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Update on Model Specification Development of Ternary Pumped Storage Technologies

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5/9/2025

For WECC Model Validation Subcommittee Meeting

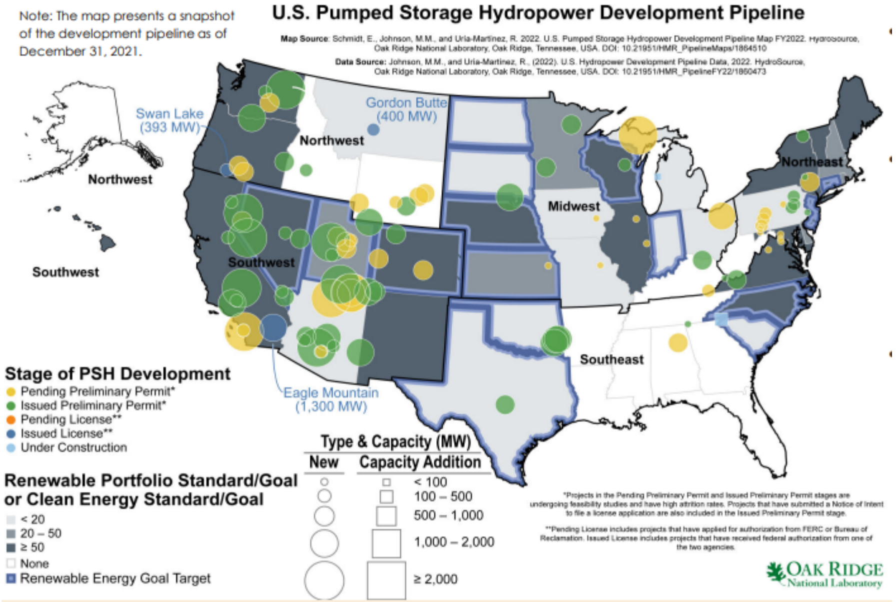
Photo by Dennis Schroeder, NREL 55200

Background

"Renewed interest in PSH development started in the late 2000s and resulted in an increased number of preliminary permit applications to FERC."

"At the end of 2021, there were **~100 PSH projects** in the FERC development pipeline; most of them are requesting or holding preliminary permits to conduct feasibility evaluation studies."

"New projects seek to complement variable renewables and provide not **only peaking energy** but also **capacity and grid services** (e.g., frequency regulation). "(FERC Order 841(2018))



Rocío Uría-Martínez, etc. "Overview of U.S. PSH fleet and development pipeline", https://westernstateswater.org/wp-content/uploads/2023/01/Pumped-Storage-101-Deck-A.pdf

Acknowledgment

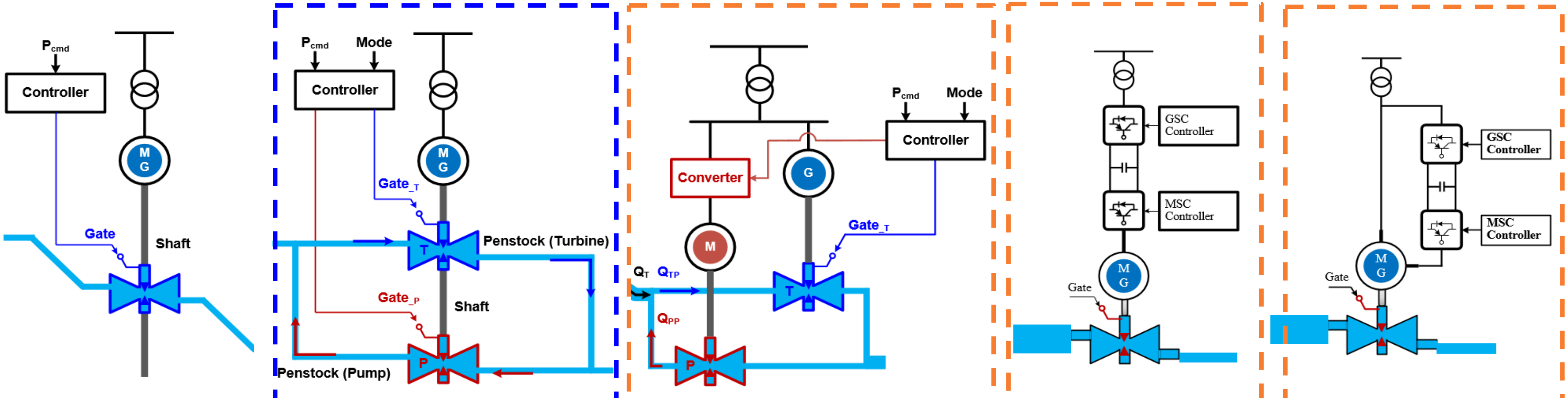
This specification development builds upon T-PSH modeling work funded by the DOE Water Power Technologies Office (WPTO), particularly the project "*Transforming the U.S. Market with a New Application of Ternary-Type Pumped-Storage Hydropower Technology*" (2017–2019).

Additionally, we will leverage "Mitigation of Modeling Gaps" project funded by DOE WPTO (2025–2028), to support future model development. Furthermore, we appreciate insights from the "*Improving Pumped Storage Valuation for Complex Vertical Utilities*" project and the "*Balancing Energy and Reliability with Craig-Hayden Pumped Storage Hydropower*" project, recognizing their valuable discussion and vendor feedback and inputs.

Types of Pumped Storage Hydro Technologies

Pumped Storage Power Plant

- Fixed Speed
- Hybrid
- Variable Speed



Reversible Pump Turbine	Ternary Set	Quaternary Set	Variable-Speed Full Converter	Variable-Speed Doubly-Fed Motor Generator
	Objective 1 (By 6/30/2025)	Objective 3	Objective 2 (By 9/30/2025)	Objective 4

[Source: Jinko Kim, Auburn University]

Progress and Timeline

- Finished outline of "Development of Model Specification for the Generic WECC Model of Ternary Pumped Storage Technologies" (by 7/30/2024)
- Finish the 1st draft of the "Development of Model Specification for the Generic WECC Model of Ternary Pumped Storage Technologies" (12/30/2024)

- 1st draft and outline is under review by hydro turbine vendors (GE) and by software vendors including (PSLF (mengxi), PSSE (Jay), PowerTech (Howell), Power World (Weber)) etc.(by 4/30/2025)

- Received feedback from PowerTech, and we plan to collect and address all the feedback and comments. (ongoing, by 5/31/2025)

