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Strategy to reduce solar power fluctuations by using battery energy storage system for UTeM's grid-connected solar system

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ABSTRACT

Recent years have witnessed the increasing uptake of solar photovoltaic (PV) installations, ranging from a few kilowatts for residential rooftops to a few megawatts for large-scale solar farms. One of the key challenges for the solar PV systems is its dependency on the solar energy, which is intermittent in nature and highly unpredictable. In this regard, battery energy storage system (BESS) is regarded as the effective solution that can smoothen the output power fluctuation from the solar PV system. Hence, this work utilized BESS that had fast response time with high power and energy density to reduce the solar output fluctuations from a real grid-connected solar system installed at the campus rooftop. The characteristic of the PV power fluctuation and the BESS storage requirement to smooth out the fluctuation within the allowable limit were determined and analyzed. More importantly, actual solar irradiance data with an interval of one minute was utilized in this work. The findings suggest that BESS with 66% of the installed solar capacity and 21% of the average daily solar generation of the installed system are required to smoothen the solar fluctuation that exceeds the ramp rate limit of 10%/min.

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1. INTRODUCTION

In recent years, the usage of renewable energy has increased significantly all around the world. As a developing country, Malaysia's government is giving support and encouragement for the development of sustainable energy in order to improve energy development in Malaysia by revising the national renewable energy mix target from 20% to 31% by 2025 [1]. In Malaysia, solar energy is one of the most common and easiest renewable energies that can be obtained, where the monthly solar irradiation is estimated to achieve 600 MJ/m^2 due to Malaysia's strategic geographical location [2]. Ho *et al*. [3] showed the potential growth of solar energy in Malaysia, where the cities received great average daily solar irradiation. Malaysia has started to introduce applications that utilize the photovoltaic (PV) systems such as feed-in tariff (FiT) and net energy metering (NEM) due to the functionality and economic aspects of the PV system [4]. As presented in [5], the power generated by solar PV in Malaysia has been leading other renewable energy since 2015. In 2016, the Energy Commission of Malaysia started the bidding process for large scale solar (LSS), offering a total of 434 MW for Peninsular Malaysia with levelized tariff from 17.68 to 24.81 sen/kWh to accelerate renewable energy production in Malaysia [6], [7].

Due to inconsistent natural phenomena such as moving clouds, the solar irradiance obtained by the PV system changes within seconds to minutes and causes PV power fluctuation. The intermittent nature of PV generation is the source of power quality issues. In Spain, the recorded PV power ramp rate is up to 90% in 1 MW PV plant and 70% in 10 MW PV plant [8]. In US, the ramp rate is up to 70% in 5 MW PV plant [9]. In Hawaii, the maximum power fluctuation for the La Ola PV power plant with an output power of 600 kW is 380 kW/min, which is equal to 63% of its output capacity [10]. Hence, this has attracted the concern of grid operators, where guidelines of PV power ramp rate limits have been introduced to reduce the effect of PV power fluctuation on the grid. The power fluctuations of PV can be compared with the most acceptable ramp rate limit, *rmax*. The PV power fluctuation needs to be maintained within *rmax* to ensure the stability of the grid, according to different countries. The electric power authority in Puerto Rico (PREPA) had imposed new grid codes which limited the maximum PV power fluctuation to 10%/min of the rated PV plant capacity [11]. In Mexico, the limitations are set around 1%/min to 5%/min. In Malaysia, the grid operator *tenaga nasional Berhad* introduced a preliminary reference, where the battery energy storage system (BESS) to be implemented must be equipped with ramp rate control with the acceptable ramp rate limit of 10%/min, in their technical guideline. Besides that, it is also mentioned in the guidelines for energy commission that the power output ramp rate shall be regulated within 15%/min of the rated PV plant capacity [12]. Research by Marcos *et al*. [13], a comparison of the PV power fluctuation has been made for different sizes of PV plant and different *rmax*. The number of fluctuations that exceed the *rmax* will decrease when *rmax* increases. When the ramp rate power control is introduced to the PV system, the fluctuation will be limited to 10%/min with the help of the energy storage system (ESS) due to its fast time response characteristics in charging and discharging [14]-[16].

