HTGS considering rigid water column during primary frequency regulation. Zhang et al. [88] studied the dynamic responses of HTGS with rigid water hammer when it was subject to load rejection. Chen et al. [89] studied parameter identification in a HTGS, where rigid model was considered.
- Elastic water hammer effect cannot be ignored when the hydropower plant has a long penstock. In other words, the elastic model should be considered to describe its dynamic performances. Under this framework, Ling et al. [52] studied the bifurcation phenomena of HTGS with an elastic water hammer model. Zeng et al. [46] derived the differential equation of elastic water column and then verified its applicability in describing transient impacts. Kishor et al. [44] performed the elastic model to investigate power response in time and frequency domain.

3.2. Hydro-turbine model

The hydro-turbine models are divided into linear and nonlinear model according to signal disturbance as shown in Table 9. The current modeling methods are divided into two categories: exterior characteristic method based on the exterior characteristic curve and internal character analysis as shown in Table 10.

Table 9 Hydro-turbine model classification.

Models	Signal disturbances	Characteristics	Ref.
Linear model	Load disturbance < ± 10% rated value, Frequency deviation < ± 8% rated value	**Advantages**: Clear physical meaning; simple structure; convenient to analyze stability in frequency domain using modern control theory; convenient for optimal design of various controllers. **Disadvantages**: Can result in errors due to simplifications.	[13,14, 52]
Nonlinear model	Load disturbance > ±10% rated value, Frequency deviation > ±8% rated value	**Advantages**: Can capture nonlinearities in HTGS operation. **Disadvantages**: Can be difficult to calculate due to complexities in the modelling.	[52, 90, 91, 92]

Table 10 Numerical solution approaches for dynamic turbine torque.

Methods	Characteristics	Ref.
Exterior characteristic	**Advantages**: Accurate solution under transient conditions **Disadvantages**: Difficult to obtain the complete characteristic curve, the application is limited	[93]
Internal characteristic	**Advantages**: High accuracy **Disadvantages**: Difficult to measure parameters of the hydro-turbine structure, the calculation very complicated	[94]

(*a*) Exterior characteristic method

The exterior characteristic method describes the relation of guide vane, head, flow, speed, torque and other parameters based on synthetic characteristic curve. In the modeling process, the hydro-turbine model is expressed as linear model near a specific operating point [78], i.e.

$$\begin{cases} m_t = e_x x + e_y y + e_h h \\ q = e_{qx} x + e_{qy} y + e_{qh} h \end{cases}, \tag{10}$$

where $e_x = \frac{\partial m_t}{\partial x}$, $e_y = \frac{\partial m_t}{\partial y}$, $e_h = \frac{\partial m_t}{\partial h}$, $e_{qx} = \frac{\partial q}{\partial x}$, $e_{qy} = \frac{\partial q}{\partial y}$, and $e_{qh} = \frac{\partial q}{\partial h}$ are the transfer coefficients of turbine torque and flow, respectively. x, y, h, q and m_t are relative deviation of speed, guide vane opening, head, flow and torque, respectively.

Considering the operating point changing frequently, variable transfer coefficients varying with speed and head are used to display the nonlinear properties of hydro-turbines [68]. To achieve this goal, Eq. (10) is modified by some scholars and several modified formulas have been proposed. For example, Shen [95] gave the nonlinear expressions of six transfer coefficients based on the comprehensive characteristic curve of hydro-turbine as:

$$\begin{cases} e_y = e_{ym}(h+1) \\ e_{qy} = e_{qym}\sqrt{h+1} \\ e_x = e_{xm}\sqrt{h+1} \\ e_{qx} = e_{qxm} \\ e_h = e_{hm} \\ e_{qh} = e_{qhm}\dfrac{1}{x+1} \end{cases}. \tag{11}$$

Thus Eq. (10) is rewritten as

$$\begin{cases} m_t = e_{xm}\sqrt{h+1}x + e_{ym}(h+1)y + e_{hm}h \\ q = e_{qxm}x + e_{qym}\sqrt{h+1}y + e_{qhm}\dfrac{1}{x+1}h \end{cases}. \tag{12}$$

Li et al. [96] gave six nonlinear transfer coefficients of HTGS under the condition of load increasing (see Fig. 6). Based on these transfer coefficient curves, the authors were able to describe the nonlinear dynamic behaviors. This is vital for maintaining stable operation under load sudden increasing.

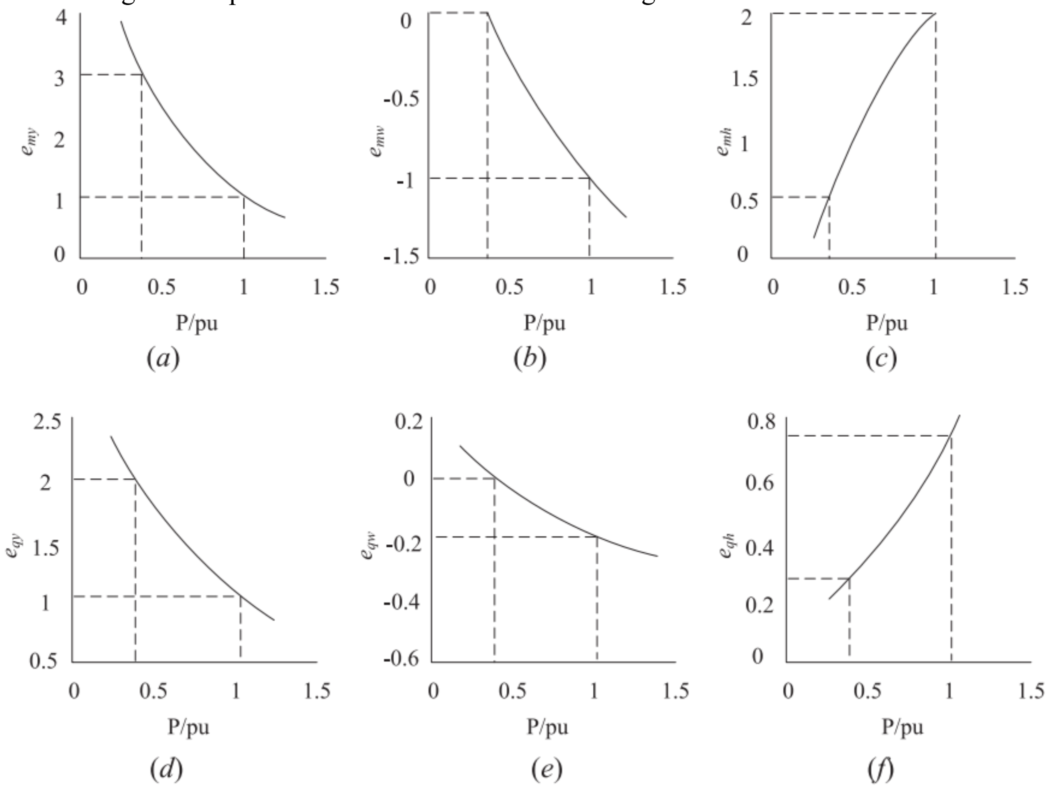
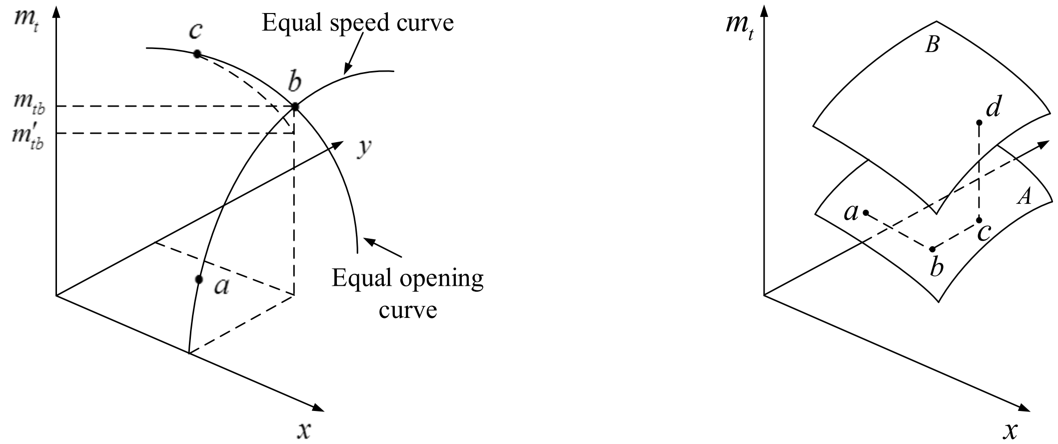


Fig. 6 Curves of transfer coefficients [96].

The transfer coefficients approximately calculated results in non-negligible accumulated error as shown in Fig. 7(*a*). To address this drawback, Zhang et al. [97] introduced the surface-cluster method to describe transfer coefficients in Fig. 7(*b*). The torque and flow at operating point *a* are expressed as

$$\begin{cases} m_{td}\left(x_d \quad y_d \quad h_d\right) = m_{ta}\left(x_a \quad y_a \quad h_a\right) + \int_{x_a}^{x_d} e_{mx}dx + \int_{y_a}^{y_d} e_{my}dy + \int_{h_a}^{h_d} e_{mh}dh \\ q_{td}\left(x_d \quad y_d \quad h_d\right) = q_{ta}\left(x_a \quad y_a \quad h_a\right) + \int_{x_a}^{x_d} e_{qx}dx + \int_{y_a}^{y_d} e_{qy}dy + \int_{h_a}^{h_d} e_{qh}dh \end{cases}. \tag{13}$$



(*a*) (*b*)

Fig. 7. The hydro-turbine torque curve [97]. (*a*) The accumulated errors of torque; (*b*) Surface-cluster method of torque.

IEEE Group give a simplified nonlinear model which is popular with scholars. It is described as [98]

$$\begin{cases} p_m = A_t h(q - q_{n1}) - D_t y \Delta\omega \\ \dfrac{dq}{dt} = \dfrac{1 - h - f_p q^2}{T_w} \\ q = y\sqrt{h} \end{cases} \tag{14}$$

where p_m is the hydro-turbine power. A_t and D_t are the proportionality and damping coefficient, respectively. q_{n1} represents the no-load flow of hydro-turbine. f_p is the water head loss coefficients.

The transfer coefficient varies with the change of operation condition, more attention should be paid to the topic that describes the transfer coefficient in real-time.

(*b*) Internal characteristic method

The internal characteristic method is based on the geometric and structural parameters to obtain the nonlinear characteristics of the hydro-turbine. It takes the expression of head, flow, torque etc as boundary conditions of the hydro-turbine. Hence, it has clear physical meaning. Some assumptions need to be made in modeling process and the selection of parameters depend on experience during transient calculation so that this method is seldom used in engineering.

The flow and torque characteristics are given by Eq. (14). For more details please see Men and Nan [99].

$$\begin{cases} f_1 = (y, n_{11}, Q_{11}) = 0 \\ f_2 = (y, n_{11}, M_{11}) = 0 \end{cases}. \tag{15}$$

where Q_{11} and M_{11} represent the unit flow and torque, respectively. n_{11} stands for unit speed.

To overcome the disadvantages of exterior and internal characteristic methods, attentions should be paid to combine the two methods so that better to deal with boundary issues. However, relevant models have not been better put forward.

3.3. Generator models

The commonly used generator models are first-order, second-order, third-order and fifth-order model etc [95] as shown in Table 11. For a detailed overview of this sort of modelling see Ref. [24]. For simplicity, the first-order model is usually used in the operating condition of a single machine. However, high-order models should be used when multiple units are in operation [100]. Regarding for the application of generator models, Fang et al. [78] analyzed hydraulic transients based on a first-order generator model. Xu et al. [101] studied the dynamic behaviors of HTGS under shock load with a second-order generator. Sharafutdinov et al. [25] studied the stability of voltage and rotor-angle using bifurcation theory in a third-order generator system. Clearly, the lower the model order, the simpler the model can be obtained, and the less accurate the results will be. However, with more and more complex of the model, the work becomes increasing harder in both data requirements, computation time and result interpretation [55].

Table 11 Different order generator models for HTGS.

