Enabling BES in Large PV Plant for Stability Enhancement of Power Systems with high RES

[1]Herlambang Setiadi, Student Member, IEEE
[2]Awan Uji Krismanto, Student Member, IEEE
School of Information Technology & Electrical Engineering
The University of Queensland
Brisbane, Australia
E-mail: [1]h.setiadi@uq.edu.au, [2]a.krismanto@uq.edu.au

[3]N. Mithulananthan, Senior Member, IEEE
School of Information Technology & Electrical Engineering
The University of Queensland
Brisbane, Australia
E-mail: [3]mithulan@itee.uq.edu.au

Abstract**—Transmission level PV plants have become a reality in recent years for encouraging more renewable energy. Large-scale PV plants can provide clean, affordable and sustainable electricity to the grid. However, they also introduce negative impacts as a result of intermittent power output and zero inertia characteristics. Hence, PV plants need an auxiliary device to overcome these concerns. One of the auxiliary devices that becoming favorable in recent years is Battery Energy Storage (BES). BES can provide fast response in providing constant active power to the grid or storing energy from PV plant along with a number of other capabilities. This paper investigates the influence of BES system installation at large-scale PV plant on small disturbance angle stability of interconnected power system. Analysis of sensitive eigenvalues, damping ratio, and phase portrait are carried out to investigate the impact of utilizing BES system in large-scale PV plant. From the simulation results, it was found that installing BES system in large-scale PV plant has significant influence in EM mode and BES system capacity also has a contribution in the dynamic behavior of the system.**

Index Terms**— BES system, large-scale PV, eigenvalue, damping ratio and phase portrait simulation.**

I. INTRODUCTION

In the last decade, global warming, climate change, and energy security are becoming the main issues all over the world. These problems emerged due to the extensive use of fossil fuels based power plants to produce electricity. To prevent further damage to the ecosystem, replacing fossil fuels with renewable energy sources (RES) is inevitable. Among numerous RES, PV power is one of most promising resources as the resources are free, abundance and its delivery at no cost. Although PV plant provides clean and environmentally friendly electricity, it potentially brings negative impact to the electricity infrastructure. The intermittent power output of PV plant due to the uncertainty of the source could introduce negative impact on power system stability [1, 2]. Moreover, the majority of PV plant is utilizing power electronics devices to convert natural energy into electricity. These power electronics devices and dynamic characteristic of PV plants might also deteriorate the dynamic performance of power system, especially in small signal stability domain.

Small signal stability and low-frequency oscillation are the ability of power system to maintain a stable condition after being subjected to small disturbance. This stability concern related to an oscillatory condition in the frequency range of 0.1-2 Hz [3]. If this oscillatory condition is not well damp, the magnitude of the oscillation may grow continuously and eventually result in loss of synchronization of synchronous generators [4]. Utilizing BES system as auxiliary device in large-scale PV plant could be considered to enhance the small signal stability and ensure the constant power output from PV. With the support of BES, the output power from PV can be maintained constant in the time of high uncertainty with PV output. Hence, PV can be considered as a dispatchable power plant.

The influence of BES system on small signal stability in single machine infinite bus has been reported in [5]. In that research, it is shown that proper tuning of the BES system gain controller has a significant impact on electromechanical modes of the system. It was also reported that by increasing the gain controller, the damping performance and system dynamic response improved considerably. A significant influence of increasing BES system capacity on the local and inter-area mode of power system considering high penetration of RESs was reported in [6]. It was also monitored that proximity of BES system plays an important role in the dynamic behavior of the system. Hence, in this paper, the possible impact of utilizing BES system as an auxiliary device in large-scale PV plant on EM mode is thoroughly investigated. Furthermore, this research also analyses the influence of BES system capacity on the system dynamic behavior.

