International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 951

PRELIMINARY STUDY ON DYNAMIC PERFORMANCE OF VARIABLE SPEED PUMP-TURBINE UNIT FOR HYBRID PHOTOVOLTAIC-PUMPED STORAGE POWER SYSTEM

Weijia Yang[1*], Jiandong Yang[1], Zhigao Zhao[1], Dinglin Li[2]

1 The State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, 430072, P. R. China (Corresponding Author: Weijia Yang)

2 China Southern Power Grid Power Generation Company, Guangzhou 510630, P.R. China

ABSTRACT

Handling the variability of renewable energies is a key for power systems towards de-carbonization and sustainability, and hybrid power system (HPS) is a promising solution for enhancing power generation by aggregating various energy resources. Meanwhile, the development, implementation and influence of variable speed pumped storage technology has been increasing all over the world. In this paper, a preliminary study on dynamic performance of variable speed unit (VSU) for hybrid photovoltaic-pumped storage power system is conducted. The main method here is numerical simulation based on timescale of seconds, by adopting MATLAB/Simulink. First, a mathematical model of the HPS is established, and a VSPSP and a photovoltaic power system are included. Then, the dynamic performance of the VSU in the HPS is simulated and discussed based on a quantitative comparison between the VSPSP and the FSPSP. The focus is to assess the two aspects: combined power output of the HPS and actuator movement. The results demonstrate the capability and advantage of applying the VSPSP for balancing photovoltaic power variation. Meanwhile, there is no fundamental distinction between the VSU and the fixed-speed unit (FSU) for the regulation movements that indicates wear and tear, despite the physical process and mechanism of active power regulation are different for the two types of pumped storage unit. The model and results could provide understandings on the detailed dynamic behaviors of HPS with VSPSP and photovoltaic power systems, for further supporting the operation and performance evaluation of HPS with multiple renewable energies.

Keywords: variable speed pumped storage plant, photovoltaic power, hybrid power system, dynamic performance, Simulation

NOMENCLATURE

Abbreviations	
DFIM	doubly fed induction machine
FSPSP	fixed-speed pumped storage plant
FSU	fixed-speed unit
HPS	hybrid power system
PV	photovoltaic
STD	standard deviation
SG	speed governor
VC	vector control
VSPSP	variable speed pumped storage plant
VSU	variable speed unit
Symbols	
A	intermediate matrix
b_p	turbine governor parameter (droop)
D_t	damping coefficient
e_y, e_ω, e_h	partial derivative of turbine power to guide vane opening, speed and head
e_{qy}, $e_{q\omega}$, e_{qh}	partial derivative of turbine discharge to guide vane opening, speed and head
H	water head
K_i	controller parameters: integral term

K_p	controller parameters: proportional term
i_{ds}	d-axis component of the stator current
i_{dr}	d-axis component of the rotor current
i_{qs}	q-axis component of the stator current
i_{qr}	q-axis component of the rotor current
L_m	magnetizing inductance
L_s	stator inductance
L_r	rotor inductance
P	number of pole pair
P_s	stator active power
Q_s	stator reactive power
P_s^*	set-point of stator active power
Q_s^*	set-point of stator reactive power
P_r	rotor active power
Q_r	rotor reactive power
R_s	stator resistance
R_r	rotor resistance
s	Laplace operator
T_a	mechanical time constant
T_{em}	electromagnetic torque
T_e	time constant of water column elasticity
T_m	mechanical torque
T_w	water starting time constant
T_y	servo time constant
V_s	stator voltage
V_{ds}	d-axis component of the stator voltage
V_{qs}	q-axis component of the stator voltage
V_r	rotor voltage
V_{dr}	d-axis component of the rotor voltage
V_{qr}	q-axis component of the rotor voltage
y	guide vane opening (GVO)
y_{PI}	GVO signal between PI terms and servo
α	elasticity coefficient of penstock
σ	leakage coefficient
ω_m	angular frequency of the rotor
ω_s	angular frequency of the stator windings
ω_r	angular frequency of the rotor windings
Ω_m	mechanical rotational speed at the rotor
Ψ_{ds}	d-axis component of the stator flux
Ψ_{qs}	q-axis component of the stator flux
Δ	stands for the deviation from the initial value

