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An improved rule-based control of battery energy storage for hourly power dispatching of photovoltaic sources

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ABSTRACT

This paper presents an improved rule-based control scheme for battery energy storage (BES) system with the goal of minimising the fluctuation output from photovoltaic (PV) sources while ensuring the operational constraints of BES are regulated at the specified ranges for safety purposes. The control scheme is formulated in accordance with the intended operational limitations of the BES, including charge/discharge current limits and state-of-charge (SOC). The simulation studies were carried out using MATLAB/Simulink to evaluate the effectiveness of an improved rule-based control scheme on the 1.2 MW PV system data acquired from a location in Malaysia. Furthermore, a comparative study on the effectiveness of an improved rule-based control scheme compared with the conventional rule-based control scheme has been carried out. The simulation results show that an improved rule-based control scheme can effectively reduce the fluctuations in the output power of the PV sources and dispatch the output to the utility grid on an hourly basis with an efficiency of up to 94.47%. Finally, the comparison results on the effects of the BESS capacity also illustrate that an improved rule-based control scheme is more effective compared to the conventional rule-based control scheme in the previous study.

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1. INTRODUCTION

Solar photovoltaic (PV) energy source is well known for its unpredictable and inconsistent output due to the intermittent nature of solar irradiance and temperature [1], [2]. High penetration of unpredictable and inconsistent solar PV output into utility grid systems caused many problems, including voltage and power fluctuations and other power quality problems [3]–[5] . Integration of solar PV systems with battery energy storage (BES) systems is proven to be effective in minimising such problems, provided that a proper control scheme is designed and managed [6]. Various types of batteries have the potential to be integrated into solar PV systems for power fluctuation mitigation purposes, such as lead acid (LA), lithium-ion (Li-ion), and nickel-cadmium batteries [7]–[10] . However, the high cost of the BES system is considered one of the obstacles that require further attention [11]. In many cases, studies associated with developing a robust and efficient control method for BES are of significant importance to providing a cost-effective BES system [12].

There are many types of control schemes for the BES system that have been suggested in in the literature to smooth out the output fluctuation of renewable energy sources [13]–[19] . However, only a few studies have been focusing on the smoothing of output fluctuation with constant output power dispatching [20]–[24]. In [20], the optimisation-based state-of-charge feedback (SOC-FB) control scheme for the valve-regulated lead-acid (VRLA) BES has been proposed for controlling the SOC of BES in accordance with the intended operational constraints, such as SOC and current limits during the smoothing and dispatching processes. The authors proposed genetic algorithm-based parametric optimisation with overall smoothing and hourly dispatch efficiency recorded equal to 84%. Consequently, heuristic optimisation-based studies have been investigated in [21] using other algorithms such as the gravitational search algorithm (GSA) and particle swarm optimisation (PSO). For this case, the result for the fluctuation mitigation efficiency was measured at 89.91% using the GSA approach. However, long computation times and an accurate BES system model were required for the optimisation processes. In [22], a simple rule-based control scheme has been suggested in. The rules in the control scheme were determined according to the specified operational constraints of the BES system. The results showed the proposed rule-based control scheme effectively smoothed the variability of the PV system's output. However, the proposed rule-based control scheme was not able to sustain the BES power at the desired level. To overcome the associated issues in [2], [6], [7], this paper introduces an improved rule-based control scheme for the BES system. The improved rule-based control scheme is able to mitigate the variability of a photovoltaic system's output and dispatch stable power to the utility grid system. The improved rule-based control scheme is also able to sustain BES power at the desired level. The rest of the paper is organised as follows: section 2 describes the details of the proposed control scheme and the simulation setup. Section 3 presents the results and discussion from the simulations. Finally, section 4 concludes the paper.

2. METHOD

In this section, the configuration and operation of the PV-BES system are described. Then, the development of an improved rule-based control scheme for mitigating output power fluctuation and the hourly output power dispatch strategy of a grid-connected PV system are discussed. Finally, the simulation set-up for the evaluation of the performance of the control schemes is presented.