The rest of the paper is organized as follows: Section II provides a dynamic model of PV plant, wind energy conversion system (WECS), BES system and power system. Section III briefly explains low-frequency oscillation and how to assess the low-frequency oscillation or small signal stability. Eigenvalue, damping ratio, and phase portrait simulation are presented in Section IV. This section also explains the impact of BES system capacity in damping performance of the system. The last section highlights the contribution, conclusions and future directions of the research.

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II. FUNDAMENTAL THEORY

A. PV Plant Model

Capturing the dynamic behavior of large-scale PV plant is crucial to analyze the small signal stability impact of PV plant. A PV plant consists of PV array, converter and associated controllers as presented in [6-8]. The converter processes the generated power from the PV array and it also serves as an interface device between PV array and the network. The converter controller is responsible for controlling the converter to produce an appropriate power to the grid [7, 8]. Fig. 1 illustrates a dynamic model of large-scale PV plant. This model divided into three main parts namely, PV array, converter and associated controller [7-10]. PV array consists of PV cell model as presented in [8]. The proposed controller comprises of PI controller, converter current limit, reactive power control and DC link capacitor. While the converter is modeled into first-order differential equation associated with inverter dynamic and low pass filter. MPPT can be assumed as a constant value due to the slow response of it. The complete model of large-scale PV plant is presented in [11].

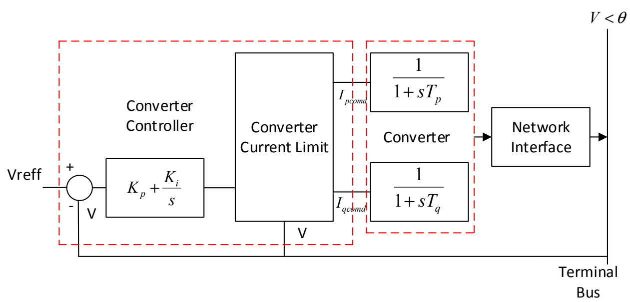

Figure 1. A dynamic model of large-scale PV plant.

B. Wind Energy Conversion System Model

In this research, wind energy conversion system (WECS), consists of wind turbine model, permanent magnet synchronous generator (PMSG) and power conversion system with an associated controller is considered. Fig. 2 shows the schematic diagram of WECS based on PMSG along with the controllers.

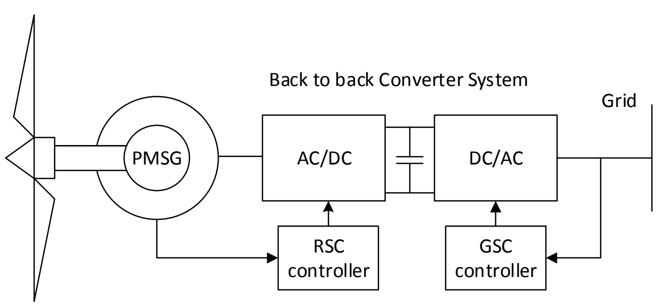

Figure 2. Electrical scheme of WECS based on PMSG.

For small signal stability analysis, WECS can be represented by the mathematical model as given by (1) - (3). While the detailed modeling procedure of WECS based on PMSG can be found in [12-14].

$$\frac{d\omega_g}{dt} = \frac{\tau_e - \tau_{w\_g}}{Jeq} - \frac{B_m}{Jeq}\omega_g \tag{1}$$

$$\frac{d_{id}}{d_t} = \frac{1}{L_{ds}+L_{is}}\left(-R_s i_d + \omega_e\left(L_{qs} + L_{is}\right)i_q + u_d\right) \tag{2}$$

$$\frac{d_{iq}}{d_t} = \frac{1}{L_{qs}+L_{is}}\left(-R_s i_q + \omega_e\left[\left(L_{ds} + L_{is}\right)i_q + \psi_f\right] + u_d\right) \tag{3}$$

Where ω_g is mechanical angular speed of generator. B_m corresponds to damping coefficient. τ_{w_g} represents aerodynamic torque. While τ_e, and J_{eq} are electromechanical torque and equivalent inertia, respectively. Generator parameters corresponding to stator resistance (R_s), leakage inductances (L_{id}, L_{iq}), generator inductances (L_d, L_q), electrical rotating speed (ω_e), magnetic flux (ψ_f) and some poles (p) are considered in this model The sub-index g described the parameter of generator side [12-14].