Models	Equations	Characteristics	Ref.
First-order	$\dot{\omega}=\frac{1}{T_{ab}}(m_t-m_{g0}-e_n\omega)$	**Advantages**: Simple calculation **Disadvantages**: Modeling inaccuracy, especially for transient processes **Applications**: Only considering the moment of inertia of the generator	[26]
Second-order	$\begin{cases}\dot{\delta}=\omega-1\\ \dot{\omega}=\frac{1}{T_{ab}}[T_m-T_e-D(\omega-1)]\end{cases}$	**Advantages**: Results are positive for the slow response excitation system **Disadvantages**: Transient electric potentials remain unchanged **Applications**: Considers the moment of inertia of the generator, output power and power angle	[24,95]
Third-order	$\begin{cases}\dot{E}'_q=\frac{1}{T'_{d0}}[E_f-E'_q-(X_d-X'_d)i_d]\\ \dot{\omega}=\frac{1}{T_{ab}}[T_m-E'_qi_q+(X'_d-X_q)i_di_q]\\ \dot{\delta}=\omega-1\end{cases}$	**Advantages**: Simple structure and considers the dynamics of the excitation system **Disadvantages**: Complex calculation **Applications**: Considering the moment of inertia of the generator, output power, power angle and the excitation system	[24, 95]
Fifth-order	$\begin{cases}\dot{E}'_q=\frac{1}{T'_{d0}}[E_f-E_q]\\ \dot{E}''_q=\frac{1}{T''_{d0}}[X_rT''_{d0}E'_q-E''_q+E'_q-Xi_d]\\ \dot{E}''_d=\frac{1}{Tv''_{q0}}[-E''_d+(X_q-X''_q)i_q]\\ \dot{\omega}=\frac{1}{T_{ab}}[T_m-T_e-D(\omega-1)]\\ \dot{\delta}=\omega-1\end{cases}$	**Advantages**: Accurate modelling of transient processes **Disadvantages**: The calculation is complex **Applications**: Considers the moment of inertia of the generator, output power, power angle, excitation system, super-transient electromotive force of *dq*-axes	[24, 95]

Note: $E_q=\frac{X_d-X_1}{X'_d-X_1}E'_q+\frac{X_d-X'_d}{X'_d-X_1}E''_q-\frac{(X_d-X'_d)(X''_d-X_1)}{X'_d-X_1}i_d$; $T_e=[E''_qi_q+E''_di_d-(X''_d-X''_q)]i_di_q$; $X_r=\frac{X''_d-X_1}{X'_d-X_1}$; $X=X'_d-X''_d$. ω and δ are the angular speed of the generator and rotor angle, respectively. e_n is the accommodation coefficient. m_{g0} is the load disturbance of the generator. m_t is the output torque of the hydro-turbine. T_{ab} is the mechanical starting time. T_m and T_e are the electromagnetic power of the generator and the electromagnetic torque of generator, respectively. E_q' and E_f are the armature transient voltage of *q*-axis and excitation voltage of the generator, respectively. D is the damping coefficient. X_d and X_q are the *dq*-axes reactance. X_d' is the *d*-axis transient reactance. i_d and i_q are the stator current of *d*-axis and *q*-axis, respectively. T_{d0}' and T_{d0}" denote the open-circuit transient and switching subtransient time constant of *d*-axis, respectively. E_q" and E_d" are the subtransient electromotive force of *dq*-axes. X_d" and X_q" are the subtransient reactance of *dq*-axes, respectively. X_1 is the stator *q*-axis winding leakage reactance. E_q is the no-load terminal transient electromotive force.

3.4. Governor model

3.4.1 Development course of Governor

The development of the governor has three periods, i.e. the mechanical hydraulic governor, electric hydraulic governor and microprocessor-based governor in Table 12. The earliest prime mover governor is traced back to the centrifugal governor of the steam engine invented by James Watt in 1782. Its operational principle is basically the same as the centrifugal governor. By 1930s, the mechanical hydraulic governor is refined following a Proportional-Integral (PI) approach. It is widely used in small and medium hydropower stations due to good static and dynamic characteristics. With the development of electronic controls, the first successful analog-electrical hydraulic governor appears in 1950s using PID regulation [39]. In the mid-1980s, microprocessor-based governors (in Fig. 8) have seen a rapid development [45].

Table 12 Comparisons of different governors.

Types	Regulation law	Characteristics	Ref.
Mechanical hydraulic	PI	**Advantages**: Good static and dynamic characteristics **Disadvantages**: Low sensitivity; Poor automation.	[9]
Electric hydraulic	PID	**Advantages**: Simple structure, faster speed response **Disadvantages**: Excessive oscillation in interconnected systems; does not guarantee a stable closed loop system for at all operating conditions	[14]
Microprocessor -based	PI, PID or more complex regulation laws	**Advantages**: Good reliability, redundancy, flexibility, improved performance and reliability **Disadvantages**: Under special circumstances, it may cause overspeed and overvoltage protection of the unit, resulting in accidental shutdown.	[45, 102]

The PI governor is expressed as [71, 98]

$$G(s) = \frac{T_d s + 1}{b_t T_d s} = \frac{1}{b_t} + \frac{1}{b_t T_d s} = k_p + \frac{k_i}{s} \tag{16}$$

The PID controller is written as [39, 103]

$$G_r(s) = \frac{Y(s)}{X(s)} = -\frac{K_d s^2 + K_p s + K_i}{b_p K_d s^2 + (b_p K_p + 1)s + b_p K_i} \frac{1}{T_{yB} T_y s^2 + T_y s + 1}. \tag{17}$$

If assume b_p=0 and T_y=0, Eq. (16) can rewritten as

$$G(s) = K_p + \frac{K_i}{s} + K_d s \tag{18}$$

where K_p, K_i and K_d are the proportional, integral and differential gain, respectively. b_p is the permanent droop. T_d and b_t are the buffer time constant and temporary droop, respectively. T_{yB} and T_y are the time constant of the first stage hydraulic amplification and the engager rely time constant, respectively.

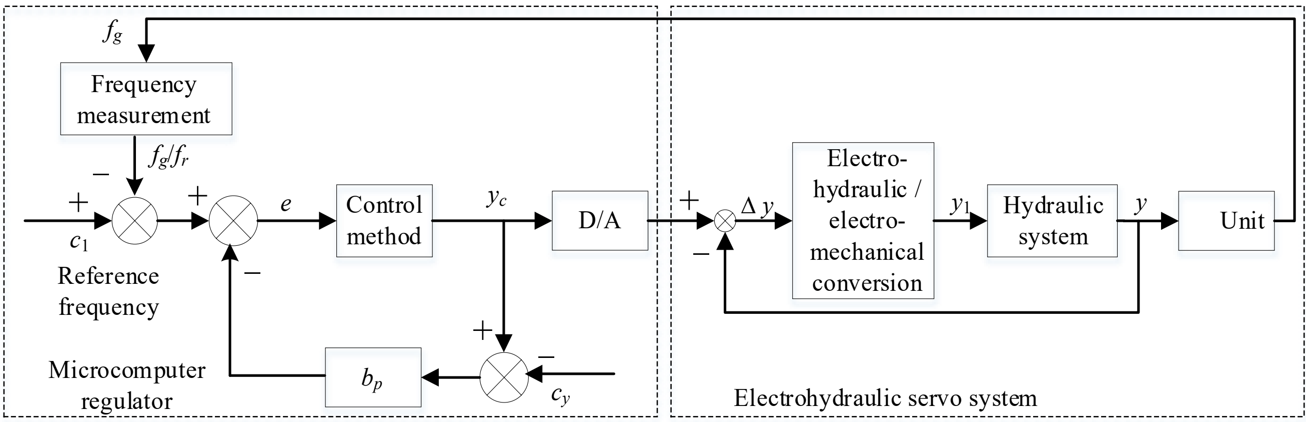


Fig. 8 Block diagram of microprocessor-based governor. f_g and f_r are the output frequency of the generator and the frequency measurement, respectively. c_1 and $\triangle y$ are the reference frequency and deviation of the servomotor displacement, respectively. e, y_1 and y are the signal deviation, position of the median servomotor and primary servomotor, respectively.

3.4.2 Application of the governor

Many researchers have discussed the designing and applications of the governor. For example, Fang et al. [104] applied an improved particle swarm optimization to adjust PID gains and obtained better results in convergence and computational ability. Jiang et al. [105] used an improved evolutionary programming method to optimize the on line PID parameters and results showed that the proposed method has the advantage of fast response and reducing overshoot. Cheng et al. [106] compared the difference between intelligent PID controller and the conventional PID, and results showed that the former has a better dynamic performance. Li et al. applied several techniques, such as fault detection and self-recovery to a microprocessor-based governor to improve its reliability [107].

Although traditional governors have been widespread used in hydropower station, they are incapable of giving optimal control performance in all operation states, especially transient conditions. To improve regulation quality, more advanced governors using intelligent control methods have been developed which will be stated in Section 5.

3.5 HTGS models

Components of HTGS exhibit strong nonlinearity, such as hydro-turbine and governor [108], and many uncertain factors exist in structural parameters due to the equipment aging, unit vibrations etc [33]. Modeling HTGS is therefore an important and difficult task. Different layouts of the hydropower plant can lead to different expressions of the system model, such as HTGS model with or without surge tank. Fig. 9 displays the canonical system model considering different operation conditions. In general, HTGS model is the coupling of modular models, which can be divided into linear and nonlinear models. The linear model is widely used in small disturbance conditions, while the nonlinear model is suitable for large disturbance conditions.

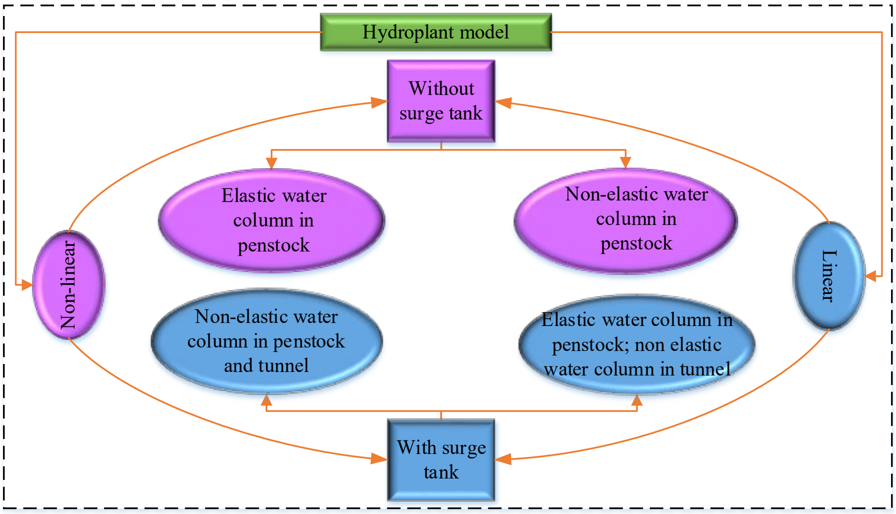


Fig. 9 Overview of HTGS model [14].

For a long time, some scholars have paid attention to establish HTGS model to study various dynamic phenomena. Most of these studies are implemented under the integer order framework. For instance, Liu and Liu [109] demonstrated the dynamic stability of a hydropower station with a linear turbine model under steady conditions. Related studies have pointed out that fluid has the property of memory. Integer order calculus has limitations in this respect because HTGS is a complex system with non-minimum phase and time-variant. Fractional order calculus has the advantages of memory and strong dependence. Hence, to overcome these drawbacks of integer order calculus, it is necessary to try to build a fractional-order mathematical model. Xu et al. [63] introduced the fractional order theory (see Eq. (19)) to analyze the dynamic performances of HTGS, and then investigated the variable law of K_p-K_d stable region when the fractional order changed.

