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CIGRE US National Committee
2017 Grid of the Future Symposium

Coordinated Battery Energy Storage Systems Sizing for Photovoltaic Ramp Rate Control

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SUMMARY

Battery energy storage system (BESS) can be used for various applications in power systems, especially for renewable energy integration. One of these applications is solar photovoltaic (PV) ramp rate control. The output power of a solar PV unit depends on the solar irradiance which varies with time due to the movement of sun and clouds. Such movements result in variability in the solar PV power output. If a single BESS is used to control the solar PV ramp rate, it will need to have both high capacity and long lifecycle to capture the large number of variations. A BESS technology with this characteristic is expected to have a high investment cost. To reduce the associated investment cost, two different BESS technologies are used in this paper for solar PV ramp rate control. One of the BESS units, mainly the one with higher lifecycle and capital cost, is used for controlling the small solar PV ramp rates while the other BESS unit with lower lifecycle and capital cost is used for controlling the large solar PV ramp rates. This way, the overall investment cost can be reduced without impacting the efficiency of solar PV ramp rate control. This paper proposes a coordinated BESS sizing model in which the optimal sizes of both BESS units are determined while taking into consideration the imposed ramp rate limits.

KEYWORDS

Solar photovoltaic, battery energy storage system, optimal sizing, ramp rate control.

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1. INTRODUCTION

The penetration of solar photovoltaic (PV) units in power systems has shown an increase in the past few years and is expected to continue growing in the near future. This is due to several factors such as the drop in solar PV technology cost, the advancements in power electronics and control methodologies, and the implementation of new regulations that allow solar PV owners to make profit when connected to the grid. If not properly controlled and managed, high solar PV penetration may introduce some challenges to the power system operation. One of the main challenges is caused by the fact that the primary source of solar PV is the solar irradiance which changes over the time causing the solar PV power to fluctuate. The variation in the solar PV ramp rate can be categorized into small ramp rates and large ramp rates due to weather changes and cloud passage. Both types of PV ramp rates may need to be addressed and controlled to ensure a reliable grid operation [1], [2].

Various methods have been discussed to solve the solar PV power variation issue and to control the ramp rate of the power injected to the grid. These methods include voltage regulating control [3], active power reserve [4], geographical dispersion [5], and energy storage integration [6]. However, it is shown that energy storage integration is the most attractive option as the installed storage can be used for other applications, such as energy arbitrage and regulation services, which increase the economic value of energy storage. Among the various available energy storage technologies, battery energy storage system (BESS) stands out to be the most mature technology that can be used for solar PV ramp rate control.

The main challenge that often faces BESS installation is the associated high investment cost. The BESS investment cost is strongly related to the selected technology and size. Sizing BESS for solar PV ramp rate control is addressed in literature and different methods are proposed to find the optimal size of the installed BESS. The work in [7] derives an analytical method to determine the required BESS maximum power and minimum capacity for controlling PV ramp rate. A statistical approach is adopted in [8] to determine the BESS size required to smooth the solar PV output power. The work in [9] uses a moving average technique to investigate BESS sizing for commercial solar PV system. In [10], the BESS size is found based on an economic dispatch solution. Although extensive, the reviewed literature only considers the installation of one BESS to control solar PV ramp rate and further ignores the variation between the BESS technologies characteristics which results in a higher total investment cost.

The solar PV ramp rate changes according to weather conditions. In the worst case, solar PV ramp rate may reach up to 100% of its rated capacity. If one BESS is used to control the solar PV ramp rate, it will need to have both high lifecycle and high capacity. A BESS with such characteristics is expensive and might not be economically viable to be purchased and installed. However, analyzing PV ramp rate variations reveals that large ramp rates rarely occur, unlike small ramp rates. Thus, in this paper, the small and large solar PV ramp rate controls are decoupled and two different BESS technologies are used to perform the PV ramp rate control. The BESS technology with higher cost and lifecycle, such as a Li-ion battery, will be used to control small solar PV ramp rates while the BESS with lower cost and lifecycle, such as a lead acid battery, will be used to control large solar PV ramp rates. A coordinated BESS sizing method is proposed to determine the optimal size for both BESS units in order to minimize the overall investment cost while satisfying the grid ramp rate control requirements.