C. Battery Energy Storage Model

Fig 3 shows the schematic diagram of BES system consists of battery cells, converter and associated controller [5, 15, 16]. While Fig. 4 illustrates the block diagram of BES system.

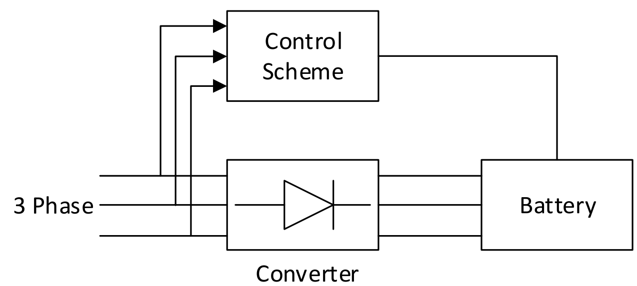

Figure 3. Schematic diagram of BES system.

Several parameters corresponding to maximum DC voltage of batteries (E_{do}), battery overvoltage (E_{b1}), average DC voltage of the battery (E_{bt}) and battery open circuit voltage (E_{boc}) are considered. Here, I_{BES} and P_{BES} represent DC current through the battery and active power from the battery, respectively. Other parameters are relating to connecting resistance (r_{bt}), internal battery resistance (r_{bs}), self-discharge resistance (r_{bp}), overvoltage resistance (r_{b1}), frequency deviation (Δf), commutating reactance (X_{co}). While K_b and T_b are controlled loop gain and time constant, respectively [5, 6, 15-19].

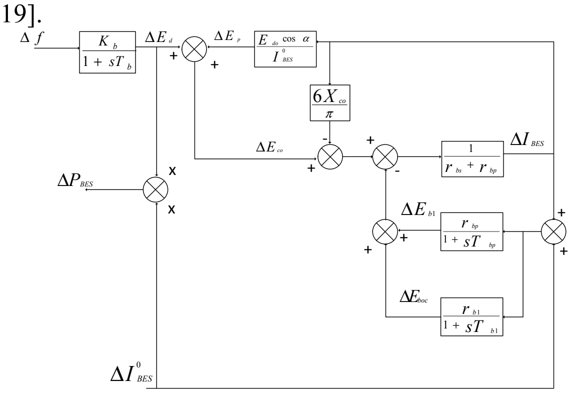

Figure 4. A dynamic model of BES.

D. Power System Model

With all elements described above, the dynamic behavior of power system for small signal stability study can be modeled as a set of differential (4) and algebraic equations (5) (DAE). In this work, a multi-machine model is developed to analyze the dynamic characteristics of local and inter-area modes respectively [20].

$$\dot{x} = f(x, y, u) \tag{4}$$

$$0 = g(x, y) \tag{5}$$

Where u is input variables respectively. While x and y represent the state and algebraic variables respectively. Machine and the associated controller is included in the differential equations while load flow and other network equations are be included in algebraic equations [20, 21].

III. Low-Frequency Oscillation

Low-frequency oscillation or small-disturbance angle stability is the ability of power system to maintain stable condition after being exposed by small disturbance [22]. This instability emerges due to insufficient damping and synchronizing torque [22]. Low-frequency oscillation can be categorized as local mode and global mode [23]. The local mode has frequency oscillation typically around 0.7-2 Hz while inter-area mode has frequency oscillation around 0.1 to 0.7 Hz [23].