2.1. System configuration and control of the hybrid PV-BES system

In the present study, a typical AC-coupled PV-BES structure for power smoothing and power dispatch is presented in Figure 1. The PV and BES systems are attached to the point of common coupling (PCC) bus via separate bidirectional voltage-sourced-converter (VSC) (PV-VSC and BES-VSC). The BES-VSC system is responsible for regulating the fluctuating output of the PV system (P_{PV}) based on an hourly power dispatch reference ($P_{SET}{'}$) through the charge and discharge of BES power (P_{BES}). The BES system is subjected to specific operational limitations in order to ensure safe and cost-effective operation. The specific operational constraints of BES are described in (1)-(3), where $SOC_{BES,min}$ and $SOC_{BES,max}$ are the minimum and maximum levels of state-of-charge (SOC) operating ranges of BES (SOC_{BES}). The $I_{BES,min}$ and $I_{BES,max}$ are the minimum and maximum allowed current of BES (I_{BES}). The $V_{BES,min}$ and $V_{BES,max}$ are the operational constraints of the BES voltage (V_{BES}). The $SOC_{BES,min}$ and $SOC_{BES,max}$ were initialised to values of 0.3 and 0.9 p.u, which is 60% of the total capacity of BES, respectively The SOC_{BES} constraint is used to prevent the BES from overcharging and overdischarging. The I_{BES} constraint was set to ±1×C_{BES} based on the BES-VSC current limit, while the V_{BES} constraint was set to 10% of the BES-rated voltage. The V_{BES} operation is used to prevent the BES from breaking down. The BES-VSC employed the current-mode control strategy that has two loops, as presented in Figure 1. The details of current-mode control are discussed in [25]. The outer control loop is used to generate the reference current ($I_{BES,ref}$) signal either to charge or discharge, while the inner control loop is used to generate the switching signals for the BES-VSC. In order to generate the optimal $I_{BES,ref}$ for output power smoothing and PV power dispatch, a control scheme is introduced in the outer control loop, as discussed in the following section.

