Model Specification for the Generic WECC Model of Ternary Pumped Storage Technologies

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Foreword

The objective of this project is to fill in the gap of advanced PSH dynamic stability models in the current WECC model libraries by developing a model specification for advanced PSH technologies for dynamic stability study and enable consistent and comprehensive evaluation of advanced PSH technologies in power system planning and operation.

Acknowledgment

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Disclaimer

List of Acronyms

PSH	Pumped Storage Hydropower
T-PSH	Ternary Pumped Storage Hydropower
C-PSH	Conventional Pumped Storage Hydropower
HSC	Hydraulic Short Circuit
WECC	Western Electricity Coordinating Council

List of Variables

$\boldsymbol{\rho}$	water density kg/m^3)
$\boldsymbol{L}$	length of the penstock (m)
$\boldsymbol{q}$	water flow of the water in the penstock (m^3/s)
$\boldsymbol{A}$	cross-sectional area of the primary penstock (m^2)
$\boldsymbol{A_{tt}}$	cross-section area of turbine part (m^2)
$\boldsymbol{A_{pp}}$	cross-section area of pump part (m^2)
$\boldsymbol{g}$	gravitational constant $(m^3kg^{-1}s^{-2})$
$\boldsymbol{H}$	dynamic head at the bottom of the penstock (m)
$\boldsymbol{H_0}$	nominal steady-state head at the bottom of the penstock (m)
$\boldsymbol{H_p}$	nominal stead state head at the bottom of the pump penstock (m)
$\boldsymbol{H_t}$	nominal stead state head at the bottom of the turbine penstock (m)
$\boldsymbol{L_c}$	length of the primary penstock (m)
$\boldsymbol{L_p}$	length of the pump penstock (m)
$\boldsymbol{L_t}$	length of the turbine penstock (m)
$\boldsymbol{T_W}$	water time constant (s)
$\boldsymbol{q_{base}}$	base water flow (m^3/s), which is chosen as the value of water flow when the gate is fully opened
$\boldsymbol{H_{base}}$	static head of the water column (m)
$\boldsymbol{\overline{q}}$	per unit water flow in the penstock (*p.u.*)
$\boldsymbol{\overline{H}}$	per unit dynamic head at the bottom of the penstock (*p.u.*)
$\boldsymbol{\Delta\omega}$	per unit difference of input frequency (*p.u.*)
$\boldsymbol{\overline{G}}$	per unit gate position (*p.u.*)
$\boldsymbol{\overline{G}_{max}}$	maximum per unit gate position (*p.u.*)
$\boldsymbol{\overline{G}_{min}}$	minimum per unit gate position (*p.u.*)
$\boldsymbol{D_{turb}}$	damping factor of friction *p.u.* on generator MVA rating
$\boldsymbol{q_{NL}}$	per unit no-load water flow (*p.u.*)
$\boldsymbol{\overline{P}_m}$	per unit mechanical power output (*p.u.*)
db1	dead band of frequency difference (*p.u.*)
$\boldsymbol{\overline{P}_{gen}}$	power order of the generator in per unit
$\boldsymbol{\overline{G}_{ref}}$	power order of the pump part in per unit
$\boldsymbol{\overline{P}_{ref}}$	power order of the turbine part in per unit
$\boldsymbol{K_d}$	distribution coefficient
$\boldsymbol{V_{elm}}$	valve velocity (*p.u./s*)
$\boldsymbol{T_g}$	gate servo time constant, *s*
$\boldsymbol{T_f}$	Filter time constant, *s*
$\boldsymbol{T_r}$	washout time constant, *s*
$\boldsymbol{A_t}$	turbine gain (*p.u.*)
$\boldsymbol{T_{w\_tt}}$	water time constant for the entire penstock length of the turbine part

T_{w_tp}	water time constant for the shared-penstock length from the turbine part to the pump part
T_{w_pt}	water time constant for the shared-penstock length from the pump part to the turbine part
T_{w_pp}	water time constant for the entire penstock length of the pump part
$\Delta\overline{H}_t$	water head differences in per unit for the turbine part
$\Delta\overline{H}_p$	water head differences in per unit for the pump part
q_t	water flow of the water in the turbine penstock (m^3/s)
q_p	water flow of the water in the pump penstock (m^3/s)
$\overline{q}_t$	per unit water flow of the water in the turbine penstock (*p.u.*)
$\overline{q}_p$	per unit water flow of the water in the pump penstock (*p.u.*)
K_p	constant of proportional
R	permanent droop, (*p.u.*)
r	transient droop, (*p.u.*)
$\overline{G}_t$	per unit gate position of turbine (*p.u.*).
$\overline{G}_p$	per unit gate position of pump (*p.u.*).
$[\overline{q}]$	matrix of water flow (*p.u.*).
$[\overline{H}]$	matrix of nominal stead state head at the bottom of the penstock (*p.u.*).

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1 Objective

Develop a model specification for a ternary pumped storage hydropower (T-PSH) dynamic model that accurately represents its unique operational characteristics and capabilities. This specification aims to enhance the understanding, evaluation, and application of T-PSH systems, facilitating their seamless integration into modern energy grids.

2 Background

Over the past century, conventional pumped storage hydropower (C-PSH) has been a dependable solution for grid stability. However, C-PSH units can only provide stability services in generating mode, not in pumping mode, and require several minutes to transition between these modes. This delay limits their ability to deliver fast frequency response, especially in grids with high renewable energy penetration.

T-PSH was originally introduced in [1] and later implemented at the Puente-Bibey underground pumped storage facility in Spain [2]. T-PSH introduces a key structural innovation by placing pump and generation turbines in separate chambers, both connected to the same shaft, as shown in Figure 1. Both turbines can be connected or disconnected via clutches according to the operation requirement. Additionally, two separate penstocks connect the pump and generation turbine to the shared common penstock, introducing a new hydraulic short circuit (HSC) operational mode. With those innovations, T-PSH can operate in generating mode, pumping mode, and HSC mode, with short switching times between different modes, and able to provide frequency regulation in pumping.

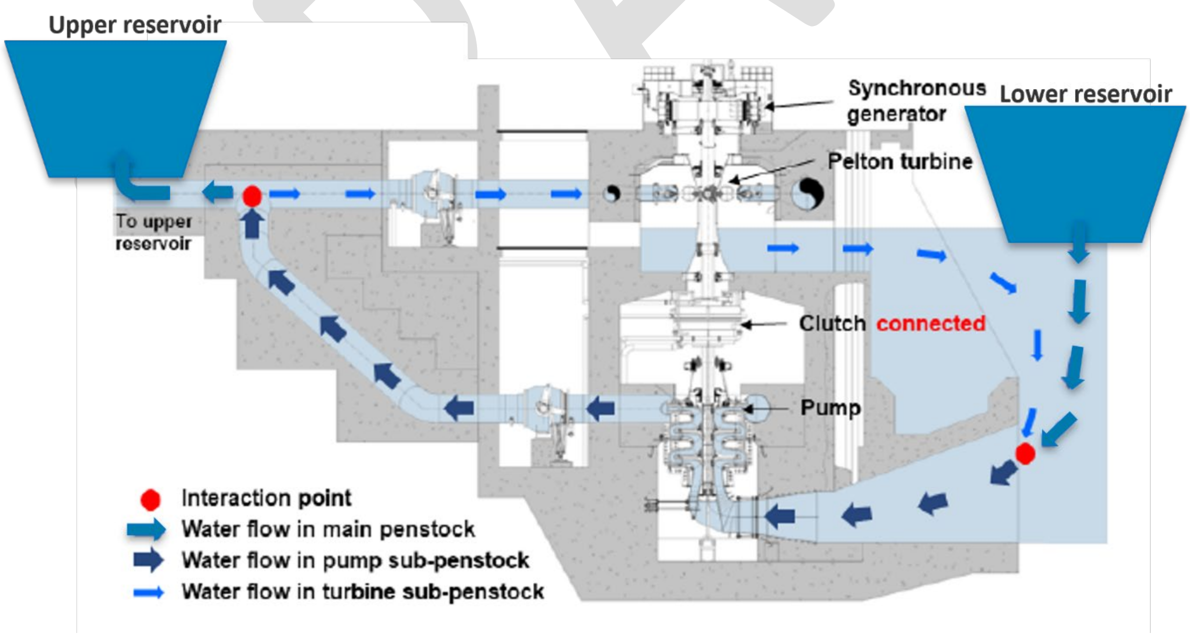

Figure 1 Water flow in HSC mode with two-stage penstock [source: GE]

Despite its advantages, T-PSH faces challenges, including higher costs due to the additional pump and a lack of comprehensive evaluation of its fast frequency response characteristics. Currently, generic T-PSH models are not widely available in the Western Electricity Coordinating Council (WECC) system and major power system software. As a result, only a limited number of T-PSH plants have been commissioned [3]. However, as renewable energy penetration increases, T-PSH's ability to provide fast frequency response and operate in HSC mode is expected to enhance its cost competitiveness relative to C-PSH. Developing accurate model specifications to capture its unique operational characteristics will be crucial for better understanding, evaluating, and integrating T-PSH into modern energy grids.

3 Model Description

T-PSH is an innovative structure of C-PSH that features two turbines, one for pumping and one for generation, replacing the single turbine in C-PSH. These turbines are housed in separate chambers, with an additional set of penstocks connecting the pump turbine to the hydraulic system. This structure enables T-PSH to operate in an HSC mode, allowing for simultaneous pumping and generation, which provides greater operational flexibility compared to C-PSH. To model T-PSH's HSC mode, a user defined turbine and governor system model is required, including the shared penstock model and additional pump turbine model. This specification will focus on the details of the user-defined turbine and governor model, which leverages the HYGOV model. Since T-PSH retains the synchronous machine used in C-PSH, so the GENSAL synchronous machine model and the IEEET1 DC exciter model for DC excitation in the C-PSH system can also be used in the T-PSH system model, as detailed in appendix A1 and A2.

