International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 8, No. 4, December 2017, pp. 1830 – 1840
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v8i4.pp1830-1840

Control Strategy of a Grid-connected Photovoltaic with Battery Energy Storage System for Hourly Power Dispatch

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Article Info

Article history:
Received Jun 11, 2017
Revised Oct 16, 2017
Accepted Oct 28, 2017

Keyword:
Photovoltaic
Power fluctuation
Battery energy storage
Control scheme
Hourly dispatch

ABSTRACT

The high penetration of fluctuated photovoltaic (PV) output power into utility grid system will affect the operation of interconnected grids. The unnecessary output power fluctuation of PV system is contributed by unpredictable nature and inconsistency of solar irradiance and temperature. This paper presents a control scheme to mitigate the output power fluctuations from PV system and dispatch out the constant power on an hourly basis to the utility grid. In this regards, battery energy storage (BES) system is used to eliminate the output power fluctuation. Control scheme is proposed to maintain parameters of BES within required operating constraints. The effectiveness of the proposed control scheme is tested using historical PV system input data obtained from a site in Malaysia. The simulation results show that the proposed control scheme of BES system can properly manage the output power fluctuations of the PV sources by dispatching the output on hourly basis to the utility grid while meeting all required operating constraints.

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1. INTRODUCTION

In recent years, grid-connected photovoltaic (PV) system is seen to enjoy the most rapid growth among the various renewable energy sources. Unfortunately, the output power from the PV system is generally unstable and unpredictable because of intermittent and uncertain characteristics of solar irradiance and temperature [1]. High penetration of fluctuated PV output power into the utility grid system will affect operation of interconnected grids [2]. Some approaches may be required to compensate the output power fluctuations in order to have a more reliable power system.

Recent advances in the prediction methods enable the solar radiation profile to be forecasted with acceptable precision [3]. Estimating solar radiation is essential in order to generate a consistent output power of PV system. There are many prediction models for prediction of solar radiation such as artificial neural network (ANN)-based model, fuzzy logic control-based model, angstrom model, empirical regression model and empirical coefficient model [3]. Several researchers have claimed that the accuracy of the forecast model can be achieved up to 90% of the rated resource capacity [4, 5]. Accurate information from prediction model may be used as a reference in mitigating output power fluctuation of PV sources.

In power system applications, energy storage system (ESS) is acknowledged as one of the best alternative techniques to mitigate the PV output power fluctuations and PV output power prediction errors [1]. Various benefits of using ESS in grid-connected PV system application are discussed in [6]. Among the various of ESS technologies capable of mitigating the fluctuating and unpredictable output power of the PV systems are pumped hydro storage (PHS), compressed air energy storage (CAES), flywheel energy storage (FES), superconducting magnetic energy storage (SMES), supercapacitors (SC) and battery energy storage (BES) system. From the literature, it has been found that BES is the most cost-effective option for fluctuation mitigation purposes compared to other technologies [7].

BES is also known as electrochemical energy storage system that may be chosen from many different types depending on the varying power application needs such as lead acid (LA), valve regulated lead acid (VRLA), Nickel-cadmium (NiCd), Lithium-ion (Li-ion), sodium sulfur (NAS) and vanadium redox (VRB) batteries [1]. The advantages and disadvantages of each of the batteries are discussed in [6]. From the literature, there are various applications of BES in grid system in performing important task of power fluctuation mitigation and output power dispatch [8, 9, 10, 11, 12]. Daud et al. [8] proposed an optimal controller of BES to smooth the output power fluctuation from the PV sources. The control system used the forecasted output power of PV system as a dispatching reference. The controller regulate the SOC of battery according to the desired operational constraints and the output power of PV system is dispatched to the grid system on hourly basis. To optimize the controller, heuristic optimization is used to obtain the optimal parameters. The overall efficiency of the controller is reported as 82% [8]. Consequently, a control scheme based on the rules has been proposed in [9]. The rules in the control scheme are build based on the desired operational constraints of BES such as state of charge (SOC) limits, charge/discharge current limits, and lifetime. The control scheme effectively smooth out the output power of PV system and dispatch out the power to grid system in hourly basis. Author in [13] proposed a coordinated control scheme to reduce the impacts of wind power forecast errors while prolonging the lifetime of BES. The energy capacity determination method from the historical data is proposed in this work. The control scheme used forecasted output power data to improve the dispatchability of wind power generation. In [10], fuzzy-based smoothing control scheme has been presented. The fuzzy wavelet filtering method is used to smoothing the fluctuate output of wind and PV systems. Authors in [11] developed adaptive control of BES and UC for smoothing output power of PV system. The proposed adaptive fuzzy-based control scheme manages the power sharing between BES and UC based on the operational constraints of BES and UC in order to sustain the system operation. Similarly, an HES system composed of Li-ion batteries and UC has been proposed in [12]. A multimode fuzzy logic-based allocator has been designed to ensure the BES and UC can be efficiently utilized as well as preventing from working under extreme conditions.