$$SOC_{BES,\min} \leq SOC_{BES}\,(t) \leq SOC_{BES,\max} \tag{1}$$

$$I_{BES,\min} \leq I_{BES}\,(t) \leq I_{BES,\max} \tag{2}$$

$$V_{BES,\min} \leq V_{BES}\,(t) \leq V_{BES,\max} \tag{3}$$

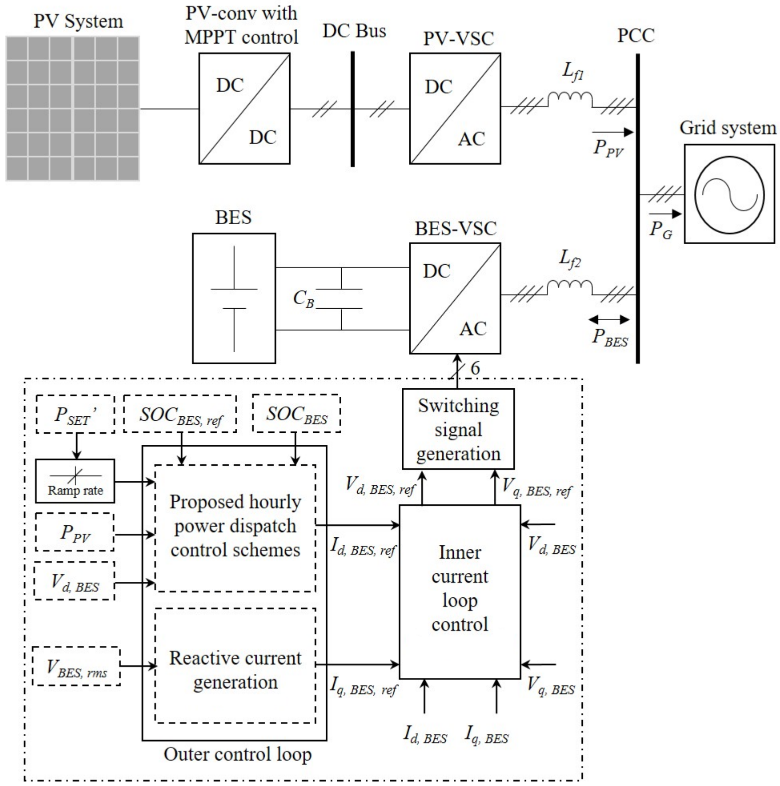

Figure 1. The general structure of the PV-BES system

2.2. An improved rule-based control scheme

The conventional rule-based control scheme of the BES system for hourly dispatch of PV system output has been introduced in [22]. The conventional rule-based control scheme is simple, requires minimal computation times, and does not require an accurate BES system model compared to an optimisation-based control scheme. The conventional rule-based control scheme can only control the BES from overcharging and overdischarging; however, it is not able to sustain the BES power at the desired level. Such an imperfection makes the conventional controller unable to support the continuous BES power required for dispatching intermittent PV output power. The rules of the controller are divided into two parts: rules for SOC_{BES} and I_{BES} constraints, respectively. For the SOC_{BES} constraint, the rules are created to guarantee the SOC_{BES} to be kept within the desired limit ($SOC_{BES,min}$ and $SOC_{BES,max}$) during the smoothing and dispatching process. Meanwhile, in the I_{BES} constraints, the rules are developed to limit the charging and discharging current of BES at the desired operational limit ($I_{BES,min}$ and $I_{BES,max}$). In the present work, some improvements to the conventional rule-based control scheme have been implemented, as suggested in [22]. The overall structure of the improved rule-based control scheme is illustrated in Figure 2. As illustrated in the figure, the SOC power correction (P_{SOC}) is added to the conventional rule-based control scheme to ensure the SOC_{BES} is maintained at the desired SOC level ($SOC_{BES,ref}$) from the beginning of the process until the end. The P_{SOC} in a unit of MW is applied to the $P_{BES,tar}$ signal, where the positive and negative values of P_{SOC} represent the shortage and the surplus energy of BES to maintain SOC_{BES} at $SOC_{BES,ref}$, respectively.

The control scheme's rules are established in accordance with the intended operational limitations of the BES system in (1)-(3). In the first stage, the rules are developed based on the BES voltage constraint mentioned in (3). In this stage, the $V_{d,\ BES}$ input is filtered to ensure the $V_{d,\ BES}$ is maintained at $\pm 10\%$ of the rated $V_{d,\ BES}$. The input of $V_{d,\ BES}$ is used to calculate the target current of the BES system, $I_{BES,\ tar}$. For the second stage, the rule based on the BES SOC constraint mentioned in (1) is developed. The rule is created to guarantee the SOC_{BES} to be kept within the desired limit ($SOC_{BES,\ min}$ and $SOC_{BES,\ max}$) during the smoothing and dispatching process. The rule automatically stops the BES operation if the SOC_{BES} reaches the maximum and minimum limits during the smoothing and dispatching processes. For the final stage, the rules are developed based on the BES current constraint mentioned in (2). The rules are developed to limit the charging and discharging current of BES at the desired operational limit ($I_{d,\ BES,\ min}$ and $I_{d,\ BES,\ max}$). The developed rule can prevent BES from overcharging and overdischarging, which can have adverse effects on BES.