The usage of ESS in electrical grids has drawn the attention of researchers in recent years. Energy produced from the PV generation at a certain time can be stored by ESS and be used when it is needed. There are plenty of applications that utilize ESS in the complete chain involving energy generation, transmission as well as distribution to end user [17], [18]. They are grid stabilization, peak shaving, load shifting, power reserve, frequency and voltage regulation, back-up power supply during outages and so on [19]-[21]. According to the overviews discussed in [22], [23], the generation of power at grid level requires a bigger scale of ESSs, whereas a smaller scale of ESSs is used at lower voltage distribution level. When the electricity bills are expensive due to the high demand charges based on peak load, ESS can be used to supply power at peak load [24], [25]. Besides that, ESS can also be utilized to support the essential supply of electricity immediately when a blackout happens [26], [27]. Besides, the characteristics of the ESSs, which are able to optimize the output from renewable sources, have driven the application of ESSs with renewable energy to solve the power shortage problem [28]-[30]. The reliability of the power supply is improved by utilizing solar and wind power generation integrated with batteries [26], [31]. The research showed that the deployment of ESS effectively assisted in reducing electricity bills [32]. There are more further studies regarding ESS-PV can be found in [33]-[36]. In this regard, an integrated ESS-PV solar system is highly effective to smooth out the power fluctuation that exceeds the acceptable ramp rate limit before supplying the power to the grid.

In this paper, the PV power fluctuations were analyzed and studied by using the solar irradiance data collected from the solar system which was installed at the rooftop of the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) located in Melaka, Malaysia. PV power ramp rate control was used to smoothen the power fluctuation to satisfy the grid operator’s requirement. The smoothen PV power’s data was compared with the original PV power’s data. The main objective of this paper is to determine the maximum power and energy capacity of the BESS required to smoothen the solar fluctuation that exceeds the ramp rate limit of 10%/min.

2. METHOD

2.1. Data collection

The solar irradiance data used in this paper was collected from the grid-connected PV system located in UTeM, Malaysia. In order to obtain precise results, actual solar irradiance data with 1 minute interval and synchronized resolution that was recorded daily during the whole of 2016 was used. This PV system was located at the rooftop of the electrical engineering faculty’s laboratory building, which is shown in Figure 1. This system consisted of 48 units of sharp thin-film solar panel with a rated output of 130 W each, which can produce a total power of 6.24 kW. The solar panel was tilted at 10º facing south to obtain the optimum output. All the solar panels were connected to three DC/AC inverters. With the consideration of system losses, the system performance ratio for thin-film solar panel is 86.67% [37], which means that the losses of the PV system are 13.33%. Therefore, the actual power output from the PV system is 5.4 kW when the solar irradiance is 1000 W/m^2. The one-year PV power output data of the system was converted from the solar irradiance data by using a related formula.

Figure 1. UTeM solar PV system

2.2. PV power fluctuations

With a total of 1,440 samples of 1-minute PV power data per day, the power fluctuation for each day can be determined. The PV fluctuation power at time t can be defined as the subtraction between two successive PV output powers with a certain sample time, Δt, and normalized with the inverter power, P^*, as shown in (1). In this project, the sample time was one minute.

$$\Delta P_{\Delta t}(t) = \frac{[P(t)-P(t-\Delta t)]}{P^*} \times 100\% \quad (1)$$

After the power fluctuation was calculated, the power fluctuation can be compared with a different value of *rmax* and the number of occurrences where the fluctuation exceeded *rmax* can be identified by using:

$$\text{abs}[\Delta P_{\Delta t}(t)] \geq rmax \quad (2)$$

The number of occurrences where the fluctuation exceeded *rmax* will be presented in percentage. In order to observe the *rmax* limitation of the power fluctuation, eight different values of *rmax*, which were 1, 3, 5, 10, 15, 20, 25, and 30 %/min, were used for comparison, respectively. In order to obtain a precise result, one-year PV power fluctuations were compared with *rmax*.