Since the cost of the large scale BES is expensive, the energy of the BES should be optimally controlled particularly in the BES application for power fluctuation mitigation of PV sources. The optimal controller of BES can reduce the maintenance cost and increase the lifetime of the BES while providing the continuous support for power fluctuation mitigation. This paper presents an optimal control scheme of grid-connected PV-BES system. The objective of the paper is to design an optimal controller of grid-connected PV-BES system so that the total output of the system can be smoothed out and dispatched on an hourly basis to the utility grid. The following sections of the paper comprises of the details of proposed BES control scheme, the description of modelling and simulation of PV-BES system, results and discussion, followed by the conclusion.

2. PROPOSED BES CONTROL SCHEME

Integrating BES with grid-connected PV system will reduce the output power fluctuation and dispatch out the output power of PV system to grid system in hourly constant. A typical grid-connected PV-BES system is illustrated in Figure 1. The BES is parallel connected to the system at the point of common coupling (PCC) through power converter. The purpose of the converter is to regulate the fluctuate output power of PV system by controlling the charge and discharge power of BES.

In order to dispatch a constant power to the grid system, a robust control scheme of BES needs to be developed. In this paper, the control scheme is included at the outer control loop of the BES-VSC as shown in Figure 1. The control goal is to ensure a continuous charge/discharge of BES power for reducing the PV power fluctuations while providing safety and economical of BES. The BES is subjected to the operational constraints such as SOC operating limits and depth of discharge (DOD), voltage exponential limits, and current limit at the desired range. The proposed control scheme is developed for hourly PV output power dispatch strategy as illustrated in Figure 2. The proposed control scheme is motivated from the conceptual design for output power smoothing used in [8, 9]. The aim of the control scheme is to generate the reference signal for charge/discharge of battery power, P_{ref_BES} while meeting all required BES operational constraints. The required BES operational constraints are described as follows:

$$SOC_{BES\_min} \leq SOC_{BES}(t) \leq SOC_{BES\_max} \tag{1}$$

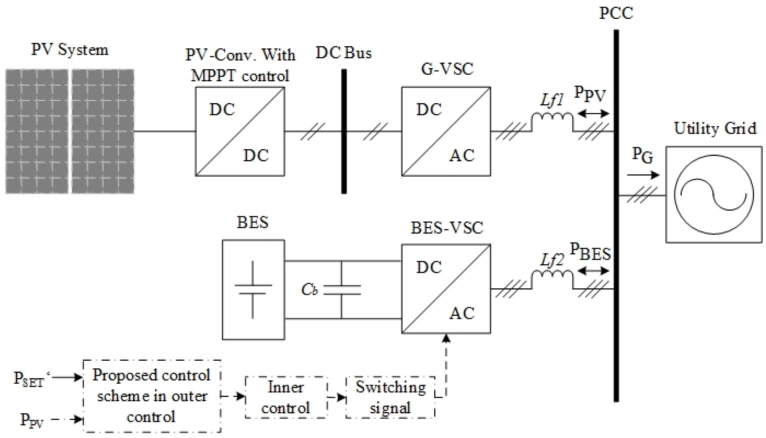

Figure 1. System configuration and control of grid-connected PV/BES system for hourly output power dispatch.

