Comparison of Battery Energy Storage Models for Small Signal Stability in Power System

by Awan Uji Krismanto

Comparison of Battery Energy Storage Models for Small Signal Stability in Power System

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***Abstract*— In the 21st century, integration of large-scale renewable energy sources (RESs) is increasing significantly. Although RESs provide clean and sustainable energy, they may adversely affect the performance of power system due to their distinct dynamic characteristics and intermittent power output. It is apparent that the integration of battery energy storage system (BESS) in power system is inevitable to accommodate more RESs. BESS could provide additional active and reactive power to the grid to overcome the energy shortfall. It is reported that the dynamics associated with BESS may significantly influence the low-frequency oscillation of the system. Therefore, it is important to analyze the various models of BESS for power system small signal stability studies. This paper investigates various models of BESS and their impacts on low-frequency oscillation for high penetration of RESs. Analysis has been conducted using Two-area power system for which the benchmark results are available for comparison purpose. Both the eigenvalue and time-domain analyses are employed in this paper to assess the impacts of various BESS models on low-frequency oscillation. From the simulation results, it is evident that the detailed model of BESS (i.e. 5th order model) could reflect the complete influence of BESS controller on low-frequency oscillation.**

***Keywords*- BESS, damping ratio, eigenvalue, small signal stability, time domain simulation.**

I. Introduction

In the last decade, integration of RESs in distribution and transmission level, as well as islanded power system, has become a reality around the world due to the requirement clean, affordable, and sustainable energy. Among numerous type of RESs, photovoltaic (PV) and wind are the promising sources to produce electricity with the appearance of advanced technology and their flexibility in operation.

Although RESs based on PV and wind are providing clean and environmentally friendly electricity, they might adversely influence stability of power systems. To transform natural energy into electricity, RESs use power electronics devices such as DC/AC, AC/DC and DC/DC converter. These devices could potentially deteriorate the stability performance, particularly small signal stability of power systems. Moreover, the uncertainty in the power output of RESs also contributes to the instability of power system.

To overcome the uncertainty and inertialess characteristics of RESs, integration of supplementary devices such as energy storage is considered. Battery energy storage system (BESS) has become more popular due to the appearance of high power voltage sourced converter (VSC). In [1], the application of BESS to augment the frequency stability of the system is discussed. It has been reported that BESS provides a promising solution to stabilize the frequency of power systems [1].

Influence of BESS in small signal stability has been studied comprehensively in [2]. It is reported that the gain of the active power controller of BESS has a significant influence on local and inter-area electromechanical mode. It is also evident that the damping performance of the system increased significantly when BESS is installed at the load bus. It is apparent that the BESS could be used as an additional device in a large-scale PV for smoothing power output, frequency support, and voltage regulation. In addition, the small signal stability performance of the system is also enhanced [3].

From papers cited earlier, it is evident that BESS has recently received more attention for power system application as it offers promising result for enhancing the stability performance during high penetration of RESs. A number of BESS models floating around for power system stability studies. However, it is yet to find the suitable and adequate model for BESS for power system small-signal stability studies. Hence, this paper aims to investigate the following key aspects:

- Investigate the existing models of BESS for small signal stability study.
- Findout the impact of the different types of BESS model on small signal stability performance of power systems.
- Compare the performance of various BESS models for small signal stability analysis in present of high penetration of RESs.

The rest of the paper is organized as follows: Section II provides mathematical modelling of PV, wind power plant, power system and small signal stability analysis. Section III briefly explains the influence of RESs and BESS integration on small signal stability analysis. Section IV provides mathematical modelling of BESS (e.g. steady-state model, third order model, fifth order model) for small signal stability study. Results are presented in Section V. Finally, the paper concludes with a discussion on results in Section VI.

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II. Dynamic Models and Small Signal Stability

A. Model of WECS

A permanent magnet synchronous generator (PMSG) with back to back converter and the associated controller, as shown in Fig. 1, is used in this paper.

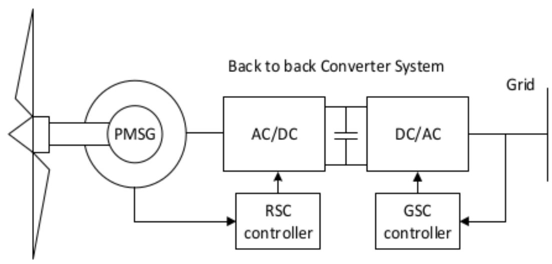


Fig. 1. Schematic diagram of WECS based on PMSG.