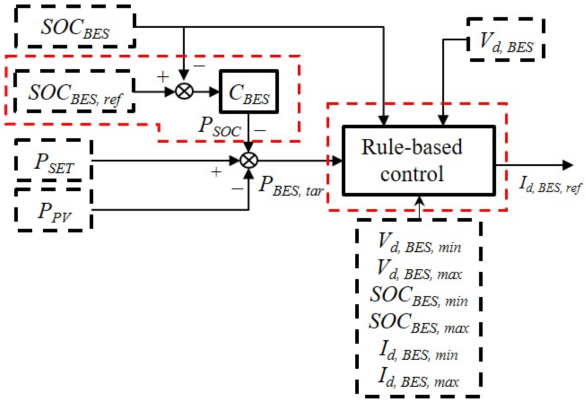

Figure 2. Improved rule-based control scheme

2.3. Simulation set-up and evaluation of the performance of the control methods

MATLAB/Simulink was used in order to verify the effectiveness of an improved rule-based control scheme. During simulation in MATLAB/Simulink, the actual P_{PV} and P_{SET}' data were used. The P_{PV} and P_{SET}' for 7 AM and 7 PM data were saved in a MAT-file. MAT-file is a binary file format used to store data in multiple variables or structures in MATLAB. The P_{PV} and P_{BES} signals were connected to the sum function block, which represented the PCC bus. In the simulation, to consider the losses of the converter, it was assumed that the BES-VSC power converter block can track the $I_{d,\ BES,\ ref}$ coming from the control scheme perfectly with losses of 5%. The BES-VSC power converter is represented as a gain block ($\eta_{BES-VSC}$) of 0.95. The Li-ion type of PowerSim battery model in MATLAB/Simulink was used as BES energy storage. For the rule-based control scheme, the rules in the control scheme are implemented in the MATLAB function block, where the C/C++ code language is used to represent the rules. The C++ code for rules control was written in the MATLAB function block editor. During the simulation process, the $P_{BES,\ tar}$ signal was used as the input MATLAB function block, while $I_{d,\ BES,\ ref}$ was the output of the control scheme.

In order to evaluate the robustness of each control scheme, case studies of varying BES capacities were considered. The purpose of the case studies is to verify the effect of the BES capacity on the control scheme's performance. For these cases, the capacity, C_{BES}, was set to 0.25 MWh (416.7 Ah), 0.3 MWh (500 Ah), and 0.35 MWh (583.3 Ah), respectively. In addition, analysis of simulation results was also given through evaluation using the performance index [22], battery health index (BHI) [26] and efficiency (η) [20] as given in (4)-(6). The value of N_x of (4) denotes the number of occurrences of the deviations, while dP_x represents the deviation between, powers delivered to the grid, PG, with respect to the power reference set-point, P_{SET}. The PI_0 and PI_{BES} of (6) represent the performance index without and with BES, respectively. For dP criteria, it was assumed that deviations exceeding $\pm$ 0.12 MW (10% of C_{PV}) are unacceptable (dP_{un}). Meanwhile, for PI and BHI, smaller values indicate high dispatching performance and effective usage of the BES device within safe operating limits.

$$PI = \sum N_x \times |dP_x| \tag{4}$$

$$BHI = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left[SOC_{BES}\left(t\right) - SOC_{BES,ref}\left(t\right)\right]^2} \tag{5}$$

$$\eta = \left[\left(PI_0 - PI_{BES}\right)/PI_0 \times 100\right] \tag{6}$$

3. RESULTS AND DISCUSSION

The simulation results are presented and discussed in this section. Section 3.1. presents the performance of PV-BES using an improved control scheme, where the details of power dispatching profiles are expounded upon. Section 3.2. provides the effects of the BES capacity on the improved control scheme performance and the PV-BES system dispatching performance compared to other control schemes.

3.1. Dispatching performance's of the PV-BES system by using an improved rule-based control scheme

Firstly, for the preliminary study, the simulation is carried out to present the dispatching performance of the PV-BES system without a control scheme. This case considers a BES size of 0.3 MWh with an initial capacity set at 60% of the total capacity. In addition, it is assumed that the BES system will be disconnected from the PV system if the SOC_{BES} is outside the desired operating constraints of BES. Figure 3 shows the dispatching performance of the PV-BES system without the control scheme of BES. From Figure 3(a), the fluctuations in the output power of PV system, P_{PV} are effectively mitigated and dispatched only from 7 AM to 8 AM due to the disconnected BES system from the system. The BES is disconnected from the system due to the SOC_{BES} level that has reached the $SOC_{BES,min}$ as illustrated in Figure 3(b). From the results, it can be concluded that without a control scheme applied to the system, a larger BES capacity is desired in order to keep the BES continuously operated within the SOC_{BES} level. Therefore, the SOC_{BES} needs to be properly controlled in order to satisfy acceptable dispatching performance using a minimum capacity of BES.