1. Introduction

Handling the variability of renewable energies is a key for power systems towards de-carbonization and sustainability, and hybrid power system (HPS) is a promising solution for enhancing power generation by aggregating various energy resources. Hydro-photovoltaic hybrid operation [1-4], such as the Longyangxia project [5, 6], has become one of the favorable solutions.

Meanwhile, the development, implementation and influence of variable speed pumped storage technology has been increasing all over the world. A key advantage of the variable speed unit (VSU) is the fast power regulation, compared to the regulation fixed-speed unit (FSU). How is the dynamic performance of VSU for hybrid photovoltaic-pumped storage power system? There is no specific study on this problem, to the best of the author's knowledge.

In this paper, a preliminary study on dynamic performance of VSU for hybrid photovoltaic-pumped storage power system is conducted. The main method here is numerical simulation by adopting MATLAB/ Simulink. A feature of this work is the special point of view of dynamic performance based on timescale of seconds, which is seldom investigated in previous works.

The content of this paper is organized as follows. In Section 2, a mathematical model of the HPS is established, and a VSPSP and a photovoltaic power system are included. In Section 3, the dynamic performance of the VSU in the HPS is simulated and discussed based on a quantitative comparison between the VSPSP and the FSPSP. The focus is to assess the two aspects: combined power output of the HPS and actuator movement. In Section 4, the main conclusions of this paper are summarized, and the future works are suggested.

2. Modelling of the hybrid power system

In this section, first, a simulation model based on MATLAB/Simulink for VSPSPs with doubly fed induction machine (DFIM) is presented. Second, the regular fixed-speed pumped storage plant is introduced as a comparative object. Third, characteristics of power output of photovoltaic power system is introduced and analyzed. Lastly, basic information and simulation settings of a real VSPSP is presented as a case study. A simplified schematic of an HPS with VSPSP and photovoltaic power plant is shown in Figure 1. All the symbols for variables in this paper are presented in the nomenclature.

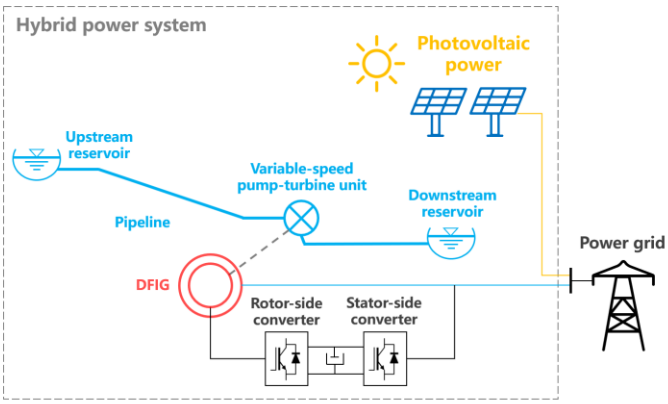

Fig 1 Simplified schematic of a hybrid power system with variable-speed pumped storage plant and photovoltaic power plant

2.1 *Variable speed pumped storage plant*

A mathematical model of VSPSPs with DFIM integrating hydraulic-mechanical-electrical subsystems is applied based on MATLAB/Simulink. The model is introduced in [7], and a brief block diagram of the integrated model is shown in Fig 2. The dynamic performance of active power regulation is the focus of this work, hence the set-point of stator active power (P_s^*) is a key for the case studies in the following content. More exactly, the varying power output of the photovoltaic power plant is input into the controller of the VSPSP as the set-point of stator active power, and this control strategy is based on the real implementation in the Longyangxia project [5, 6].