- Based on the last meeting's feedback, we are working on revising the hydro governor model from HYGOV to H6E. (ongoing, plan to be finished by 5/31/2025)

[PSH specification_v2.docx]

Table of Contents

T-PSH Turbine Model Upgrade: HYGOV → H6E

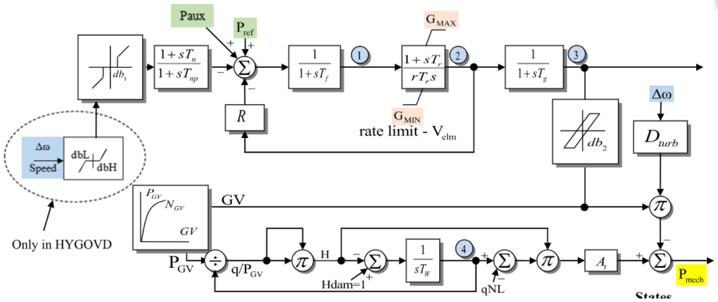
Updates we have done:

1. A gate-power nonlinear curve.
2. PID speed control.

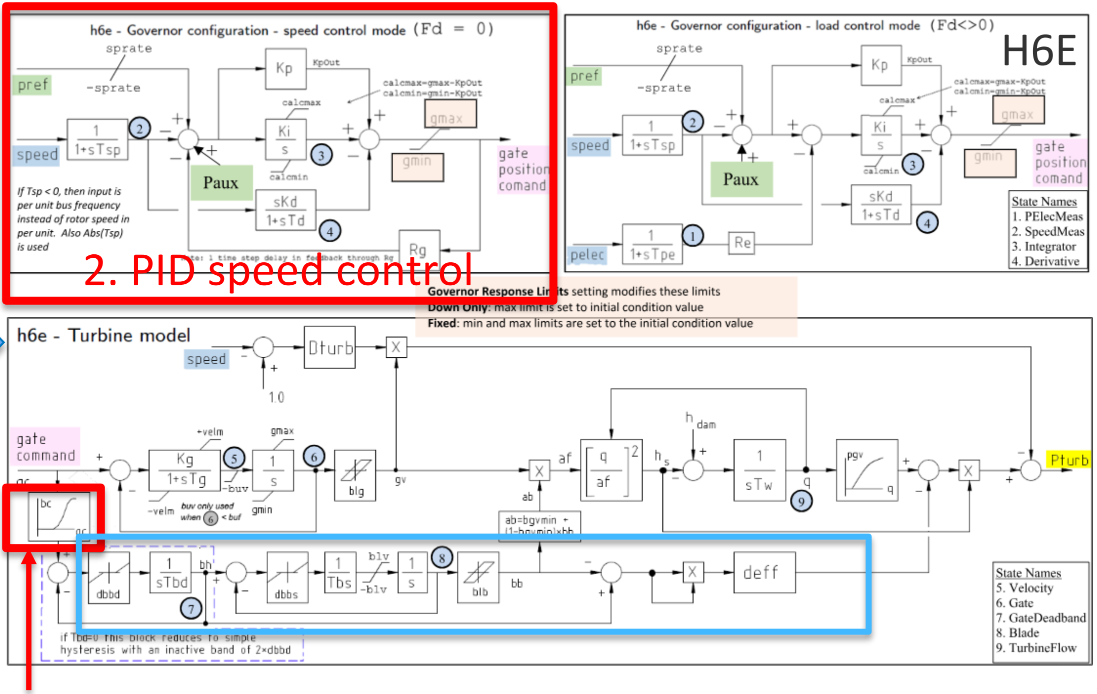
Next step:

1. Work on turning the parameters
2. Work on the blue block.

HYGOV Model



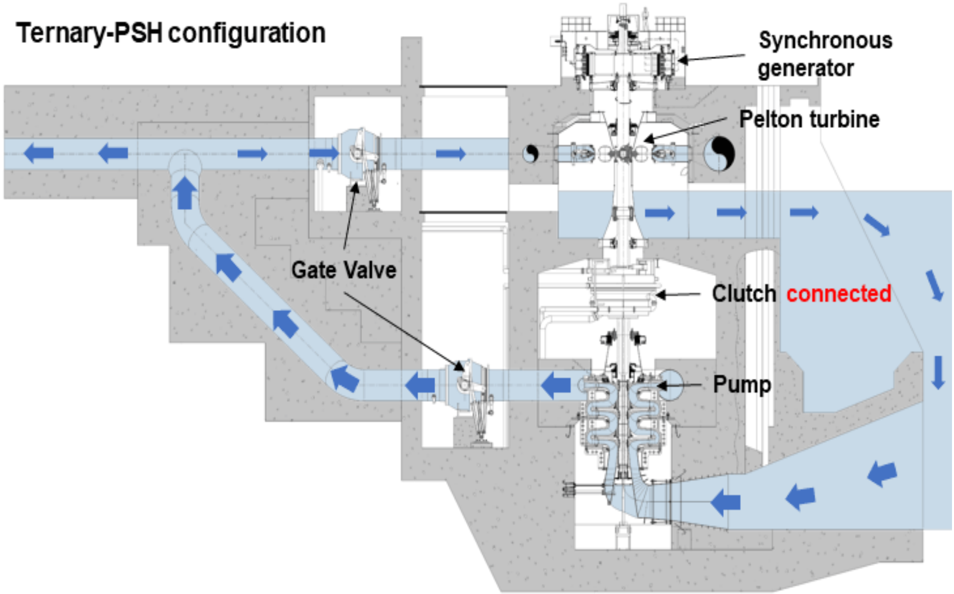
H6E Model



1. Gate-power nonlinear curve

Ternary Pumped Storage Hydro

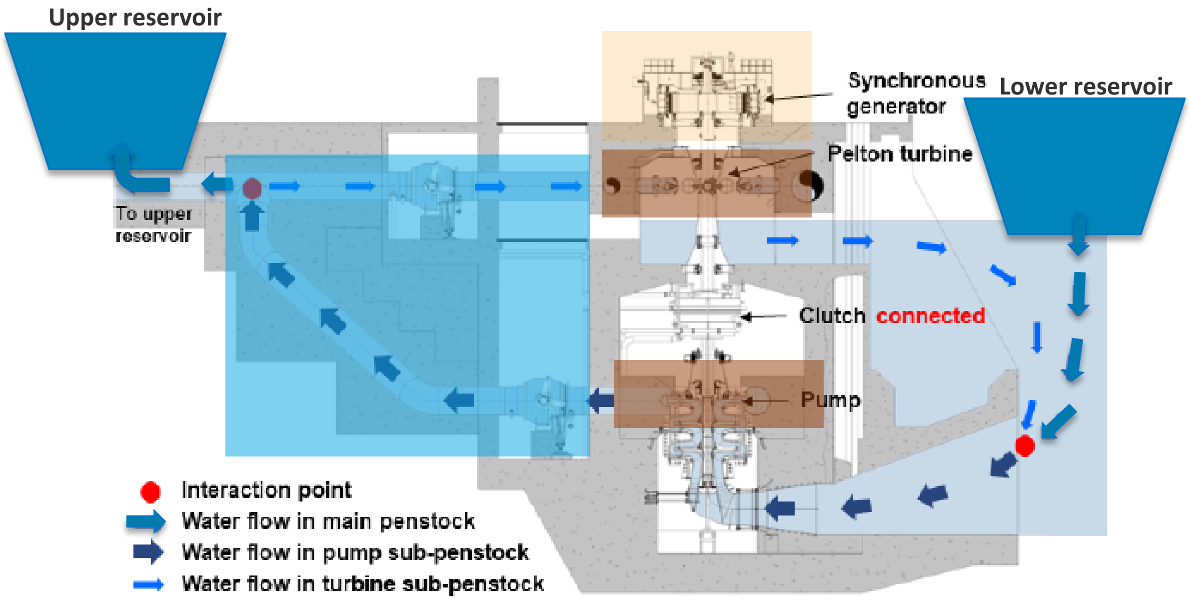
- The fastest-acting and advanced pumped storage hydropower (PSH) system available today
- Separate Pelton turbine, motor-generator and multi-stage pump stacked on a single shaft
- Continuously rotating in a single direction
- Technology commissioned at Kops II facility in Austria – 2008
- Can move quickly from pumping to generating at an estimated 20–40 MW/second



Hydraulic-short circuit mode (HSC)

Source: GE Renewable Energy

Configuration and Modeling



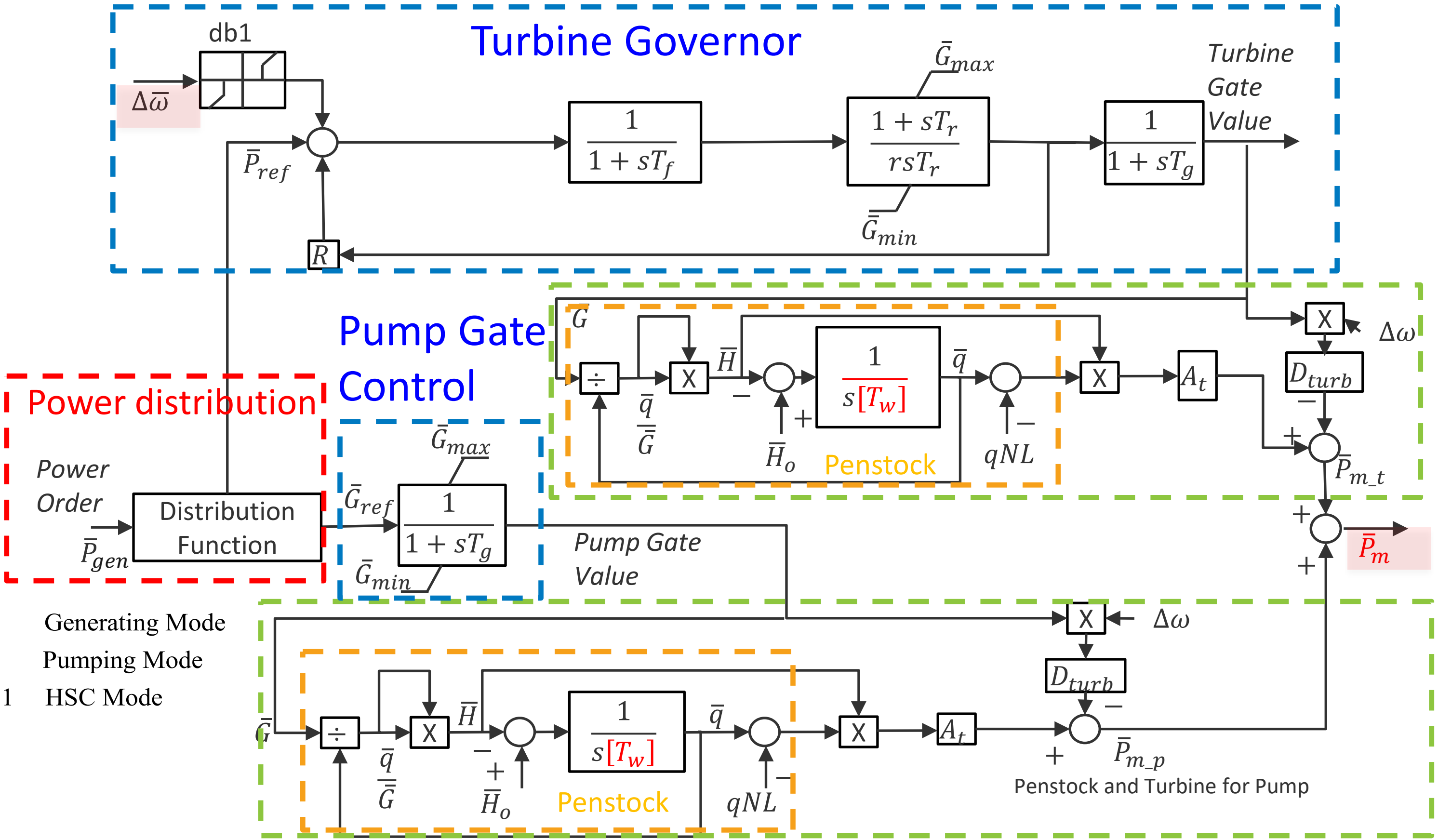
Modified figure based on GE Renewable Energy

Modeling

- Full dynamic Model=GENSAL+IEEET1+ User-defined Governor and Turbine Model
- Simulate three operation modes in one model and switch among different modes seamlessly.