Figure 4(a) to Figure 4(d) present the dispatching operation of PV-BES system output power, $V_{d,\ BES}$ profiles, SOC_{BES} profiles and $I_{d,\ BES}$ profile at 90% accuracy of P_{SET} forecast using conventional rule-based and improved rule-based control schemes, respectively. As shown in Figure 4(a), the dispatching operation of the PV-BES system by using an improved rule-based control scheme can track the P_{SET} perfectly while keeping the BES operational constraints at the desired limits. As evident from the Figure 4(b) to Figure 4(d), all operating constraints of BES are varied within the desired operating ranges. Some spikes exist in the dispatching output mostly between 11 AM and 3 PM because of the current block inside the controller for safe operation purposes. Meanwhile, Figure 4(a) also illustrates the poor dispatching performance of conventional rule-based control scheme. The conventional rule-based nearly failed to track the P_{SET} perfectly between 1 PM to 7 PM due to insufficient BES energy.

Figures 5 and 6 illustrate the dP curves, the corresponding histograms, and the normal distribution curves of dP for conventional rule-based and improved rule-based control schemes, respectively. In Figure 5(a), by using a conventional rule-based control scheme, the dP occurred up to 0.45 MW. The calculated unacceptable of dP is equal to 3.64% instead of 42.1% without using the control scheme, as illustrated in Figure 5(b). Meanwhile, the dP curve in Figure 6(a) illustrated by using an improved rule-base control scheme shows that most of the time the dP occurs within ± 0.12 MW. The calculated unacceptable of dP is equal to 0.01%, as illustrated in Figure 6(b). The obtained results prove that the performance of the improved rule-based control scheme is better than that of the conventional rule-based control scheme.