$$I_{max\_ch} \leq I_{BES}(t) \leq I_{max\_dis} \tag{2}$$

$$V_{BES\_min} \leq V_{BES}(t) \leq V_{BES\_max} \tag{3}$$

As shown in Figure 2, the input of the control scheme is $P_{SET}{}'$ which is determined from the hourly average of forecasted P_{PV}. The details of $P_{SET}{}'$ and P_{PV} are described in the next chapter. The SOC feedback signal of BES (SOC_{BES}) every one hour is used to determine the energy difference of BES to maintain the SOC_{BES} at desired SOC level (SOC_{ref_BES}). In this case, the SOC_{ref_BES} is set at 0.6 p.u which is the most ideal SOC starting value for the selected SOC range. The different energy of BES in MWh is added to $P_{SET}{}'$ in order to ensure that SOC_{BES} maintained at SOC_{ref_BES} at the end of every hour.

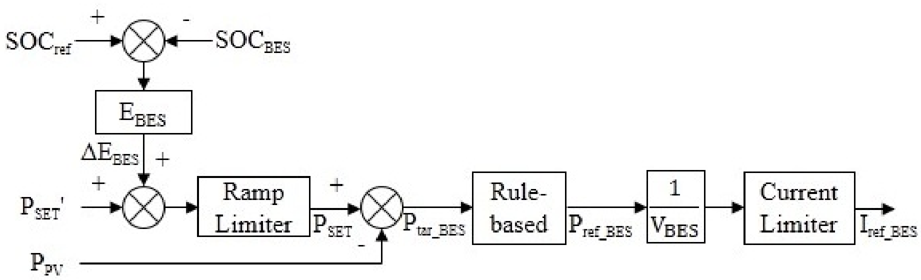

Figure 2. Outer loop control of BES-VSC.

To reduce the negative impacts from the drastic change of power every sub-hourly, the ramp rate limiter is also applied as illustrated in Figure 2. The rate limiter (Δ_{rr}) of $\pm$ 0.03 MW/min (up and down ramp rates) is applied to prevent overshooting when $P_{SET}{}'$ changes so as to avoid significant up/down ramps of total output power to the grid. Figure 3 gives the proposed ramp rate concept. As illustrated in Figure 3, the line of BCF and area of $OABCFG$ represent the power reference ($P_{SET}{}'$) and total energy reference ($E_{SET}{}'$) delivered to the grid system without ramp rate, while line of ACF and area of $OACFG$ represent the power reference (P_{SET}) and total energy reference (E_{SET}) delivered to the grid system with traditional ramp rate, respectively. By comparing of the total energy reference, the total energy is reduced if the traditional ramp rate control is applied. This energy reduction occurrance is because of the cut-off power during the ramp rate transition. To overcome the shortage of energy delivered, the flexible ramp rate control is proposed in this paper. As shown in Figure 3, the solid line of ADE and area of $OACFG$ represent the P_{SET} and E_{SET} delivered to the grid system with proposed ramp rate strategy without energy reduction. Based on the figure, the P_{SET} ramps up at 0.03MW/min rate at the beginning of hour t and retains steady until the end of the hour. So, the ramping duration τ_{rr} at hour t is calculated by using Equation 4 [14]. The hourly energy is expressed by Equation 5 [14] where E_R is energy delivered in ramping operation and E_S is energy delivered during stable

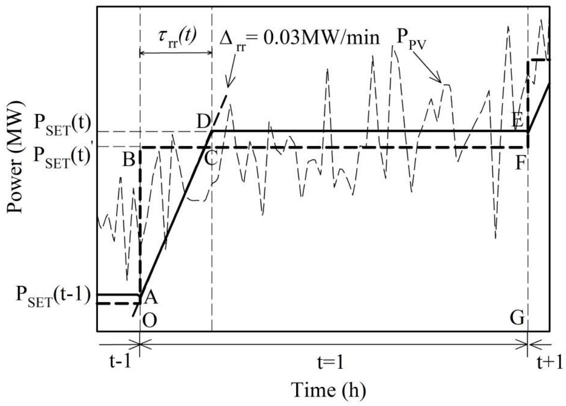

Figure 3. Illustration of ramp rate control.