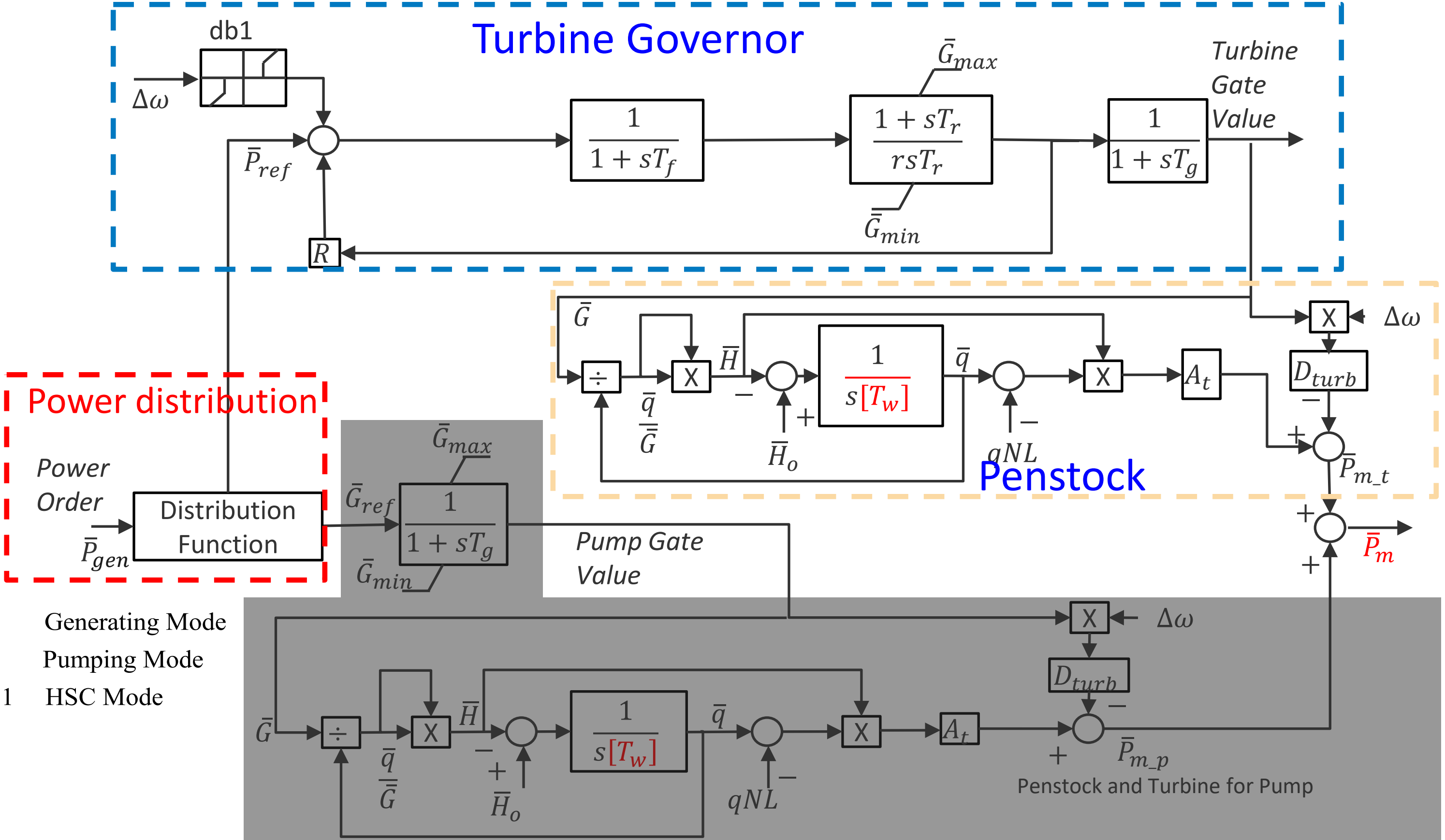
- This specification focuses on the **governor and turbine model**, **shared penstock model**, and the **control model for three operational modes (generating, pumping, and hydraulic short-circuit)** of the T-PSH system.

User-defined Dynamic Governor-turbine Model



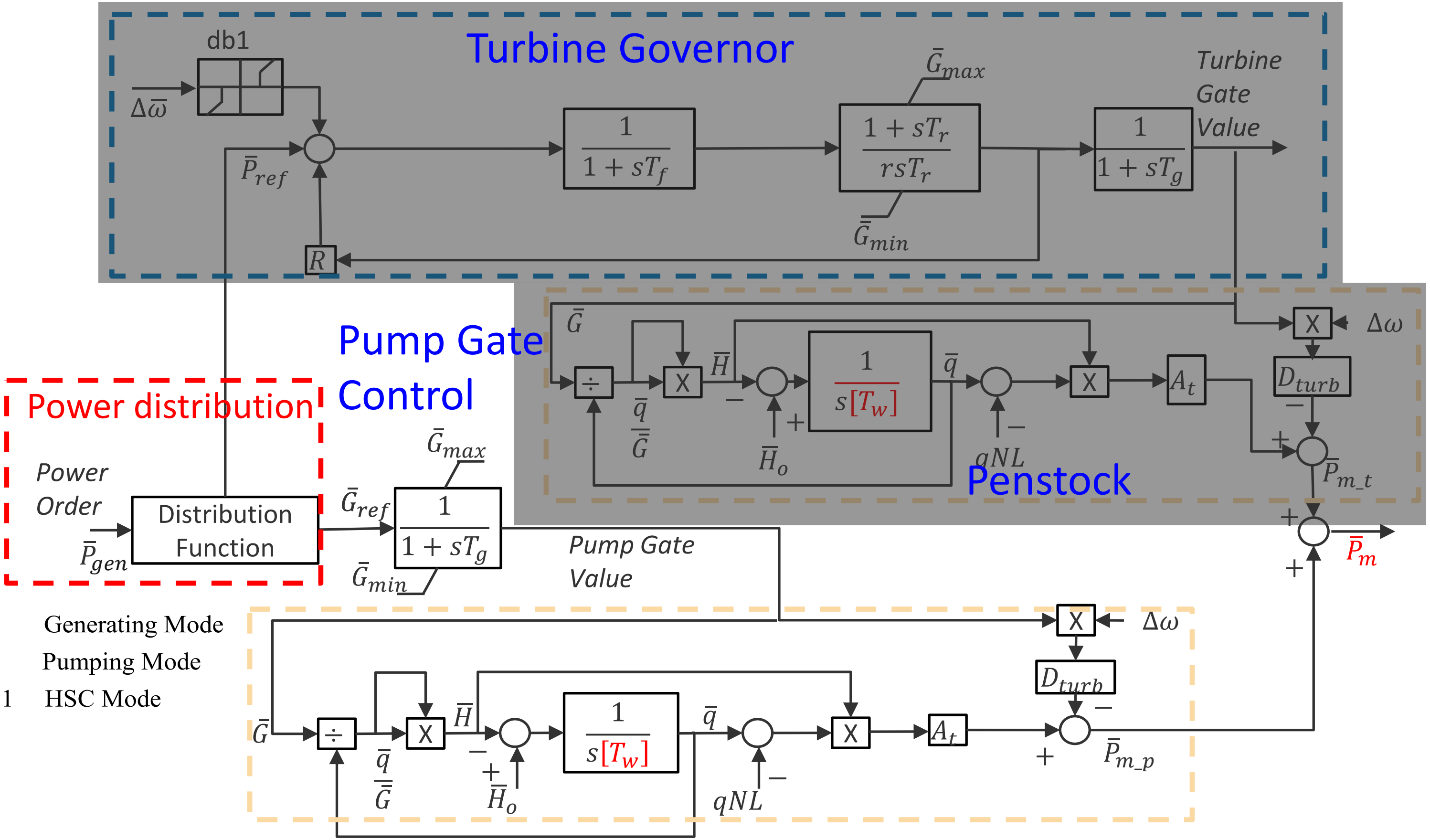
$$K_d = \begin{cases} 0 & \text{Generating Mode} \\ 1 & \text{Pumping Mode} \\ >1 & \text{HSC Mode} \end{cases}$$