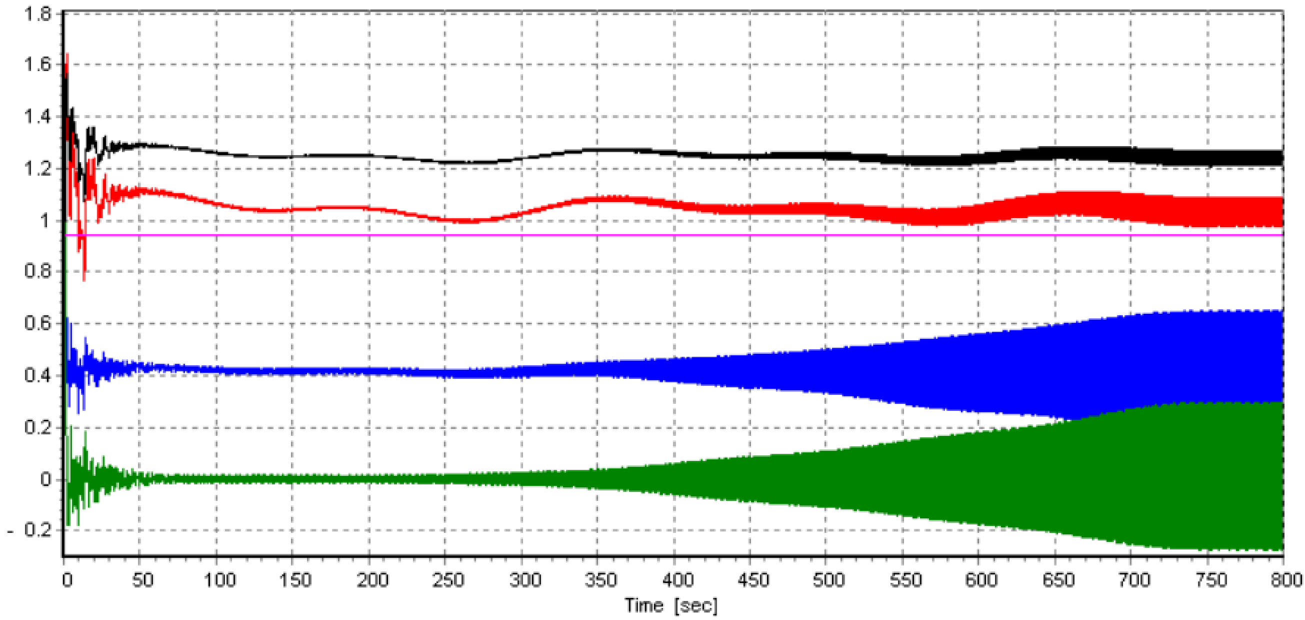
$$\begin{cases} D^q x_1 = x_2 \\ D^q x_2 = x_3 \\ D^q x_3 = -a_0 x_1 - a_1 x_2 - a_2 x_3 + y \\ D^q \delta = \omega_0 \omega \\ D^q \omega = \dfrac{1}{T_{ab}}[m_t - \dfrac{E_q' V_s}{X_d'} \sin\delta - \dfrac{V_s^2}{2}\dfrac{X_d' - X_q}{X_d' X_q} \sin 2\delta - D_t \omega] \\ D^q y = \dfrac{1}{T_y}(-k_p(r-\omega) - \dfrac{k_i}{\omega_0}\delta - k_d D_t^q \omega - y) \end{cases} \tag{19}$$

where x_1, x_2 and x_3 are state variables of penstock system. ω_0 is the rated speed of the generator. a_0, a_1 and a_2 are the intermediate variables related to transfer coefficients. V_s is the voltage of infinite power system.

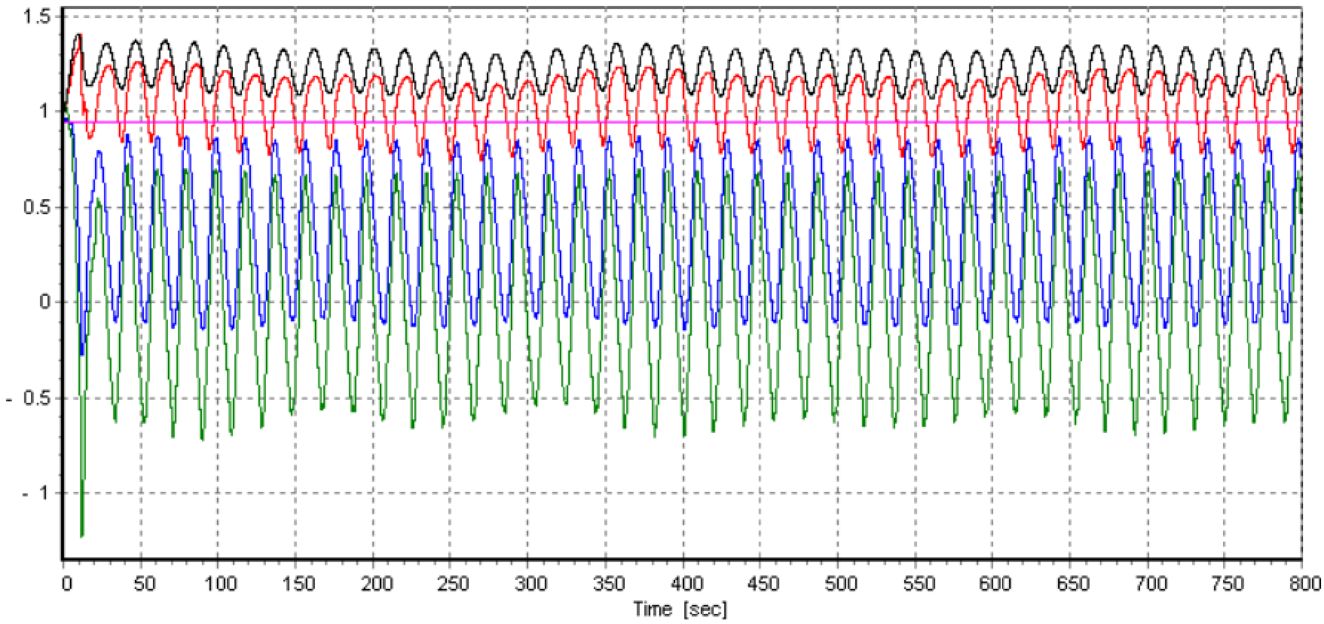
In general, HTGS regulates the hydro-turbine speed to provide stable power to the grid without considering shaft vibration. Nevertheless, the shaft system model controls the vibration performances instead of the speed. In fact, HTGS and the shaft system model interact with each other. Unfortunately, related studies on the unified model are rare. Hence, this is a hot issue to couple these two models to better understand the properties of the hydropower plant.

4. Stability analysis

As the key of the hydropower plant, HTGS's stability has the considerable influence on the power system. Hence, it is an essential task to study the stability of HTGS. For example, Nicolet et al. [110] studied the transient performances of a pump-turbine plant under runaway condition, where the output variables (i.e., the head, discharge, torque oscillation, rotational speed and turbine guide vane opening) are displayed in Fig. 10. As shown in Fig. 10, it clearly showed that fluctuation phenomena of all output variables shows significant differences with the rotating inertia increasing. Specifically, there only existed elastic oscillation mode with a smaller rotating inertia 0.08, while only rigid oscillation mode occurred with a larger rotating inertia 1.66. The fluctuation of elastic oscillation mode variables in Fig. 10(*a*) were relatively smaller in comparison with those of rigid oscillation mode in Fig. 10(*b*). However, the amplitudes of elastic oscillation mode variables decreased between 0s and 250s, and they strongly increased between 250s and 800s. In other words, the system showed instability characteristics. The variables in Fig. 10(*b*) showed equal amplitude oscillations. In other words, the system was in a transient stability process. In brief, the rotating inertia had a significant influence on the stability of the system, and special attention should be paid to the switching time of rigid mode and elastic mode.



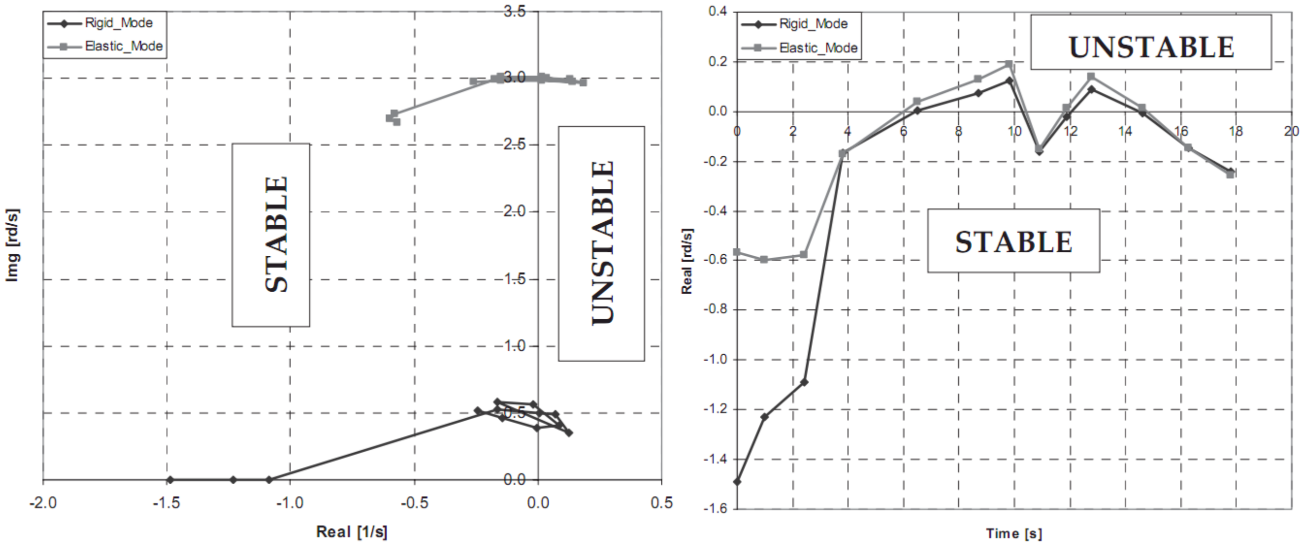
(*a*)



(*b*)

Fig. 10 Time evolution under different rotating inertia values [110]. (*a*) Rotating inertia value 0.08; (*b*) Rotating inertia value 1.66. The red, blue, green, black and magenta lines represent the head, discharge, torque oscillation, rotational speed and turbine guide vane opening, respectively. The unit of *y*-axis is "p.u.".

Nicolet et al. [111] applied eigenvalue analysis theory to a pump-turbine power station to investigate the oscillation modes. The complex eigenvalues and the real parts of the eigenvalues were displayed in Fig. 11(*a*) and 11(*b*), respectively. From Fig. 11(*a*), the real parts of the eigenvalues changed from the left hand side (i.e., negative) to the right hand side (i.e., positive), indicating that the oscillation modes changed from stable to unstable. From Fig. 11(*b*), it was clear that the real parts of elastic mode are relatively larger compared with those of rigid mode before 16s. The real part of the eigenvalue reflects the damping characteristics of the oscillation mode. In other words, the damping of rigid mode is larger than that of elastic mode. Hence, the rigid mode may bring high risk for the plant operation.



(*a*) (*b*)

Fig. 11 Eigenvalues distribution of rigid and elastic modes during transient process [111]. (a) Complex eigenvalues; (b) Real parts of the eigenvalues.

Pérez-Díaz et al. [29] presented the influence of the hydraulic short-circuit on the load-frequency regulation. Fig. 12 showed the frequency oscillation when the plant was subject to 65 MW loss in different initial situation. From Fig. 12, the frequency fluctuation diminished significantly with the number of pump units or Pelton increasing. This is mainly because the system inertia increases with the number of units increases. Also, shutting-down or starting-up one pump unit or Pelton was capable for supplying secondary load-frequency regulation, thus significantly reduced the time for frequency recovery to 50Hz.

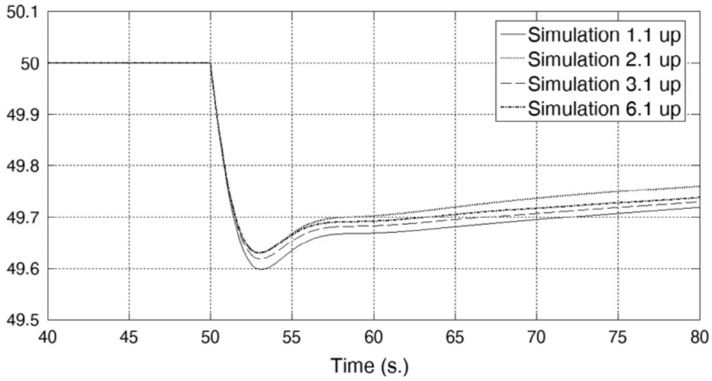


Fig. 12 Frequency deviation after a sudden loss of 65 MW of generation in different cases [29].