The mathematical representation of a dynamic model of wind energy conversion system (WECS) based on PMSG can be represented by (1)-(5). The detailed modeling procedure of WECS based on PMSG can be found in [4].

$$\frac{d\omega_g}{dt} = \frac{\tau_e - \tau_{w\_g}}{J_{eq}} - \frac{B_m}{J_{eq}}\omega_g \quad (1)$$

$$\frac{di_d}{dt} = \frac{1}{L_{ds} + L_{is}}\left(-R_s i_d + \omega_e\left(L_{qs} + L_{is}\right) i_q + u_d\right) \quad (2)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs} + L_{is}}\left(-R_s i_q + \omega_e\left[\left(L_{ds} + L_{is}\right) i_q + \psi_f\right] + u_d\right) \quad (3)$$

$$\omega_e = p\omega_g \quad (4)$$

$$\tau_e = 1.5p\left(\left(L_{ds} + L_{is}\right) i_d i_q + i_q \psi_f\right) \quad (5)$$

In (1)-(4), ω_g is angular speed (mechanical) of the generator, and B_m corresponds to damping coefficient. τ_{w_g} represents aerodynamic torque. While τ_e, and J_{eg} 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 poles (p) are considered in this model. The sub-index g described the parameter of generator side [4].

B. Model of PV plant

A dynamic model of PV plant comprises of PV array, converter, and associated controller. The converter is used as an interface between generated power from PV array and the network. Converter controller is responsible for controlling the power output of PV plant. Fig. 2 shows the dynamic control block diagram of large-scale PV plant. The main dynamics of the PV plant is converter dynamic and controller dynamic [3]. The converter can be represented as a set of the first order model corresponding to the aggregated model of the inverter and low pass filter dynamic. The converter controller consists of converter limit, PI controller, and a reactive power controller [3]. MPPT of PV plant is a logic algorithm to tracking maximum power from PV array. Hence, there is no dynamic characteristics that can be captured from MPPT (can be assumed as constant value) [5]. Moreover, the DC parts of this modelled is assumed as a constant value due to the fast response. The complete model of large-scale PV plant can be found in [6].

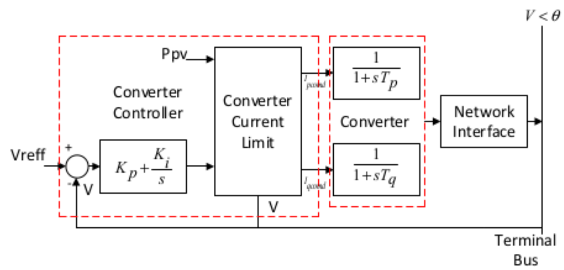


Fig. 2. Schematic diagram of PV system.

C. Model of power system

Small signal model of power system comprises a set of linearized equations of nonlinear differential and algebraic equations (DAE). In this study, a multi-machine model will be developed to investigate the dynamic behavior of local power plant (local modes) and entire power system (local and inter-area modes), respectively. A nonlinear mathematical model of the power system can be captured by (6) and (7) [7].

$$\dot{x} = f\left(x, y, u\right) \quad (6)$$

$$0 = g\left(x, y\right) \quad (7)$$

In (6) and (7), x and y represent the state and algebraic variables, respectively. Machine and the associated controller is to be included in the differential equations while load flow and other network equations are included in algebraic equations [7].

D. Small signal stability

The complexity and nonlinearity of power systems increased significantly due to load uncertainty and integration of RESs. One important concern corresponds to the increment of RES penetration in the power system is the risk of low-frequency instability, which potentially results in partial or even full blackout. Low-frequency oscillation can be categorized as small disturbance rotor angle stability [8]. This stability is defined as the ability of power system to maintain stable condition after being subjected to a small disturbance [9]. Low-frequency oscillation can be classified as a local and global or inter-area, depending on the participation of various devices in power systems. The local mode has a frequency around 0.7 to 2 Hz. The inter-area mode is associated with generators in multiple areas. It is characterized by an oscillatory frequency in the range of 0.1 to 0.7 Hz [9].