Generating Mode



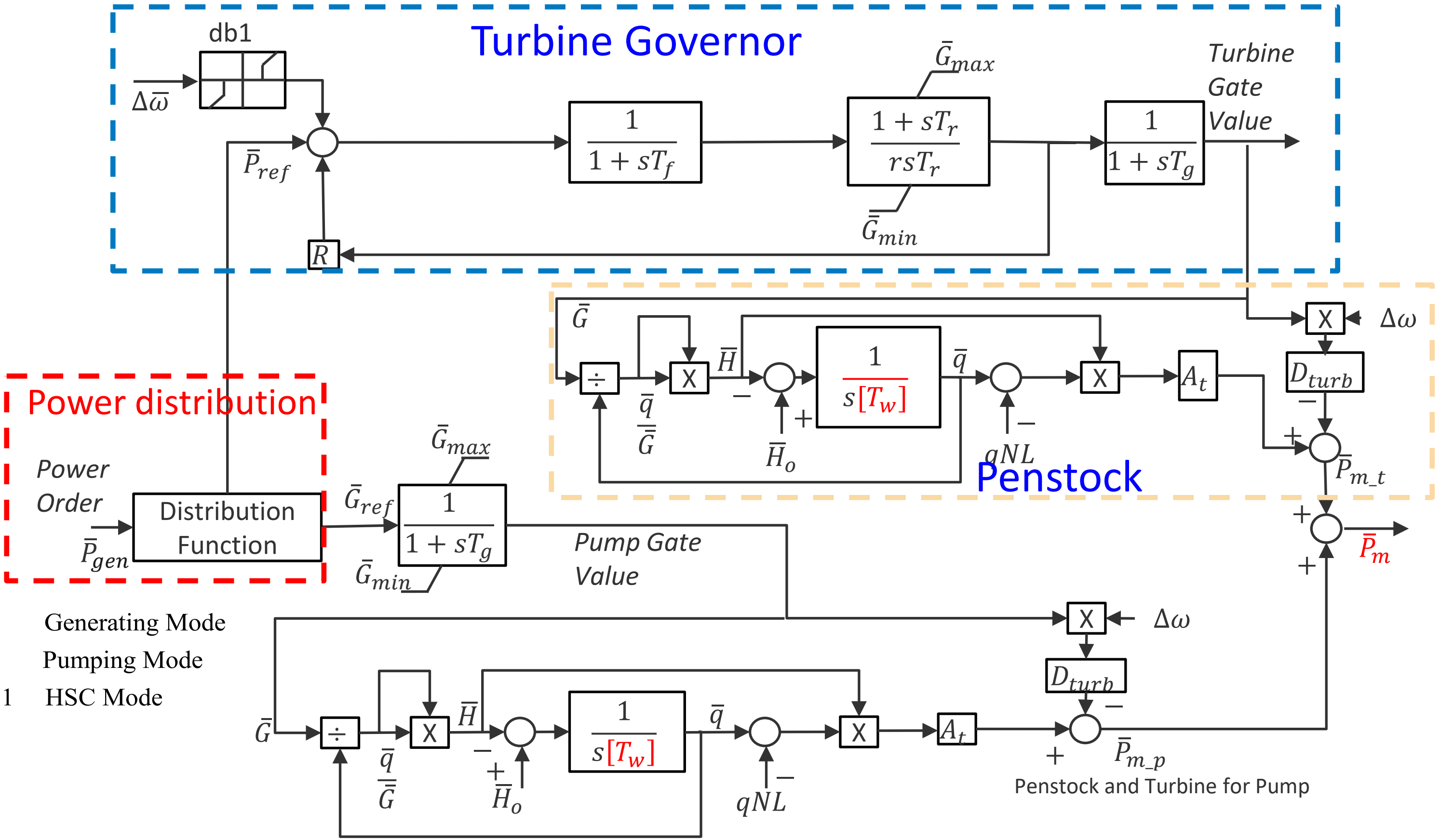
$$K_d = \begin{cases} 0 & \text{Generating Mode} \\ 1 & \text{Pumping Mode} \\ >1 & \text{HSC Mode} \end{cases}$$

Pumping Mode



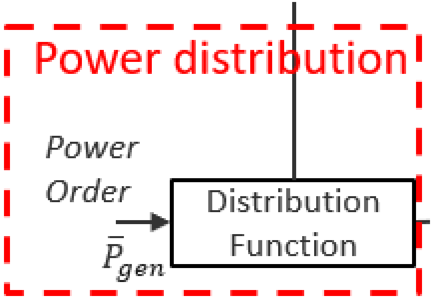
$$K_d = \begin{cases} 0 & \text{Generating Mode} \\ 1 & \text{Pumping Mode} \\ >1 & \text{HSC Mode} \end{cases}$$

