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Power System Resiliency Enhancement with Ternary Pumped – Storage Hydropower

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Abstract: This paper investigates, how Ternary Pumped Storage Hydropower (T-PSH) can help enhance power system resiliency by contributing primary frequency regulation in both pumping and generating modes. As renewable penetration increases, power system inertia decreases. Simultaneously, the frequency of storms and earthquakes have increased. As such power system resiliency is a key issue in low inertia power systems. To cater to this issue, the authors investigate the ability of T-PSH to provide primary frequency support in pumping and generating mode. The governor dynamics of the IEEE 9-bus system and T-PSH have been modeled and integrated. When the system is subjected to a step increase or decrease in load, results display that not only can the T-PSH provide pump mode regulation using the hydraulic short-circuit, but it can also transit smoothly between pumping and generating mode within a few seconds using the clutch. By changing its mode, the T-PSH unit can provide a regulation capability equal to twice that of the unit rating.

Keywords: energy storage, pumped storage hydro, ternary pumped storage hydro, dynamic simulation, dynamic modeling, inertia, renewable energy, power system.

1. INTRODUCTION

The development of mankind requires enormous but crucial amounts of energy. Primitively, this energy has been derived from fossil-fuel based natural resources. However, environmental awareness among the nations has considerably increased, leading to a rapid growth of renewable energy. Although renewable energy is beneficial for our planet, harnessing the same with existing infrastructure possesses certain challenges that need to be dealt with. This paper looks at power system resiliency as the issue and suggests ternary pumped-storage hydro (T-PSH) as a remedy. Through simulations of different events, the authors show that the T-PSH is ahead of its primitive alternative, the conventional PSH (C-PSH).

Power system resiliency and reliability are subtly different. Reliability reflects and idea that the light must be on in a consistent manner. This is a binary view of system performance where the system is either functional or failed. Reliability is generally measured by interruption indices such as *load not served*. Resiliency is the ability of the system to recover itself after a disruptive event. A more resilient system will experience disruptive events of lesser magnitude and/or duration. Resilience can thus be thought of an idea of the system existing in the space between functional and failed. Resiliency enhancement builds upon the fact that, disruptive events cannot be predicted with completely certainty but when they do occur, the system should adapt and recover (Clark, 2016). Resiliency indices are currently under development.

With the increase of renewable energy penetration, system inertia is decreasing as renewable energy displaces synchronous generators from the schedule. The retirement of aging or polluting fossil-fuel based gas or coal plants could also be a reason of further decrease of system inertia. Removing synchronous generators from the schedule also results in removal of the associated primary and secondary frequency regulation services provided by these units, which further worsens the situation. With the growing frequency of storms and earthquakes (Centre for Climate and Energy Solutions, 2019) and decreasing power system inertia, power system inertial resources and primary frequency resources become a key requirement for network stability.

C-PSH is the most widely used PSH technology around the world. However, to suit low inertia power systems, C-PSH is not sufficient. Much work has been dedicated to the portfolio expansion of PSH which have resulted in the development of adjustable speed – PSH (AS-PSH) (Nag and Lee, 2018) and Ternary – PSH. These developments are mainly aimed at providing the required power system flexibility.

The remaining part of this paper is divided into three sections. Section 2 describes T-PSH and its advantages over C-PSH. Section 3 presents the mathematical modelling of the T-PSH and section 4 presents the results of the studies performed on the system namely, step increase and decrease of load. Section 4 also mentions the sequence of clutch and valve operations for mode change.

2. TECHNOLOGY DESCRIPTION

The T-PSH is a fixed speed system that uses a synchronous machine. The three main components of the T-PSH are the synchronous machine, the turbine and the pump (Koratirov and Guzowski, 2013). The T-PSH is unique in its construction as the turbine and pump share the same shaft as that of the synchronous machine. A clutch disconnects the pump and the turbine. Fig. 1 shows a schematic of the T-PSH. Having both pump and turbine on the same shaft makes the direction of rotation of the pump and the turbine the same. Also, the turbine and the pump share the same penstock, which means that the unit can either be operating as a pump or a turbine at any instant.