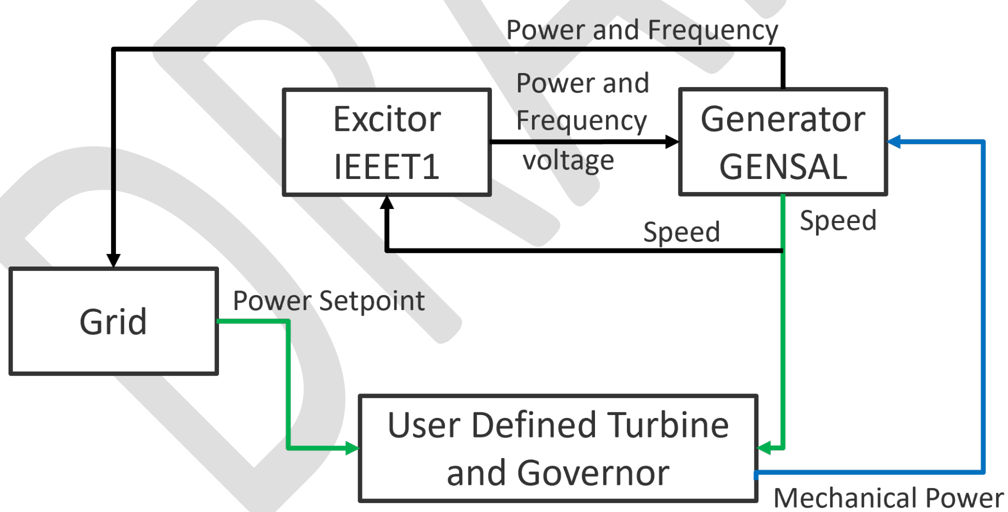

Figure 2 T-PSH system

3.1 T-PSH Turbine and Governor System

As mentioned previously, the turbine and governor model used in C-PSH cannot be directly applied to T-PSH due to its innovative governor structure. Therefore, a user-defined turbine and governor model, shown in Figure 2, has been developed based on the HYGOV model. HYGOV is a widely used hydropower turbine and governor model that provides a simple representation of a hydroelectric plant governor, including a basic hydraulic model of the penstock with an unrestricted head race and tail race, without a surge tank. In this user defined model, HYGOV is adapted to represent the turbine component within the governor. To accurately model the additional pumping and HSC modes, a pump section with a detailed water flow regulator and penstock system has been added. A distribution block is also integrated into the turbine and governor model ensures precise allocation of power references between the turbine and pump, facilitating efficient power control and smooth transitions between operational modes. And a shared penstock matrix has been implemented to describe hydraulic interactions between the turbine and pump penstocks during HSC mode [4]. This chapter is organized into the following sections: shared penstock and turbine modeling, distribution block modeling, governor modeling.

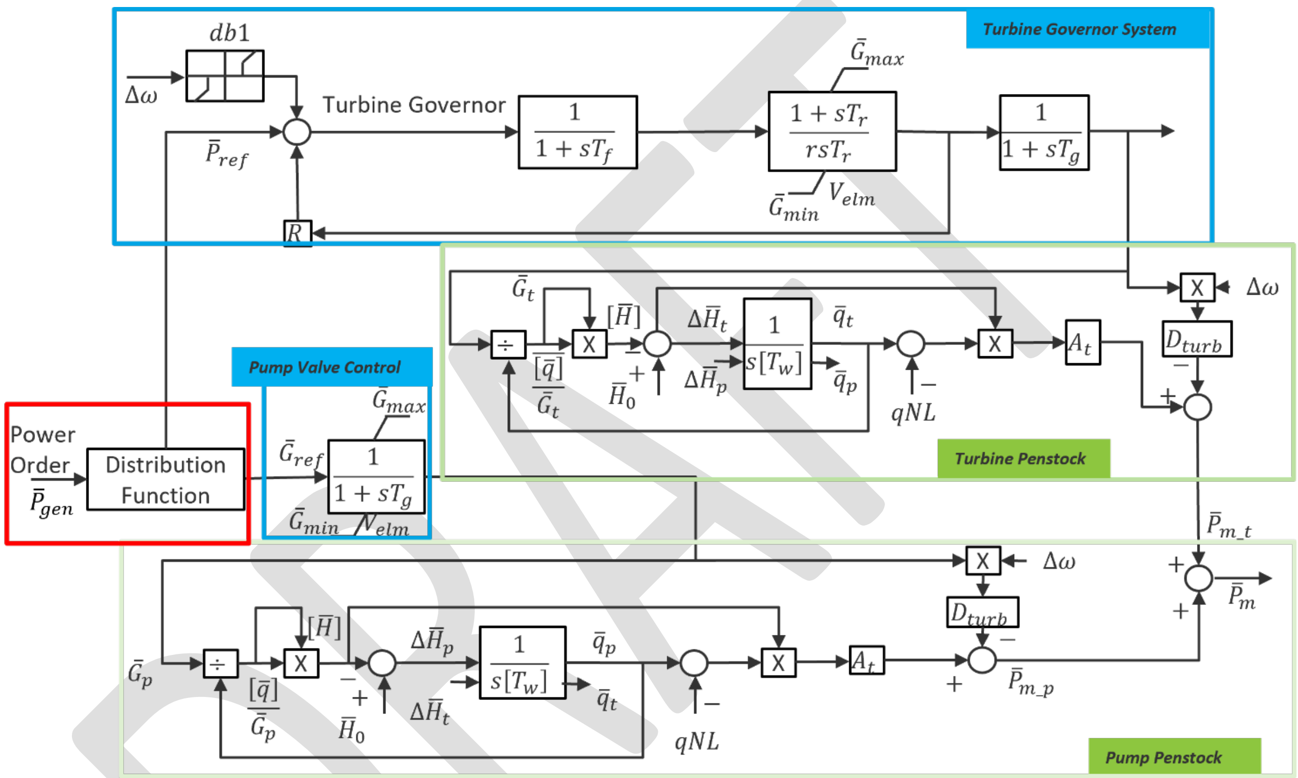

Figure 3 T-PSH turbine and governor system

3.1.1 Shared Penstock and Turbine Model

T-PSH features a set of separate, parallel penstocks, with water flow in the pump and turbine sections moving independently between the upper and lower reservoirs. While the pump and turbine operate with opposing flow directions, the reservoir in the T-PSH system acts as an infinite water source, preventing any interaction between the water flows in the parallel penstocks.

The turbine and penstock characteristics are determined by three fundamental equations, as given in Equations (1), (2), and (3) [5].

The velocity of the water in the penstock is given by Equation (1)

$$q = K_u G\sqrt{H} \tag{1}$$

Turbine mechanical power is proportional to the product of pressure and flow shown in Equation (2).

$$P = K_p H q \tag{2}$$

The acceleration of water column due to a change in head at the turbine, characterized by Newton's second law of motion, expressed as Equation (3)

$$(\rho LA)\frac{dq}{dt} = A\rho g(H_0 - H) \tag{3}$$

Where q is the water flow of the water in the penstock (m^3/s), K_u is a constant of proportionality, G is gate position, H_0 is the nominal steady-state head at the bottom of the penstock (m), H is the dynamic water head at the bottom of the penstock (m), K_p is a constant of proportionality, P is the mechanical power of the turbine, L is the length of the penstock (m), A is the cross-sectional area of the primary penstock (m^2), $\rho$is the water density (kg/m^3), g is the gravitational constant $(m^3 kg^{-1} s^{-2})$, t is time (s).

By dividing both sides by $A\rho g H_{base} q_{base}$, the acceleration equation in normalized form becomes:

$$\frac{(\rho LA)dq}{A\rho g H_{base} q_{base} dt} = \frac{A(\rho g)(H_0 - H)}{A\rho g H_{base} q_{base}} \tag{4}$$

Whereby definition,

$$T_W = \frac{L q_{base}}{g H_{base}} \tag{5}$$

Where T_W is water starting time (s), it represents the time required for a head H_{base} to accelerate the water in penstock from standstill to the velocity q_{base}, T_W varies with load. (Typically, at full load is between 0.5-4)

$$T_w \frac{d\bar{q}}{dt} = \frac{(H_0 - H)}{H_{base}} \tag{6}$$

This equation describes the effect of back pressure applied at the end of the penstock when the gate is closed, causing the water in the penstock to decelerate. Positive pressure changes results in a negative acceleration change.

After normalizing the Equation (1), and (2), we have Equation (7), and (8):

$$\bar{H} = \left(\frac{\bar{q}}{\bar{G}}\right)^2 \tag{7}$$

$$\bar{q} = \frac{(\bar{H}_0 - \bar{H})}{T_W s} \tag{8}$$

In an ideal turbine model, the output mechanical power is proportional to the water flow and head. However, when the turbine operates with less than 100% efficiency, a minimum water flow, known as the no-load water flow q_{NL}, is required for operation. Always, in the turbine runner and pump runner, frictional resistance appears on the rotating shaft. After adding these factors to the ideal model of turbine, a more realistic model can be expressed:

$$\bar{P}_m = A_t \left(\frac{(\bar{H}_0 - \bar{H})}{T_W s} - q_{NL} \right) \bar{H} - \Delta\omega \bar{G} D_{turb} \tag{9}$$

Where $\bar{P}_m$ is per unit mechanical power output (p.u.), $\bar{q}$ is per unit water flow of the water in the penstock (p.u.), q_{NL} is per unit no load water velocity(p.u.), $\bar{H}_0$ is the per unit nominal steady-state head at the bottom of the penstock (p.u.), $\bar{H}$ is the per unit dynamic water head at the bottom of the penstock (p.u.), $\bar{G}$ is per unit gate position (p.u.), D_{turb} the damping factor of friction p.u. on generator MVA rating), $\Delta\omega$is the per unit difference of input frequency (p.u.), A_t is per unit turbine gain (p.u.)

Combining the velocity of water in penstock model, acceleration of water column model, and turbine mechanical power, we have the hydro turbine model for turbine mode and pump mode in T-PSH shown in Figure 4:

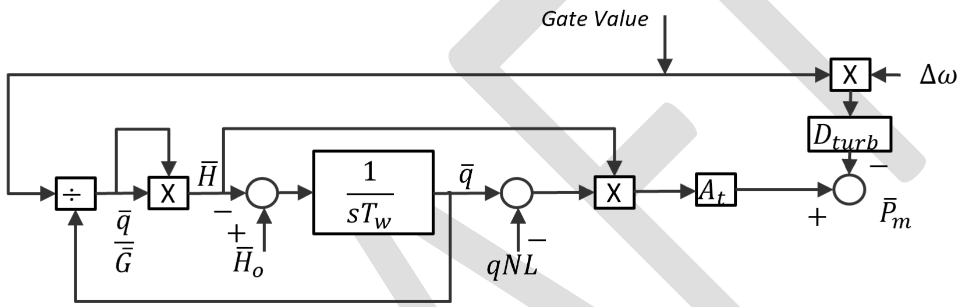

Figure 4 Block Diagram of Turbine Model

In the T-PSH system, the main penstock connects the reservoirs, while two separate penstocks link the turbine and pump. During HSC mode, the pump runner moves water from the lower to the upper reservoir, while the water passing through the turbine merges with the lower reservoir flow and recirculates to the pump. This hydraulic short-circuit flow affects the overall water dynamics of the T-PSH system. Traditional parallel penstock modeling methods are insufficient to capture the complex interaction between turbine and pump flows under HSC conditions. To accurately represent this behavior, a new shared penstock time matrix is developed by leveraging the common tunnel time constant matrix introduced in 1999 by Hannett, L.N. et al. [6].