Pérez-Díaz et al. [11] proposed a control system to keep the water level of surge tank constant, where the variations of tail water level were considered. Then they applied the control system to a real hydropower plant, and given the stability region using Routh-Hurwitz criterion in Fig. 13. The results showed that the stability zone is expanded with the increases of the proportional gain K, while the unstable zone decreases with the integral time constant T_i increasing. In other words, T_i and K have the opposite influence on the stable operation of hydropower station.

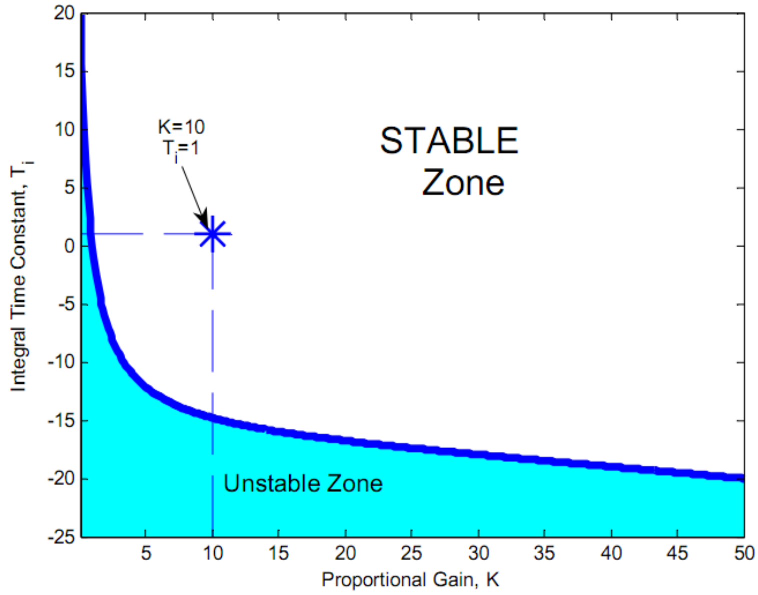


Fig. 13 Stable region of hydropower plant [11].

Yu et al. [20] presented the stability of HTGS during small load disturbance process, namely -5% rated load. The authors simulated the stable region of an interconnected plant (B) and isolated plant (A) in Fig. 14. The results showed that the stable region and the regulation quality in an isolated condition is poor in comparison with those of in an interconnected condition. In other words, the system stability was enhanced in the interconnected condition.

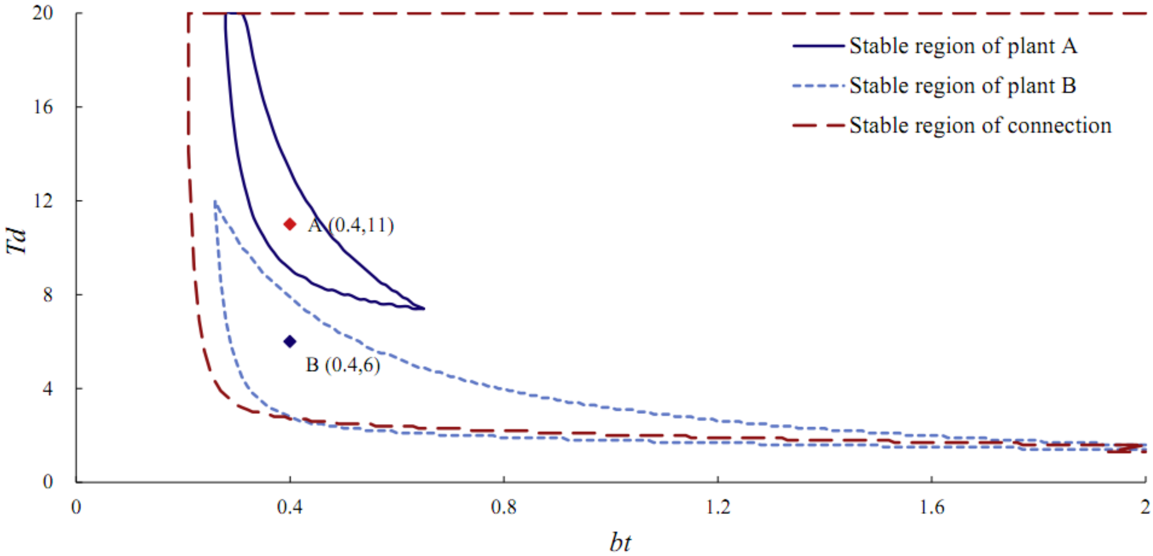


Fig. 14 Stable region under different plants [20].

Yang et al. [41] revealed ultra-low frequency oscillations using the experimental investigation and theoretical analysis. The system stability region is shown in Fig. 15 based on Routh-Hurwitz stability condition. If the K_p and K_i are in the stability region, the system is stable from the viewpoint of theoretical perspective. The system is unstable when system parameters are in the unstable zone. Meanwhile, the attenuation of the oscillations increase with the stability margin increasing.

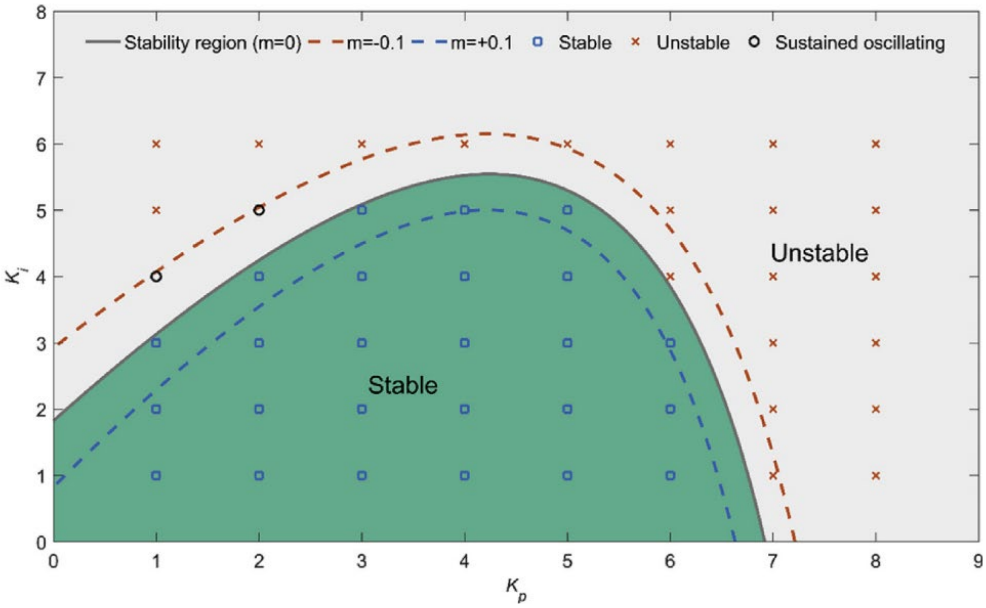
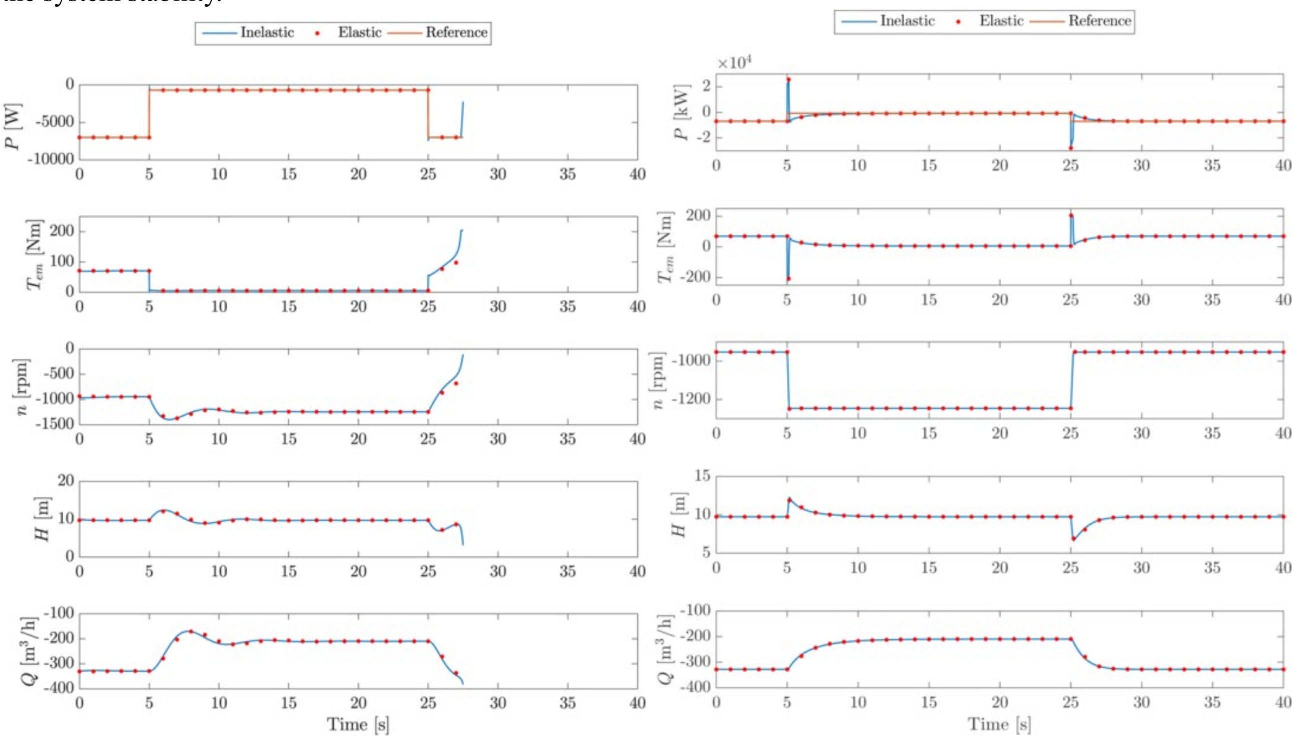


Fig. 15 The stability and stability margin regions [41].

Mercier et al. [112] proposed two different control methods to study the power system stability. One is using electromagnetic torque to control power directly and the other is using rotational speed to control power indirectly. The simulation results under the two control methods are shown in Fig. 16. From Fig. 16(*a*), the speed collapse due to power increase at t=25s, and the system lose stability. Fig. 16(*b*) shows that the speed collapse phenomenon is avoided using rotational speed to control power. This is because the flow has enough time to adjust, so as to maintain the system stability.



(*a*) (*b*)

Fig. 16 Simulation results with two different control methods [112]. (*a*) Direct control method using electromagnetic torque; (*b*) Indirect control method using rotational speed. P, T_{em}, n, H and Q are the power, electromagnetic moment, rotational speed, head and flow, respectively.

Guo et al. [60] investigated the operation characteristics of a HTGS with surge tank using Hopf bifurcation theory. The stable domain distribution was plotted in Fig. 17(*a*). S_1, S_3 and S_6 representing different operation state in Fig. 17(*a*) were selected to detailed simulate the phase space trajectories as shown in Figs. 17(*b*)-(*d*). Finally, the authors concluded that K_p and K_i should avoid specific bifurcation points to improve the system stability.