2.3. BESS storage requirement

Smoothing of PV power fluctuation by using BESS will lead to a significant additional cost for the PV plant operator. Therefore, the battery storage has become important, where a reduction in battery size will help in the reduction of the additional cost. The required maximum battery power and energy capacity to smooth out the PV power fluctuation can be determined via the worst fluctuation model. This model can be used to determine the size of battery for any size of PV plant and maximum acceptable ramp rate limit. BESS will respond to the rapid changes of PV power according to the worst fluctuation model. Firstly, the time constant, τ(s), for the worst fluctuation of the PV system needs to be determined. The time constant can be determined by using (3). The shortest perimeter of the PV plant, l(m), is calculated based on the dimension from the datasheet of the solar panel.

$$\tau = (x \times l) + y \quad (3)$$

Where x=0.042 second per meter and y=-0.5 s. After the time constant is obtained, the battery power can be calculated by using (4):

$$P_{BAT,MAX}(t) = \frac{P^*}{100}\left[90 - (\tau \cdot rmax)\left(1 + ln\frac{90}{\tau \cdot rmax}\right)\right] \quad (4)$$

where P^* is the inverter power, τ is in seconds and *rmax* is in % per second. The battery will discharge as long as the power fluctuation reaches the PV output power of 10%, where the battery energy expressed in kWh can be calculated by:

$$E_{BAT,MAX}(t) == \frac{0.9P^*}{3600}\left[\frac{90}{2 \cdot rmax} - \tau\right] \quad (5)$$

the capacity of the battery will be doubled to smooth out either positive or negative fluctuation as in (6):

$$C_{BAT} = 2 \cdot E_{BAT,MAX} \quad (6)$$

2.4. Ramp rate control

Ramp rate control is triggered under the condition when the fluctuation of PV power is more than the prescribed acceptable ramp rate limit, *rmax*, before being injected into the grid. As mentioned earlier, TNB, the grid operator, and *Suruhanjaya Tenaga* (ST) in Malaysia had set their guidelines for the ramp rate limitation. According to ST, the ramp rate of the power delivery shall be controlled within 15%/min. However, this work considered a more stringent $rmax$ of 10%/min [11]. The basic block diagram of the PV power ramp rate control is shown in Figure 2. $P_{PV}(t)$ indicates the PV output power, $P_G(t)$ is the output power to the grid and $P_{BAT}(t)$ is the power from or to the battery. At first, the maximum power point tracking (MPPT) enables the inverter to allow all the PV power output to flow into the grid. After applying ramp rate control, $P_{PV}(t)$ will be delivered to the ramp rate limiter. The power fluctuation is compared with *rmax* by the limiter. If the PV power fluctuation exceeds *rmax* as shown in (7), the control will be activated.

$$|[\Delta P_{\Delta t}(t)]| \geq rmax \quad (7)$$

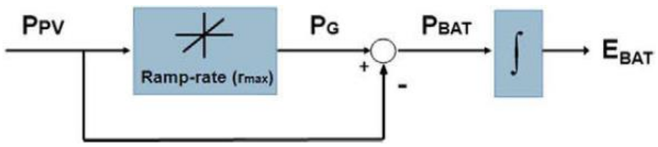


Figure 2. Basic block diagram of PV power ramp rate control [14]

The corresponding power shortage or excess is then compensated from the BESS, either by discharging from or charging to the battery. P_G represents the smoothed output power injected to the grid after the ramp rate control process. For simplicity, all the potential electronic converters and battery losses are neglected here.