Based on Newton's law of motion Equation (3), a function is derived for water flow in primary penstock located between higher reservoir and the first red split point in Figure 3, we have:

$$(H_0 - H) = \frac{L_c}{g(A_C)} \frac{dq}{dt} \tag{10}$$

In the first red split point, the water flow continuity equation is:

$$q = q_p - q_t \tag{11}$$

Water flow can be split into two parts to flow into the secondary penstocks. Equation (10) can be rewritten as:

$$(H_0 - H) = \frac{L}{g(A_C)}(\frac{dq_t}{dt} - \frac{dq_p}{dt}) \tag{12}$$

Where A_C is the cross-sectional area of the primary penstock (m^2), q_t is the water flow of the water in the turbine penstock (m^3/s), q_p is the water flow of the water in the turbine penstock (m^3/s), L_c is the length of the primary penstock (m). Water flow in the pump part secondary penstock (from the first split point to pump runner) can be written as:

$$\left(H - H_\mathrm{p}\right) = -\frac{L_p}{gA_{pp}}\frac{dq_p}{dt} \tag{13}$$

Combine the Equation (12) and (13), we have

$$\left(H_0 - H_p\right) = -\left(\frac{L_c}{gA_c} + \frac{L_p}{gA_{pp}}\right)\frac{dq_p}{dt} + \frac{L_c}{gA_c}\frac{dq_t}{dt} \tag{14}$$

Where L_p is the length of the pump penstock (m), A_{pp} is cross-section area of pump part (m^2), H_p is the nominal steady state head at the bottom of the pump penstock (m), H is the dynamic water head (m), In the first interaction point for the turbine:

$$(H_0 - H) = -\frac{L_c}{gA_c}\left(\frac{dq_p}{dt} - \frac{dq_t}{dt}\right) \tag{15}$$

Water flow in the turbine part secondary penstock (from the first split point to turbine runner) can be written as:

$$(H - H_t) = \frac{L_t}{gA_{tt}}\frac{dq_t}{dt} \tag{16}$$

Combine the Equation (12) and (16), we have

$$(H_0 - H_t) = \left(\frac{L_c}{gA_c} + \frac{L_t}{gA_{tt}}\right)\frac{dq_t}{dt} - \frac{L_c}{gA_c}\frac{dq_p}{dt} \tag{17}$$

Where L_t is the length of the turbine penstock (m), $A_{tt}$is cross-section area of turbine part (m^2), H_t is the nominal steady state head at the bottom of the turbine penstock (m). Equation (14) and (17) describe the relationship between water head and water flow in the penstock. By dividing both sides by $H_{base}q_{base}$, the second order shared penstock matrix can be defined as:

$$T_{w11} = \frac{q_{base}}{H_{base}}\left(-\frac{L_t}{gA_t} + \frac{L_c}{gA_C}\right) \qquad T_{w12} = -\frac{L_c}{gA_c}\frac{q_{base}}{H_{base}} \tag{18}$$

$$T_{w22} = -\frac{q_{base}}{H_{base}}\left(\frac{L_p}{gA_p} + \frac{L_c}{gA_C}\right) \qquad T_{w21} = \frac{L_c}{gA_c}\frac{q_{base}}{H_{base}} \tag{19}$$

Where T_{w11} is the water time constant for the entire penstock length of the turbine part, T_{w12} is the water time constant for the shared-penstock length from the turbine part to the pump part , T_{w21} is the water time constant for the shared-penstock length from the pump part to the turbine part, T_{w22} the water time constant for the entire penstock length of the pump part, q_{base} is the base water flow (m^3/s), which is chosen as the value of water flow when the gate is fully opened, and $H_{base}$is the static head of the water column (m). After collecting the water time constants, a second order shared penstock water flow model can be written as[7]:

$$\begin{bmatrix} T_{w11} & T_{w12} \\ T_{w21} & T_{w22} \end{bmatrix} \begin{bmatrix} \frac{d\bar{q}_t}{dt} \\ \frac{d\bar{q}_p}{dt} \end{bmatrix} = \begin{bmatrix} \Delta\bar{H}_t \\ \Delta\bar{H}_p \end{bmatrix} \tag{20}$$

Where $\Delta\bar{H}_t$ is the turbine head differences in per unit for the turbine part $\Delta\bar{H}_p$ is the turbine head differences in per unit for the pump part, $\bar{q}_t$ is the per unit water flow of the water in the turbine penstock (p.u.), $\bar{q}_p$ is the per unit water flow of the water in the turbine penstock (p.u). The shared penstock matrix $[T_W]$ expressed as:

$$[T_W] = \begin{bmatrix} T_{w11} & T_{w12} \\ T_{w21} & T_{w22} \end{bmatrix} \tag{21}$$

When T-PSH works in the generating or pumping mode, this water time constant is still suitable by only setting value for T_{w11} or T_{w22} and set other three elements as zero. When T-PSH works in HSC mode, T_{w12} and T_{w21} in the second order shared penstock matrix describe the interaction between two separate secondary penstocks whose water flow are in a different direction at the same time. Replacing *d*/*dt* in Equation (20) with the Laplace operator *s*, it can be written as:

$$\begin{bmatrix} \bar{q}_t \\ \bar{q}_p \end{bmatrix} = \frac{1}{s[T_W]} \begin{bmatrix} \Delta\bar{H}_t \\ \Delta\bar{H}_p \end{bmatrix} \tag{22}$$

After analyzing shared penstock model, the complete hydro penstock and turbine model with detailed shared penstock matrix, shown in Figure 5 and 6, is developed to use in the turbine part and the pump part.

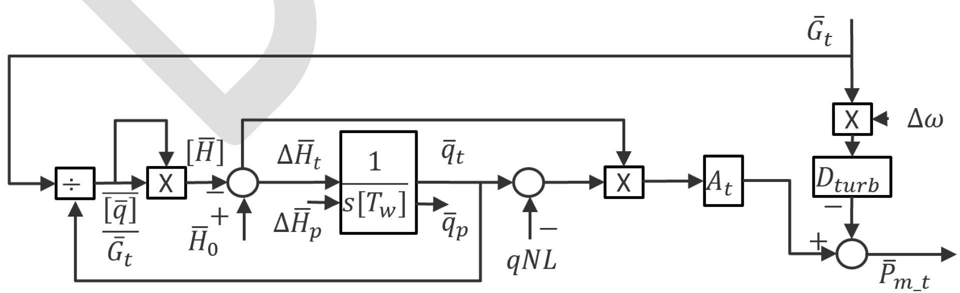

Figure 5 Block diagram of turbine penstock model in turbine mode

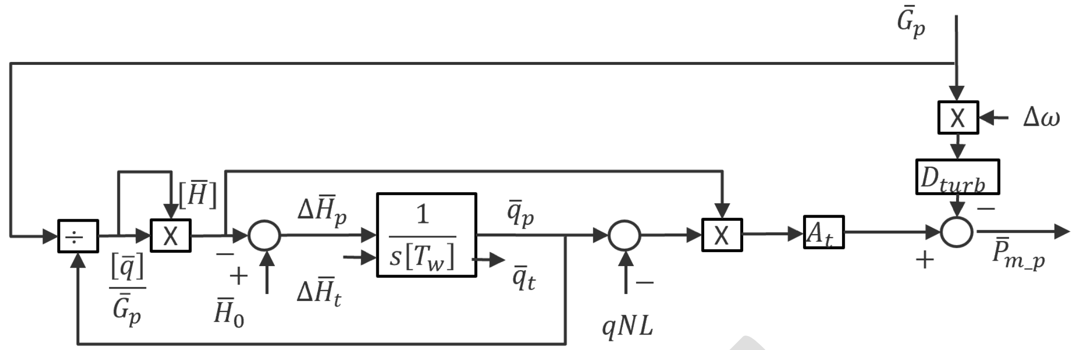

Figure 6 Block diagram of turbine penstock model in pump mode

Where $[\bar{q}] = \begin{bmatrix}\bar{q}_t \\ \bar{q}_p\end{bmatrix}$ is the per unit matrix of water flow (p.u.), $[\bar{H}] = \begin{bmatrix}\bar{H}_t \\ \bar{H}_p\end{bmatrix}$ is the matrix of nominal Steady state water head at the bottom of the penstock (p.u.).

3.1.2 Governor Model

The innovative structure of the T-PSH system, incorporating an additional pump and the HSC operation mode, makes it unsuitable to directly use the C-PSH governor model. Additionally, in the T-PSH system, the pump operates at a fixed setting in both pumping and HSC modes, however, turbine is operated as conventional hydropower generation with a droop controller to provide frequency control. Therefore, the gate controllers and governor model for each component must be modeled separately.

To address these challenges, three key developments have been implemented. First, a distribution block has been integrated into the governor model to allocate power references to both the turbine and pump sections, enabling control and mode switching in the T-PSH system. Second, a water flow regulator model has been designed to control the gate position of the additional pump. Third, a governor model based on the 'HYGOV' has been developed to provide frequency control in turbine mode.

3.1.2.1 Distribution Block

In T-PSH, the pump and turbine are connected to the same shaft and through separate penstock connect to the common penstock. To allocate power reference and control the operational mode, the distribution block is integrated into the governor model system. Within this block, a distribution coefficient, K_d is defined to determine the T-PSH operation mode. This coefficient is specified in the governor model and shared between the turbine and pump sections. In this T-PSH model the definition of K_d and the power reference calculation are provided in Equations (23), (24), and (25) [7]:

$$K_d = \begin{cases} 0 & Generating\ Mode \\ 1 & Pumping\ Mode \\ > 1 & HSC\ Mode \end{cases} \tag{23}$$

$$\bar{G}_{ref} = -K_d \times |\bar{P}_{gen}| \tag{24}$$

$$\bar{P}_{ref} = |1 - K_d| \times |\bar{P}_{gen}| \tag{25}$$

Where $\bar{P}_{gen}$is per unit power order of the generator (p.u.), $\bar{G}_{ref}$is the power order of the pump part (p.u), $\bar{P}_{ref}$is the power order of the turbine part (p.u.), and K_d is the distribution coefficient. The K_d governs different operation modes. Equation (24) and (25) determine the power order for each component during both initialization and simulation. In pumping or generating modes, the K_d is set to 0 or 1 to control the operation mode. In HSC mode, the K_d value reflects the proportion of the two mechanical outputs, influencing the combined torque that drives the synchronous machine. The detailed operation mode and power order in different modes is shown in Table 1. This setup provides a flexible approach for engineers or power system planners to incorporate specific operating conditions into future model development and extend the operational logic [7].