Hydraulic Short-Circuit Mode



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

Three Control Modes



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

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

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

K_d	$\bar{P}_{ref}$(pump)	$\bar{G}_{ref}$(turbine)	Pm (Steady state)	Modes
0	0	$\lvert\bar{P}_{gen}\rvert$	$\lvert\bar{P}_{gen}\rvert$	Generating
1	-$\lvert\bar{P}_{gen}\rvert$	0	-$\lvert\bar{P}_{gen}\rvert$	Pumping
K_d>1	$-K_d \times \lvert\bar{P}_{gen}\rvert$	(K_d-1)× $\lvert\bar{P}_{gen}\rvert$	-$\lvert\bar{P}_{gen}\rvert$	Hydraulic short circuit

Operation Mode Controller

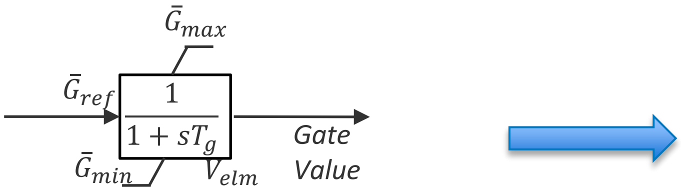
A **distribution coefficient K_d** is specified through the power distribution block.

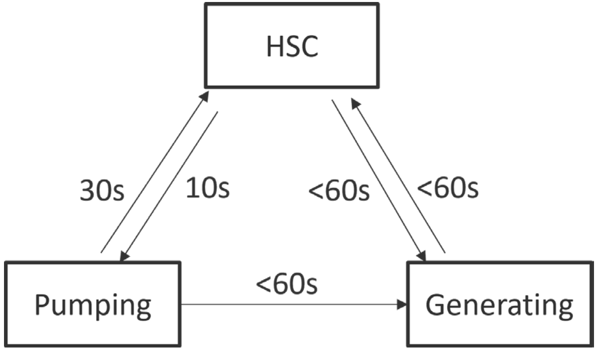
$$K_d = \begin{cases} 0 & Generating\ Mode \\ 1 & Pumping\ Mode \\ > 1 & HSC\ Mode \end{cases}$$

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

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

A **transition time control parameter V_{elm}** control the time spent for the injector to open from 0% to 100% per unit.





Input and Output Channels and Parameters

Input Channel	Symbol	Description
IC0	K_d	Operation modes coefficient: 0 in generating mode, 1 in pumping mode, 2 in HSC mode
IC1	P_{order}	Power order for the entire T-PSH system, MW.
IC2	$\bar{G}_{ref}$	Power order for the pump's hydraulic turbine and governor system, MW.
IC3	$\bar{P}_{ref}$	power reference for the turbine's hydraulic turbine and governor system, MW.
IC4	$\Delta\bar{\omega}$	frequency error from the grid

Output Channel	Symbol	Description
OC0	$\bar{G}_t$	Turbine gate value, pu
OC1	$\bar{G}_P$	Pump gate value, pu
OC2	$\bar{P}_m$	mechanical power output of the T-PSH system, MW
OC3	$\bar{P}_{m\_p}$	mechanical power output from the pump, MW
OC4	$\bar{P}_{m\_t}$	mechanical power output from the turbine, MW
OC5	$\bar{\omega}$	Speed, pu

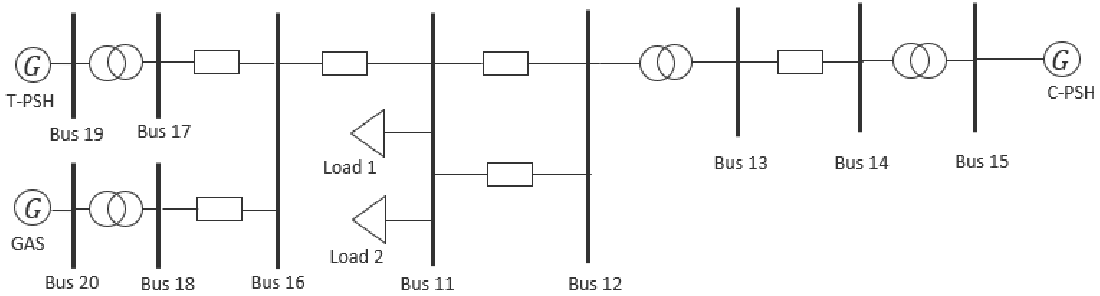
Parameters

Parameter	Symbol	Description	Example Value
V0	Tg	Gate servo time constant, s.	0.5
V1	Tw11	Water time constant for the entire penstock length of the pump part, s.	-1.17
V2	Tw12	Water time constant for the shared-penstock length from the pump part to the turbine part, s.	0.43
V3	Tw22	Water time constant for the entire penstock length of the generator part, s., s.	1.17
V4	Tw21	Water time constant for the shared-penstock length from the turbine part to the pump part, s.	0.43
V5	At	Turbine gain, pu	1.48
V6	Dturb	Turbine damping factor, pu	0.3
V7	qnl	No-load flow at nominal head, pu	0.1
V8	hdam	Head available at dam, pu	1
V9	R	Permanent droop (R), pu	0.04
V10	r	Temporary droop (r), pu	0.31
V11	Tf	Filter time constant, s.	0.05
V12	Tr	Washout time constant, s.	6.88
V13	Gmax	Maximum gate opening, pu of mwcap	1
V14	Gmin	Minimum gate opening, pu of mwcap	0
V15	Kd	Operation mode distribution coefficient	0—generating mode 1—pumping mode 2—HSC mode
V16	Velm	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
V17	db1	intentional deadband	
V18	db2	Unintentional deadband	

Model Simulation

Test system: 3-gen Small System

In this system, there are three voltage levels, 24 kV, 34.5 kV and 230 kV. The test T-PSH unit is placed on Bus 19; a gas turbine and a C-PSH unit are placed on Bus 20 and Bus 15.