$$P_G = P_{PV} + P_{BAT} \quad (8)$$

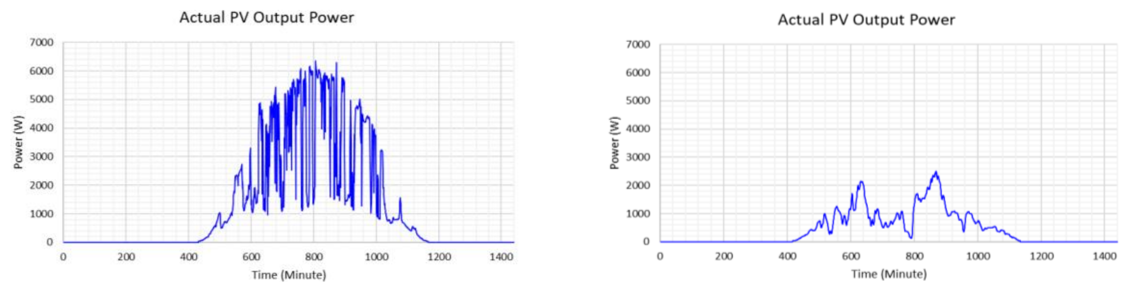
3. RESULTS AND DISCUSSION

3.1. PV power output

The PV output power is directly proportional to the solar irradiance. The solar irradiance data from year 2016 corresponded to a total of 352 days, where it was converted into PV output power with the consideration of system losses. The solar irradiance data for some of the days in 2016 was not recorded as the system was under maintenance. Two examples of a daily actual PV output using 1-minute solar irradiance data are shown in Figure 3(a) and Figure 3(b), which show the severity and frequency of the PV power fluctuation. From Figure 3(a), it can be seen that 06 January 2016 was a sunny day and the PV system had high production of energy, where the total PV output power of the day was 1,810 kW and the maximum PV output power reached 6.3 kW. From Figure 3(b), it can be observed that 01 December 2016 was a cloudy or rainy day and the PV system had low production of energy, where the total PV output power of the day was only 614 kW and the maximum PV output power reached 2.5 kW.

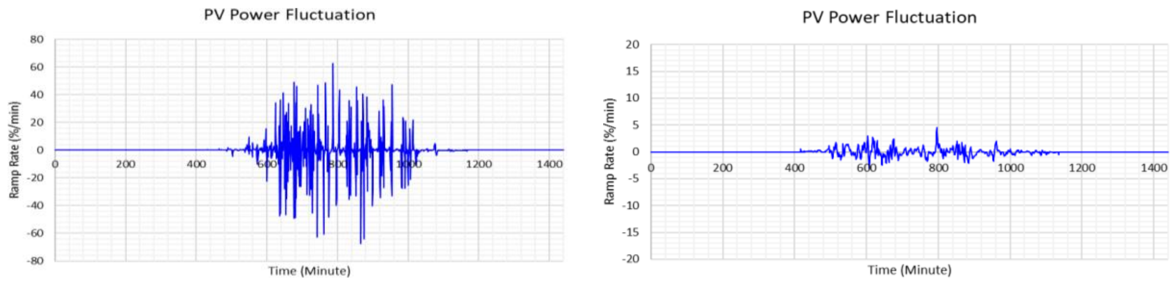
3.2. PV power fluctuations without BESS

The PV power fluctuation was determined by using the related equation, as mentioned in the previous section. There are two types of power fluctuation, which are upward fluctuation and downward fluctuation. From Figure 4(a), it can be seen that the PV power fluctuation occurred on 06 January 2016 and the maximum upward fluctuation was up to 62.6% while the maximum downward fluctuation was 67.6%. In another example, the PV power fluctuation shown in Figure 4(b) (cloudy or rainy day) was lesser compared to Figure 4(a) (sunny day). The maximum upward fluctuation was up to 4.5% while the maximum downward fluctuation was 3.1%. The occurrence of PV power fluctuation was very low, which means that the PV power fluctuation is acceptable and can be inserted into the grid as frequency variation.



(a) (b)

Figure 3. PV output power of the UTeM PV system no.3 on (a) 06 January 2016 and (b) 01 December 2016



(a) (b)

Figure 4. PV power fluctuation on (a) 06 January 2016 and (b) 01 December 2016

Next, the one-year PV power fluctuation was used for comparison with different maximum allowable ramp rate limit values, *rmax*, which were 1, 3, 5, 10, 15, 20, 25, and 30 %/min, respectively. Table 1 shows the number of occurrences where the fluctuation exceeded *rmax* in all the months of 2016. In the comparison, the number of occurrences where the fluctuation exceeded *rmax* is shown in minutes and percentage. The total number of PV power fluctuation that exceeded *rmax* was converted from minutes to percentage by dividing it with the total number of minutes in 352 days. For *rmax*=1%/min, the power fluctuation exceeded *rmax* for 17.92% of the time, while this value dropped to 0.89% when *rmax*=30%/min. The total number of power fluctuations that exceeded the maximum allowable ramp rate limit of 10%/min was 20,527 minutes in 352 days, which is equal to 4.05%. For large-scale solar plants, the large amount of PV penetration can negatively affect the stability and reliability of the grid. Therefore, the implementation of an energy storage system in the PV system is needed to smooth out the PV power fluctuation.