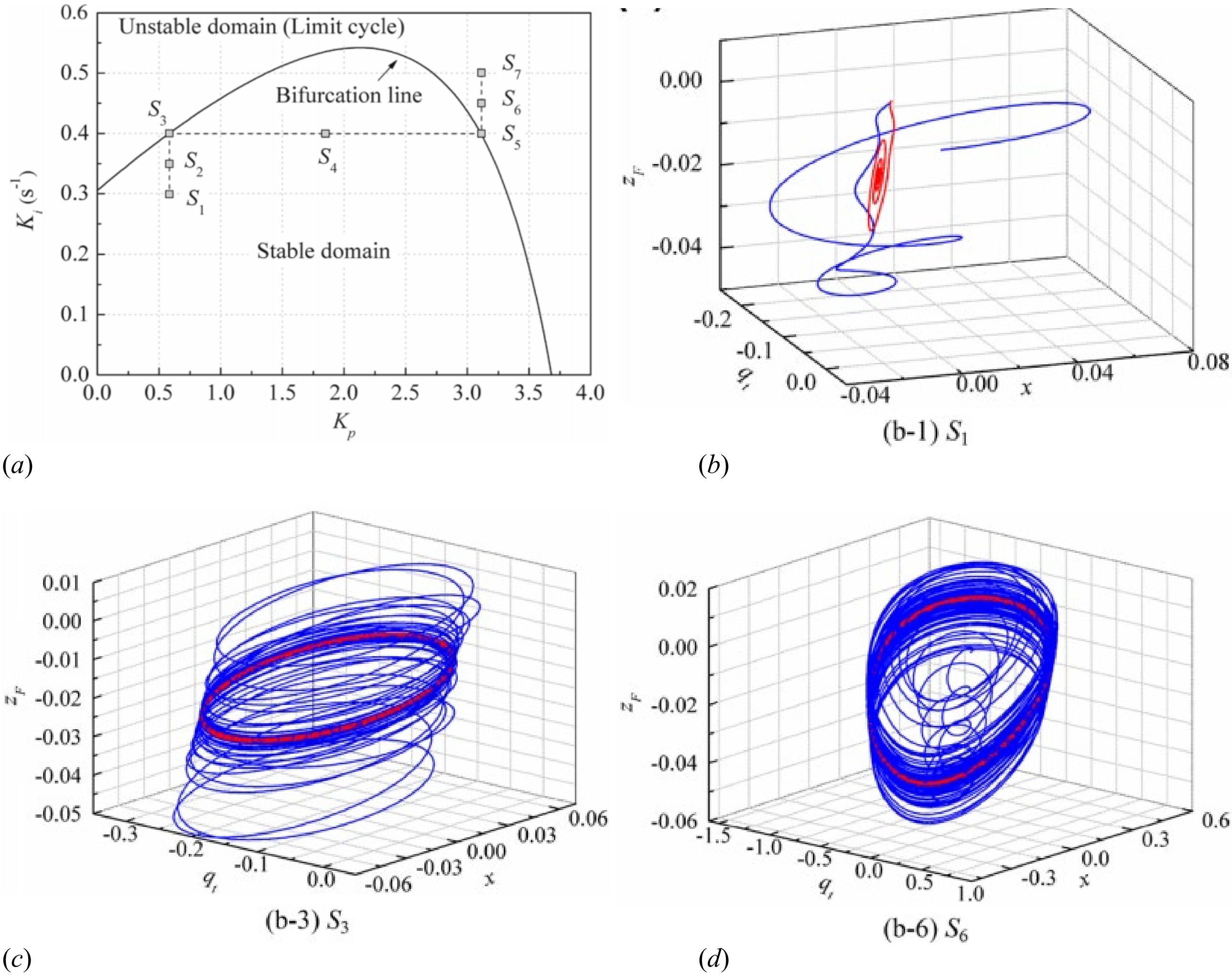


Fig. 17 Dynamic characteristics of HTGS [60]. (*a*) stable domain distribution of HTGS; (*b*) the phase space trajectories of at S_1; (c) the phase space trajectories at S_3; (*d*) the phase space trajectories at S_6. q_t and Z_F are the flow of penstock and water level change of upstream surge tank, respectively.

5. Control methods

To maintain the quality and reliability of electricity supply, governor is used to control the generator speed to achieve the objective. This is usually conducted by the governor through a certain control strategy. The control strategy mainly includes off-line control (i.e., off-line pre-decision, real-time matching), on-line quasi real-time control and on-line real-time control [113]. The off-line control needs massive calculations because many factors of system structures, power flow mode and fault situation should be considered, leading to poor ability to adapt to the change of power grid operation mode. For online quasi real-time control, the controller collects the operation condition, and analyzes the expected accidents regularly. It has the ability to adapt to the change of power grid operation condition, while this method needs 5 minutes to give transient control strategy to cope with accidents. Regarding on-line real-time control, the control measures and control quantities of the relevant control equipment in the power grid are calculated online when a fault occurs. Then the real-time controller can be implemented timely, accurately and reliably by means of high-speed communication. This process requires very high calculation speed of stability control, generally within 0.2 seconds. Limited by the control algorithms technology, the calculation speed cannot up to the requirement of on-line real control, so the existing control strategy mostly depend on off-line control strategy [114, 115]. Here, different control methods based on off-line control strategy are reviewed in this section, which include the classical and modern control methods. Classical control theory has been extensively used in the conventional method of turbine governor design, such as PID control. On the other hand, recent investigations have stressed the significance of modern control theory. The application of modern control techniques in hydropower plant is an area of considerable interest. Table 13 is listed to display a brief review of different control methods.

Table 13 Comparison of control methods.

Control methods	Advantages	Disadvantages	Ref.
PID	Simple structure, strong robustness, and easy to implement	Lower control quality under complex conditions	[14, 36, 116]
FOPID	Better adjustability and flexibility, and great freedom in designing	Complex parameter optimization problems	[116, 117]
SMC	High robustness against the disturbances, insensitivity to model errors, more freedom in designing	Chattering phenomena due to discontinuity of sign function	[54, 118, 119]
FC	strong anti-interference ability, fast response, simple design and easy to implement	Diffcult to construct fuzzy rules and membership functions	[15, 54, 120]
FTC	Manage any component failures and keeps good control qualities	Greatly influenced by the delay of fault detection and separation resulting to serious stability problem	[121, 122]
PC	Easy to implement	Abundant computation and difficult to achieve fast control and long prediction	[123]

5.1 The Classic control method

The classical PID control is a preferred selection due to its robustness and practicability. It accounts for 84% in the control system, and if the improved type is considered, it will exceed 90% [42]. Although it is widely used in various fields, it has some drawbacks, such as limitations in dealing with complex systems and time-delay systems.

5.2 Modern/Artificial Intelligence (AI) control method

To overcome the drawbacks of traditional control methods, series of advanced control methods have attracted scholars' attention, such as fractional-order PID control (FOPID), sliding mode control (SMC), predictive control (PC), fuzzy control (FC), fault tolerant control (FTC) [124-125].

(*a*) Fractional-order PID control (FOPID)

Podlubny extended the classical integer-order PID control to FOPID by introducing the integrator order λ and differentiator μ [35]. The generalized transfer function of FOPID is given by [126]

$$G(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \tag{20}$$

Using the discrete transfer function to calculate the FOPID output, it is expressed as [116]

$$u(k) = K_p e(k) + \frac{K_i}{h_1^{-\lambda}} \sum_{j=0}^{k} q_j e(k-j) + \frac{K_d}{h_1^{\mu}} \sum_{j=0}^{k} d_j e(k-j) \tag{21}$$

q_j and d_j are written as

$$\begin{cases} q_0 = 1;\ q_j = \dfrac{\lambda + j - 1}{j} q_{j-1} \\ d_0 = 1;\ d_j = 1 - \dfrac{\mu + 1}{j} d_{j-1} \end{cases} \tag{22}$$

where h_1 and e are the sampling period and control error, respectively.

The FOPID is a topical issue in research for its better adjustability and flexibility. It has been widely applied in different fields, such as nuclear energy, wind energy and hydro energy [127] and related literatures show that FOPID methods have advantages over traditional PID methods [116]. Apart from the advantages, one of the main challenges is the parameters optimization.

(*b*) Sliding mode control (SMC)

SMC has the advantage of high robustness against the disturbances and insensitivity to model errors. This provides the designers with more freedom, helps to meet satisfy special requirements and certain robustness conditions [118-119]. When the load changes, the speed control is conducted to keep the power quality. The speed deviation signal (i.e. the difference between the generator speed x(t) and referenced speed) is transformed to regulation signal u(t) based on SMC rule. Then the guide vane opening is changed according to u(t) to adjust the hydro-turbine flow. Finally, the regulated variable, namely the generator speed x(t) is controlled to keep in a good agreement with the referenced speed. The SMC law is the switching control (u_{eq}) coupling with the equivalent control (u_{sw}), namely $u=u_{sw}+u_{eq}$ (see Fig. 18) [54]. sgn(s) presents the sign function, sgn(s)=1 when s>0, sgn(s)=0 when s=0 and sgn(s)=−1 when s<0. Nevertheless, the SMC is easy to lead to 'chattering' problem due to the discontinuity of sign function, so that result in low control accuracy.

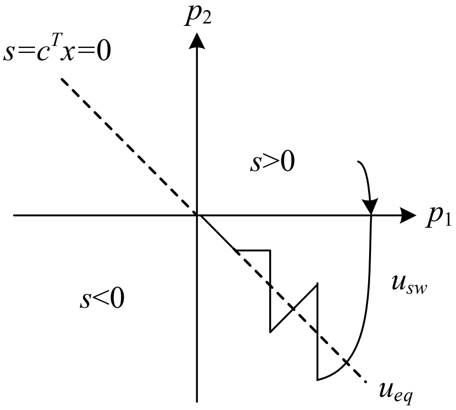
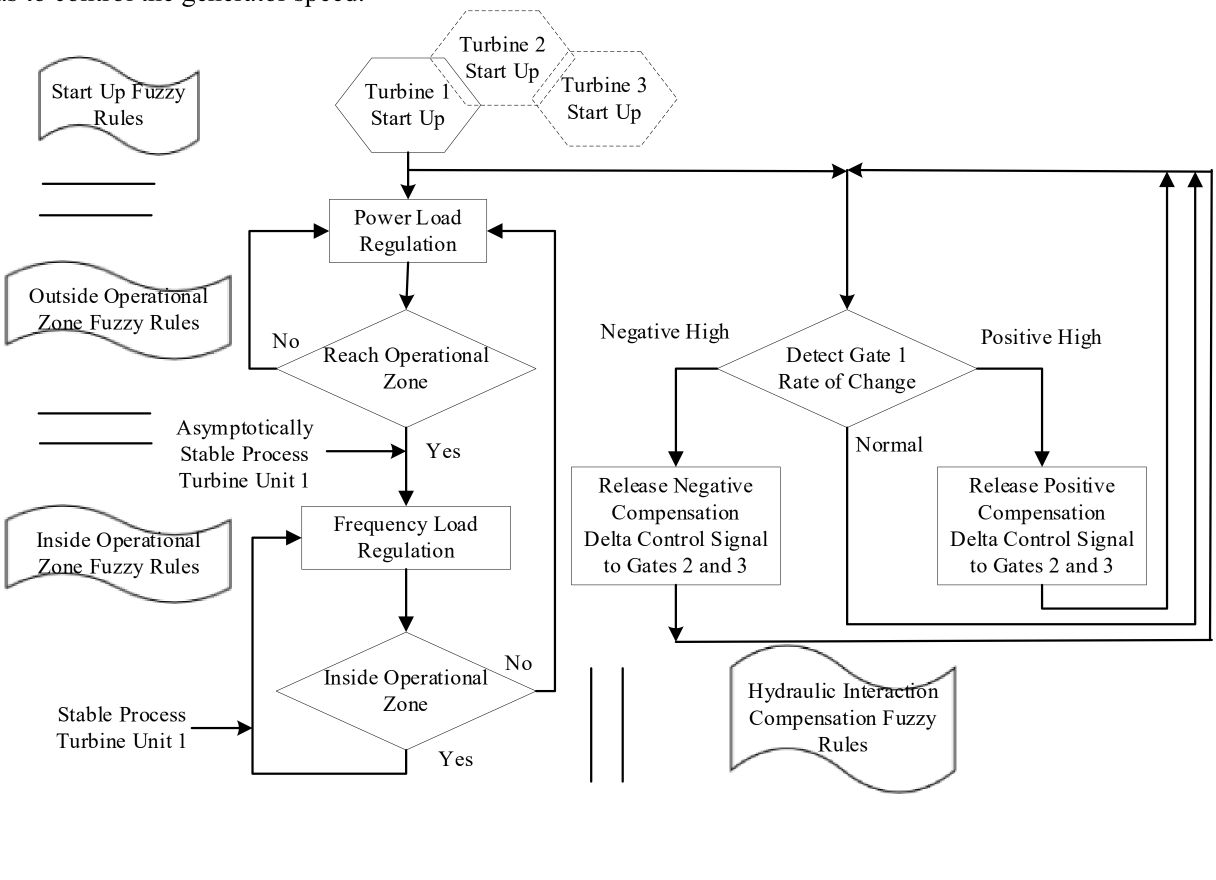