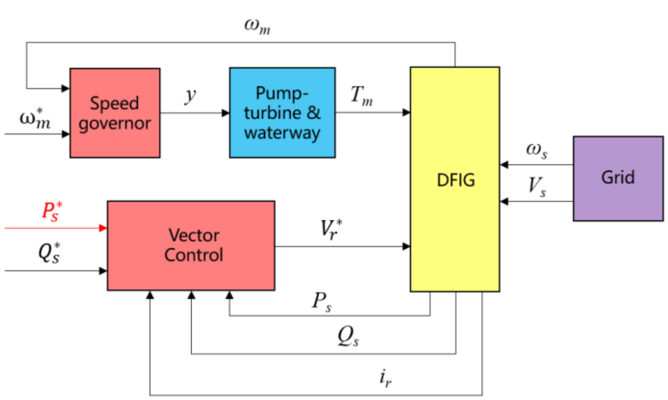

Fig 2 Brief block diagram of the integrated model of VSPSPs [7]

2.2 *Regular fixed-speed pumped storage plant as a comparative object*

An important method adopted in this paper to evaluate and demonstrate the dynamic performance of a VSPSP is through comparisons with a regular fixed-speed pumped storage plant (FSPSP). More exactly, a standard model of regular FSPSP [8, 9] with synchronous machine is also built, for simulating the dynamic processes of the FSPSP. The models of the VSPSP and the FSPSP share exactly the same hydraulic-mechanical subsystem (including pump-turbine, speed governor system, and waterway system).

2.3 *Characteristics of power output of photovoltaic power plant*

In this paper, the power output of the photovoltaic power plant is an important objective, leading to the power variation in the HPS and the regulation of pumped storage unit. It is analyzed here and treated as a key input to the numerical model for the controller of pumped storage unit.

The methodology here is to compute the photovoltaic power changes (ramps) based on real statistical characters [10, 11] by applying Pearson system random numbers. More specifically, the average, standard deviation, skewness, and kurtosis of the power change of photovoltaic power plant is applied and analyzed. Among these four values, the average and the skewness are set to zero, and the focus is on varying the standard deviation and the kurtosis.

The histogram of the computed power change (ramps) for 7200 seconds with 1-second sampling time is shown in Fig 3, and the time domain demonstration of the power output of photovoltaic power plant for 3600 seconds is presented in Fig 4. It is clearly shown that a large amount of power changes for 1-second interval are with small amplitude.

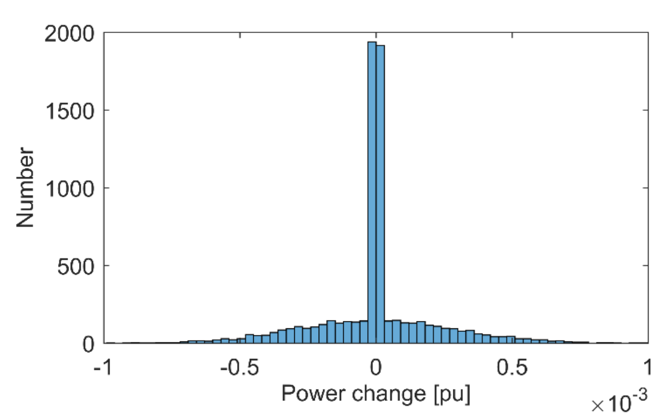

Fig 3 Histogram of the computed power change (ramps) for 7200 seconds with 1-second sampling time (interval)

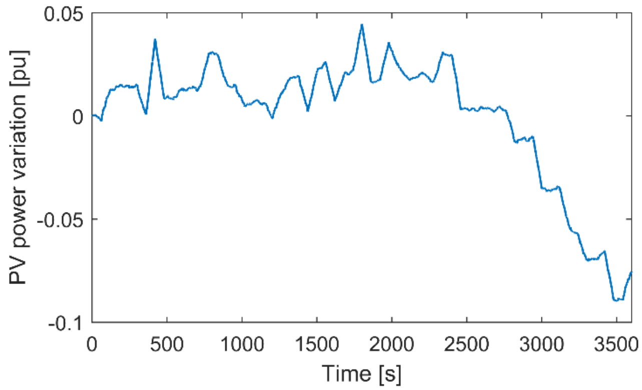

Fig 4 Time domain demonstration of the power output of photovoltaic power plant for 3600 seconds with small variations based on timescale of seconds.