Low-frequency oscillation can be examined by monitoring system eigenvalues of reduced system state matrix. The eigenvalues will reflect various modes in the system, including oscillatory and non-oscillatory. To determine system eigenvalues, state space model has to be constructed. State space representation of the system can be determined using (6), which can be obtained by linearizing (4) and (5) [24-26].

$$\begin{bmatrix} \frac{d}{dt}\Delta x \\ 0 \end{bmatrix} = \begin{bmatrix} A & & B \\ C & D_{11} & D_{12} \\ & D_{21} & J_{LF} \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + E[\Delta u] \tag{6}$$

Where Δx is a vector of state variables. Δy represents a vector of algebraic variables. Δu corresponded to the input vector. J_{LF} is the load-flow Jacobian. A and B are plant matrix and control or input matrix, respectively. While output matrix and feedforward matrix are denoted by C and D, respectively. Furthermore, the reduced system state matrix of the entire system can be defined using (7) [25].

$$A_{sys} = \left(A - B \left[\begin{pmatrix} D_{11} & D_{12} \\ D_{21} & J_{LF} \end{pmatrix}^{-1} \right] C \right) \tag{7}$$

The eigenvalue of the system matrix carries information about the stability of the system and they can be determined using (8) [24].

$$\det(\lambda \boldsymbol{I} - \boldsymbol{A_{sys}}) = 0 \tag{8}$$

Where I is the identity matrix, and λ is eigenvalues of matrix A_{sys}. Furthermore, complex eigenvalue indicate frequency oscillation (f) and damping ratio (ξ) which can be described as given in (9), (10), and (11) [23, 24, 27-30].

$$\lambda_i = \sigma_i \pm j\omega_i \tag{9}$$

$$f_i = \frac{\omega_i}{2\pi}\ (Hz) \tag{10}$$

$$\xi = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{11}$$

IV. Results and Discussion

Two case studies are reported in this research. All of the case studies were carried in MATLAB/SIMULINK environment. A four-machine 12 buses two-area power system was used as a test system. A modification was made to the system by replacing generator 2 in area 1 with 350 MW WECS aggregated model and 350 MW PV plant as shown in Fig. 5. Furthermore, 60 kWh BES system which was commonly employed in practical work was installed in PV plant. Hence, the system consists of three synchronous generators, one aggregated WECS, and PV plant. Each synchronous generator was presented by a ninth order model with exciter and governor. The PV plant was modeled by ninth order model consists of sixth order converter with the associated controller and third order BES system. While WECS consists of the wind turbine drive train, permanent magnet synchronous generator, rotor and grid side converter including the associated controller and it was modeled as an eleventh order model.

Observation of eigenvalues and damping of electromechanical mode was conducted to identify the impact of integrating RESs to the system and also impact of utilizing small BES system in PV plant. Phase portrait simulation was conducted to validate the eigenvalue of the system and to observe the dynamic behavior of the systems. Finally, a variation of BES system was conducted to observe the impact of BES system capacity in low-frequency oscillation.

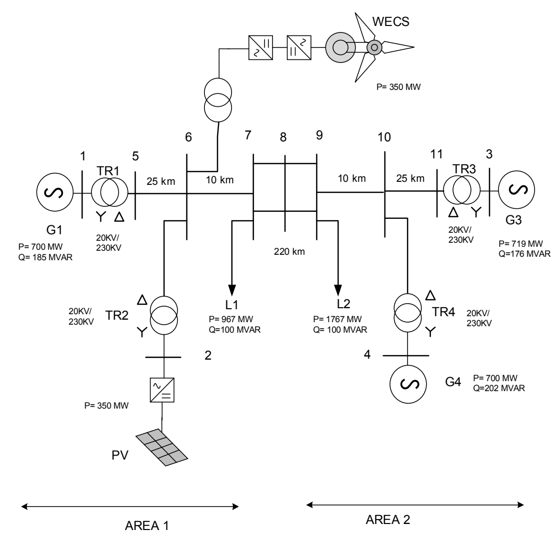

Figure 5. Two-area power system with WECS and PV plant replacing generator 2.