Table 1 Operation mode control of T-PSH

Mode	**Coefficient** K_d	**Pump** $\bar{G}_{ref}$	**Turbine** $\bar{P}_{ref}$	**Steady state** $\bar{P}_m$
Generating	0	0	$\lvert\bar{P}_{gen}\rvert$	$\lvert\bar{P}_{gen}\rvert$
Pumping	1	-$\lvert\bar{P}_{gen}\rvert$	0	-$\lvert\bar{P}_{gen}\rvert$
Hydraulic Short Circuit	$K_d > 1$	$-K_d \times \lvert\bar{P}_{gen}\rvert$	(K_d-1)× $\lvert\bar{P}_{gen}\rvert$	-$\lvert\bar{P}_{gen}\rvert$

The interaction between the constant negative pump torque and the positive turbine torque results described in Equation (26)

$$\bar{P}_m = \bar{P}_{m\_t} + \bar{P}_{m\_p} \tag{26}$$

where $\bar{P}_m$ is per unit total mechanical power output (p.u.), $\bar{P}_{m\_t}$ is the per unit mechanical power output of the turbine (p.u.), $\bar{P}_{m\_p}$ is the per unit mechanical power output of the pump (p.u.). This function describes the combined torque on the shaft.

3.1.2.2 Governor Model in Turbine

In the T-PSH system, the pump operates at a fixed setting in both pumping and HSC modes, while the turbine functions as a conventional hydropower generator with a droop controller for frequency regulation. This distinct characteristic necessitates separate governor models for the turbine and pump. To enable governor control across different modes and align with the distribution block, two distinct models have been developed within the T-PSH governor system. In pump mode, a water flow regulator model is designed to control the gate position of the additional pump. In turbine mode, a governor model based on the "HYGOV" framework has been developed to regulate frequency during turbine operation. Figure 6 presents the schematic of T-PSH's turbine governor system.

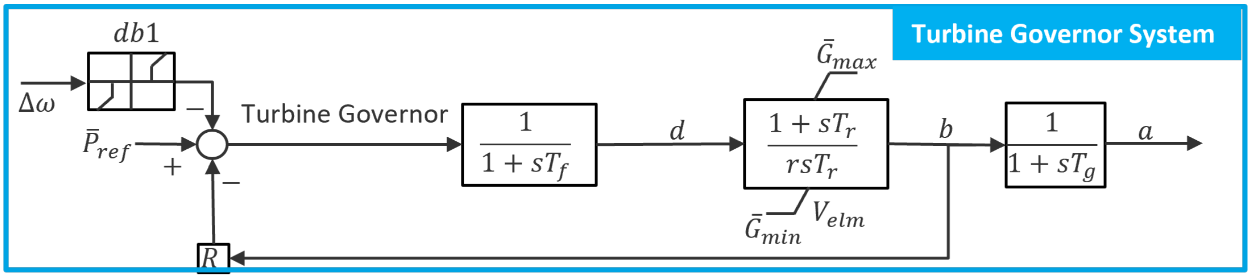

Figure 6 Transfer function diagram of the T-PSH turbine governor system

Where T_g is gate servo time constant (s), T_f is filter time constant (s), T_r is washout time constant (s), V_{elm} is valve velocity (p.u./s), R is permanent droop (p.u.), r is transient droop (p.u.), $\bar{G}_{max}$is maximum per unit gate position (p.u.), $\bar{G}_{min}$ is minimum per unit gate position (p.u.), D_{turb} is damping factor of friction on generator MVA rating (p.u.). db1 is the deadband, $\bar{G}_p$ is per unit gate position of pump (p.u.), $\bar{G}_t$ is per unit gate position of turbine (p.u.).

In turbine mode, droop characteristics (R) are necessary to maintain stable parallel operation of multiple units. Second, transient (or temporary) droop (r) is essential for stable control performance. Due to the water inertia in hydro turbines, a change in gate position initially results in a power change that is opposite to the intended direction. This happens because, while the water flow remains unchanged due to inertia, the pressure across the turbine decreases, causing the initial power response to counter the gate adjustment. This behavior is illustrated in the transfer function and figure below, where the initial shift in power $\bar{P}_{m\_t}$ moves in the opposite direction of the gate change [5].

$$\frac{\Delta\bar{P}_{m\_t}}{\Delta\bar{G}_t} = \frac{1 - T_w s}{1 + \frac{1}{2}T_w s} \tag{26}$$

In older hydro units, the governor function is achieved through mechanical and hydraulic components. A dashpot is utilized to provide compensation for transient droop (r). Assuming the fluid flow within the dashpot through the needle valve is directly proportional to the pressure in the dashpot, the transfer function of the dashpot is given as follows:

$$\frac{d}{\bar{G}_t} = \frac{sT_r}{r(1 + sT_r)} \tag{27}$$

The transfer function of relay valve and gate servomotor is:

$$\frac{\bar{G}_t}{a} = \frac{1}{s} \tag{28}$$

The transfer function of pilot valve and pilot servo is:

$$\frac{a}{b} = \frac{1}{1 + sT_g} \tag{29}$$

Combining the Equations (28) and (29):

$$\frac{\bar{G}_t}{b} = \frac{1}{s(1 + sT_g)} \tag{30}$$

Where T_g is the pilot valve servomotor time constant.

$$\bar{G}_t = \frac{T_r s + 1}{rT_f T_r s^2 + RT_r s + rT_r s + R}\left(\frac{1}{1 + T_g s}\right)(\bar{P}_{ref} - \Delta\omega) \tag{31}$$

Modern speed governor systems for hydraulic turbines utilize electrohydraulic mechanisms, incorporating features such as speed sensing, permanent and temporary droop, while offering increased flexibility and improved measurement precision. However, the dynamic behavior of these electric governors is typically designed to closely mimic that of traditional mechanical-hydraulic governors. This similarity allows the use of this governor model as a representative generic model for hydraulic turbine governors.

3.1.2.3 Valve Control Model in Pump

Unlike the turbine part, no droop control function is employed in the pump part. The initial gate reference of the pump is calculated from the power order and distribution block. It is kept constant if there is no change in the gate reference. The gate value of the pump part cannot respond to the frequency disturbance.

The servo motor drives the needle valve within the nozzle, adjusting the water flow into the pump runners. The physical response delay of the servo motor is represented by a first-order delay, with its transfer function shown in (32) [9].

$$\bar{G}_p = (\frac{1}{1 + T_g s})(\bar{G}_{ref}) \tag{32}$$

Where T_g is gate servo time constant (s).

3.1.2.4 Transition time

The T-PSH system, equipped with an additional pump, enables operation in three distinct modes: generating mode, pumping mode, and HSC mode. It maintains a consistent water flow direction in the penstock across all operating modes. This unique feature significantly accelerates mode transitions, allowing the T-PSH system to switch modes in under one minute, the effects of hydraulic transients are greatly minimized, allowing the machine to quickly transition from full pumping mode to full generating mode. The transition time of T-PSH model is shown in Table 2. A represents the transition from pumping to generating, B from generating to pumping, C from pumping to HSC, D from HSC to pumping, E from generating to HSC, and F from HSC to generating.

Table 2 Transient time of T-PSH [9].

Mode change	A Pumping to Generating	B Generating to Pumping	C Pumping to HSC	D HSC to Pumping	E Generating HSC	F HSC to Generating
Transition time	<60s	<60s	30s	10s	<60s	<60s

4 Parameters, Variables and input and output channels of the T-PSH Turbine and Governor System

The T-PSH turbine and governor system has 2 input channels, 5 output channels, 19 parameters.

4.1 Inputs Channels

The input for the model can be described as follows:

Power generation input: P_{gen} is total power order for the entire T-PSH system. P_{gen_pump}: Power order specifically for the pump's hydraulic turbine and governor system. $P_{gen\_turbine}$: Power order for the turbine's hydraulic turbine and governor system.

Frequency error input: $\Delta\omega$ is the frequency error of the grid.

These inputs allow the distribution block to determine the appropriate operation mode and allocate power accordingly to the pump and turbine systems.

Table 3 Input channels of the T-PSH turbine and governor model

Input Channel	Symbol	Description
IC0	P_{gen}	Power order for the entire T-PSH system, MW.
IC1	$\Delta\omega$	frequency error from the grid, p.u.

4.2 Outputs Channels

The output for the T-PSH system model can be described as follows:

- **Gate value output:** the turbine gate value g_t and pump gate value g_p.
- **Mechanical power output**: In all operation modes, the mechanical power output of the T-PSH system is represented by $\bar{P}_m$.
- **Mechanical power output in different mode**:

- **Pumping Mode**: The mechanical power output from the turbine and governor model in pump mode is $\bar{P}_m = \bar{P}_{m\_p}, \bar{P}_{m\_t} = 0$
- **Generating Mode**: The mechanical power output from the turbine and governor model in turbine mode is$\bar{P}_m = \bar{P}_{m_t}, \bar{P}_{m_p} = 0$
- **HSC Mode**: The mechanical power output of the T-PSH system is $\bar{P}_m = \bar{P}_{m\_p} + \bar{P}_{m\_t}$, reflecting the combined output in this mode.

The mechanical power $\bar{P}_m$ is the input for generator model. The output structure ensures that the system provides accurate mechanical power values corresponding to the different operation modes.

Table 4 Output channels of the T-PSH turbine and governor model

Input Channel	Symbol	Description
OC0	$\bar{G}_t$	Turbine gate value, p.u.
OC1	$\bar{G}_p$	Pump gate value, p.u.
OC2	$\bar{P}_m$	mechanical power output of the T-PSH system, p.u.
OC3	$\bar{P}_{m\_P}$	mechanical power output from the pump, p.u
OC4	$\bar{P}_{m\_t}$	mechanical power output from the turbine, p.u.

4.3 Parameters

T-PSH turbine and governor system model have 19 input parameters.