2.4 Study case and settings

A real VSPSP currently in feasibility study stage is applied as the study case in this paper. The VSPSP will operate in a hybrid power system with renewable energy sources in southern China. The rated power of the unit is 10 MW that is also the power base in the simulation, and the synchronous speed is 1000 rpm. Values of other parameters are given in Table 1.

Table 1 Values of parameters of the pumped storage plant

DFIM		Pump-turbine	
Para.	Value	Para.	Value
T_a	10.0 s	e_y	0.9 pu
L_s	1.3230 pu	e_ω	-0.8 pu
L_r	1.3682 pu	e_h	1.45 pu
R_s	0.0045 pu	e_{qy}	0.66 pu
R_r	0.0022 pu	$e_{q\omega}$	0.1 pu
L_m	1.2297 pu	e_{qh}	0.47 pu
Waterway and governor		Controllers	
Para.	Value	Para.	Value
T_e	0.36 s	K_p (SG)	3.0
T_w	1.57 s	K_i (SG)	1.0
α	0.5 pu	b_p (SG)	0
T_y	0.2 s	K_p (VC)	0.1
Backlash	0 pu	K_i (VC)	10
Rate limit	0.1 pu/s	/	/

(1) "SG" and "VC" are short for speed governor and vector control respectively.

(2) The parameters for the pump-turbine, waterway, governor and the controller (for SG) of the FSPSP have the same values with the ones in this table.

3. Dynamic performance in the hybrid power system: power output and actuator movement

The evaluation of dynamic performance of the variable-speed unit (VSU) in the HPS is based on a quantitative comparison between the VSPSP and the FSPSP. The same simulation scenarios and operating conditions are adopted in the two PSPs, to investigate the differences in the following two aspects regarding the dynamic performance: combined power output of the HPS and actuator movement [9, 12, 13] of the pumped storage unit. The power output indicates the regulation quality, and the actuator movement reflects the wear and tear of the pumped storage units. A smooth combined power output with less actuator movement indicates an overall good performance. The total time length of each simulation case is 3600 seconds with a simulation timestep that is 5 milliseconds.

Regarding the aspect of power output, Fig 5 is the illustration of the power variations of the VSU and the FSU and the power reference that is the reverse of the photovoltaic power variation. Power variations of the power output of HPS with two types of pumped storage unit are shown in Fig 6. Table 2 clearly demonstrates that the variation of VSPSP-PV hybrid power is improved by an order of magnitude, compared to the case for FSPSP-PV hybrid power in terms of the average and standard deviation.

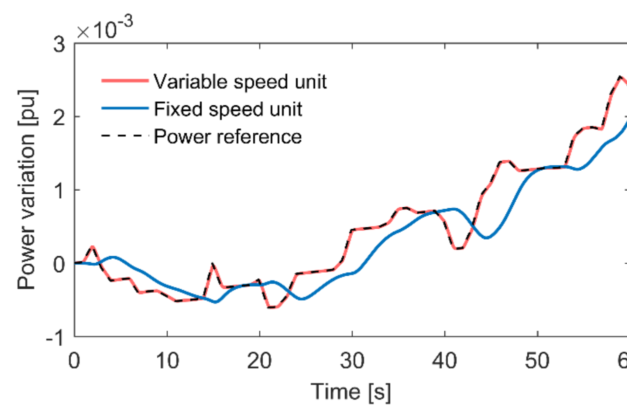

Fig 5 Illustration of the power variations of the VSU and the FSU and the power reference