Low-frequency oscillation can be examined by monitoring system eigenvalues of the reduced system state matrix. The eigenvalues will reflect various modes in the system, including oscillatory and non-oscillatory modes. State space representation of the system can be determined using (8) by linearizing equations (6) and (7) [10].

$$\begin{bmatrix}\Delta\dot{x}\\ 0\end{bmatrix}=\begin{bmatrix}A & & B\\ C & D_{11} & D_{12}\\ & D_{21} & J_{LF}\end{bmatrix}=\begin{bmatrix}\Delta x\\ \Delta y\end{bmatrix}+E\left[\Delta u\right] \quad (8)$$

In (8), Δx is a vector of state variables. Δy represents a vector of algebraic variables. Δu corresponds to the input vector. J_{LF} is the load-flow Jacobian. A and B are plant and control or input matrices, respectively. While output and feedforward matrices are denoted by C and D, respectively. Furthermore, the reduced system state matrix of the entire system can be defined using (9) [10].

$$A_{sys}=\left(A-B\left[\begin{pmatrix}D_{11} & D_{12}\\ D_{21} & J_{LF}\end{pmatrix}^{-1}\right]C\right) \quad (9)$$

The eigenvalues of the system matrix carry the key information about the system stability, and they can be determined using (10) [10]:

$$\det\left(\lambda I - A_{sys}\right) \quad (10)$$

In equation number (10), I is the identity matrix and λ is eigenvalues of matrix A_{sys}. Furthermore, complex eigenvalue indicates frequency oscillation (f) and damping ratio (ξ) which can be described as given in (11), (12), and (13) [11].

$$\lambda_i=\sigma_i \pm j\omega_i \quad (11)$$

$$f_i=\frac{\omega_i}{2\pi} \quad (12)$$

$$\xi=\frac{-\sigma_i}{\sqrt{-\sigma_i^2+-\omega_i^2}} \quad (13)$$

III. Influence of BESS and RES on Small Signal Stability

In recent years, the integration of RESs is increasing significantly due to the global warming and climate change concerns. The integration of RESs is resulting in emerging new problems in power system. As reported on [12], the low inertia or inertia-less characteristics of RESs could have a significant impact on frequency stability of power system. The high penetrations of RESs also have a negative influence on small signal stability. As reported in [13], the high penetration of PV plant resulting on deteriorating damping performance of power system due to the inertia-less characteristic of PV plant.

The impact of power system based on a wind turbine is reported [14]. In those papers, the integration of power system based on wind power plant could bring positive and negative influence on low-frequency oscillation. Furthermore, another majors problems of RESs is the uncertainty and intermittent power output [15]. The uncertainty characteristic of RESs could potentially bring negative influence on the damping performance of power systems [16]. For handling the uncertainty on the power output of RESs additional devices such as BESS is essential.

BESS can be used for storing and releasing energy to the grid to provide frequency support [17]. As reported in [18], BESS has been implemented to maintain the frequency in Microgrid. Conversely, integration of BESS also influences small signal stability performance of power systems. As reported in [19], integration of BESS has a significant influence on the dynamic behavior of the power systems. Another research reported that by integrating BESS, the damping performance of the system is increased [20]. Furthermore, the variation of BESS controller could also introduce negative impact on the system regarding possible interaction with other elements in the power system [21]. Considering the above factors, integration of RESs and BESS has a significant influence on small signal stability performance of power system. Hence, it is essential to deeply study the significant impact of RESs and BESS. Moreover, determination of a suitable and adequate model of BESS is also important for capturing the dynamic behavior of BESS which would influence small signal stability performance of power systems.

IV. BESS Model for Small Signal Stability

A. Steady state model (Type-1)

The steady state model of BESS can be assumed as an active and reactive power injection/absorption considering all four quadrants operations. Hence the energy variation of BESS in a given period can be expressed as (14) [22].

$$\begin{aligned}E_{BESS}(t)&=E_{BESS}(t-1)-\frac{P_{BESS}^{disch}(t)}{\eta_d}\Delta t\\ E_{BESS}(t)&=E_{BESS}(t-1)-\eta_c P_{BESS}^{ch}(t)\Delta t\end{aligned} \quad (14)$$

In (14), E_{BESS} and Δt are the total energy stored in the BESS unit and the time duration. P_{BESS}^{disch} and P_{BESS}^{ch} are the charge and discharge power of the BESS unit. While η_d and η_c are discharge and charge efficiencies of the BESS [22]. In this model, the dynamics of BESS are neglected.