Table 1. Number of fluctuations exceeded *rmax* in 2016

rmax (%/min)	1	3	5	10	15	20	25	30	Number of days
Jan	8190	4882	3829	2492	1785	1317	947	710	30
Feb	6504	3956	2962	1861	1294	929	666	462	23
Mar	7410	4291	3384	2184	1538	1118	816	593	27
Apr	8073	4147	3057	1845	1230	847	539	326	30
May	7687	3920	2829	1681	1112	768	515	356	31
Jun	6929	3611	2547	1424	908	606	399	255	30
Jul	7227	3925	2808	1586	1049	713	494	311	28
Aug	8473	4227	2934	1618	1030	709	465	305	31
Sep	8577	4744	3366	1896	1195	822	586	405	30
Oct	8010	3961	2605	1397	848	591	397	271	31
Nov	5796	2844	1921	997	632	420	283	199	30
Dec	7960	4167	2906	1546	992	650	454	337	31
Total number of fluctuations exceeded *rmax* (minute)	90836	48675	35148	20527	13613	9490	6561	4530	
Total number of fluctuations exceeded *rmax* (%)	17.92	9.60	6.93	4.05	2.69	1.87	1.29	0.89	

3.3. BESS storage requirements

Two representative examples will be discussed in this section to show the results of ramp rate control. Figure 5(a) shows the ramp rate control result with *rmax* of 10%/min on 06 January 2016. The blue line represents the actual PV output power, P_{PV}, and the red line represents the smoothed PV output power, P_G. Initially, all the PV power output was injected into the grid, where it is shown as the actual PV power in Figure 5(a). When the power fluctuation was more than *rmax* of 10%/min, the ramp rate control was activated, and the PV power was smoothed to be within 10%/min. For the fluctuation that was lesser than 10%/min, the PV output power was directly injected into the grid without smoothing. The power fluctuation of the smoothed PV power was lower than the actual PV power. The results in Figure 5(a) correspond to the total of 1,440 samples of that day, while Figure 5(b) is the zoomed-out version of Figure 5(a) which shows the result for 10 minutes for a better comparison. From Figure 5(b), it can be observed that the PV output power was fluctuating significantly between 2.5 kW to 5.5 kW in 10 minutes. The highest PV power fluctuation occurred between the 729th minute and 73th minute from 2.5 kW to 5.5 kW. By using ramp rate control, the PV power fluctuation of the PV output power that exceeded *rmax* of 10%/min was controlled and smoothed to be within 10%/min, as shown in Figure 5(c). The maximum upward and downward PV power fluctuation was 10%. The smoothed PV power had less fluctuation, which can be observed in Figure 5(b). The smoothed PV power range was maintained within 4.2 kW to 5.4 kW in these 10 minutes as the PV power fluctuation was reduced.