A. *Case Study I*

In this case study, observation of eigenvalue and damping of the electromechanical mode due to the integration of RESs and utilizing 60 kWh BES system in PV plan was carried out. Table 1 shows the comparison of the electromechanical modes of the investigated system. It was monitored that replacing one synchronous generator with 350 MW WECS and 350 MW PV plant, resulting in deterioration of the system damping, one of the local and inter-area modes. The investigated eigenvalues departed to the right-hand side of the complex plane, indicated by decreasing in the real part of those eigenvalues. It was monitored that even though one synchronous generator has been replaced by WECS and PV plant, the system damping enhanced significantly when BES system was installed to in PV plant. The damping performance of the monitored eigenvalues under different scenario is depicted in Fig.6. The blue one corresponded to the conventional system where all of the generators was a synchronous generator. While the red one related to the system when 350 MW WECS and 350 MW PV plant replacing 1 synchronous generator in area 1. Furthermore, the yellow one corresponded to the modification system with BES system was installed in large-scale PV plant.

TABLE I. EIGENVALUE COMPARISON OF THE CASES

Cases	**Eigenvalue**		
	Local 1	***Local 2***	***Inter-Area***
Base case	-0.3248+6.7577i	-0.3407+7.0183i	-0.068+2.6088i
With PV and WECS	-0.2828+6.5823i	-0.3410+7.0114i	-0.032+3.0247i
With BES	-0.8575+6.554i	-0.3368+7.0166i	-0.564+3.0096i

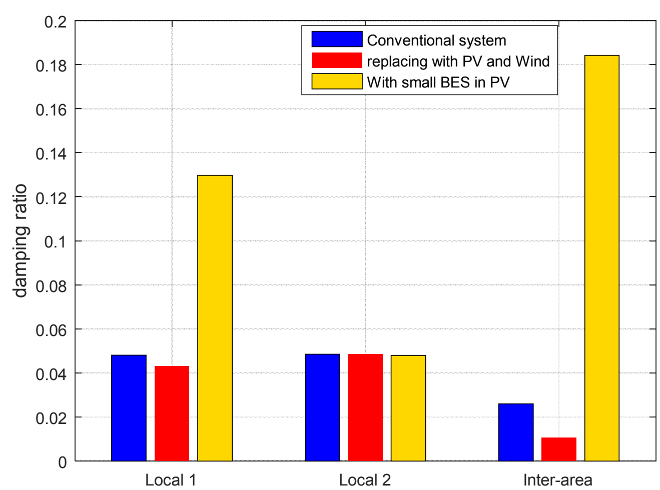

Figure 6. Two-area power system with WECS and PV plant replacing generator 2.

To validate and verify the eigenvalues analysis, phase portrait simulation was carried out. To excite the sensitive eigenvalues, small perturbation was applied in the system by giving 0.05 step input of load changes. Figs. 7-9 depict the phase portrait of generator 1, 3, 4 rotor speed and load angle. The initial condition of the sensitive eigenvalues is represented by A while the steady state operating point is given by B. It was observed that the oscillatory condition of the system became worse after replacing one synchronous generator in area 1 with the aggregated WECS and PV plant, indicated by more circular oscillation in the phase portrait. It has happened due to zero or inertialess characteristic of PV plant and WECS. It was also found that the best condition was obtained with the proposed system, i.e. utilizing BES system in PV plant, indicated by the less circular oscillatory condition. Furthermore, more research has been conducted to analyze the influence of BES system capacity on low-frequency oscillation.

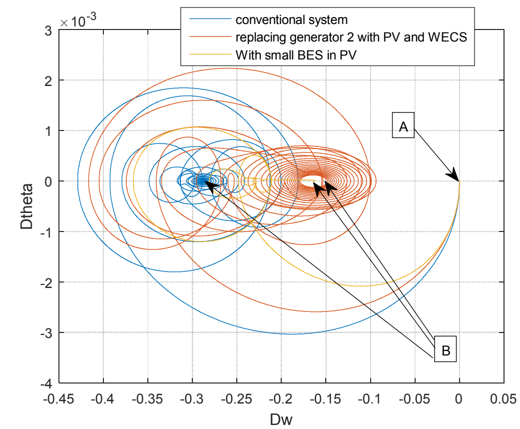

Figure 7. The oscillatory condition of rotor speed and load angle of G1.