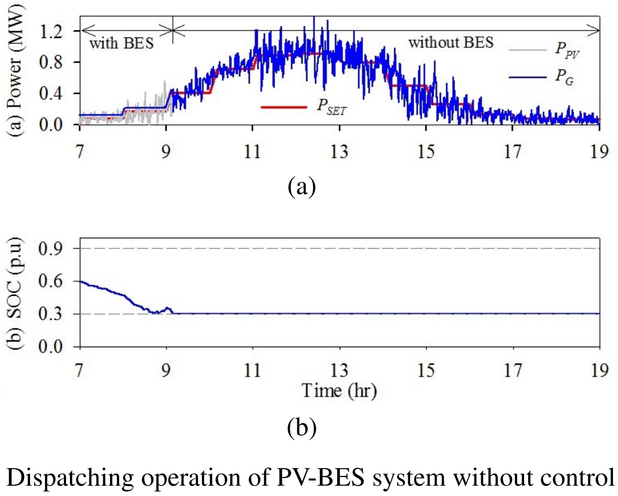

Figure 3. Dispatching operation of PV-BES system without control scheme

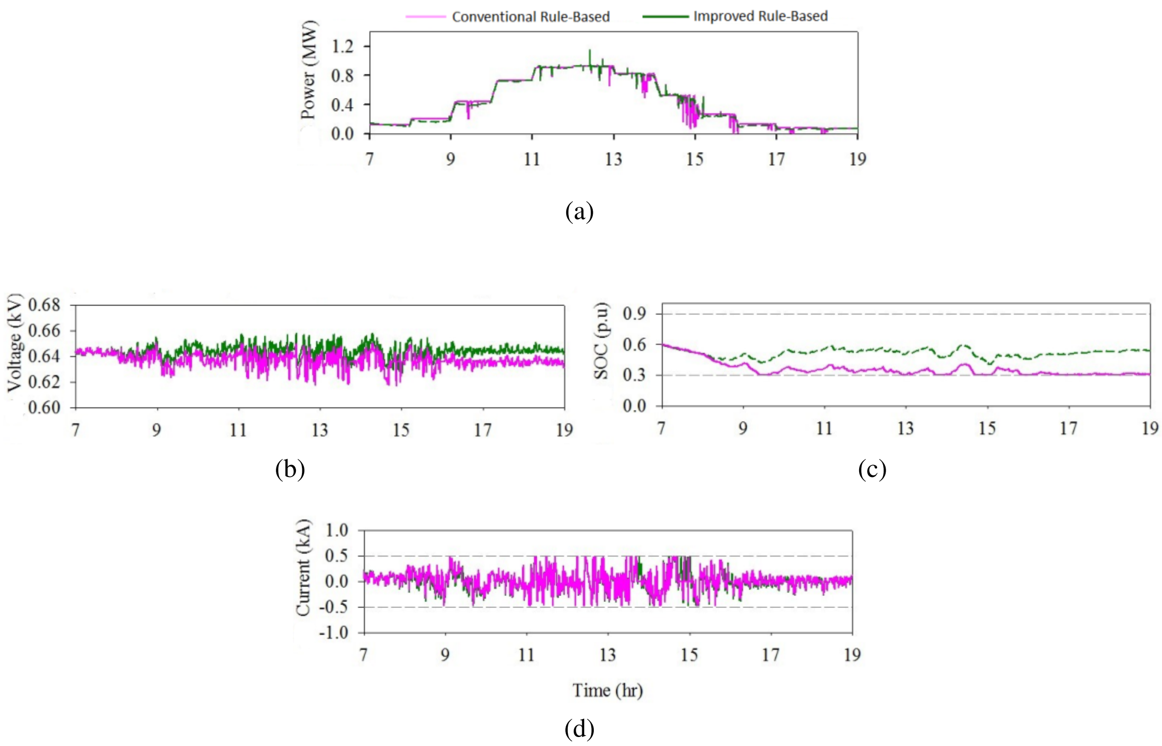

Figure 4. Performance of PV-BES using different control schemes

Finally, Table 1 gives the details of extracted results from Figures 5 and 6. The results clearly show that the improved rule-based control scheme is more efficient in the dispatching process with a performance index, PI, of 36.83 and an efficiency of 94.5% compared to the conventional rule-based control scheme with PI and η of 109.0115 and 83.6%, respectively. Besides that, in terms of regulation of the state-of-charge, SOC_{BES}, using an improved control scheme, the SOC_{BES} is maintained at a minimum SOC_{BES} of 0.43 p.u and the BHI measured around 0.0817. From the results, it can be proved that the improved control scheme can optimally smooth the fluctuation of P_{PV}, and extend the lifetime of the BES system. By effectively managing P_{PV} fluctuations, the improved control scheme aids in maintaining grid stability and reliability. Also, prolonging the BES system's lifespan is economically significant. BES systems are a substantial investment in PV system infrastructure, and increasing their longevity means better returns on investment and reduced overall system maintenance and replacement costs.

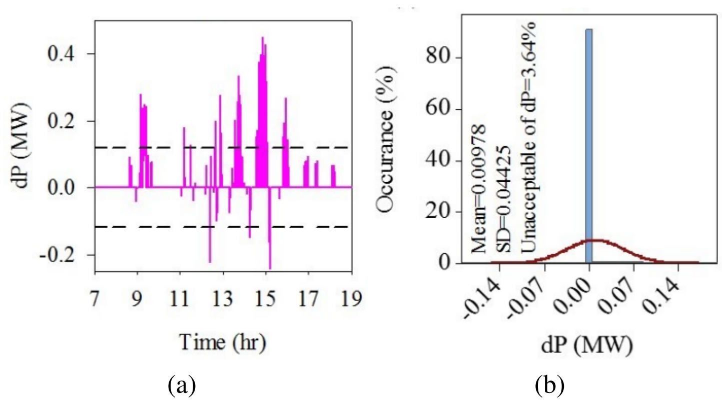

Figure 5. dP profile: (a) it responding histogram and (b) it distribution profile by using conventional rule-based control scheme

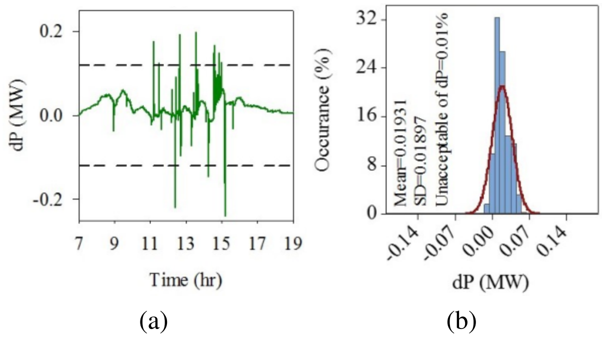

Figure 6. dP profile: (a) it responding histogram and (b) it distribution profile by using an improved rule-based control scheme