B. Third order model (type-2)

Fig. 3 shows the block diagram of BESS comprises of battery cells, converter, and the associated controller [23]. This is the dynamic model widely used for stability studies in power system, on particular, frequency stability of power system.

In this model, the battery cells are modelled into second order time delay and gain while the converter and the associated controller are modelled into the first-order model of gain and time delay. Since the model is initially developed for the frequency stability studies in power system, therefore, only the active power controller is used for this model.

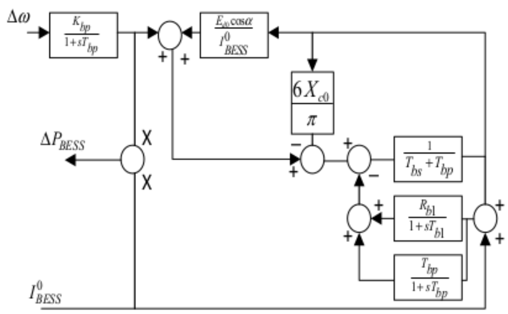


Fig. 3. Block diagram of third order model of BESS [23].

C. Fifth order model (type-3)

The fifth order model of BESS was first introduced by C Liu in 1995 [24]. The model consist of battery cells, converter and power control dynamic model. The battery cell is modeled into the second order model, while the converter dynamic is modeled into first order model. Furthermore, the power control dynamic is consist of active and reactive model and each controller is presented as first order model with gain constant. The main advantage of this model is the easy implementation of the BESS control system than steady-state or third order model. The active power controller of BESS can be calculated using (15) [24]:

$$\Delta P_{BES} = \frac{K_{BP}}{1+sT_{BP}} \Delta\omega \tag{15}$$

In (15), K_{BP} and T_{BP} are the control loop gain and rotor speed measurement device time constant respectively. The changes in the reactive power of the converter can be determined by (16) [24].

$$\Delta Q_{BES} = \frac{K_{BQ}}{1+sT_{BQ}} \Delta V_t \tag{16}$$

In (16), K_{BQ} and T_{BQ} are the control loop gain and terminal voltage measurement device time constant respectively. The firing angle of the converter can be calculated using (17) [24].

$$\alpha_R = \frac{K_R}{1+sT_R}\left(\alpha_R^* + K_M \Delta I_{BES}\right) \tag{17}$$

In (17), K_R and T_R are the converter loop gain and the firing angle time delay constant respectively. K_M and I_{BESS} are used to stabilize the BESS under constant current operation so that BESS can release more power from batteries. The α_R^* can be described using (18) [24].

$$\alpha_R^* = \tan^{-1}\left(\frac{Q_{BES}^*}{P_{BES}^*}\right) \tag{18}$$

In (18), P_{BES}^* and is active and reactive power output of converter controller. The dynamic behavior of battery cells can be calculated using (19) and (20) [24].

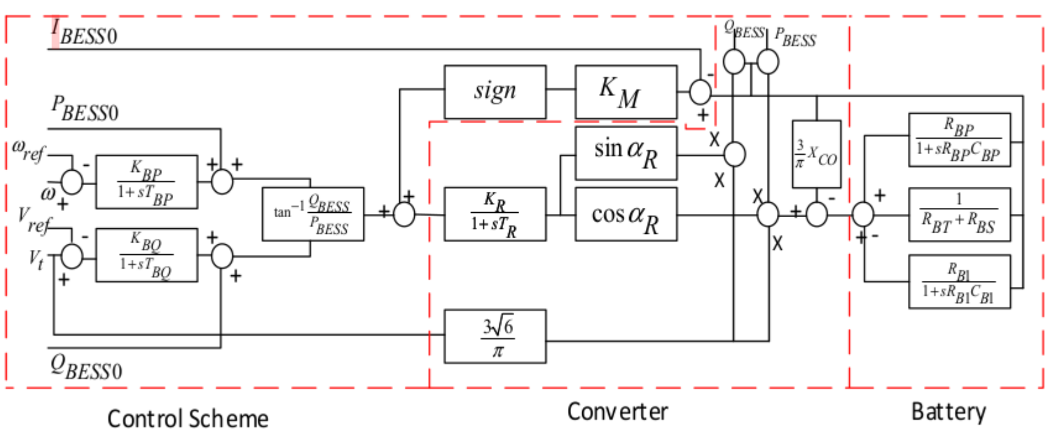
$$V_{BOC} = \frac{R_{BP}}{1+sR_{BP}C_{BP}} I_{BES} \tag{19}$$

$$V_{B1} = \frac{R_{B1}}{1+sR_{B1}C_{B1}} I_{BES} \tag{20}$$

In (19) and (20), R_{BP} and C_{BP} are used to describe the self-discharging of a battery. While R_{B1} and C_{B1} are the representation of energy and voltage during charging and discharging. Moreover, V_{BOC} and V_{B1} corresponded to battery open-circuit voltage, and battery voltage [24]. Fig. 4 illustrates the block diagram of BESS dynamic model.