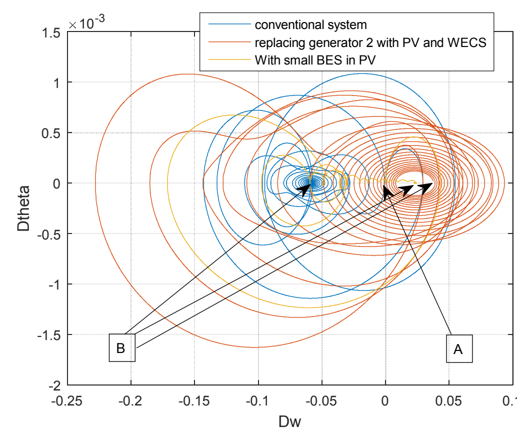

Figure 8. The oscillatory condition of rotor speed and load angle of G3.

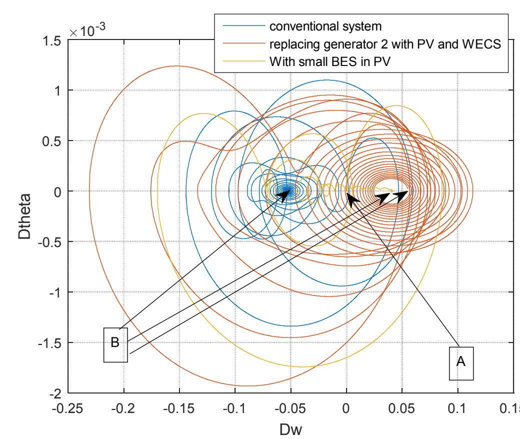

Figure 9. The oscillatory condition of rotor speed and load angle of G4.

B. *Case Study II*

In this case, study, increasing the load demand was considered to analyze how much load capacity can be increased when BES system was installed in large-scale PV plant as an auxiliary device. The load demand was increased gradually from 50 MW until 500 MW in steps of 50 MW. To analyze the impact of increasing load in small signal stability, the damping ratio of the local mode in area 1 and inter-area were monitored. Figs. 10-11 illustrate the damping value fluctuation of the local mode in area 1 and inter-area mode due to increasing load demand. It was found that the system damping deteriorated considerably when the load demand was increased. It was noticeable that damping ratio of the local mode in area 1 became critical under 5% limit when the load was further increased more than 400 MW. While the load could not be increased more than 453 MW to maintain the damping of inter-area modes above the critical value. Further increase of the load beyond 400 MW would lead to the more oscillatory condition which eventually resulted in an unstable situation. It was also found that installing BES system as an auxiliary device in large-scale PV plant could increase the load demand margin above the 400 MW limit.

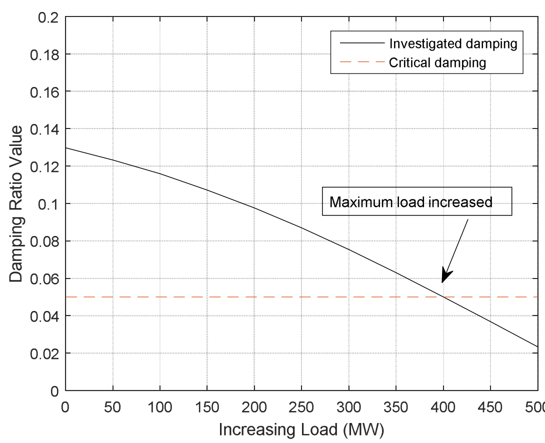

Figure 10. Damping value of local mode area 1 due to the increased load demand.