Test event:

1. Performance of T-PSH under Different Events
   a. Dynamic response of T-PSH in generating mode
   b. Dynamic response of T-PSH in pumping mode
   c. Dynamic response of T-PSH in HSC mode
2. Operation Mode Switching
   a. Dynamic response of T-PSH in operation mode switching

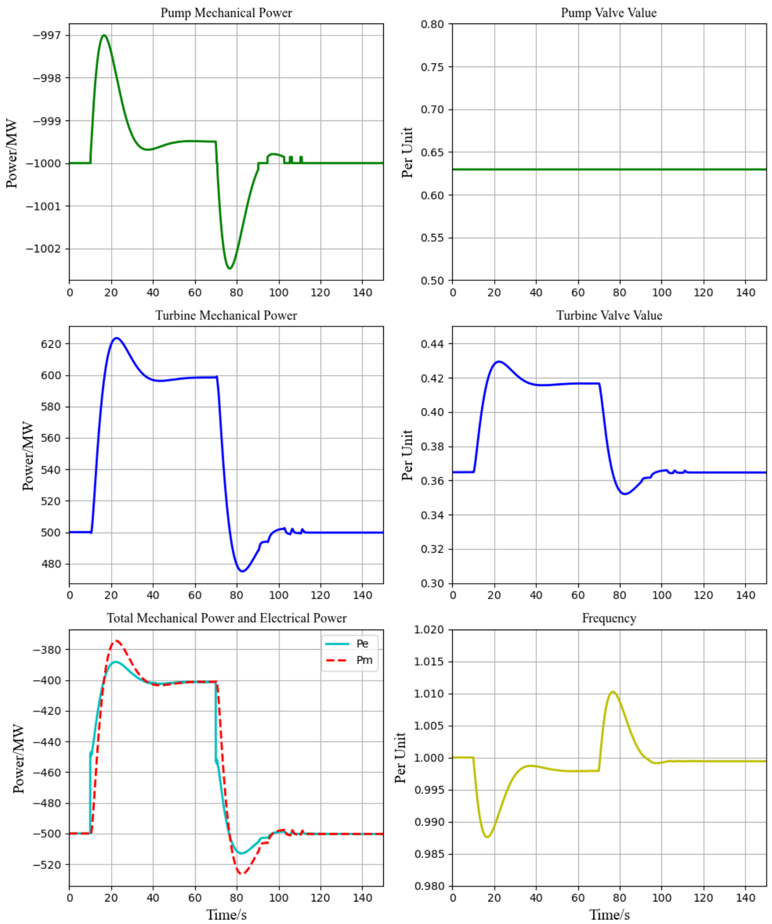
Case 3: T-PSH in HSC mode

T-PSH is pumping 500MW at HSC mode. The valve velocity is 1/20 p.u./s.

- t=10s, add load 2 (100 MW)
- t=70s, trip load 2 (100 MW)

Observation:

- Turbine governor adjust the valve reference to let mechanical power output meet the power demands.
- Pump part kept the power output constant.
- Small variance in the mechanical power of pump output caused by the frequency fluctuation.



Your feedback, suggestions, and contributions are invaluable. Let's collaborate!

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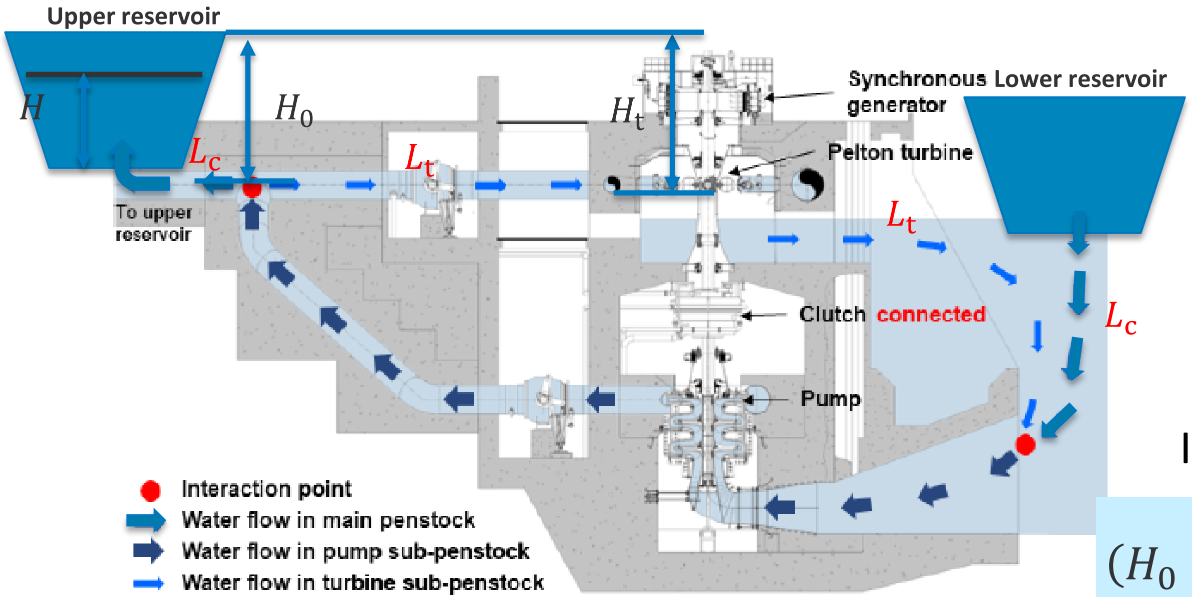
Shared Penstock and Turbine Model for Turbine



Newton's law of motion

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

$$\frac{dq}{dt} = \frac{gA}{L}(H_0 - H)$$

$$q = q_p - q_t$$

In the first interaction point

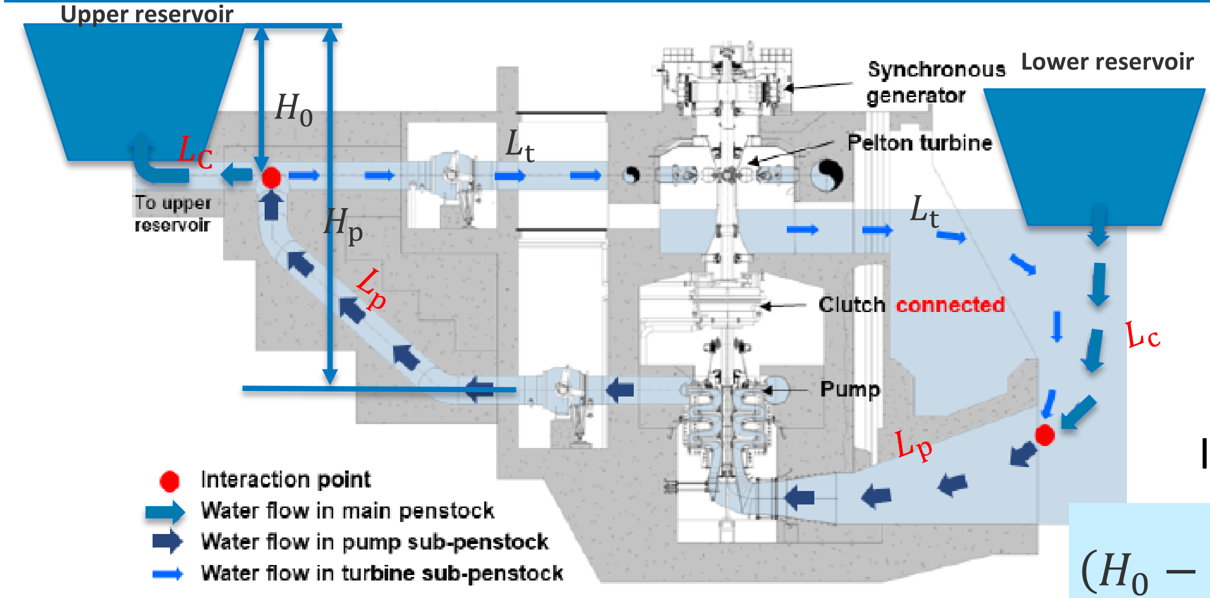
$$(H_0 - H) = -\frac{L_c}{gA_c}\left(\frac{dq_p}{dt} - \frac{dq_t}{dt}\right)$$