This model is located at system bus #___IBUS

Machine identifier #___ID

Voltage #___KV

Table 5 Parameters of the T-PSH turbine and governor model [7]

Parameter	Symbol	Description	Example Value
V0	T_g	Gate servo time constant, s.	0.5
V 1	T_{w11}	Water time constant for the entire penstock length of the pump part, s.	-1.17
V 2	T_{w12}	Water time constant for the shared penstock in HSC mode, s.	0 in pumping or generating mode; nonzero in HSC mode;
V 3	T_{w22}	Water time constant for the entire penstock length of the generator part, s., s.	1.17

Parameter	Symbol	Description	Example Value
V 4	T_{w21}	Water time constant for the shared penstock in HSC mode, s	0 in pumping or generating mode; nonzero in HSC mode;
V 5	A_t	Turbine gain, p.u.	1.48
V 6	D_{turb}	Turbine damping factor, p.u.	0.3
V 7	qNL	No load flow at nominal head, pu	0.1
V 8	$\bar{H}_0$	Head available at dam, pu	1
V 9	R	Permanent droop (R), pu	0.04
V 10	r	Temporary droop (r), pu	0.31
V 11	T_f	Filter time constant, s.	0.05
V 12	T_r	Washout time constant, s.	6.88
V 13	$\bar{G}_{max}$	Maximum gate opening, pu of mwcap	1
V 14	$\bar{G}_{min}$	Minimum gate opening, pu of mwcap	0
V 15	K_d	Operation mode distribution coefficient	0—generating mode 1—pumping mode >1—HSC mode
V 16	V_{elm}	Maximum gate velocity, pu/s.	0.05—generating mode, pump mode, HSC mode 0.04—generating mode to pump mode 0.0333—pump mode to HSC mode 0.01666—HSC mode to generating mode
V 17	$db1$	intentional deadband	

5 Model Testing

The system used for T-PSH dynamic performance validation is a 3-generator, 10-bus system, as shown in Figure 8.

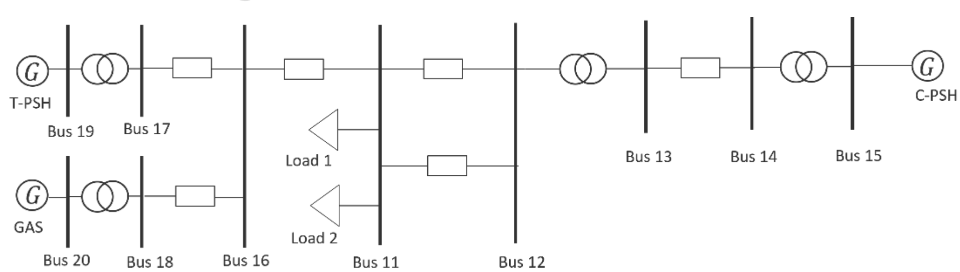

Figure 8 Diagram of the 3-gens system [9]

This system operates at three voltage levels: 24 kV, 34.5 kV, and 230 kV. The generators are located on three different buses, with their parameters shown in Figure 8. Specifically, the T-PSH unit is connected to Bus 19, the gas turbine is connected to Bus 20, and the C-PSH unit is connected to Bus 15. In various simulation scenarios, different generator capacities are selected to maintain system balance. Notably, the T-PSH capacity exceeds the actual PSH size to emphasize its influence and response within the system. To better analyze T-PSH behavior, the gas turbine's governor and exciter are disabled in certain cases, preventing it from responding to frequency events. The details are shown in Table 6. Additionally, the swing bus is assigned to different buses in each simulation. Two loads, with different rated capacities, are connected to Bus 11. The smaller load 2, a 100 MW load, is used to create system disturbances. Tripping or connecting this load triggers over-frequency or under-frequency events. More details on the system's dynamic model are provided in Appendices B.

Table 6 Details of system dynamic model components [9]

Bus number	Generating Mode Case	Pumping Mode Case	HSC Mode Case
Bus 15 C-PSH	GENSAL IEEET1 HYGOV 28.9MW		
Bus 19 T-PSH	GENSAL IEEET1 EPCTRB		
	1176 MW	1276 MW	1276 MW
Bus 20 Gas	GENROU EXAC1 GAST		
	200 MW	2400 MW	2400 MW

5.1 T-PSH Pumping Mode

In the pumping mode case, the T-PSH is operated as an inductive load which absorbed 500 MW power from the system at the beginning. The valve velocity limit was set as 1/20 p.u./s, and only 1000 MW load 1 was connected to the system. The 100 MW frequency events were applied at 10 seconds and 50 seconds, respectively, by connecting and tripping load 2 [9].

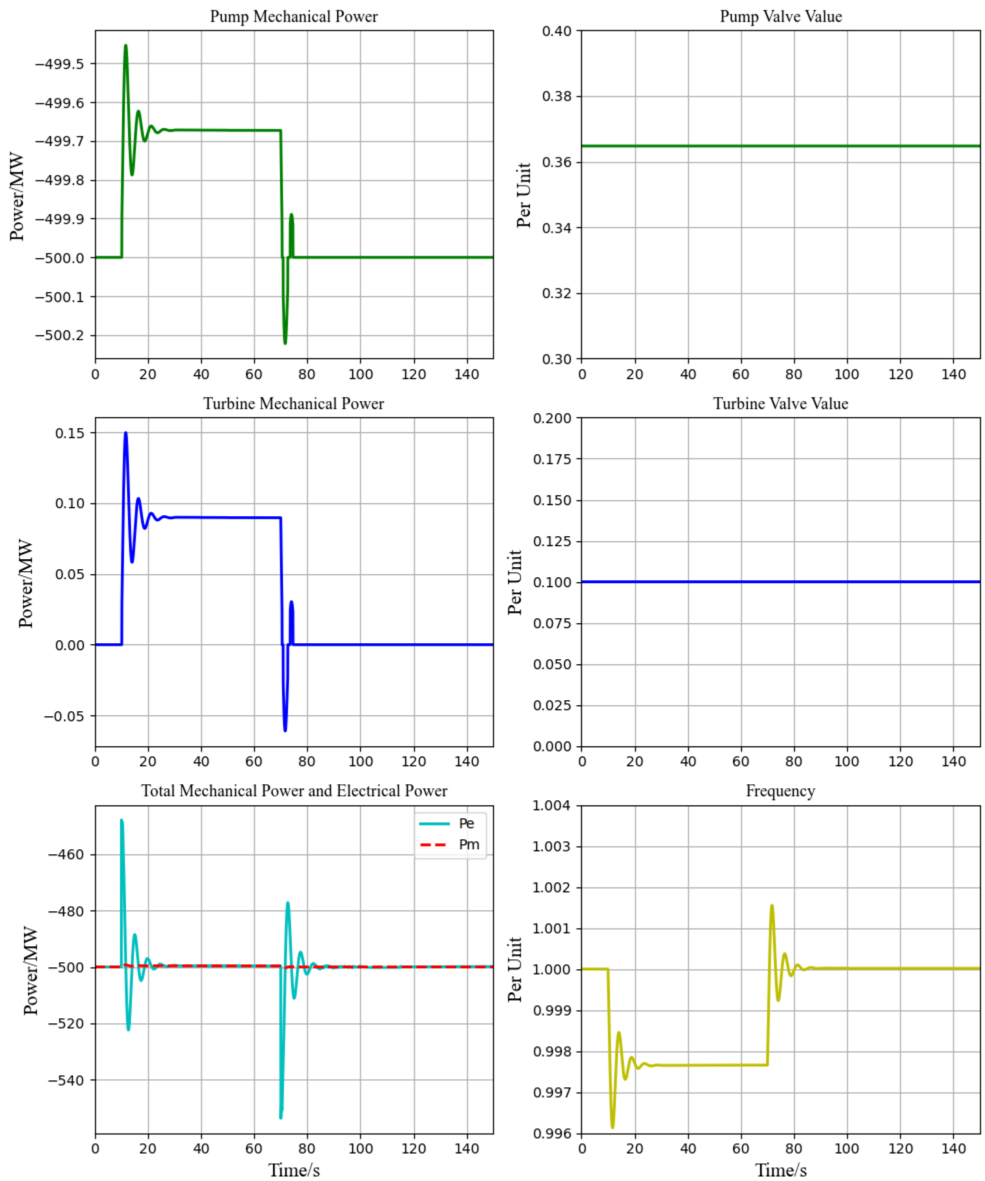

Figure 9 Dynamic response of T-PSH in pumping mode

After the frequency events, the T-PSH did not respond due to its fixed pump output. The pump section lacks a governor, and the turbine section was disabled in this simulation, meaning the T-PSH, operating in pumping mode, did not react to any frequency disturbances in the system. Especially, the small variances in the mechanical power output after the frequency events were caused by the frequency fluctuations. These fluctuations, although they cannot affect the gate value, it slightly impacted the frictional resistance on the shaft, which caused the variances in the mechanical power output in both the turbine part and the pump part. Although the turbine section being disabled, the gate in the turbine part still opened to its minimum value because there was no-load water flow in the turbine penstock. However, this no-load water flow resulted in zero mechanical power output from the turbine section. This case illustrates that the T-PSH in the pumping mode cannot respond to frequency events, which means no power regulation ability in the pumping mode.

5.2 T-PSH Generating Mode

In the generating mode case, the test T-PSH, as the main generator in the system, supplies 83.70% of the generating capacity. The test T-PSH unit was the main response unit for the frequency event whereas the gas turbine is operated to not respond to the frequency event. Before the simulation, the valve velocity was 1/20 p.u./s, which means the injector needed 20 seconds to open from minimum to the maximum (same in opposite action) when the larger loads (1000MW) on Bus 11 were connected into the system [9].