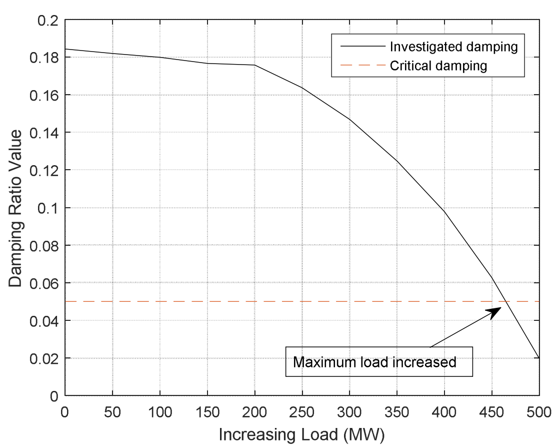

Figure 11. Damping value of inter-area mode due to the increased load demand.

C. *Case Study III*

In this case study, a variation of BES system capacity was considered. To evaluate the influence of BES system capacity, the damping ratio of the local mode area1 and inter-area were monitored. Fig. 12 shows the damping value fluctuation of local mode area 1 due to the variation of BES system capacity. While Fig. 13 illustrates the damping value fluctuation of inter-area mode. It was found that increasing BES system capacity brought positive impact on system dynamic response. Damping value of local mode area 1 and inter-area mode increased moderately as BES system increased.

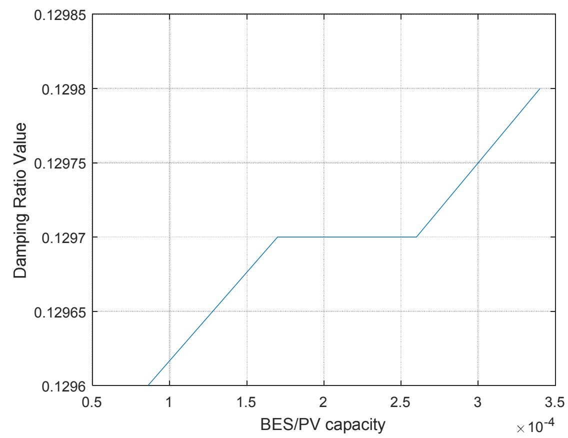

Figure 12. Damping value of local mode area 1 due to the variation of BES system capacity.

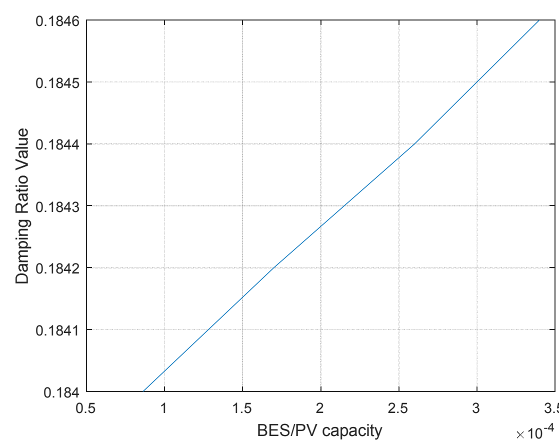

Figure 13. Damping value of inter-area mode due to the variation of BES system capacity.

CONCLUSIONS

This paper investigates the impact of utilizing small BES system in large-scale PV plant on low-frequency oscillation of interconnected power system considering high penetration of RESs. From the simulation results, it was found that replacing a synchronous generator with large-scale PV plant and WECS resulted in deterioration of damping on some electromechanical modes. It was noticeable that installing small BES in PV plant could provide additional damping on the system weak modes.

It was also monitored that the system with small BES in PV plant has the best damping performance indicated by highest damping ratio values. It was also found that the capacity of BES system did not have significant influence in system dynamic. Further research is required to find a proper intelligent methodology for optimizing the capacity of BES system.

ACKNOWLEDGMENT

The first author is very grateful to the Ministry of Finance of Indonesia Government for awarding him the Endowment Fund of Education Scholarship for his doctoral degree studies at the University of Queensland Australia.

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