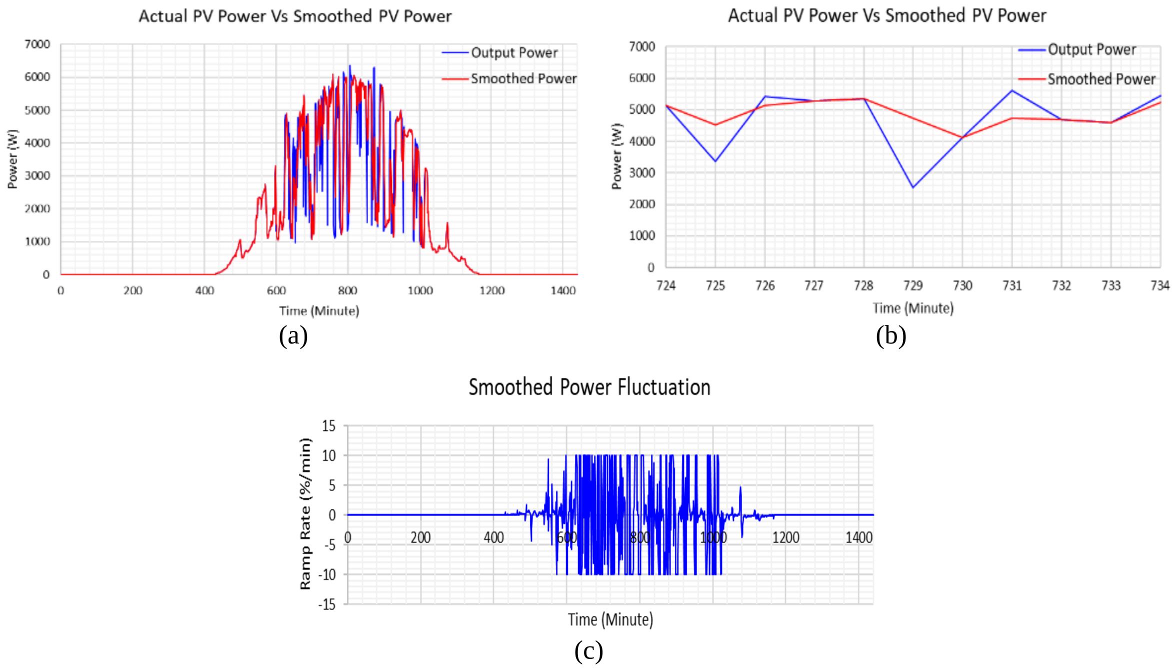


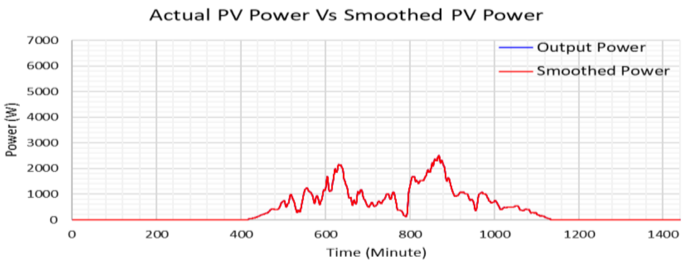
Figure 5. The results for (a) ramp rate control with *rmax* of 10%/min on 06 January 2016, (b) ramp rate control with *rmax* of 10%/min on 06 January 2016 between the 724th minute and 734th minute, and (c) smoothed PV power fluctuation with ramp rate control *rmax* of 10%/min on 06 January 2016

In order to make a clearer comparison, the result for ramp rate control with *rmax* of 10%/min on 01 December 2016 is used as another example, which is presented in Figure 6(a). In Figure 6(a), no changes between the smoothed PV power and actual PV power were observed. This is because the PV power fluctuation did not exceed *rmax* of 10%/min. Therefore, there was no difference between the PV output power and smoothed PV power. From Figure 6(b), the PV power fluctuation of the smoothed PV power was the same as the actual PV power as the PV power fluctuation of that day did not exceed 10%/min.

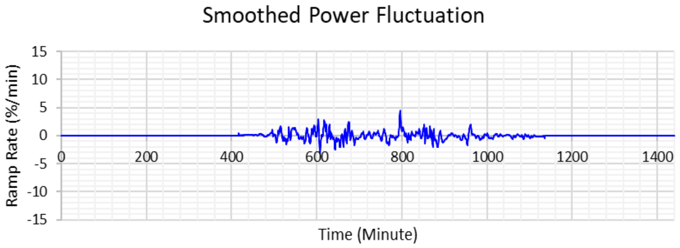
In order to reduce the PV power fluctuation, the difference between the actual PV power and smoothed PV power will be compensated by BESS where the extra power will be charged into the battery and the battery will be discharged when there is a shortage of power. Figure 7(a) shows the charging and discharging power of the battery on 06 January 2016. The maximum charging or discharging power of the battery was 3.6 kW. From Figure 7(b), it can be seen that the battery did not charge or discharge the power to smooth out the PV power fluctuation on 01 December 2016. This is because the PV power fluctuation of that day was low and the ramp rate control was not activated to reduce the fluctuation.