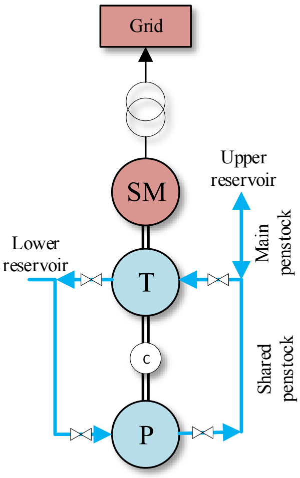


Fig. 1. Functional diagram of T-PSH.

SM=synchronous machine, T=turbine and P=Pump.

Another unique structural feature of the T-PSH is the hydraulic short-circuit (HSC). With the HSC, a part of (or all) the water pumped by the pump is transferred to the turbine by opening the turbine inlet via the governor. The clutch connects the turbine and pump. This in turn causes the turbine to produce torque that is supplied to the shaft. This mechanical torque from the turbine will reduce the current drawn from the grid while still rotating at the synchronous speed. The remaining part of the water is pumped up to the upper reservoir.

Table 1. Advantages of T-PSH over C-PSH

	CPSH	TPSH
Pump-mode regulation	Completely incapable	Fully capable with hydraulic short-circuit
Time required for Mode change	In the order of minutes	In the order of seconds
Design optimization and efficiency	Poor partial-load efficiencies in the generating mode as pump-turbine is optimized primarily for pumping.	Having a separate pump and a separate turbine allows optimization of each with separate objectives and hence a much-improved partial-load efficiency is observed.

The hydraulic short circuit takes advantage of the fact that the head generated by the pump is either equal or greater than that of the upper reservoir at any instant of its operation as long as the pump rotates at synchronous speed. The turbine being connected right next to the pump experiences the pump generated head, which is in fact the rated head of the turbine, which enables it to generate power. A few notable advantages of T-PSH are listed in Table 1.

3. DYNAMIC MODELLING

The dynamic model of the T-PSH is displayed in Fig. 2 which has been constructed with subparts from Demello et al. (1992). A PIDGOV governor has been implemented to control the turbine and respond to system frequency deviations. The flow dynamics, assuming non-linear non-elastic water column, can be used to describe the relation between head and discharge.

$$\frac{dq_t}{dt} = \frac{H_t - h - h_l}{T_w} \tag{1a}$$

$$\frac{dq_p}{dt} = \frac{-[H_p - h - h_l]}{T_w} \tag{1b}$$

Where H_t, H_p, h, and h_l define the available head for the turbine, generated head by the pump, head at turbine entrance head loss due to friction as $h_l = f_p Q^2$, and T_w is the water starting time constants to accommodate the interaction between the turbine and pump, or vice versa. Since the turbine and pump are connected, it is required that we consider the interaction between the two. This can also be found in Demello et al. (1992), as the team described plants with multiple units. Collectively, the hydraulic dynamics for the pump and turbine and their mutual connection can be given by (1):

$$\begin{bmatrix} Tw_{tt} & Tw_{tp} \\ Tw_{pt} & Tw_{pp} \end{bmatrix} \begin{bmatrix} \frac{dq_t}{dt} \\ \frac{dq_p}{dt} \end{bmatrix} = \begin{bmatrix} \Delta h_t \\ \Delta h_p \end{bmatrix} \tag{2}$$

Here Tw_{tt}, Tw_{tp}, Tw_{pp}, Tw_{pt} are the water starting time constants to accommodate the interaction between the turbine and pump or vice versa. Where the discharge and the head for the turbine is given by

$$q_t = G\sqrt{h} \tag{3}$$

where G is the turbine gate and h is the head at turbine inlet. Similar representation for the pump can also be done.

The power output from the turbine or input to the pump is given by:

$$P_m = A_t h\ (q - q_{nl}) - DG\Delta\omega \tag{4}$$

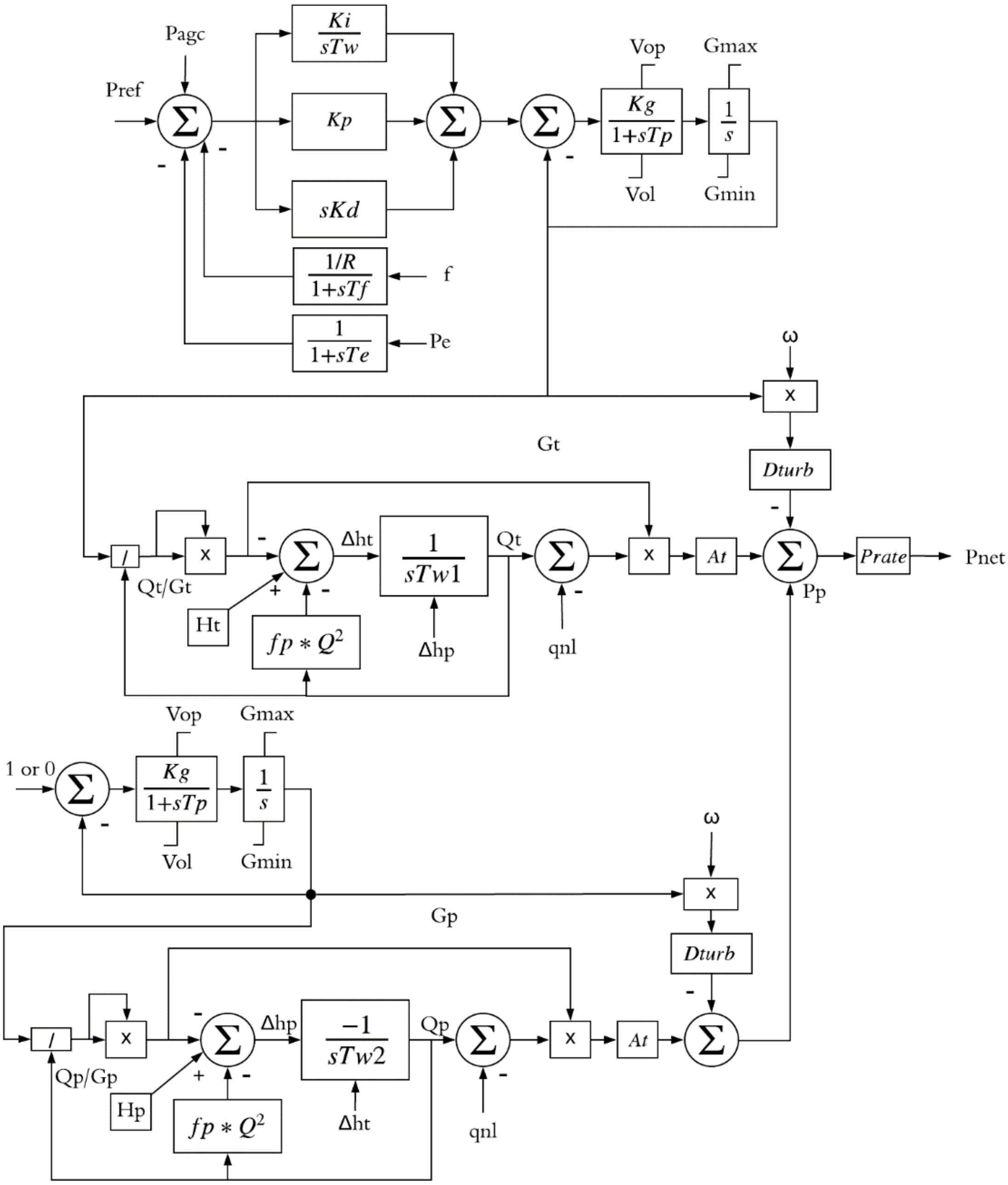


Fig. 2. Dynamic model of T-PSH.

Finally, the power from the turbine and pump are summed up to give the net output power:

$$P_{shaft} = P_t + P_p \tag{5}$$

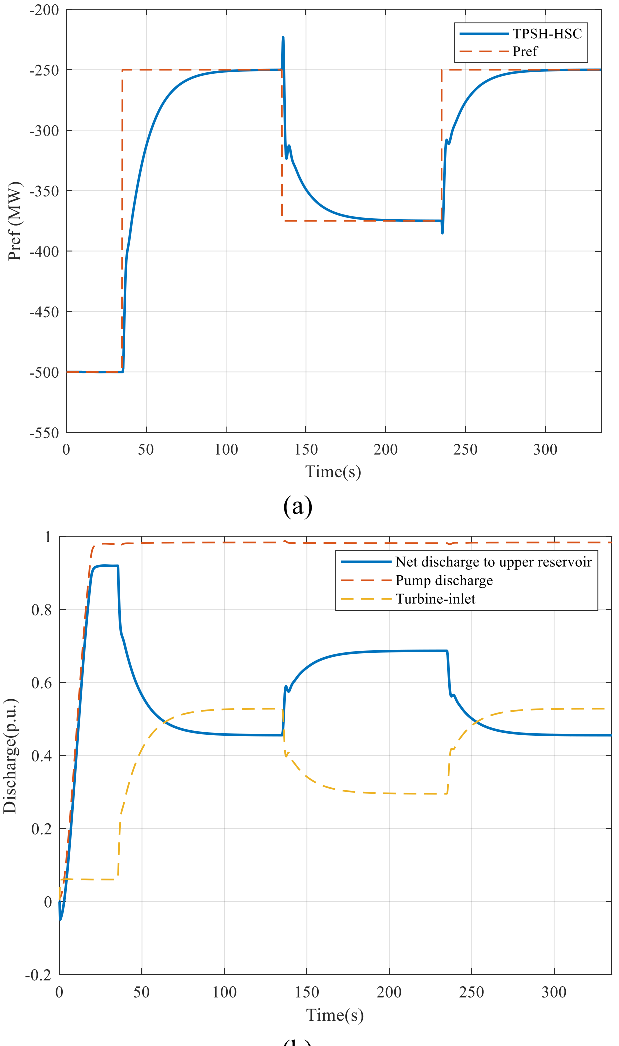
The head and discharge immediately at the pump outlet is given by:

$$H_p = [H_0 + H_1(q) + H_2(q)^2](1+\Delta\omega)^2 \tag{6}$$

where H_0, H_1, and H_2 are coefficients for relating discharge and head.

4. RESULTS AND DISCUSSION

The model described above was integrated to the IEEE 9-bus system. The thermal plants were equipped with IEEET1 governors. One of the thermal plants were replaced by a fixed output generator which represented a PV farm of equivalent capacity. The differential equations for the system were solve using a Runge Kutta 4 numeric differential equation solver (Judah, S., 2014). The entire system was simulated on a MATLAB platform.



(a)

(b)

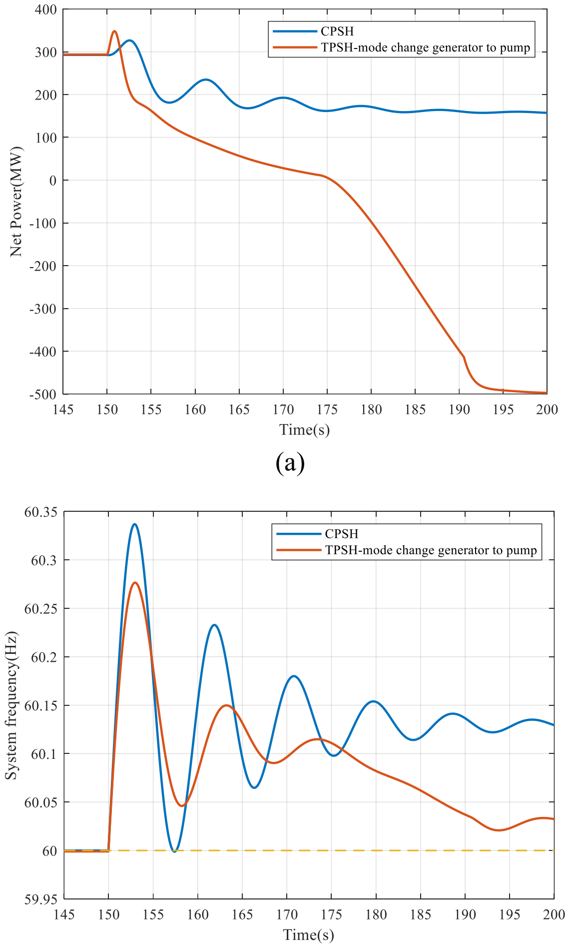
Fig. 3. (a) Pump mode power reference tracking with hydraulic short circuit, (b) Water flow distribution.

4.1 Reference Tracking in Hydraulic Short Circuit Mode

To realize the benefits of the hydraulic short circuit that is facilitated by the structure of the T-PSH, several set-points were tracked as can be seen in Fig. 3 (a). The results clearly display the expected reverse characteristics of the turbine governor system. As discussed before, the discharge from the pump is divided into two parts when the hydraulic short circuit is in use. Fig. 3 (b) shows the same results. Since shaft rotates at a constant speed, the pump's discharge remains constant. However, the turbine inlet flow varies as the power reference to its governor is changed. This results in the variation in the net flow to the upper reservoir.