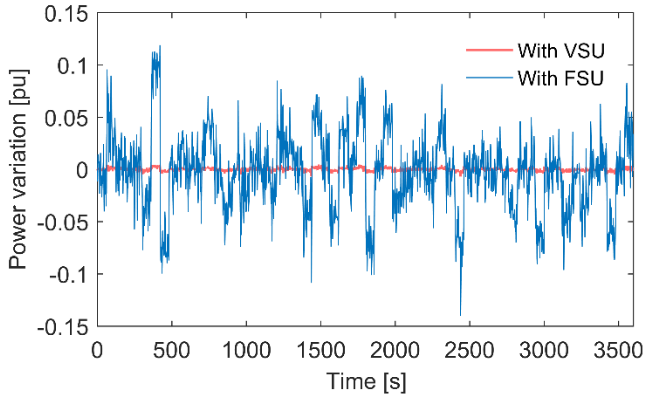

Fig 6 Power variations of the power output of HPS with two types of pumped storage unit

Table 2 The average and the standard deviation of the combined power output of the HPS with two types of pumped storage unit. The ratio value means the ratio between the values of "FSPSP-PV" and "VSPSP-PV".

	Average [pu]	STD [pu]
FSPSP-PV	2.68×10^{-2}	3.57×10^{-2}
VSPSP-PV	9.40×10^{-4}	1.29×10^{-3}
Ratio	3.50%	3.62%

Regarding the aspect of actuator movement, two main indicators are applied: the accumulated distance and amount of regulation movements [9, 12, 13]. The time domain illustration and statistics are shown in Fig 7 and Fig 8. It is shown that there is no fundamental distinction between the VSU and the FSU for the regulation movements; while the physical process and mechanism of active power regulation are different for the two types of pumped storage unit. Further study needs to be conducted on this issue.

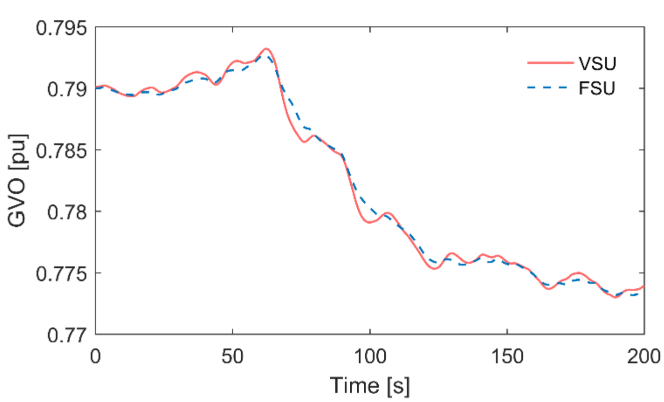

Fig 7 Time domain illustration of guide vane opening (GVO) of two types of pumped storage unit

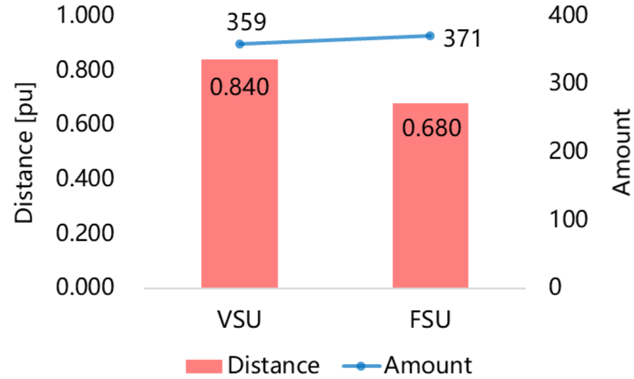

Fig 8 Statistics of the distance and amount of regulation movements during 3600 seconds of two types for pumped storage unit