In Table 2, it can be observed that the maximum charging or discharging power of the battery was 4.14 kW in March, which is equal to 0.66 of 6.24 kW of the PV system. The maximum energy capacity in

September of 2016 was 5.24 kWh. The required battery energy capacity was 10.48 kWh, where the capacity of the battery was doubled to smooth out either positive or negative fluctuation. By comparing the result of the worst fluctuation model and ramp rate control, the maximum power obtained from the worst fluctuation model was 5.54 kW, where the maximum power obtained from ramp rate control was 4.14 kW. There was a big difference of 9.59 kWh between the worst fluctuation model and ramp rate control. The battery capacity of 0.89 kWh calculated from the worst fluctuation model was insufficient to smooth out the PV power fluctuation as the required energy capacity obtained from the ramp rate control was 10.48 kWh. Therefore, this shows that the worst fluctuation model is not suitable to be used in Malaysia to identify the required power and energy capacity of battery. From the result above, the required maximum power and energy capacity of the battery are 4.14 kW and 10.48 kWh for the 6.24 kW PV system, which are equal to 0.66 kW and 1.68 kWh for every 1 kW_p PV system installed.

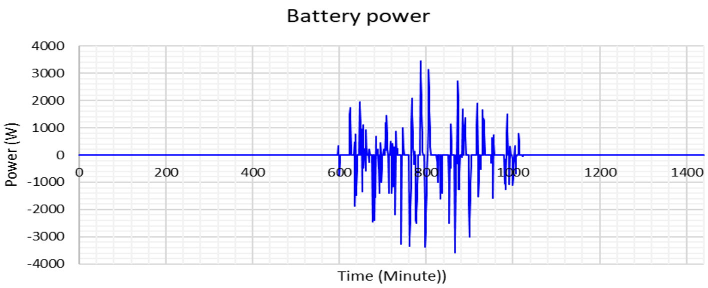


(a)

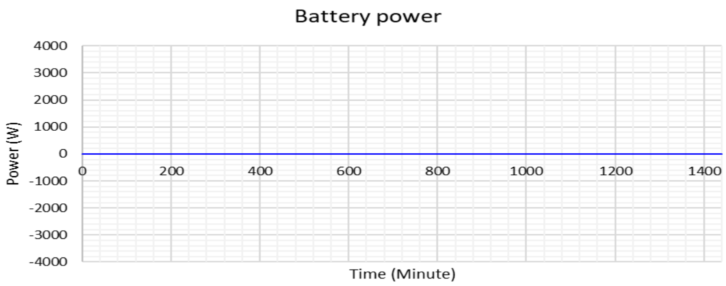


(b)

Figure 6. The results for (a) Ramp rate control with *rmax* of 10%/min on 01 December 2016 and (b) smoothed PV power fluctuation with ramp rate control *rmax* of 10%/min on 01 December 2016



(a)



(b)

Figure 7. Battery power on (a) 06 January 2016 and (b) 01 December 2016

Table 2. Battery power and energy capacity in 2016

Month	Charging (W)	Discharging (W)	Charging (Wh)	Discharging (Wh)
Jan	3,691.75	-3,605.22	3,448.10	-4,852.21
Feb	3,467.42	-3,832.36	2,837.01	-4,039.46
Mar	4,143.98	-3,924.30	5,171.65	-4,623.34
Apr	3,294.89	-3,235.40	4,149.56	-3,784.48
May	3,278.67	-3,388.89	3,230.50	-4,052.20
Jun	3,032.71	-3,086.03	2,640.07	-3,048.56
Jul	2,885.93	-2,916.32	3,202.25	-3,715.75
Aug	3,430.10	-3,527.45	3,484.10	-4,323.70
Sep	3,913.49	-3,673.47	3,809.91	-5,236.27
Oct	3,156.34	-3,507.87	3,210.47	-2,968.03
Nov	3,724.20	-3,309.06	2,780.49	-3,151.97
Dec	3,543.67	-3,376.02	2,937.70	-4,465.45

4. CONCLUSION

This paper has presented a ramp rate control with BESS to smooth out PV power fluctuation that exceeds *rmax* of 10%/min. The required power and energy capacity of the BESS system to smooth all the power fluctuations to be within the allowable limit of 10%/min for UTeM's 6.24 kW_p PV system are 4.14 kW and 10.48 kWh, respectively. This represents the BESS power rating of 66% of the solar installed capacity and 21% of the average daily solar generation. It is worth noting that the smoothened power that is injected into the grid will not affect the stability of the grid.

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