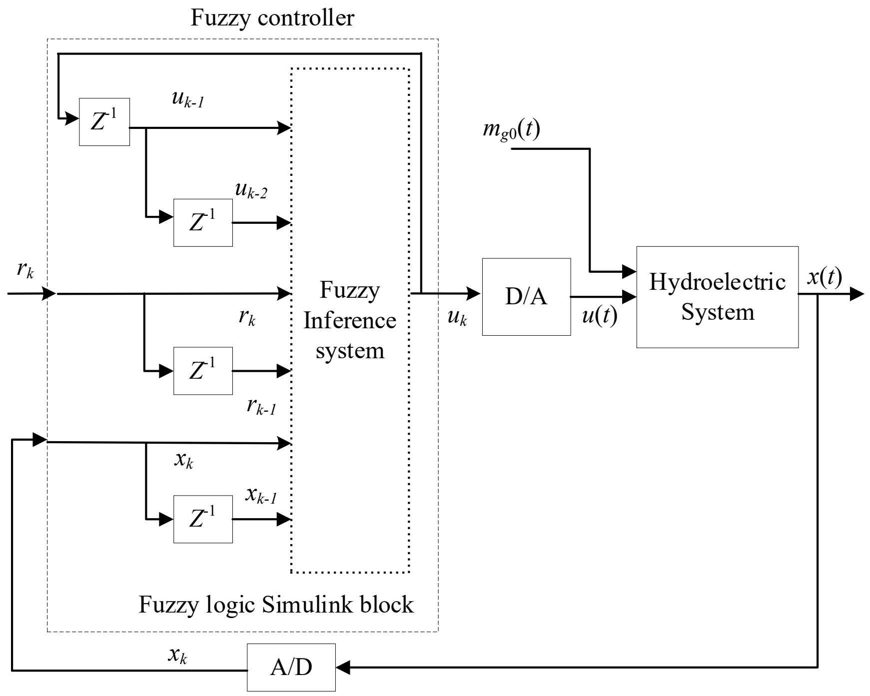
Fig. 18 The sliding mode controller [54]. p_1 and p_2 denote the sliding mode surface.

(*c*) Fuzzy control (FC)

FC has the advantages of simple design and anti-interference ability. It is suitable for the uncertain signals/systems. Some hydropower plants have been successfully applied FC by replacing PID controller (see Fig. 19) [15, 54, 120]. It is also suitable to deal with systems with complex or highly nonlinearity [15]. However, it is difficult to construct fuzzy rules and membership functions for FC method, which are often determined by operating experiences and intuitiveness [119]. As shown in Fig. 19, the core control task of FC is to regulate the generator speed x(t) tracking the reference speed r(t) by regulating the guide vane opening, where the guide vane opening is controlled using the output signal u(t). Specifically, the signal deviation e_k at time k is the deviation between the measured and desired speed, i.e. e_k=x_k-r_k. To minimize the signal deviation, the input signal e_k is converted to the regulation signal u_k through FC system. Then u_k is used as the input signal of the hydroelectric system to regulate the guide vane opening so as to control the generator speed.



(*a*)

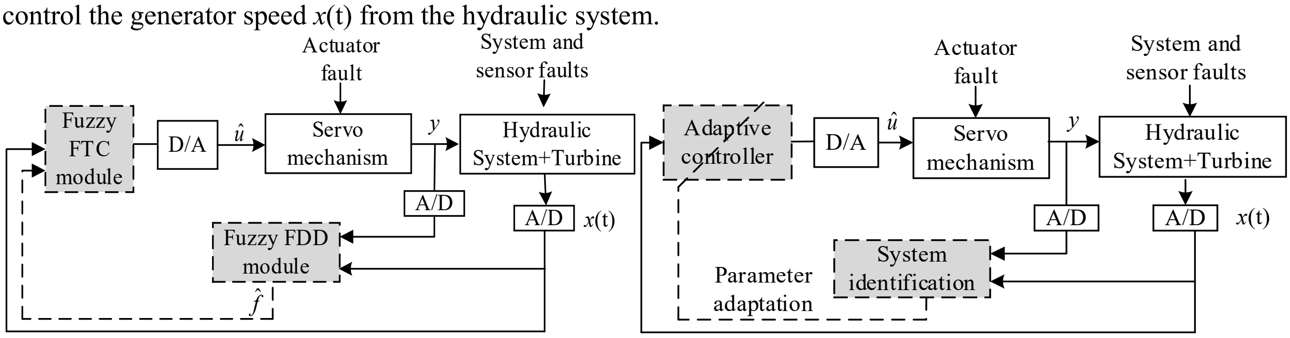


(*b*)

Fig. 19 Nonlinear fuzzy controllers. (*a*) FC flowchart of a plant with three turbine [120]; (*b*) Block diagram of FC [15]. r_k and x_k represent the samples of the continuous time signals r(t) and x(t), respectively. u_k is the control signal u(t) at the sampling time t_k. m_{g0} is the load torque. Z is the unit advance operator.

(*d*) Fault tolerant control (FTC)

FTC is able to manage any malfunctions and maintain the system properties simultaneously [121]. It automatically deals with faults based on the following methods, namely active or passive fault tolerant control scheme (AFTCS/PFTCS) [12, 16, 128].The PFTCS is robust to a certain set of presumed faults, while AFTCS reacts actively to the system faults using a control accommodation method, thus the stability and the final performance of the system are maintained [121]. Figs. 20(*a*)-(*b*) demonstrates how the AFTCS and PFTCS are achieved. As for AFTCS in Fig. 20(*a*), the fault signal ($\hat{f}$) generated from Fault Detection and Diagnosis (FDD) module is input to FTC module to compensate the actuator fault effect. Then the control signal ($\hat{u}$) is generated through the Digital-to-Analog (D/A) converters. The servo mechanism drives the guide vane opening (y) by control signal ($\hat{u}$) to carry out the demand motion, i.e. adjusting the generator speed x(t) to minimize the deviation between the output speed and reference speed. With reference to PFTCS in Fig. 20(*b*), the process of coping with faults in PFTCS is similarly to that of AFTCS. It is worth highlighting that difference of these two methods is the faults signal generating process. PFTCS conducts the on-line system identification first and then the fault tolerance signal is generated through the parameter adaption mechanism. Finally, the adaptive controller utilizes the output signal (y) from the servo mechanism to control the generator speed x(t) from the hydraulic system.



(*a*) (*b*)

Fig. 20 Fault tolerant control schemes: (*a*) Diagram of AFTCS; (*b*) Diagram of PFTCS [16].

In general, FTC has the capability to manage any component failures and keeps good control qualities. Nevertheless, there are some drawbacks. FTC is greatly influenced by the delay of fault detection and separation, and the long time delay will cause serious stability problem [122].

(*e*) Predictive control (PC)

In 1967, Lee and Markus first proposed the concept of PC [129]. Chen and Shaw first developed the nonlinear PC using the Lyapunov function [130]. It predicts the system's future state using a discrete model [123]. Meanwhile, it is easy to apply and couple with traditional methods, such as combining with neural networks or adaptive algorithm. The flowchart of the adaptive PC algorithm and the implementation of PC method in a hydropower plant are shown in Fig. 21(*a*) [131] and Fig. 21(*b*) [15], respectively. To success implement PC method, the first step is to collect the turbine mechanical power sequences $p_{(k)}$, which are used as input signal of step 2. In step 2, the predicted turbine mechanical power $\hat{p}_{(k)}$ is generated by an adaptive neuroidentifier (ANI). Then, according to the difference between the measured power $p_{(k)}$ and $\hat{p}_{(k)}$, the weights are updated based on the cost function $J_i(k)$ in step 3. The next step is to generate the controller's output $u(k)$ by an adaptive neurocontroller (ANC). Based on the updated weights in step 3, the predicted power $\hat{p}_{(k+1)}$ is produced by ANI under the regulation of $u(k)$. Computing the deviation between $\hat{p}_{(k+1)}$ and the reference signal, weights of ANC are updated utilizing the back propagation method in step 6. This process is repeated during each sampling period to achieve the target that the controlled process output can track the reference value [15]. The most advantage of PC is that it has the capacity to predict the future states and take corresponding control measures to maintain the system in a high quality. Apart from the merits, one of the main drawbacks is abundant computation and difficult to achieve fast control and long prediction [123].

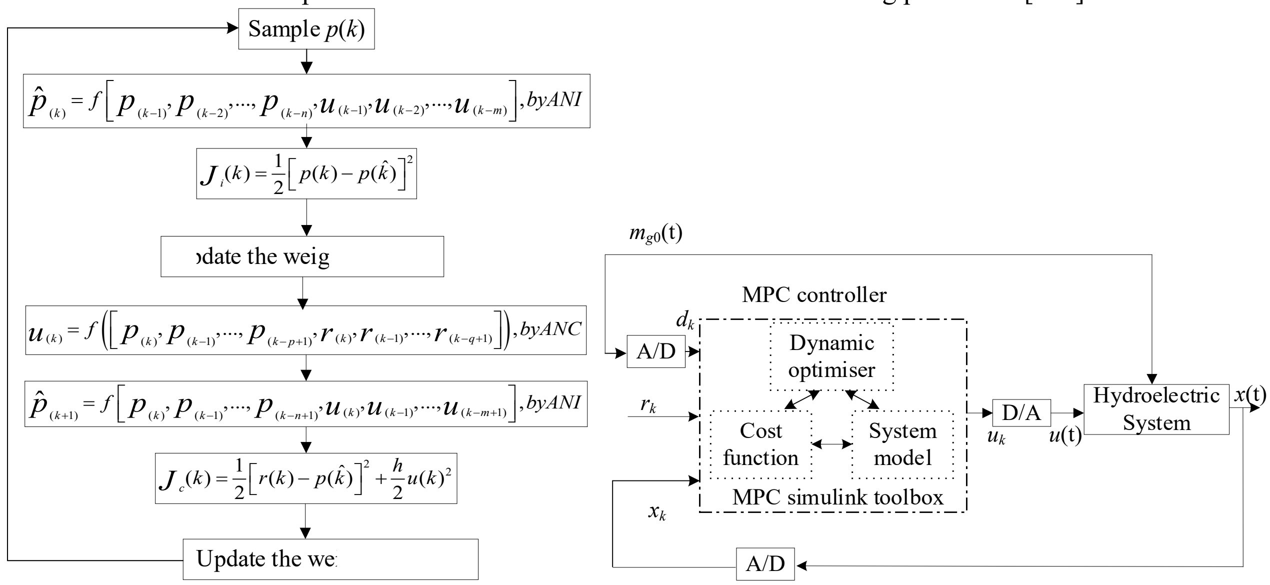
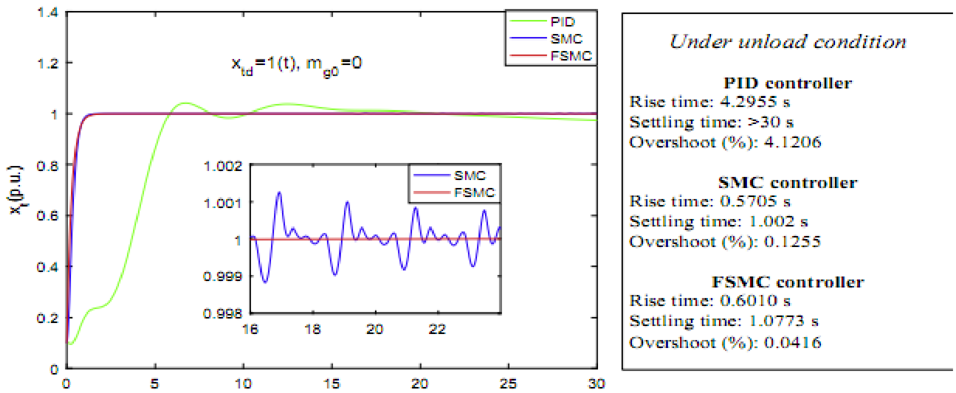
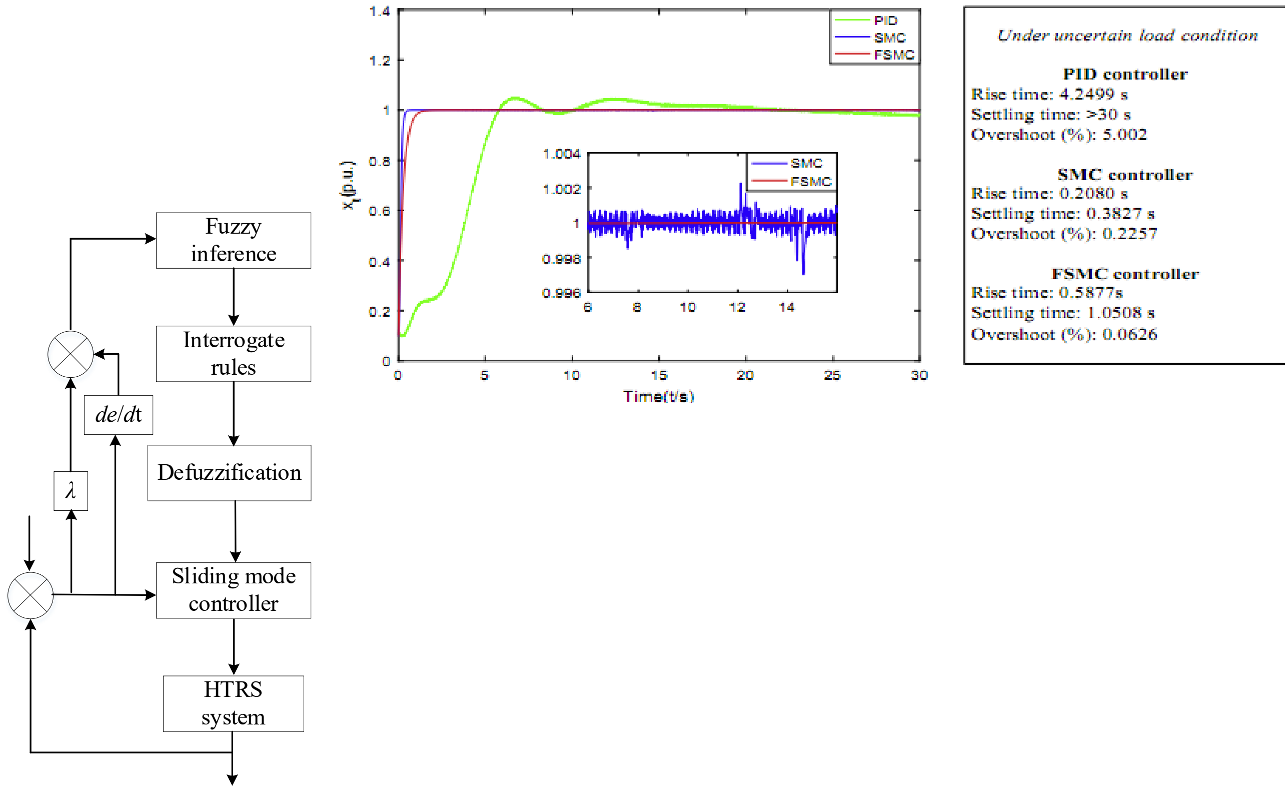