4. Conclusion

In this paper, a preliminary study on dynamic performance of VSU for hybrid photovoltaic-pumped storage power system is done, by adopting MATLAB /Simulink based on timescale of seconds. The results demonstrate the capability and advantage of applying the VSPSP for balancing photovoltaic power variation. Meanwhile, there is no fundamental distinction between the VSU and the FSU for the regulation movements that indicates wear and tear, despite the physical process and mechanism of active power regulation are different for the two types of pumped storage unit. The model and results could provide understandings on the detailed dynamic behaviors of HPS with VSPSP and photovoltaic power systems, for further supporting the operation and performance evaluation of HPS with multiple renewable energies.

This paper delivers the methodology and result based on a preliminary work, and future study could be conducted from the following aspects: (1) refining the simulation model; (2) study on control strategy; (3) more comprehensive evaluation under various conditions; (4) physical model experiment and validation as a long-term work.

ACKNOWLEDGEMENT

The authors are thankful for the support from the National Natural Science Foundation of China (No.51809197, No.51879200, No.51839008) and the National Key Research and Development Program of China (No.2017YFB0903700).

REFERENCE

[1] Ming B, Liu P, Guo S, Zhang X, Feng M, Wang X. Optimizing utility-scale photovoltaic power generation

for integration into a hydropower reservoir by incorporating long- and short-term operational decisions. Applied Energy. 2017;204:432-45.
[2] Ma T, Yang H, Lu L, Peng J. Pumped storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization. Applied Energy. 2015;137:649-59.
[3] Ming B, Liu P, Guo S, Cheng L, Zhou Y, Gao S, Li H. Robust hydroelectric unit commitment considering integration of large-scale photovoltaic power: A case study in China. Applied Energy. 2018;228:1341-52.
[4] Meshram S, Agnihotri G, Gupta S. Advanced photovoltaic/hydro hybrid renewable energy system for remote areas. Journal of Renewable & Sustainable Energy. 2014;6:013140.
[5] Fang W, Huang Q, Huang S, Yang J, Meng E, Li Y. Optimal sizing of utility-scale photovoltaic power generation complementarily operating with hydropower: A case study of the world's largest hydro-photovoltaic plant. Energy Conversion & Management. 2017;136:161-72.
[6] Pang X, Zhang W. Hydro-photovoltaic complementary technology research and application [in Chinese]. Journal of Hydroelectric Engineering. 2017;36:1-13.
[7] Yang W, Yang J. Advantage of variable-speed pumped storage plants for mitigating wind power variations: Integrated modelling and performance assessment. Applied Energy. 2019;237:720-32.
[8] Yang W, Norrlund P, Chung CY, Yang J, Lundin U. Eigen-analysis of hydraulic-mechanical-electrical coupling mechanism for small signal stability of hydropower plant. Renewable Energy. 2017;115:1014-25.
[9] Yang W, Norrlund P, Saarinen L, Yang J, Zeng W, Lundin U. Wear reduction for hydro power turbines considering frequency quality of power systems: a study on controller filters. IEEE Transactions on Power Systems. 2017;32:1191-201.
[10] Shedd S, Hodge B-M, Florita A, Orwig K. A statistical characterization of solar photovoltaic power variability at small timescales. 2nd Annual International Workshop on Integration of Solar Power into Power Systems Conference Lisbon, Portugal, 2012.
[11] Wu Z, Jiang X, Ma H, Ma S. Study on fluctuations characteristics of photovoitaic power output in difflerent time scale [In Chinese]. Modern Electric Power. 2014;31.
[12] Yang W, Norrlund P, Saarinen L, Witt A, Smith B, Yang J, Lundin U. Burden on hydropower units for short-term balancing of renewable power systems. Nature Communications. 2018;9:2633.
[13] Yang W, Norrlund P, Saarinen L, Yang J, Guo W, Zeng W. Wear and tear on hydro power turbines–Influence from primary frequency control. Renewable Energy. 2016;87:88-95.