state operation. The equation represents the correlation between E_{SET} and P_{SET}.

$$\tau_{rr}(t) = \frac{|P_{SET}(t) - P_{SET}(t-1)|}{\Delta_{rr}} \tag{4}$$

$$E_{SET}(t) = E_R(t) + E_S(t) = \tfrac{\tau_{rr}(t)}{2}(P_{SET}(t) - P_{SET}(t-1)) + (\tau - \tau_{rr}(t))$$
$$= \frac{|P_{SET}^2(t) - P_{SET}^2(t-1)|}{2\Delta_{rr}} + \left(\tau - \frac{|P_{SET}(t) - P_{SET}(t-1)|}{\Delta_{rr}}\right) P_{SET}(t) \tag{5}$$

To ensure the SOC operational of BES is within the desired limit, the rules-based control in [9] is used. The developed rules-based control is as illustrated in Figure 4. The input of the rules-based control, P_{tar_BES} is a deviation of P_{SET} and P_{PV} while the output is P_{ref_BES}. In the present study, the SOC_{BES_min} and SOC_{BES_max} are set to 0.3 p.u and 0.9 p.u, respectively. To ensure that the output of the outer loop control, I_{ref_BES} stays within required operational constraint of I_{BES}, the current limiter block is applied. The maximum charge/discharge current of BES should not exceed $\pm 1 \times C_{BES}$ amperes.

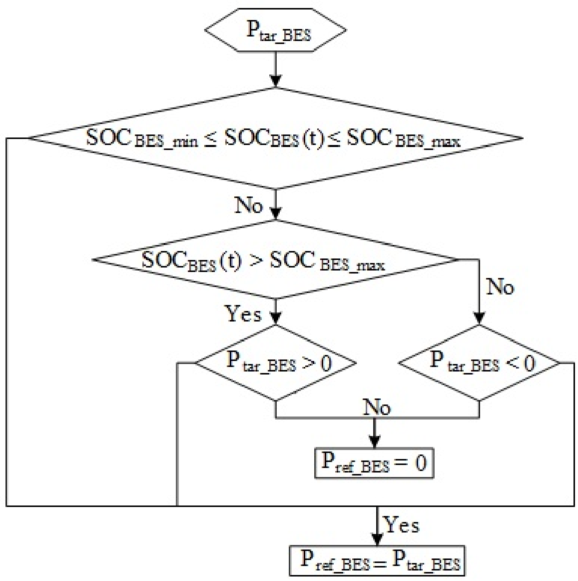

Figure 4. Flowchart of rules-based control.

3. MODELLING AND SIMULATION OF PV-BES SYSTEM

The simulation for validating the proposed control scheme is carried out using Matlab/Simulink. This section describes the method of obtaining PV output power profile (P_{PV}), hourly set-point power profile ($P_{SET}{}'$), BES power and energy rating. Besides that, the details of BES system model is also presented.

3.1. Output power of PV system (*PPV*) and determination of power reference profile (*PSET′*)

The one-year Malaysian historical radiation and temperature data are used in producing the P_{PV} output power data [8]. The hourly average of radiation and temperature are manipulated by adding random noise to represent the actual radiation and temperature data. The added random noise data are extracted according to the Malaysia weather characteristic where the intermittent of clouds are occurred between 11AM to 3PM. Figure 5 shows the one-day P_{PV} of which extracted from manipulated radiation and temperature data by using 1.2 MW grid-connected PV system model [8]. In this regards, 5% power loss through the converter is assumed and maximum power point tracking (MPPT) operation is considered in the PV system model. The P_{PV} data obtained are used to evaluate the proposed control scheme.

$P_{SET}{}'$ is a set-point power profile that is used as a reference to dispatch a constant power to the grid system in a certain period. For this study, the one-hour dispatch period is chosen. The magnitude of $P_{SET}{}'$ is determined from hourly average of P_{PV}. The ideal $P_{SET}{}'$ represents the dispatch reference without any error of forecast model. To represent the error of forecast model, 10% mean absolute error (MAE) is added into $P_{SET}{}'$ as illustrated in Figure 5.