V. SIMULATION RESULTS

This section aims to investigate the impact of different models of BESS on small signal stability considering high RES integration. The analysis has been carried out using MATLAB/SIMULINK. The multi-machine power system is considered in this research. Two area system popularly known as “Kundur” power system has been used. A modification has been made to the system by replacing one synchronous generator with 350 MW WECS aggregated model (wind farm) and 350 MW PV plant. Furthermore 100 MW BESS has been installed in load bus in area 1 as shown in Fig 5. Eigenvalue analysis has been conducted to identify the impact of various BESS models on the small signal stability of the system. Later,



time-domain simulations are used to validate the results.

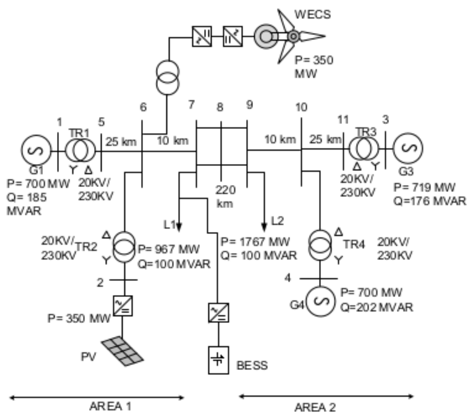


Fig. 5. AC test system with renewable energy generation and BESS.

Table 1 shows the comparison of electromechanical mode with different BESS models. In general, the BESS installation results in improvement of the system damping. It is evident from Table I that integration of BESS in load bus in area 1 makes the eigenvalues of local mode area 1 and inter-area mode move towards the left half plane, indicating enhancement of system damping and dynamic response. This movement is due to additional power from BESS to the load which reduces the stress on other synchronous machines.

Table 1. Eigenvalue comparison of the cases

Cases	Local mode 1	Local mode 2	Inter-area
Without BESS	-0.28+6.58i	-0.34+7.01i	-0.03+3.03i
With Type-1 BESS	-0.29+6.29i	-0.34+7.01i	-0.04+3.03i
With Type-2 BESS	-3.73+4.48i	-0.34+7.01i	-0.29+3.41i
With Type-3 BESS	-0.3+6.3i	-0.34+7.01i	-0.04+2.91i

The damping performance of the system with different BESS models is illustrated in Fig. 6. It can be observed that Type-1 BESS could enhance the damping performance of the system. It is also found that the damping performance of the system with Type-2 BESS increase significantly from 0.0429 to 0.6397 for the local mode in area 1. Furthermore, the inter-area mode is also enhanced significantly from 0.0105 to 0.0855. It is also observed that that Type-3 BESS could enhance the damping performance of the system gradually from 0.0429 to 0.0474 for the local mode in area 1. The increased damping is also observed in inter-area mode (from 0.0429 to 0.0474) when fifth-order model BESS utilized in bus load area 1. As can be seen from the results different model of BESS give different results and it is important to choose the most appropriate model for small signal stability considering BESS capabilities and dynamics. It was also observed that regardless of the model proximity of BESS play an important role in the system dynamic indicated by the damping performance on local mode area 2 remains in its position.

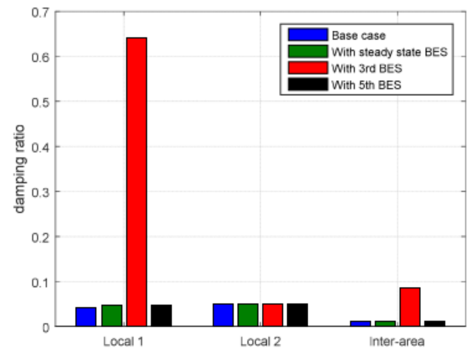


Fig. 6. Damping comparison of different scenarios.