Fig. 21 Predictive control method. (*a*) The adaptive predictive control. ANI is an adaptive neuroidentifier. ANC stands for an adaptive neurocontroller [131]; (*b*) Block diagram of a hydropower system with the model predictive control (MPC) law [15]. $r_{(k)}$ is the reference input signal at time step k. $p_{(k)}$ is the turbine mechanical power at the time step k. $\hat{p}_{(k+1)}$ is predicted turbine mechanical power at time step $(k+1)$. $J_i(k)$ and $J_c(k)$ is the cost function for the ANI and ANC, respectively.

5.3 Hybrid control method

Although single control method has its advantages, there exists certain limitations in each method. To overcome these drawbacks, the hybrid control is a better choice to combine the advantages of each method to achieve a better control performance [54]. For example, Chen et al. [36] proposed a Fuzzy Sliding Mode Control (FSMC) based on FC and SMC in Fig. 22(*a*) to overcome the chattering effects of SMC. The speed signal of HTGS is selected as the input signal of the fuzzy system, and then it is handled using the fuzzy rule. The processed signal is converted to control signal using SMC rule to drive the servo system to adjust the guide vane opening to control system speed. The simulation results based on PID, SMC and FSMC are shown in Fig. 22(*b*). The results clearly showed that FSMC had a better performance in reducing chatting and overshoot no matter under unload condition or uncertain load condition.

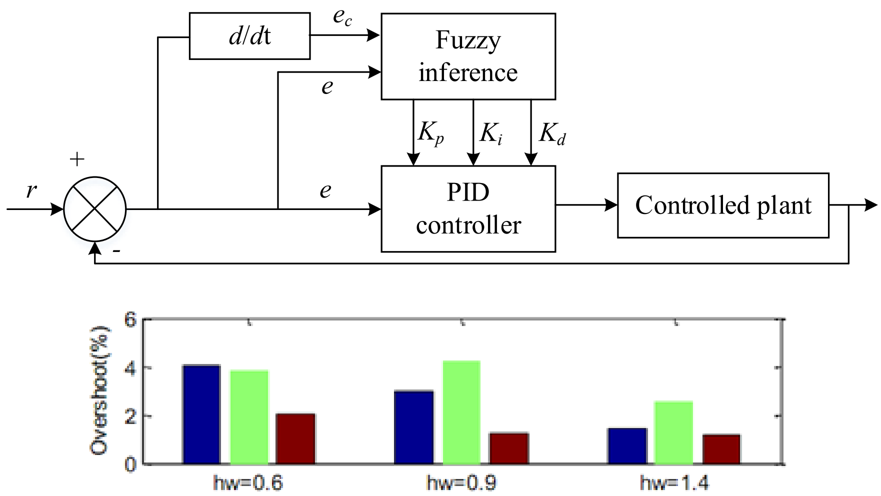




(*a*) (*b*)

Fig. 22. FSMC method in a hydropower plant [36]. (*a*) The diagram of FSMC in the hydro-turbine regulating system (HTRS); (*b*) Comparisons of different controllers. x_t and x_{td} are the actual and desired speed output. λ is a positive constant.

To overcome the control problem of HTGS with elastic water hammer, Li et al. [37] designed a fuzzy-PID controller in Fig. 23(*a*) and then applied it to a hydropower plant to evaluate its efficacy in Fig. 23(*b*). The fuzzy-PID is the combination of the traditional PID and fuzzy logic inference. Based on the input signals, i.e. the speed deviation (e) and differential deviation (e_c), PID parameters are adjusted utilizing fuzzy inference to regulate the controlled plant to achieve system's stability. The results showed that designed controller (marked as red) is better to improve the overshoot compared with the traditional PID controller (marked as blue) and nonlinear PID controller (marked as green).

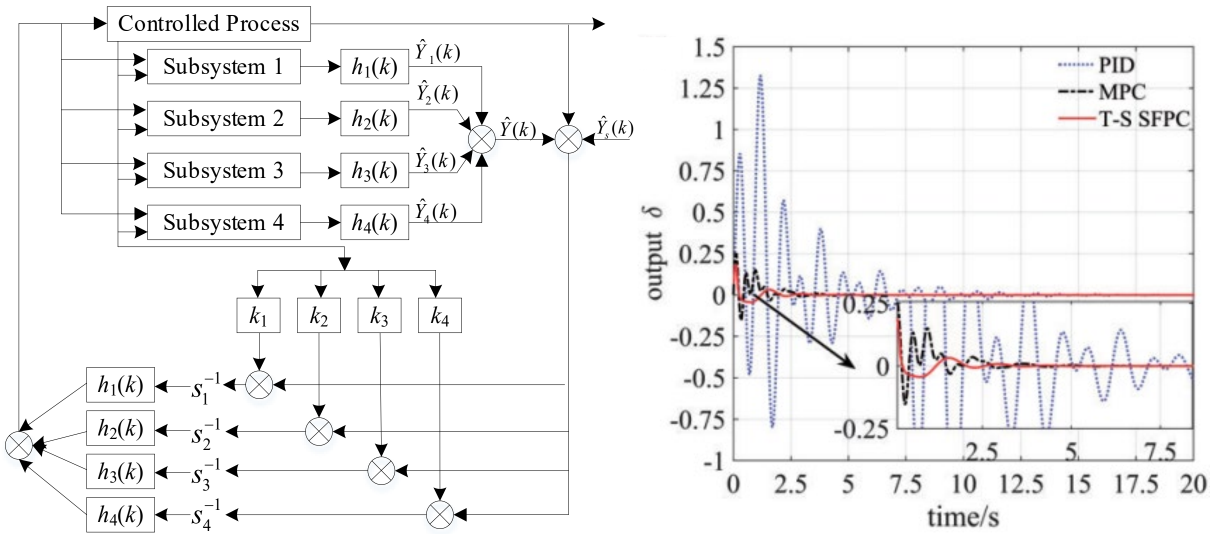


(*a*)

(*b*)

Fig. 23 The diagram of HTGS with a fuzzy-PID controller [37]. (*a*) Structure of fuzzy-PID controller; (*b*) The overshoot of different controllers. h_w is the characteristic coefficient of penstock.

Yi et al. [34] designed a T-S SFPC controller coupled by state feedback predictive control and Takagi-Sugeno fuzzy model as shown in Fig. 24(*a*). The controlled objective is the error between the actual output $y(k)$ from the controlled process and prediction output $\hat{Y}(k)$ from the model inference. The control rule is the combination of the feedback predictive control and the T–S fuzzy model. Then a comparison of PID, MPC and T-S SFPC method was carried out in Fig. 24(*b*). The results showed that the fluctuation of rotor angel δ with the SFPC approach is smaller than that of other methods.



(*a*) (*b*)

Fig. 24 The T-S SFPC controller in a HTGS [34]. (*a*) Block diagram of T-S SFPC controller; (*b*) Control performances of different control methods. $y(k)$ and $\hat{Y}(k)$ denote the system output matrix and predicted value. δ is the rotor angel.

Along with the promotion of energy structure reformation towards low-carbon power generation, the structure and operation-mode of the power system are more and more complex. The demand for the dynamic response speed of the controller is higher and higher. Fortunately, the on-line quasi real-time control has attracted more and more attentions, which has become one of the most important development directions. Not limited to on-line quasi real-time control, establishing on-line real-time controller is the final goal with the continuous improvement, enrichment, update and development of power system theory and technical means.

6. Challenges

Under the current energy structure of China, the thermal power, gas power, nuclear power and hydropower have the ability to undertake peak and frequency regulation. In the scenario of the power system without any hydropower: 1) For the traditional thermal units, the minimum operating load is high due to the limitation of technical means and heating requirements, which leads to the lack of flexibility in peak and frequency regulation so that it is difficult to meet the power grid requirements; 2) Regarding the nuclear power units, the power regulation rate is about 0.25%-5% of the rated capacity per minute [141]. While its peak and frequent operation have a certain impact on the safety and economy of the units' operation; 3) For gas-fired units, although it has the advantages of fast start-up and stop, flexible operation, stable and reliable operation performance etc., its operation cost is high. In addition, the use of thermal power and gas power in peak and frequency regulation further lead to the increase of carbon dioxide emissions, which is difficult to achieve the strategic goal of sustainable development. Compared with thermal power, gas power and nuclear power, hydropower has the characteristics of clean and pollution-free, fast ramp rate, low operating cost and flexibility operation etc., which is the first choice for peak and frequency regulation of power system. However, there are also stability challenge for the HGUs in dealing with the uncertain electric loads from power systems.