Table 1. Extracted results of PV-BES dispatching performance using conventional rule-based and improved rule-based control schemes

Parameters (unit)		Rule-based	
		Conventional	Improved
$P_{PV,\ rated}$ (MW)		1.2	
P_{SET} accuracy (%)		90	
C_{BES} (MWh)		0.287	
$SOC_{BES,\ i}$ (p.u)		0.6	
$V_{d,\ BES}$ (kV)	Max	0.6512	0.6593
	Min	0.6172	0.6285
SOC_{BES} (p.u)	Max	0.6000	0.6274
	Min	0.3009	0.4337
$I_{d,\ BES}$ (kA)		±0.478	
PI		109.0115	36.8371
BHI		0.2525	0.0817
η (%)		83.6447	94.4732

3.2. Effect of BESS capacity on the dispatching operation of PV-BES system

Table 2 presents the effect of BES sizes on the dispatching performance for each control scheme, respectively. For the unacceptable value of dP, the results are evaluated and analysed through the normal distribution of dP. For the conventional rule-based control, the unacceptable value of dP is reduced from 3.64% to 2.81% if the size of BES changes from 0.287 to 0.35 MWh. However, with the improved control scheme, the unacceptable level of dP can be reduced further to nearly 0%. Based on the results, it can be concluded that by using an improved control scheme, the size of the BES can be reduced, which contributes to a minimum cost. In terms of the PI, BHI and η criteria, the results are also provided in Table 2, respectively. From the PI results, by using 0.35 MWh of BES, the PI of a PV-BES system with improved rule-based control can be achieved up to 30.5. However, for conventional rule-based systems, the PI is only reduced up to 98.7. In terms of BHI criteria, the increased BES size can decrease, or, in other words, improvise the BHI for the case using an improved rule-based control scheme. On the other hand, the results are totally different from those of the conventional rule-based control scheme. The decreasing BHI of the former control scheme is due to the reduction of the charging and discharging depth levels of BES. By using 0.35 MWh of BES, the BHI for an improved rule-based control scheme is 0.0681, while the conventional rule-based control scheme is only 0.2539. From the results, it is evident that the increasing BES size and the use of an improved rule-based control scheme can prolong the BES system's life. Finally, Table 2 also compares the η of the PV-BES system with conventional rule-based and improved rule-based control schemes. From the results, the expansion of the C_{BES} can increase the η of the PV-BES system with conventional rule-based and improved rule-based control schemes. As evident, by increasing BES to 0.35 MWh, improved rule-based and conventional rule-based control schemes increased the overall efficiency of PV-BES systems to 95.4 and 85.2, respectively. Overall results manifest 10.2% deviation in efficiency when the improved rule-based control scheme is used instead of the conventional rule-based control scheme.

Table 2. Effects of C_{BES} on dispatching performance by using a rule-based control scheme

	Rule-based control scheme					
	Conventional			Improved		
C_{BES} (MWh)	PI	BHI	η (%)	PI	BHI	η (%)
w/o BES	666.5	-	-	666.5	-	-
0.20	136.7	0.2420	79.5	67.8	0.1114	89.8
0.25	117.3	0.2494	82.4	45.3	0.0923	93.2
0.287 (optimal)	109.0	0.2525	83.6	36.8	0.0817	94.5
0.35	98.7	0.2539	85.2	30.5	0.0681	95.4

4. CONCLUSION

An improved rule-based control scheme for the BES system to smooth out and dispatch the fluctuation of the PV system on an hourly basis to the utility grid is presented. The operational constraints for BES are considered to ensure providing continuous power regulation and safe operation service. Simulation results show good performance of the proposed control scheme compared to other previously developed methods through the analysis of efficiency, which has been measured at around 94.47% (at BES = 0.287 MWh). The results also demonstrate that the proposed control scheme was able to minimise the unacceptable deviation completely by using a 0.35 MWh BES system. The BHI is also the lowest, i.e., 0.0817 (at BES = 0.287 MWh), compared to other control schemes. In conclusion, the overall results clearly indicate the proposed control scheme's capability to mitigate the PV system's output power fluctuation with a better life of the BES system.

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