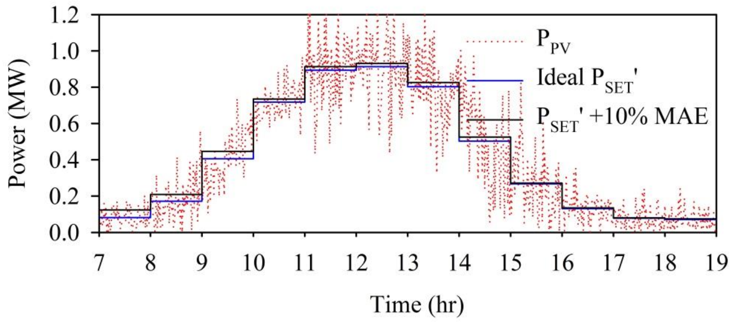

Figure 5. Power profile of P_{PV} and $P_{SET}{}'$.

3.2. Determination of BES power and energy capacity

The required energy of BES (E_{BES}) is determined based on the output power profile (P_{PV}) and power set-point profile ($P_{SET}{}'$) in Figure 5 by using Equation 6 [9], where P_{ref_BES} is power reference of BES without using control scheme that is obtained using Equation 7. Figure 6 illustrates the BES power rating and BES energy rating, respectively. From the figure, a total of 0.3 MWh size of BES and ±0.6 MVA converter rating are required if there is no error in forecast considered. On the other hand, a minimum 0.9 MWh size of BES is required when 10% error in forecast is considered. This clearly shows the need for a proper control and management of BES SOC in order to minimize the BES energy rating when the error in forecast is considered. In this paper, 0.3 MWh size of BES is selected and used with the proposed control scheme in the simulation study.

$$E_{BES}(t) = E_{BES}(0) + \int_0^t P_{ref\_BES}(t)dx \tag{6}$$

$$P_{ref\_BES}(t) = P_{SET}{}'(t) - P_{PV}(t) \tag{7}$$

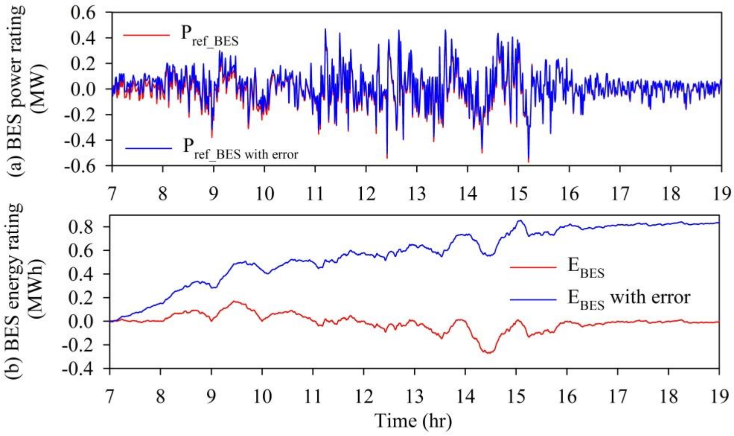

Figure 6. Power and energy rating for BES.

3.3. Modelling of BES system

In the present study, the lithium-ion battery is used as BES because of its excellent performance such as high energy density and high capacity. The lithium-ion battery model is modelled based on the dynamic equivalent circuit as illustrated in Figure 7 [15]. The dynamic model gives the relationship between voltage, current and the available charge (SOC) of the battery.

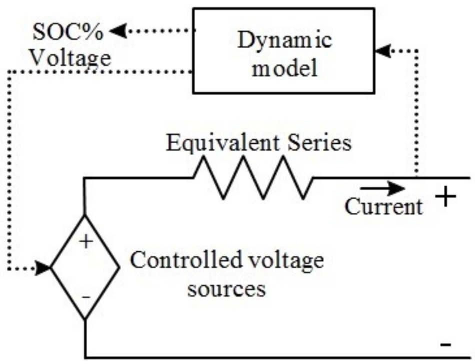

Figure 7. Equivalent circuit of battery simulation model.