6.1 Combining the HTGS and shaft model

The shafting vibration is severe in the non-optimal conditions, causing the control effect of PID governor cannot guarantee the stability of the generator speed, which seriously threatens the power generation reliability of HTGS in the non-optimal working conditions. Traditional modeling methods adopts the ideal turbine model based on linearization characteristics of stable operation points, while this method is dangerously inaccurate for small guide-vane opening conditions. So, an accurate model is urgent to quantify the interaction mechanism of HTGS control and shaft vibration. The first challenge is to find appropriate transfer parameters. For example, the generator speed is a common parameter for HTGS and shaft model, but only this parameter to combine the two models leads to a negligible impact of shaft vibration on th HTGS's control effect. This is because the generator angular frequency is controlled within 0.2Hz after passing through the PID controller [5]. The second parameter is the hydraulic force acting on the blade. Forces on the runner blades generate the dynamic torque of the hydro-turbine used in HTGS and the unbalanced hydraulic forces causing the shaft vibration. However, the analytic formula of the hydraulic force is too complex and covers lots of runner parameters, such as resistance coefficient C_x, excretion coefficient s, runner diameter D_r [132]. This is obviously not suitable for large-scale power system simulation. The second challenge is the vortex belt effect in draft tubes [133]. Vortex belt in part loads causes the dramatic influence on the dynamic torque of the hydro-turbine and shaft vibration. The kind of phenomenon is very complex. The dynamic wake vortices, blade passage vortices, tailrace vortices and clearance vortices of double row guide vane cascades are the main causes of runner imbalance and are key factors that cause HTGS instability. The oscillation of hydro-turbine generator units and changes in rotational speed can also lead to sudden changes in the sealing clearance force and induce hydraulic imbalances experienced by the runner. Therefore, the coupling mechanism between the adjustment parameters in various conditions and the changes of turbulence state that leads to hydraulic imbalance of runner are still unclear. However, the coupling modelling principle is still an attempted method. At present, the classical models applying this principle are roughly divided into four categories, i.e. 1D characteristic method + the characteristic curve of hydraulic turbine [134], equivalent circuit theory + the characteristic curve of hydraulic turbine + 1D hydro acoustic [135], transient boundary condition + 3D hydro-turbine [136], and equivalent circuit theory + 3D hydro-turbine + 1D hydro acoustic [137]. However, the transfer parameters and coupling mechanism between the full three-dimensional turbine model and the one-dimensional acoustic model are still immature, and the governor control is not considered in these models. Therefore, a general method to combine HTGS and shaft model is an important challenge for generation reliability evaluation of hydraulic turbines in non-optimal conditions. In addition, the control methods is the other challenge because of the high dimensional nonlinearity of the coupling model of HTGS and shaft.

6.2 Control methods of HTGS with intermittent renewable energies

The main challenge of HTGS to regulate the power variation of intermittent renewable energies, which have been observed by the authors when carrying out the literature review to prepare the paper, is summarized as: (1) to improve the modeling methods of HTGS to possible evaluate its potential feasibility, (2) to revise the control methods traditionally or seek new technologies used to eliminate the power tracking delay and difference, such as technologies of variable-speed pumped storage plants. The first challenge along with the papers are described in subsection 6.1. The second challenge along with the published papers where some researchers have been preliminarily studied are summarized in Table 14. Specifically, considering the ongoing complementary projects in China, further hydropower stations on the operation strategy of more flexible, such as the hybrid wind-hydro power system, become mandatory [138]. Control methods and variable speed units are two effective direction currently. The traditional PID controller shows an obvious insufficient regulating capacity problem, as shown in Fig. 25 [30]. This makes the PSGS's power response lagging behind the wind power fluctuation and further impacts the power supply reliability of the hybrid power system. As it can be seen in Fig. 26, the revised control methods not only to predict hydropower compensation for intermittent power fluctuation in advance but also to consider the complementary regulation on power quality [31]. Variable speed operation is a well-known solution to enhance HTGS's flexibility. Advantages of variable speed units are well validated to mitigate wind power variations [32], and its trends and challenges are well descripted in Ref. [138]. However, this kind of technology is obviously not suitable for the traditional hydropower stations like the wind-hydro-solar hybrid complementary system in Yalong River. So, the method of revising the control methods is one of the least costly but most effective directions for these existing HTGS.

Table 14 Summary of researches where they have been preliminarily studied.

Challenge	Preliminarily studied researches
Revising the control methods to eliminate the power tracking delay and difference	[30], [31]
Seek new technologies used to eliminate the power tracking delay and difference	[32], [112], [139]

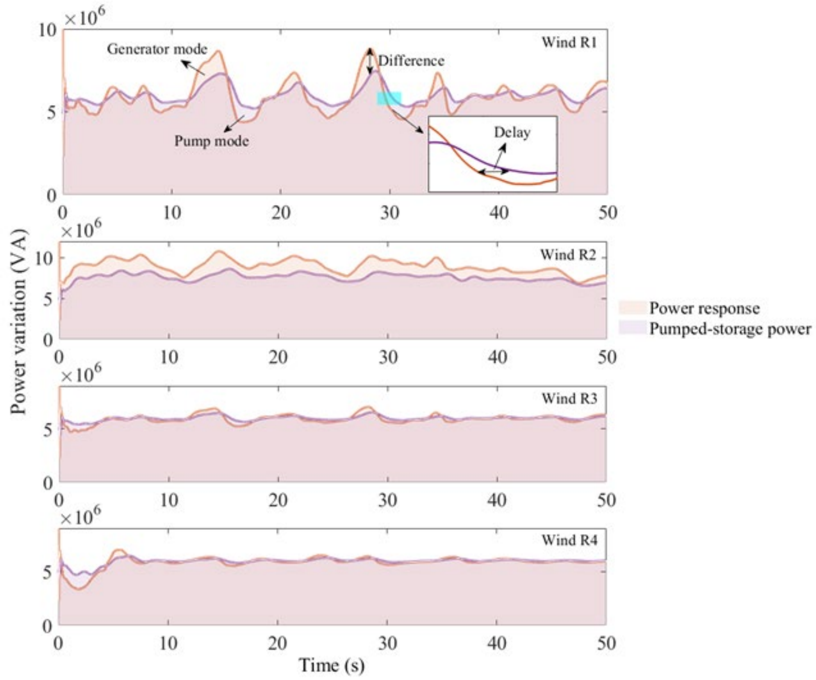


Fig. 25 Power responses of HTGS under random wind disturbances (R1 to R4) [30]. The power response and pumped-storage power response are shown with the soild lines in orange and pink, respectively. The power response represents the pumped-storage demand that needs to be met due to the fluctuation of wind energy, while the pumped-storage power response is the actual response.

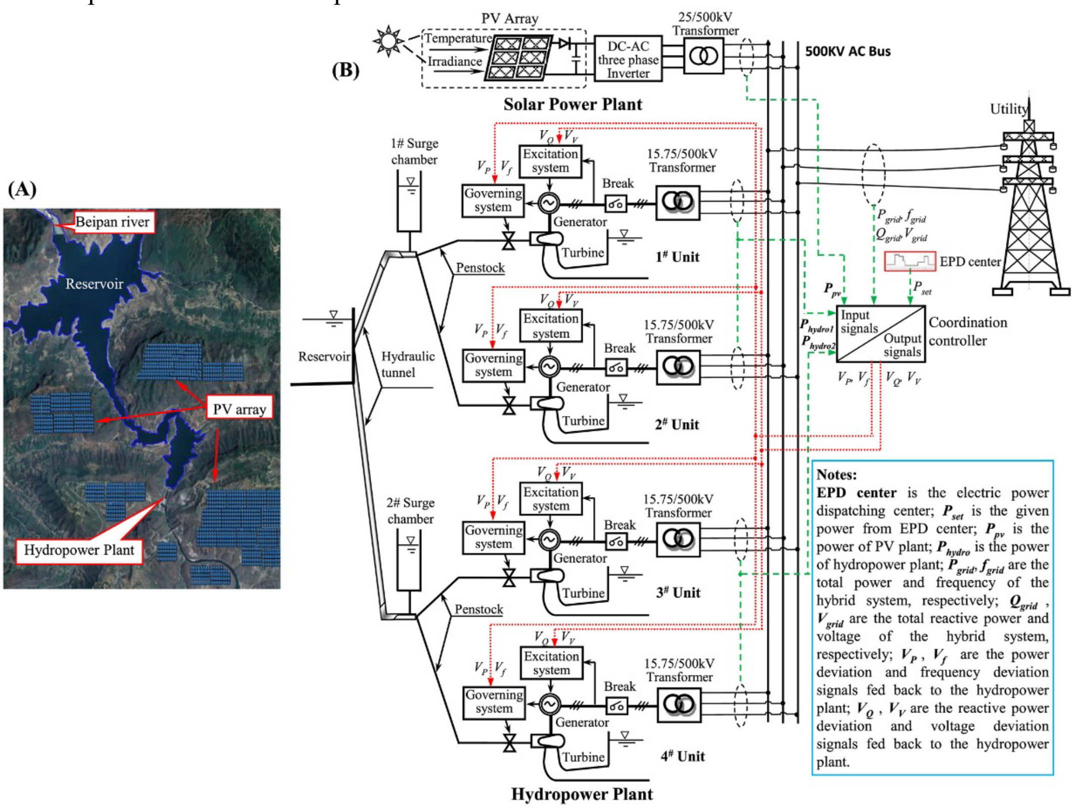


Fig. 26 The scenario of a solar-hydro hybrid system [31]. (A) The map of the hybrid system; (B) The diagram of the hybrid system.

6.3 Uncertain nature of load on the overall performance and stability of the hydropower system

The uncertain nature of load is mainly from two aspects: 1) the uncertain consumptions, and 2) the uncertain power supply from generation systems. The hydroelectric generating units should be adjusted continuously to suppress the power uncertainty in the electric power system. In other words, the HGU should switched from the traditional power supply mode to the regulation mode. For these hydropower stations, the designed output power of HGU changes from 65% to 100%. The HGUs frequently cross the low and medium load areas when it operates in the regulation mode. During this process, the pressure pulsation and HGUs' speed change dramatically, which brings huge security risks to the stable operation of HGUs. To cope with the changing of hydropower operation mode caused by the load uncertainty, optimizing the installed capacity of different energies and reserve capacity of hydropower are effective direction currently. Regarding with the stability operation of HGUs, the reasonable design of hydro-turbine runner is an effective method to deal with the variation of HGUs to realize the stable operation of full load operation of HGUs. This measure has been verified in *Fengman* hydropower generating system in China [140]. In addition, the synergism control strategy considering AGC and primary frequency regulation is also an effective method to reduce HGUs' variation during the adjustment and protection calculation of transient process. This is also the demand side management may take positive response measures.

7. Conclusions

Hydropower plant layouts are not following the same pattern because each water source has its own structure, so modular models and stability analysis methods are proposed to cope with these difference. The unified model of HTGS is established based on the coupling of modular models. Selecting a suitable unified model and stability analysis method is the key factor to conduct a research work. The important prerequisite to make a clear choice is understanding the characteristics of each model and stability analysis method, which contributes to explore the potential flexibility of HTGS in mitigating power variations from intermittent renewable energies. The main achievements in the aspects of modelling, stability analysis and control methods are summarized as:

First, applicable conditions of the penstock model, surge tank model, hydro-turbine model, generator model and governor model are discussed based on the layouts of hydropower plants. The coupling methods using these modular models are classified. Methods of stability analysis, such as bifurcation theory and Lyapunov theory, are compared from the perspective of advantages, disadvantages and applications. Additionally, merits and demerits of control methods are summarized.

Second, current achievements of the above three aspects have been properly described and discussed. Hence, two challenges and possible development directions to be coped with in future have been identified, which are

(1) The first challenge is how to combine HTGS and shaft model for generation reliability evaluation of HTGS in non-optimal conditions, and vortex belt effect in draft tubes should also be considered during this process. The possible solution to cope with this challenge is to find appropriate transfer parameters to quantify the interaction mechanism of HTGS and shaft vibration. Additionally, the control methods based on the coupling model of HTGS and shaft is another headache because of the coupling model's high dimensional nonlinearity, and deep learning intelligent control algorithm is an attempted direction.

(2) The second challenge is to revise the control methods traditionally or seek new technologies used to eliminate the power tracking delay and difference when HTGS is used to regulate the power variation of intermittent renewable energies. The possible revised control methods not only to predict hydropower compensation for intermittent power fluctuation in advance but also to consider the complementary regulation on power quality. Variable speed technology also is an attempted solution to enhance HTGS's flexibility.

(3) The third challenge is how to cope with the uncertainty nature of load. The possible method to deal with this challenge is to optimizing the installed capacity of different energies, reserve capacity of hydropower, and make synergism control strategy considering AGC and primary frequency regulation during the adjustment and protection calculation of transient process.

Acknowledgments

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