To validate the eigenvalue analysis, time domain simulation has been carried out. A small perturbation is made in the system by giving 0.05 pu step input of load. Fig 7 show the rotor speed of generator 1. As observed from Fig. 7, a system with type-2 BESS and type-3 BESS experienced lower rotor speed oscillations than a system with the steady-state BESS model. Table 2 illustrate the detailed overshoot and settling time comparison of different scenarios. From table 2, it can be seen that the system experienced the worst overshoot and settling time when Type-1 BESS is considered. Furthermore, When BESS is represented by Type-3 model, the magnitude of the oscillation can be decreased (i.e. damped).

From the results, it is found that the different model of BESS provides different results. It is evident that the dynamic presentation of BESS influences the system dynamic. Furthermore, Type-2 BESS only considers active power and this model usually used for load frequency control study [23]. Moreover, the advantages of fifth order model is easy to add and modify the controller compare to the third order model. Hence, it is suggested that fifth order model is more suitable for small signal stability study [25].

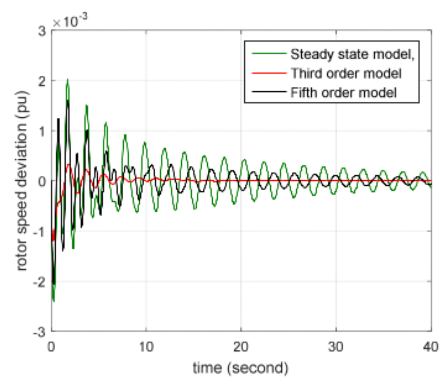


Fig. 7. The oscillatory condition of rotor speed G1.

Table 2. Detailed features of overshoot and settling time G1

Cases	Steady state model	Third order model	Fifth order model
Overshoot	-0.002412	-0.001192	-0.00206
Settling time	>40	19.53	>40

VI. CONCLUSIONS

In this paper, the various BESS system models and their impacts on small signal stability performance of power system are investigated. Three different BESS models (Type-1, Type-2, and Type-3) are integrated into the test system to examine and compare the effect on the system dynamic performance. From the simulation results, it is found that the integration of BESS at load bus could enhance the damping performance of the system. It is also found that different dynamic representation has a different impact on the small signal stability performance of power system. Hence, for small signal stability study, the authors suggested to utilize Type-3 BESS rather than Type-2 BESS due to more detail representation.

The time domain simulation is used to validate the eigenvalue analysis results. Both the time domain and eigenvalue analysis results are agreeing on each other. Further research is needed to investigate more detail about what dynamic of Type-3 BESS is influenced in the system performance. Utilizing additional power oscillation damping (POD) controller in BESS for enhancing the small signal stability performance of power system can also considered as further research.

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REFERENCES

[1] P. Prajapati and A. Parmar, "Multi-area Load Frequency Control by various conventional controller using Battery Energy Storage System," in *2016 International Conference on Energy Efficient Technologies for Sustainability (ICEETS)*, 2016, pp. 467-472.

[2] H. Setiadi, A. U. Krismanto, and N. Mithulananthan, "Influence of BES system on local and inter-area oscillation of power system with high penetration of PV plants," in *Applied System Innovation (ICASI), 2017 International Conference on*, 2017, pp. 1-4.

[3] H. Setiadi, A. U. Krismanto, and N. Mithulananthan, "Enabling BES in Large PV Plant for Stability Enhancement on Power Systems with High RES," in *2017 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia)*, Auckland, New Zealand, 2017.

[4] Y. Zou and J. He, "Comprehensive modeling, simulation and experimental validation of Permanent Magnet Synchronous generator wind power system," in *2016 IEEE/IAS 52nd Industrial and Commercial Power Systems Technical Conference (I&CPS)*, 2016, pp. 1-9.

[5] M. El-Shibini and H. Rakha, "Maximum power point tracking technique," in *Electrotechnical Conference, 1989. Proceedings.'Integrating Research, Industry and Education in Energy and Communication Engineering', MELECON'89., Mediterranean*, 1989, pp. 21-24.

[6] K. Clark, N. W. Miller, and R. Walling, "Modelling of GE Solar Photovoltaic Plants for Grid Studies," General Electrical International, Inc., Schenectady, NY2010.