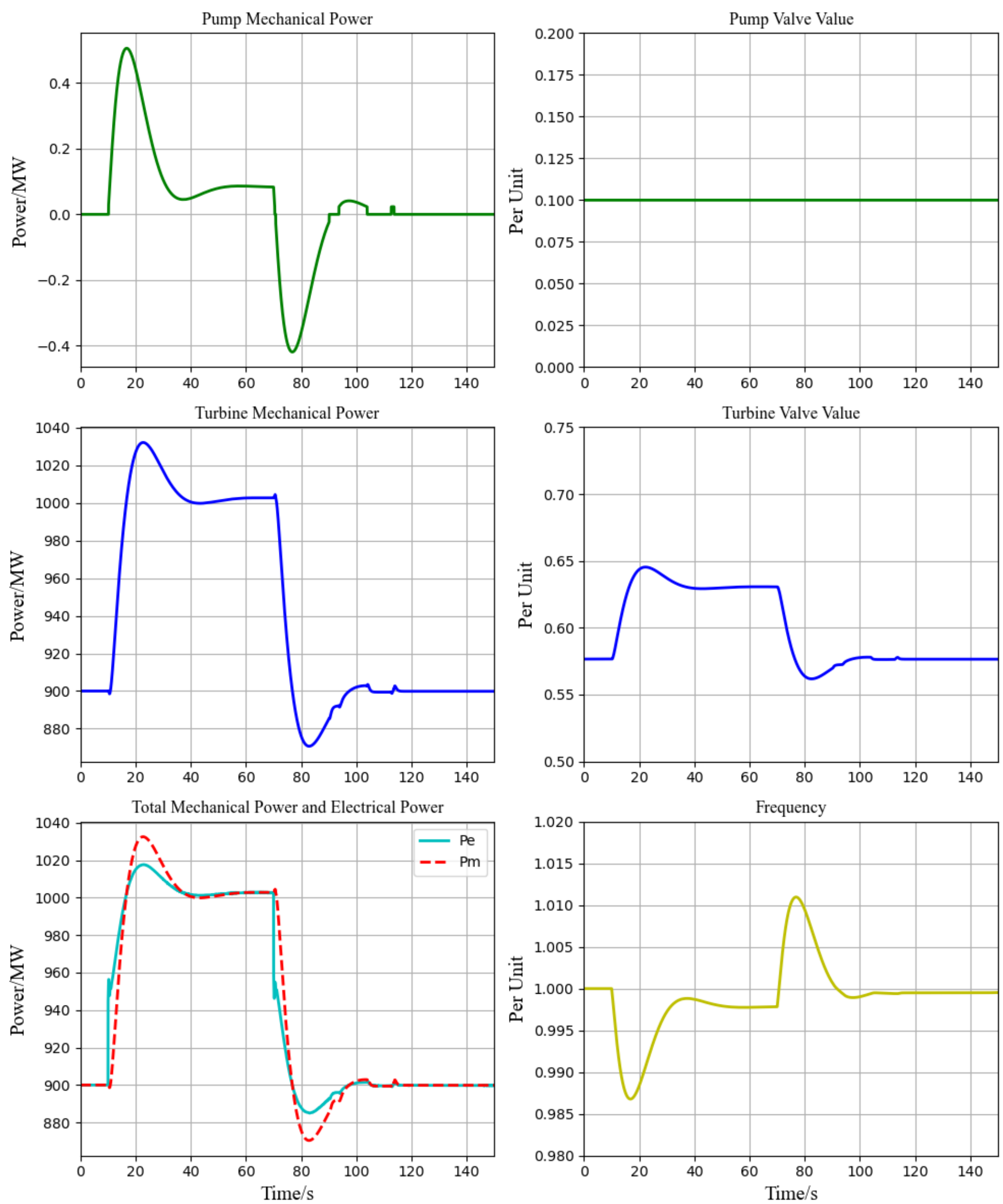

Figure 10 Dynamic response of T-PSH in generator mode

At the beginning of the simulation, the T-PSH, in the generating mode, supplied 900 MW (0.765 p.u.) power to the system. At 10 seconds, load 2 with rated power is 100 MW was connected to apply an underfrequency event, and at 50 seconds, the same load was tripped from the system to apply an over frequency event. Throughout the simulation, although the pump part in the T-PSH is disabled, the gate in the pump part still opened to its minimum value because there is no-load water flow in the pump part penstock. However, only no-load water flow in the penstock made the mechanical power output from pump part zero. When frequency events occur, the frequency difference is not zero. The governor in the turbine part adjusted the valve reference according to the frequency reference to make the mechanical power meet the system requirement to help the system frequency return to balance. Because of governor adjustment, T-PSH in generating mode provided frequency regulation when a system contingency occurred.

5.3 T-PSH Hydraulic Short-Circuit Mode

In this simulation, the T-PSH was set in the HSC mode absorbing 500 MW (-0.392 p.u.) power from system as the initial condition. The valve velocity limit was kept same as the previous cases (1/20 p.u./s). And only 1000MW load was connected in the system. At 10 seconds, the 100 MW load 2 was added to the system to apply an under-frequency event, and it was tripped at 70 seconds to apply an over-frequency event [9].

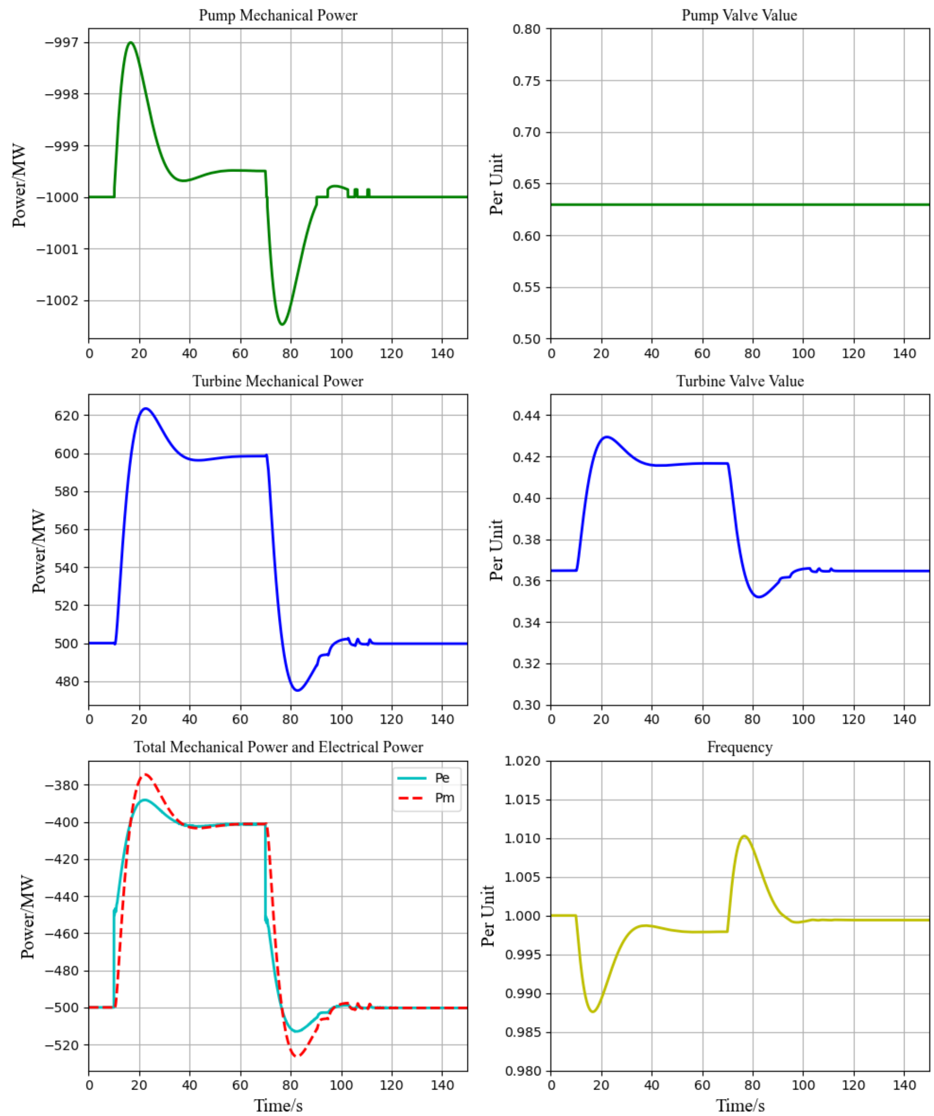

Figure 11 Dynamic response of T-PSH in HSC mode

Because the T-PSH in HSC mode is a combination of turbine and pump, after each frequency event, the turbine part adjusted the valve reference by using the governor to let mechanical power output meet the power demands. At the same time, the pump part kept the power output constant, although there was a small variance in the mechanical power output caused by the frequency fluctuation after the system frequency event. This case illustrates that the turbine part gives the T-PSH system frequency regulation ability in HSC mode. Compared with the pure pumping mode, T-PSH in the HSC mode can provide power adjustment to help stabilize the system after the frequency event.

5.4 Operation Mode Change in T-PSH

Another important feature in T-PSH technology is operation mode switching which is validated in this case. Three operation modes are switched clockwise according to the sequence from generating mode, to pumping mode, then to HSC mode, and finally back to generating mode.

The different transition times from actual operation, according to actual operation data shown in Figure 12, for each switching event was set as 25seconds, 30 seconds and 60 seconds separately which means the valve velocity was, 1/30 p.u./s, and 1/60 p.u./s, respectively. In this case, Bus 20 was assigned as the swing bus where the gas turbine was located. To help the system remain steady during the T-PSH operation mode switching, the governor model and exciter model were enabled in the gas turbine system to regulate the grid frequency. At the beginning, the T-PSH was operated in the generating mode with 500 MW (0.392 p.u.) power output. The switching event was applied at 10 seconds, 30 seconds and 150 seconds sequentially as shown in Figure 5.15. The results verify the operation mode switching ability of T-PSH. Especially, the design of the user-defined governor model allowed the T-PSH system to do the switching during the simulation case. The different transition times used in this case demonstrate that the user-defined governor model can modify the valve velocity limit during the simulation. During the simulation two parameters are modified, one is mode K_d, one is gate valve V_{elm}