Turbine part secondary penstock

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

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

Shared Penstock and Turbine Model for Pump



Newton's law of motion

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

$$\frac{dq}{dt} = -\frac{gA}{L}(H_0 - H)$$

$$q = q_p - q_t$$

In the first interaction point

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

Pump part secondary penstock

$$(H - H_p) = -\frac{L_p}{gA_{pp}} \frac{dq_p}{dt}$$

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

Shared Penstock and Turbine Model

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

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

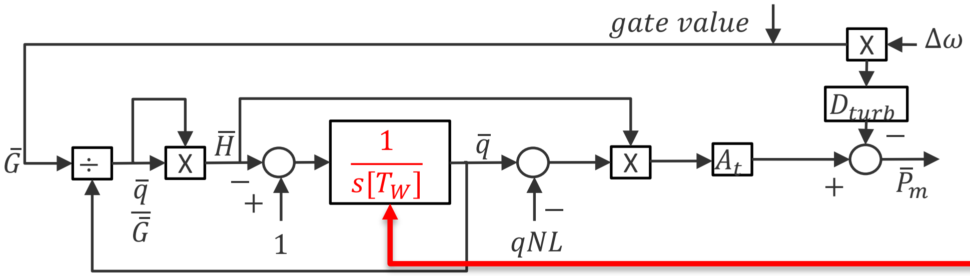
$$T_{w\_tt} = \frac{q_{base}}{H_{base}}\left(\frac{L_t}{gA_t} + \frac{L_c}{gA_c}\right) \quad T_{w\_tp} = -\frac{L_c}{gA_c}\frac{q_{base}}{H_{base}}$$

$$T_{w\_pp} = -\frac{q_{base}}{H_{base}}\left(\frac{L_p}{gA_p} + \frac{L_c}{gA_c}\right) \quad T_{w\_pt} = \frac{L_c}{gA_c}\frac{q_{base}}{H_{base}}$$

Normalize With q_{base} H_{base}

Second Order Shared Penstock Matrix

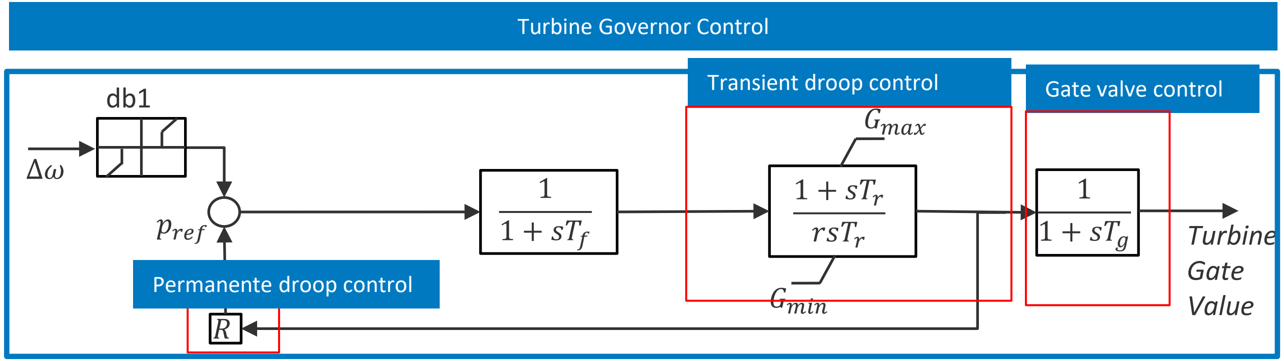
$$\begin{bmatrix} T_{w\_tt} & T_{w\_tp} \\ T_{w\_pt} & T_{w\_pp} \end{bmatrix}\begin{bmatrix} \frac{d\bar{q}_t}{dt} \\ \frac{d\bar{q}_p}{dt} \end{bmatrix} = \begin{bmatrix} \Delta\bar{H}_t \\ \Delta\bar{H}_p \end{bmatrix}$$

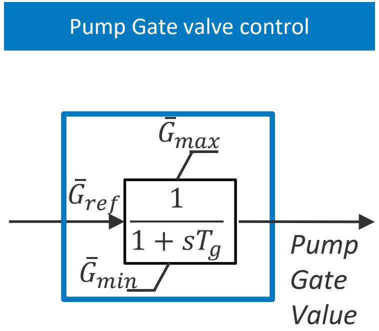


$$\begin{bmatrix} \bar{q}_t \\ \bar{q}_p \end{bmatrix} = \frac{1}{s[T_W]}\begin{bmatrix} \Delta\bar{H}_t \\ \Delta\bar{H}_p \end{bmatrix}$$

Governor Modeling in Turbine Mode and Pump Mode

- **Permanente droop control**: The basic function to control speed and/or load.
  - involves feeding back speed error to control the gate position.
- **Transient (temporary) droop control** : Hydro turbines have a peculiar response due to water inertia: a change in gate position produces an initial turbine power change which is opposite to that sought.
  - a large transient (temporary) droop with a long resetting time is required
- **Gate valve control**: In the real gate valve for the Pelton turbine, there are two mechanical devices to control the water flow
  - injector and deflector





$$\bar{G} = \frac{T_r s + 1}{rT_f T_r s^2 + RT_r s + rT_r s + R}\left(\frac{1}{1+T_g s}\right)\Delta\omega$$

$$\bar{G} = \left(\frac{1}{1+T_g s}\right)(G_{ref})$$