4.2 Mode Change Capability

To display the mode change capability of the model, a load trip event and a load addition event were simulated. For the load trip event, the T-PSH plant was initially set to work as a generating unit with its pump as idle. Later, as the disturbance occurs the plant changes its mode from generating mode to pumping mode as displayed in Fig. 4 (a) within 45 seconds. As a result of which, the primary

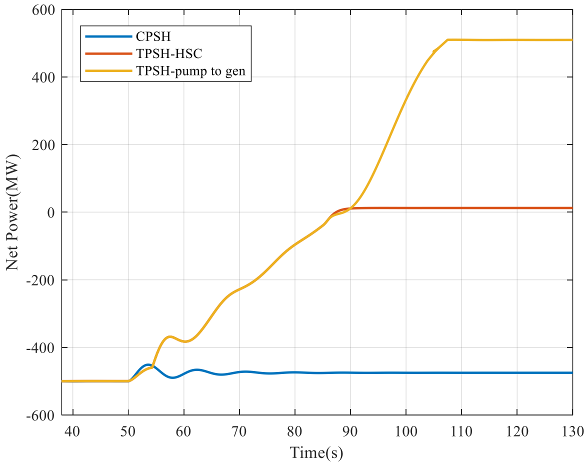


(a)

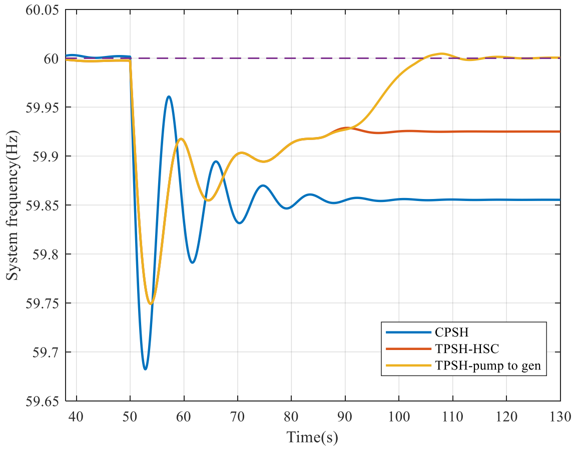
(b)

Fig. 4. Comparison of (a) power output with (b) system frequency of C-PSH and T-PSH during a load trip event.

regulation provided to the system is twice that of the units capacity (2×500MW) as compared to the droop based response of the C-PSH plant providing only 120MW of regulation for the same event. This results in a visibly better frequency profile with a reduced overshoot and significant



(a)



(b)

Fig. 5. Comparison of (a) system frequency with (b) Power output from C-PSH and T-PSH during a generator trip event.

proximity to the 60Hz standard.

For the load addition event, the T-PSH plant was initially set to work as a pump. Later as the load was added to the system, the plant could either use its hydraulic short-circuit and remain in pumping mode or change from pumping mode to generating mode. Again, the mode change allows the plant to provide regulation capacity of twice that of the unit rating (2× 500MW). This is a significant contribution of the T-PSH technology as the primitive C-PSH unit provides no support at all. Fig. 5 (a) and (b) display the frequency profile and the net power from the T-PSH unit when the disturbance is simulated.

The process of mode change was realized by controlling the setpoints Pref for the turbine and 1 or 0 reference for the pump. The pump can only be turned on or off which is indicated by the input status switch. However, a certain sequence of operation was followed to prevent output power transients. For pump to generator, when the system is initially operating in pump mode, the turbine inlet gate is opened to make the net power zero. The pump outlet gate is slowly closed until it reached its lower limit and is then disconnected from the shaft using the clutch. For generator to pump mode, first the turbine gates are closed and simultaneously the clutch is engaged to engage the pump. When the turbine gate is completely closed, the pump outlet is opened. The turbine controller parameters are set to match the mode change timings as mentioned in the report from Argonne National Laboratory (Koratirov and Guzowski, 2013) for a Francis turbine. Thus, pump to generator is completed within 60 seconds and generator to pump is completed in 45 seconds.

5. CONCLUSION

This paper displays the effectiveness of T-PSH in enhancing power system resiliency by contributing to primary frequency regulation. With the ability to change its mode from generating to pumping and vice versa, T-PSH provides primary regulation capacity twice that of the unit's rating and hence significantly improves system resilience. Also, with the help of the developed model, the hydraulic short-circuit has been simulated and shown that the T-PSH is capable of pump-mode regulation.

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