The mathematical equation of the dynamic model are described based on the following equations:

$$V_{Bat} = E_{Bat} - R_{int} I_{Bat}, \tag{8}$$

$$SOC = 100(\frac{\int I_{Bat} dt}{Q}), \tag{9}$$

$$E_{Bat\_disc} = E_0 - [K(\frac{Q}{Q - it} i^*)] - [K(\frac{Q}{Q - it} it)] + Ae^{(-B)(it)}, \tag{10}$$

$$E_{Bat\_charg} = E_0 - [K(\frac{Q}{it - 0.1Q} i^*)] - [K(\frac{Q}{Q - it} it)] + Ae^{(-B)(it)}, \tag{11}$$

$$it = \int I_{Bat} dt \tag{12}$$

where V_{Bat} is the battery voltage (V), R_{int} is the battery internal resistance (Ω), I_{Bat} is the battery current (A), Q is the cell capacity (Ah), E_{Bat_disc} is battery electromotive force during discharge (V), E_{Bat_charg} is battery electromotive force during charge (V), E_0 is battery open-circuit voltage (V), K is polarisation resistance (Ω), it is actual battery current (Ah), i is filtered current (A), A is exponential zone voltage (V) and B is exponential zone time constant inverse (Ah)$^{-1}$.

4. RESULTS AND DISCUSSION

This section presents the simulation results and discussions. The first part discusses about the proposed controller performance for dispatching the total output of PV-BES system. The second part provides the case studies to evaluate the effects of initial values of BES SOC to the dispatching performance.

4.1. Effects of proposed controller to the dispatching performance of PV-BES

Figure 8 illustrates the effect of the proposed scheme on the dispatching performance of PV-BES system. The simulation results show graphically which summarises the output power dispatch curve, SOC, BES voltage and current profiles of the PV-BES system. For the case of uncontrolled SOC_{BES}, it is clearly shown in the Figure 8(a) that the power can be smoothly delivered to the grid system without any fluctuated output. However, the parameters of BES exceeds the lowest limit of desired operational constraints as evident in Figure 8(b), (c) and (d), where the lowest V_{BES}, SOC_{BES} and I_{BES} are 0.56 kV, 0.1 p.u and ±0.7 kA, respectively. Therefore, to meet the acceptable dispatching performance with safe battery operation, the SOC_{BES} needs to be properly controlled.

For a controlled SOC_{BES}, the power delivered to the grid system is consistent with the fluctuations have been minimized to a certain level. Consequently, all the BES parameters constraints are satisfied as shown in Figure 8(b), (c) and (d), respectively. From Figure 8(a), there are some spikes exist mostly between 11 AM and 3 PM. The visibility of the spikes that occur is because of current blocking in the current operational limits ($\pm 1 \times C_{BES}$) of I_{BES}. In practice, there are many ways to eliminate such spikes, for example by installing high power storage device such as supercapacitor [8, 16]. Output power in Figure 8(a) also shows reduction of output power dispatch due to controller setting in maintaining the SOC_{BES} at the end of sub-hourly the same as the initial SOC_{BES}. As evident in Figure 8(c), the SOC_{BES} level is maintained to remain the value close to initial SOC_{BES} at the end of the day compared to the SOC_{BES} in previous case. The lowest SOC_{BES} is measured around 0.36 p.u. Besides that, the simulation results also show voltage and current profiles of the PV-BES system in Figure 8(b) and (c), respectively. Based on Figure 8(b), the result shows the minimum voltage of the BES which is 0.6381 kV does not exceed the lowest boundary of V_{BES}. Meanwhile, in Figure 8(d) shows maximum charge and discharge current profiles that has been limited to $\pm 1 \times C_{BES}$ for safety purposes. From the curve, the I_{BES} does not exceed ±0.5 kA.