[7] D. Lastomo, H. Setiadi, and M. R. Djalal, "Optimization of SMES and TCSC using particle swarm optimization for oscillation mitigation in a multi machines power system," *Journal of Mechatronics, Electrical Power, and Vehicular Technology,* vol. 8, pp. 11-21, 2017.

[8] H. Setiadi and K. O. Jones, "Power System Design using Firefly Algorithm for Dynamic Stability Enhancement," *Indonesian Journal of Electrical Engineering and Computer Science,* vol. 1, pp. 446-455, 2016.

[9] A. U. Krismanto and N. Mithulananthan, "Identification of Modal Interaction and Small Signal Stability in Autonomous Microgrid Operation," *IET Generation Transmission & Distribution,* 2017.

[10] P. W. Sauer and M. Pai, "Power system dynamics and stability," *Urbana,* 1998.

[11] D. Lastomo, H. Setiadi, M. Faisal, A. Ashfahani, G. Bangga, G. Hutomo, *et al.*, "The effects of energy storages on small signal stability of a power system," in *2017 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, 2017, pp. 52-57.

[12] M. Nahid Al, N. Modi, and R. Yan, "Low inertia power systems: Frequency response challenges and a possible solution," in *2016 Australasian Universities Power Engineering Conference (AUPEC)*, 2016, pp. 1-6.

[13] R. Shah, N. Mithulananthan, and R. C. Bansal, "Oscillatory stability analysis with high penetrations of large-scale photovoltaic generation," *Energy Conversion and Management,* vol. 65, pp. 420-429, 1// 2013.

[14] S. Lamichhane and N. Mithulananthan, "Possible impact of large scale wind energy integration on small signal stability," in *2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 2015, pp. 1-5.

[15] L. E. Jones, *Renewable energy integration: practical management of variability, uncertainty, and flexibility in power grids*: Academic Press, 2014.

[16] A. Krismanto, N. Mithulananthan, and I. Kamwa, "Oscillatory Stability Assessment of Microgrid in Autonomous Operation with Uncertainties," *IET Renewable Power Generation,* 2017.

[17] T. Kerdphol, K. Fuji, Y. Mitani, M. Watanabe, and Y. Qudaih, "Optimization of a battery energy storage system using particle swarm optimization for stand-alone microgrids," *International Journal of Electrical Power & Energy Systems,* vol. 81, pp. 32-39, 2016.

[18] T. Kerdphol, Y. Qudaih, and Y. Mitani, "Battery energy storage system size optimization in microgrid using particle swarm optimization," in *IEEE PES Innovative Smart Grid Technologies, Europe*, 2014, pp. 1-6.

[19] H. Setiadi, N. Mithulananthan, and M. J. Hossain, "Impact of Battery Energy Storage Systems on Electromechanical Oscillations in Power Systems," in *2017 IEEE Power and Energy General Meeting*, Chicago, USA, 2017.

[20] X. Sui, Y. Tang, H. He, and J. Wen, "Energy-Storage-Based Low-Frequency Oscillation Damping Control Using Particle Swarm Optimization and Heuristic Dynamic Programming," *IEEE Transactions on Power Systems,* vol. 29, pp. 2539-2548, 2014.

[21] H. Setiadi, A. U. Krismanto, N. Mithulananthan, and M. Hossain, "Modal interaction of power systems with high penetration of renewable energy and BES systems," *International Journal of Electrical Power & Energy Systems,* vol. 97, pp. 385-395, 2018.

[22] D. Q. Hung, N. Mithulananthan, and R. Bansal, "Integration of PV and BES units in commercial distribution systems considering energy loss and voltage stability," *Applied Energy,* vol. 113, pp. 1162-1170, 2014.

[23] A. Adrees, H. Andami, and J. V. Milanović, "Comparison of dynamic models of battery energy storage for frequency regulation in power system," in *2016 18th Mediterranean Electrotechnical Conference (MELECON)*, 2016, pp. 1-6.

[24] C.-F. Lu, C.-C. Liu, and C.-J. Wu, "Dynamic modelling of battery energy storage system and application to power system stability," *IEE Proceedings-Generation, Transmission and Distribution,* vol. 142, pp. 429-435, 1995.

[25] S. Chandra, D. F. Gayme, and A. Chakrabortty, "Coordinating wind farms and battery management systems for inter-area oscillation damping: A frequency-domain approach," *IEEE Transactions on Power Systems,* vol. 29, pp. 1454-1462, 2014.

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