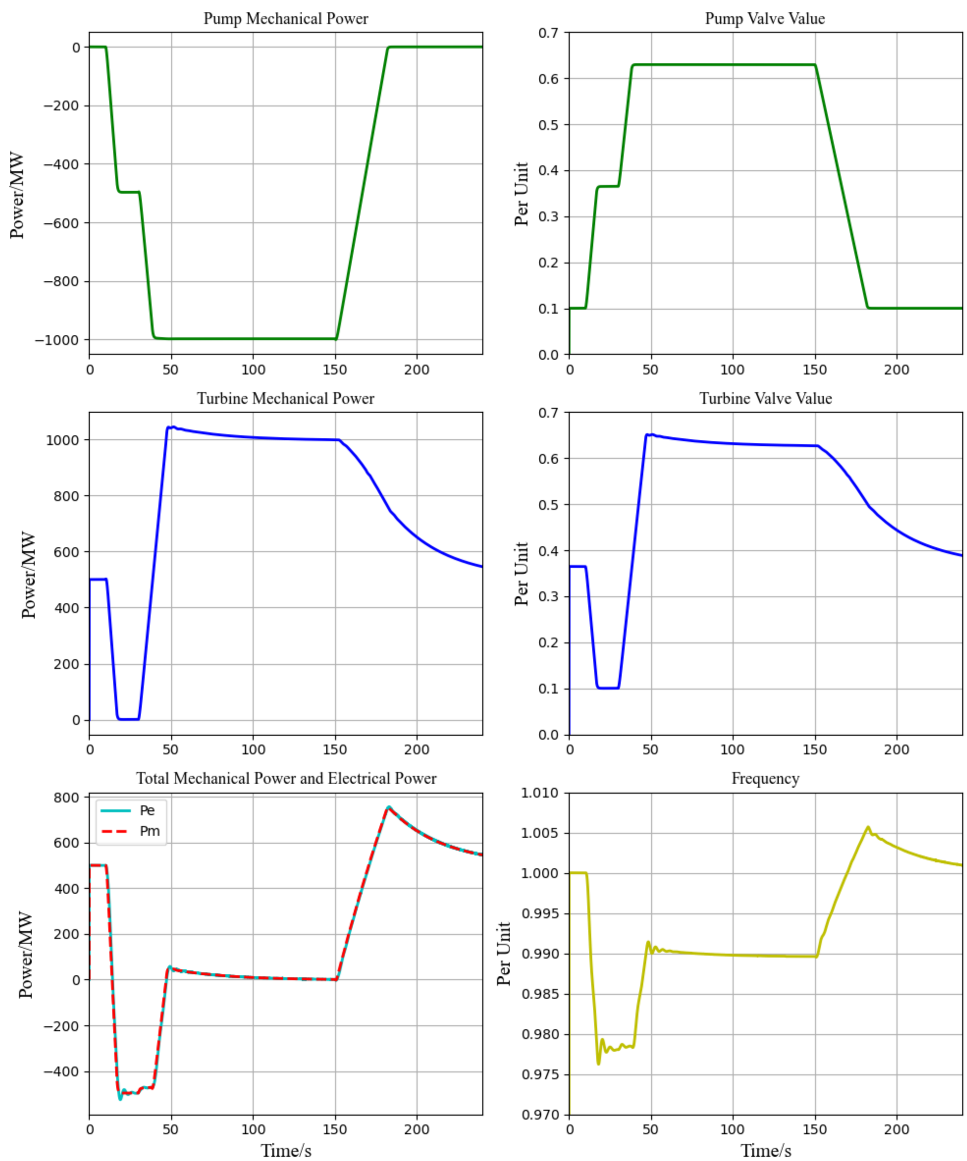

Figure 12 Dynamic response of T-PSH in mode transition

The system transitions through various operating modes over time as follows: t = 0 s: The system starts in Generating mode with a coefficient (K_d) of 0 and a valve velocity of 1/20. t = 10 s: It switches to Pumping mode with a coefficient (K_d) of 1 and a valve velocity of 1/25. t = 30 s: The system enters the HSC mode with a coefficient (K_d) of 2 and a valve velocity of 1/30. t = 60 s: The system remains in HSC mode, maintaining a coefficient (K_d) of 2 but with an increased valve velocity of 1/20. t = 150 s: The system transitions back to Generating mode with a coefficient (K_d) of 0 and a valve velocity of 1/60. t = 210 s: The system continues in Generating mode with a coefficient (K_d) of 0 and returns to a valve velocity of 1/20.

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Appendix A. T-PSH system

A.1 T-PSH Synchronous Machine and Excitation System

Since T-PSH technology retains the synchronous machine used in C-PSH technology, the model of the synchronous machine and its DC excitation system in the C-PSH system model can be used in the T-PSH system model. When implementing the machine system used in T-PSH system in the PSLF platform, the built-in salient pole synchronous machine and its DC exciter models are adopted.

The synchronous machine is the core of the entire T-PSH system and is used to convert electrical energy into kinetic energy in the pumping mode or to convert kinetic energy into electrical energy in the generating mode. An existing three-phase salient pole machine model in the PSLF platform is used in this study. This model is called GENSAL, which means salient pole synchronous machine is represented by equal mutual inductance rotor modeling [10].

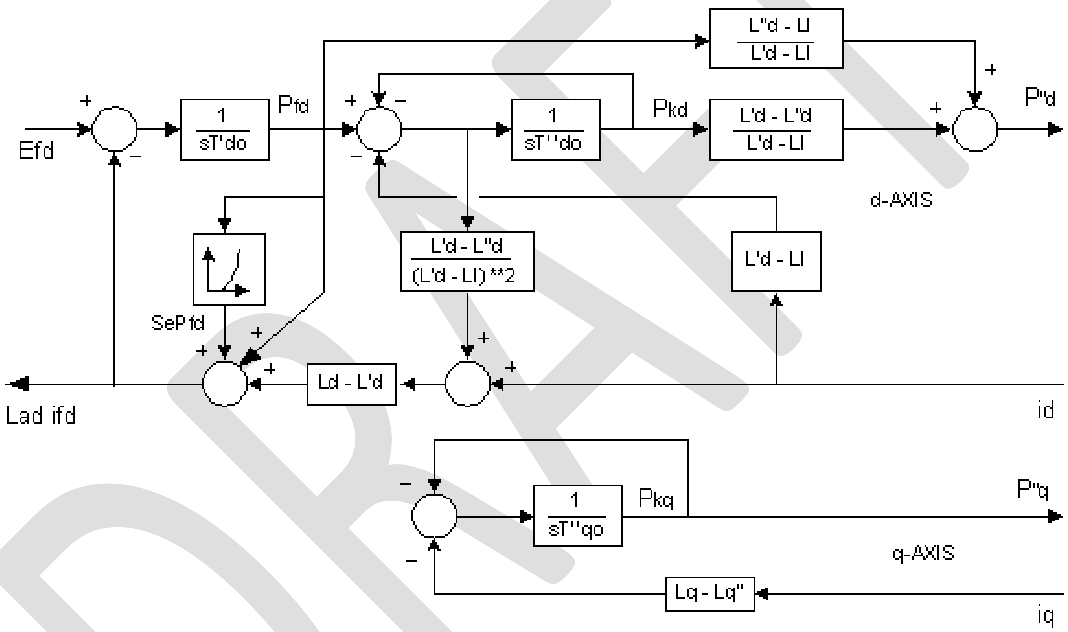

Figure 13. Block diagram of the GENSAL [10]

Table 7 Parameters of the T-PSH Turbine and Generator Model [10]

Symbol	Description	Default Data
Tpdo	D-axis transient rotor time constant	7.0
Tppdo	D-axis sub-transient rotor time constant	0.03
Tppqo	Q-axis sub-transient rotor time constant	0.035
H	Inertia constant, sec	3.0
D	Damping factor, pu	0.0
Ld	D-axis synchronous reactance	1.2
Lq	Q-axis synchronous reactance	0.8

Symbol	Description	Default Data
Lpd	D-axis transient reactance	0.22
Lppd	D-axis sub-transient reactance	0.20
Ll	Stator leakage reactance, pu	0.16
S1	Saturation factor at 1 pu flux	0.05
Ra	Stator resistance, pu	0.0
Rcomp	Compounding resistance for voltage control, pu	0.0
Xcomp	Compounding reactance for voltage control, pu	0.0

The excitation system in the synchronous generator provides DC current to the field winding, which induces three-phase voltages on the armature winding. Meanwhile, the additional functions of exciter include voltage control, reactive power flow control, system stability enhancement and generation system protection [11]. In this T-PSH specification, the IEEE (1968) Type 1 DC excitation system model is used to model the DC exciter. This excitation system is representative of a modern system in service. In the later IEEE standard [12], this IEEE (1968) Type 1 DC exciter has been modified as Type DC1A DC excitation system. When implementing this excitation system in PSLF, the existing exciter model 'IEEET1' shown in Figure 14 is used.

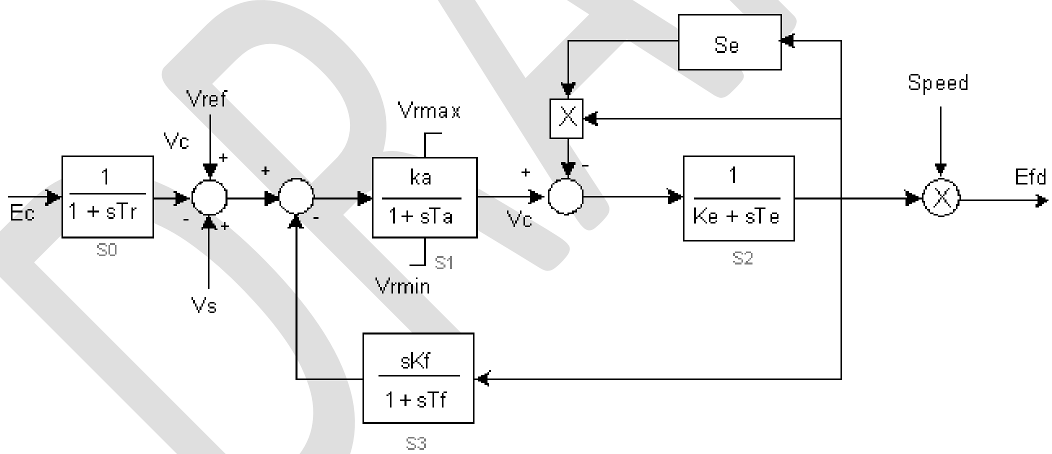

Figure 14. Block diagram of the IEEET1 [10]

Table 8 Parameters of the T-PSH Excitation Model [10]

Symbol	Description	Default Data
Tr	Transducer time constant, sec.	0.0
Ka	Voltage regulator gain (> 0.)	50.0
Ta	Voltage regulator time constant, sec. (> 0.)	0.02
Vrmax	Maximum control element output, p.u. (note c)	1.0

Symbol	Description	Default Data
Vrmin	Minimum control element output, p.u	-1.0
Ke	Exciter field resistance line slope margin, p.u. (note b)	-0.06
Te	Exciter field time constant, sec (> 0.)	0.6
Kf	Rate feedback gain, p.u.	0.09
Spare	Required entry of zero	0.0
E1	Field voltage value, 1 (note d)	2.8
SE1	Saturation factor at E1 (note d)	0.04
E2	Field voltage value, 2 (note d)	3.73
SE2	Saturation factor at E2 (note d)	0.33