In addition to the results of the dispatching performances of PV-BES system, the effectiveness of proposed control scheme is determined using the performance index (PI) shown in Equations 13 and 14 [17] where, N_x represents the number of occurrences of deviations and dP is the difference of the total output and the desired set point. The total output power, P_G in this case is measured at the PCC system bus where the PV system is connected.

$$PI = \sum N_x \times |dP_x| \tag{13}$$

$$dP = P_{SET} - P_G \tag{14}$$

The power deviation, dP is illustrated in Figure 9 and it is verified that if the proposed control scheme is not used to smooth out the P_{PV} output and dispatch on an hourly basis, the unacceptable deviation will occur. The deviation without mitigation scheme that exceeds ±0.12 MW (10%) from the total PV capacity is found to be approximately 20% as illustrated in Figure 9(a). With the proposed control scheme, the unacceptable deviations greatly improved as shown in Figure 9(b), in which the deviations decreased to less than 1%.

4.2. Effects of initial SOCBES to the dispatching performance of PV-BES

In order to evaluate the robustness and flexibility of the performance of the proposed control scheme, the following three critical cases of storage initial SOC_{BES} are considered. The initial SOC_{BES} is set to nearly full charge of 90% (case 1), nearly full discharged at 30% (case 2) and the average 60% (case 3), respectively. Figure 10(a) and (b) provides the simulation results of power profile and SOC_{BES} profile, respectively. For case 1 and 2, the control scheme has adjusted the $P_{SET}{}'$ to increase (for case 1) and decrease (for case 2)

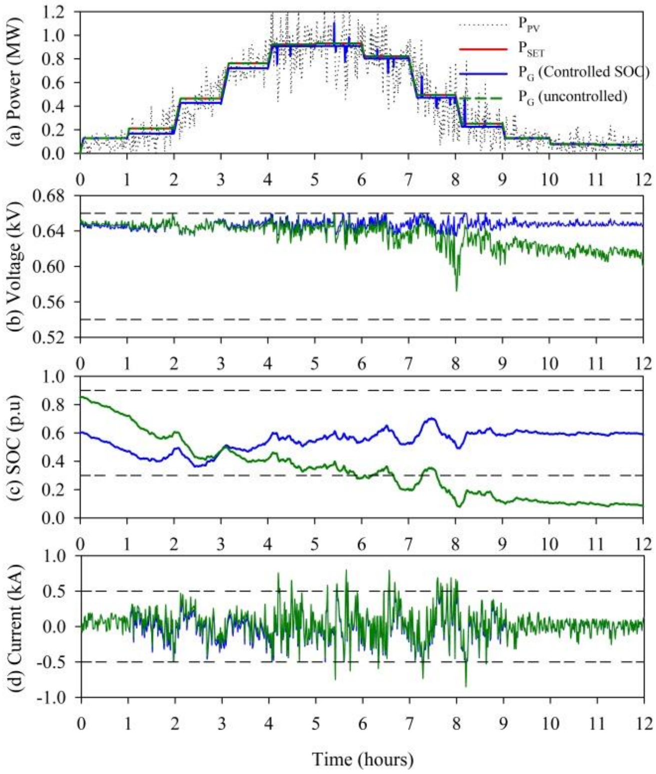

Figure 8. Comparison of dispatch performance of PV-BES using proposed control scheme. (a) Power profile of P_{PV}, P_{SET} and P_G, (b) Voltage profile of BES, (c) SOC profile of BES and (d) Current profile of BES.

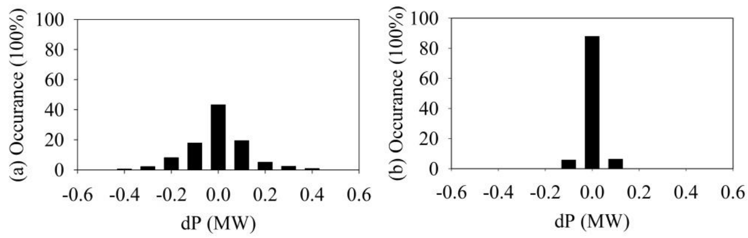

Figure 9. Comparison of dP. (a) Before mitigation, (b) After mitigation.

as illustrates in Figure 10(a). The adjusted P_{SET}' caused the discharge rate is increased and charge rate is decreased if high initial SOC is set. In contrast, for the case 2, low starting value of the SOC causes the controller to adjust the P_{SET}' so that charging activities are more than the discharging. This scenario indicates that, through the proposed control scheme, the SOC_{BES} can be restored to its typical conditions without adding more energy storage capacity as illustrated in Figure 10(b). For case 3, 60% is assumed as nominal initial of SOC_{BES}. This case is expected as regular operating condition of the BES during clear day or less impact of cloud cover to the PV system output power fluctuation. In this case, P_{SET}' is remain unchanged at early stage due to the ability of the BES to charge and discharge. As illustrated in Figure 10(b), SOC_{BES} is remain stable within the controllable range that reflects the effectiveness of the proposed scheme.

5. CONCLUSION

This paper investigates the control design issues of large scales BES to be integrated with grid-connected PV system so that the output power from PV system can be smoothed out and dispatched on an

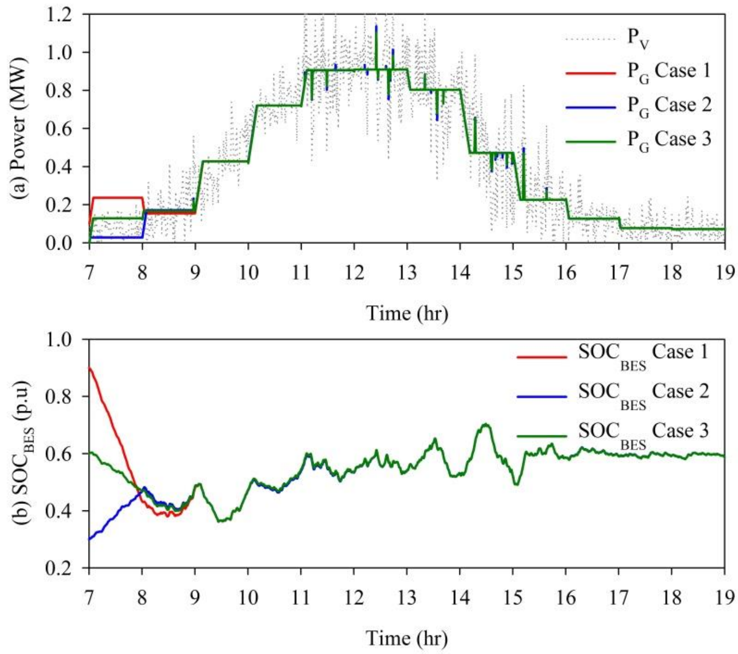

Figure 10. Effects of initial SOC_{BES} to the dispatching performance of PV-BES. (a) Power profile, (b) SOC of BES profile.

hourly basis like a conventional generator. For such purpose, the control scheme has been proposed with the goal of using BES to provide power smoothing of the PV system while maintaining the BES operational constraints at the desired level. The simulation of the proposed control scheme has been carried out using the historical PV system input data of a site in Malaysia. Besides that, determination size of BES and BES modelling also has been addressed. From the simulation results, the proposed control scheme is found to be effective. The results indicates that the dispatching performance was improved and the required operational constraints for BES have been met. The SOC of BES is controlled at level the same as initial SOC during the end of the day to ensure continuous power support for next day power smoothing operation. The proposed control scheme also can significantly reduce the power fluctuation with the unacceptable deviations of 10% PV capacity have been reduced from 20% to less than 1%. The results from case studies of the effects of initial SOC of BES indicates the flexibility and robustness of the control scheme that any level of SOC can be properly regulated even during the critical conditions of power fluctuation mitigation.

ACKNOWLEDGMENTS

The authors would like to acknowledge Universiti Malaysia Terengganu, Malaysia and Ministry of Higher Education Malaysia (MOHE) for the financial support of this research. This research is supported by MOHE under the Fundamental Research Grant Scheme (FRGS), Vot No. 59418 (Ref:FRGS/1/2015/TK10 /UMT/02/1).

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