Appendix B. Test system

```
Dynamic model table for 3-gen system with T-PSH in generating mode

gensal 19 "HYDRO-LV-NEW"  24.00 "1 ": #9 mva=1176.0000 12.0000 0.0730 0.3400 /
    5.5800 0.0000 1.0500 0.7000 0.2770 0.2000 0.1300 0.1700 0.3600 0.0000 /
    0.0000 0.0000
genrou 20 "GAS-LV-NEW  "  24.00 "1 ": #9 mva=200.0000 6.0000 0.0400 0.6000 /
    0.0500 3.0000 0.0000 1.8000 1.7500 0.4000 0.4000 0.2000  0.1600 0.1500 /
    0.3000 0.0000 0.0000 0.0000 0.0000
gensal 15 "PS-HYDRO    "  24.00 "1 ": #9 mva=28.9000 12.0000 0.0730 0.3700 /
    5.5800 0.0000 1.0500 0.7000 0.2770 0.2000 0.1300 0.1700 0.3600 0.0000 /
    0.0000 0.0000
ieeet1 19 "HYDRO-LV-NEW"  24.00 "1 ": #1 0.0500 50.0000 0.0600 1.0000 -0.4000 /
    0.2060 1.6300 0.0200 1.2000 0.0000 2.5000 0.0200 3.6000 0.0400
ieeet1 15 "PS-HYDRO    "  24.00 "1 ": #1 0.0500 50.0000 0.0600 1.0000 -0.4000 /
    0.2060 1.6300 0.0200 1.2000 0.0000 2.5000 0.0200 3.6000 0.0400
hygov  15 "PS-HYDRO    "  24.00 "1 ": #1 mwcap=28.9000 0.0400 0.3100 6.8800 /
    0.0500 0.5000 0.0500 1.0000 0.0000 1.7200 1.4800 0.3000 0.1000 0.0000 /
    0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 /
    0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 1.0000 0.0000 0.0000 /
    0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
epctrb 19 "PS-HYDRO    "  24.00 "1 ": #7 "hygovt.p" 3.0000  "Tg" 0.5000 /
    "Tw11" -1.1700 "Tw12" 0.0000 "Tw22" 1.1700 "Tw21" 0.000  "At" 1.4800 /
    "Dturb" 0.3000 "qnl" 0.1000  "hdam" 1.0000 "Tr" 6.8800   "Tf" 0.0500 /
    "R" 0.0400      "r" 0.3100    "Gmax" 1.0000 "Gmin" 0.0000 "Kd" 0.0000 /
    "Velm" 0.0500
vmetr  19 "HYDRO-LV-NEW"  24.00 "1 ": #9 0.0000
imetr  19 "HYDRO-LV-NEW"  24.00 "1 " 17 "HYDRO-HV-NEW" 230.00  "1 "  1: #9 0.0000
fmetr  19 "HYDRO-LV-NEW"  24.00 "1 ": #9 0.0000
fmetr  15 "PS-HYDRO    "  24.00 "1 ": #9 0.0000
vmetr  15 "PS-HYDRO    "  24.00 "1 ": #9 0.0000
imetr  15 "PS-HYDRO    "  24.00 "1 " 14 "WF-LOW2     "  34.50  "1 "  1: #9 0.0000
vmetr  20 "GAS-LV-NEW  "  24.00 "1 ": #9 0.0000
imetr  20 "GAS-LV-NEW  "  24.00 "1 " 18 "GAS-HV-NEW  " 230.00  "1 "  1: #9 0.0000
fmetr  20 "GAS-LV-NEW  "  24.00 "1 ": #9 0.0000
vmetr  11 "LOAD        " 230.00 "1 ": #9 0.0000
fmetr  11 "LOAD        " 230.00 "1 ": #9 0.0000
vmetr  13 "WF-LOW      "  34.50 "1 ": #9 0.0000
fmetr  13 "WF-LOW      "  34.50 "1 ": #9 0.0000
```

```
Dynamic model table for 3-gen system with T-PSH in pumping mode

gensal 19 "HYDRO-LV-NEW"  24.00 "1 ": #9 mva=1276.0000 12.0000 0.0730 0.3400 /
    5.5800 0.0000 1.0500 0.7000 0.2770 0.2000 0.1300 0.1700 0.3600 0.0000 /
    0.0000 0.0000
genrou 20 "GAS-LV-NEW  "  24.00 "1 ": #9 mva=2400.0000 6.0000 0.0400 0.6000 /
    0.0500 3.0000 0.0000 1.8000 1.7500 0.4000 0.4000 0.2000  0.1600 0.1500 /
    0.3000 0.0000 0.0000 0.0000 0.0000
gensal 15 "PS-HYDRO    "  24.00 "1 ": #9 mva=28.9000 12.0000 0.0730 0.3700 /
    5.5800 0.0000 1.0500 0.7000 0.2770 0.2000 0.1300 0.1700 0.3600 0.0000 /
    0.0000 0.0000
ieeet1 19 "HYDRO-LV-NEW"  24.00 "1 ": #1 0.0500 50.0000 0.0600 1.0000 -0.4000 /
    0.2060 1.6300 0.0200 1.2000 0.0000 2.5000 0.0200 3.6000 0.0400
ieeet1 15 "PS-HYDRO    "  24.00 "1 ": #1 0.0500 50.0000 0.0600 1.0000 -0.4000 /
    0.2060 1.6300 0.0200 1.2000 0.0000 2.5000 0.0200 3.6000 0.0400
exac1  20 "GAS-LV-NEW  "  24.00 "1 ": #9 0.0500 1.0000 1.0000 40.0000 0.1000 /
    5.0000 -5.0000 0.5000 0.2000 1.0000 0.1000 0.6000 1.0000 1.0000 0.0300 /
    2.0000 0.3000
gast   20 "GAS-LV-NEW  "  24.00 "1 ": #9 mva=2400.0000 0.0500 0.5000 0.5000 /
    3.0000 1.5000 3.0000 1.1000 0.0000 0.0000 0.0 /
    99.0000 99.0000 99.0000  99.0000
hygov  15 "PS-HYDRO    "  24.00 "1 ": #1 mwcap=28.9000 0.0400 0.3100 6.8800 /
    0.0500 0.5000 0.0500 1.0000 0.0000 1.7200 1.4800 0.3000 0.1000 0.0000 /
    0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 /
    0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 1.0000 0.0000 0.0000 /
    0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
epctrb 19 "PS-HYDRO    "  24.00 "1 ": #7 "hygovt.p" 3.0000  "Tg" 0.5000 /
    "Tw11" -1.1700 "Tw12" 0.0000 "Tw22" 1.1700 "Tw21" 0.000  "At" 1.4800 /
    "Dturb" 0.3000 "qnl" 0.1000  "hdam" 1.0000 "Tr" 6.8800   "Tf" 0.0500 /
    "R" 0.0400      "r" 0.3100    "Gmax" 1.0000 "Gmin" 0.0000 "Kd" 1.0000 /
    "Velm" 0.0500
vmetr  19 "HYDRO-LV-NEW"  24.00 "1 ": #9 0.0000
imetr  19 "HYDRO-LV-NEW"  24.00 "1 " 17 "HYDRO-HV-NEW" 230.00  "1 "  1: #9 0.0000
fmetr  19 "HYDRO-LV-NEW"  24.00 "1 ": #9 0.0000
fmetr  15 "PS-HYDRO    "  24.00 "1 ": #9 0.0000
vmetr  15 "PS-HYDRO    "  24.00 "1 ": #9 0.0000
imetr  15 "PS-HYDRO    "  24.00 "1 " 14 "WF-LOW2     "  34.50  "1 "  1: #9 0.0000
vmetr  20 "GAS-LV-NEW  "  24.00 "1 ": #9 0.0000
imetr  20 "GAS-LV-NEW  "  24.00 "1 " 18 "GAS-HV-NEW  " 230.00  "1 "  1: #9 0.0000
fmetr  20 "GAS-LV-NEW  "  24.00 "1 ": #9 0.0000
vmetr  11 "LOAD        " 230.00 "1 ": #9 0.0000
fmetr  11 "LOAD        " 230.00 "1 ": #9 0.0000
vmetr  13 "WF-LOW      "  34.50 "1 ": #9 0.0000
fmetr  13 "WF-LOW      "  34.50 "1 ": #9 0.0000
```

```
Dynamic model table for 3-gen system with T-PSH in HSC mode

gensal 19 "HYDRO-LV-NEW"   24.00 "1 ": #9 mva=1276.0000 12.0000 0.0730 0.3400 /
     5.5800 0.0000 1.0500 0.7000 0.2770 0.2000 0.1300 0.1700 0.3600 0.0000 /
     0.0000 0.0000
genrou 20 "GAS-LV-NEW  "   24.00 "1 ": #9 mva=2400.0000 6.0000 0.0400 0.6000 /
     0.0500 3.0000 0.0000 1.8000 1.7500 0.4000 0.4000 0.2000  0.1600 0.1500 /
     0.3000 0.0000 0.0000 0.0000 0.0000
gensal 15 "PS-HYDRO    "   24.00 "1 ": #9 mva=28.9000 12.0000 0.0730 0.3700 /
     5.5800 0.0000 1.0500 0.7000 0.2770 0.2000 0.1300 0.1700 0.3600 0.0000 /
     0.0000 0.0000
ieeet1 19 "HYDRO-LV-NEW"   24.00 "1 ": #1 0.0500 50.0000 0.0600 1.0000 -0.4000 /
     0.2060 1.6300 0.0200 1.2000 0.0000 2.5000 0.0200 3.6000 0.0400
ieeet1 15 "PS-HYDRO    "   24.00 "1 ": #1 0.0500 50.0000 0.0600 1.0000 -0.4000 /
     0.2060 1.6300 0.0200 1.2000 0.0000 2.5000 0.0200 3.6000 0.0400
hygov  15 "PS-HYDRO    "   24.00 "1 ": #1 mwcap=28.9000 0.0400 0.3100 6.8800 /
     0.0500 0.5000 0.0500 1.0000 0.0000 1.7200 1.4800 0.3000 0.1000 0.0000 /
     0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 /
     0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 1.0000 0.0000 0.0000 /
     0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
epctrb 19 "PS-HYDRO    "   24.00 "1 ": #7 "hygovt.p" 3.0000  "Tg" 0.5000 /
     "Tw11" -1.1700 "Tw12" 0.0000 "Tw22" 1.1700 "Tw21" 0.000  "At" 1.4800 /
     "Dturb" 0.3000 "qnl" 0.1000  "hdam" 1.0000 "Tr" 6.8800  "Tf" 0.0500 /
     "R" 0.0400     "r" 0.3100    "Gmax" 1.0000 "Gmin" 0.0000 "Kd" 2.0000 /
     "Velm" 0.0500
vmetr  19 "HYDRO-LV-NEW"   24.00 "1 ": #9 0.0000
imetr  19 "HYDRO-LV-NEW"   24.00 "1 " 17 "HYDRO-HV-NEW" 230.00  "1 "  1: #9 0.0000
fmetr  19 "HYDRO-LV-NEW"   24.00 "1 ": #9 0.0000
fmetr  15 "PS-HYDRO    "   24.00 "1 ": #9 0.0000
vmetr  15 "PS-HYDRO    "   24.00 "1 ": #9 0.0000
imetr  15 "PS-HYDRO    "   24.00 "1 " 14 "WF-LOW2     "  34.50  "1 "  1: #9 0.0000
vmetr  20 "GAS-LV-NEW  "   24.00 "1 ": #9 0.0000
imetr  20 "GAS-LV-NEW  "   24.00 "1 " 18 "GAS-HV-NEW  " 230.00  "1 "  1: #9 0.0000
fmetr  20 "GAS-LV-NEW  "   24.00 "1 ": #9 0.0000
vmetr  11 "LOAD        "  230.00 "1 ": #9 0.0000
fmetr  11 "LOAD        "  230.00 "1 ": #9 0.0000
vmetr  13 "WF-LOW      "   34.50 "1 ": #9 0.0000
fmetr  13 "WF-LOW      "   34.50 "1 ": #9 0.0000
```