The rest of the paper is organized as follows: Section 2 introduces and formulates the proposed coordinated BESS sizing model. In Section 3, a numerical example is presented to test the validity of the model and show its merits. Section 4 concludes the paper.

2. OPTIMAL BESS SIZING - OUTLINE AND FORMULATION

Figure 1 shows the PV-BESS structure studied in this paper. This system is connected to the grid via DC/AC inverter. For the sake of simplicity, the power electronic converters are not shown in the figure. The solar PV power signal fluctuates with time due to the variation in solar irradiance. If the PV power is fed to the grid as it is, it may negatively impact grid voltage values and cause considerable load-generation mismatch. Therefore, BESS units are integrated into the solar PV to control the ramp rate and to ensure a mitigated solar PV output. BESS 1 is installed to handle the large solar PV ramp rate while BESS 2 is used to mitigate the small solar PV ramp rate. It must be noted that BESS 2 is expected to perform high number of charging/discharging cycles while BESS 1 is expected to perform long charging/discharging periods. The produced PV power signal must comply with the grid ramp rate requirements as shown in Figure 1.

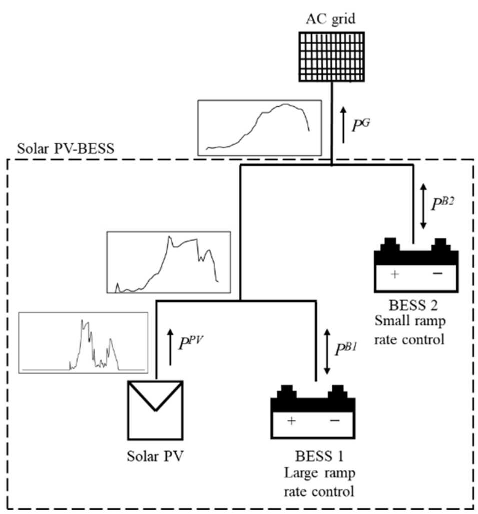


Figure 1. Studied PV-BESS structure for ramp rate control application

The objective of the BESS optimal sizing problem is to minimize the overall investment cost associated with installing the BESS units while satisfying the grid ramp rate requirement. The BESS investment cost can be divided into two parts: power rating cost in \$/kW and energy rating cost in \$/kWh. The objective function is defined by (1).

$$\min \sum_{i \in \mathrm{E}} P_i^R CP_i + C_i^R CE_i \tag{1}$$

where index i indicates the BESS technology, P_i^R and C_i^R represent the BESS optimal power rating and energy rating size, respectively, and CP_i and CE_i represent the BESS annualized power rating and energy rating costs, respectively. In this work, two BESS technologies are installed and therefore the BESS technology set E contains two members.

The power transferred to the grid (P_{dt}^G) is the summation of the solar PV power (P_{dt}^{PV}) and the installed BESS power (P_{idt}^B) as given by (2). Indices d and t represent days and considered time periods within each day, respectively. That is, if each hour is divided into an identical set of minutes (n), then the considered time periods for each day (t) is equal to 24×(60/n). In this work, 5-minute solar PV data is used (i.e., n=5). Since the sizing problem is solved for one year, a total number of 105,120 time periods will be considered. The change in the power transferred to the grid in all of the considered time periods should follow a permissible ramp rate limit imposed by the grid operator (3).

$$P_{dt}^{G} = P_{dt}^{PV} + \sum_{i \in \mathrm{E}} P_{idt}^{B} \qquad \forall d, \forall t \qquad (2)$$

$$\left| P_{dt}^{G} - P_{d(t-1)}^{G} \right| \le \Delta \qquad \forall d, \forall t \qquad (3)$$

The installed BESS units are governed by a set of constrains that model their operation as follow:

$$P_{idt}^{B} = P_{idt}^{dch} + P_{idt}^{ch} \qquad \forall i \in \mathrm{E}, \forall d, \forall t \qquad (4)$$

$$0 \le P_{idt}^{dch} \le u_{idt} P_{i}^{R} \qquad \forall i \in \mathrm{E}, \forall d, \forall t \qquad (5)$$

$$-(1 - u_{idt}) P_{i}^{R} \le P_{idt}^{ch} \le 0 \qquad \forall i \in \mathrm{E}, \forall d, \forall t \qquad (6)$$

$$u_{idt} - u_{id(t-1)} \le \gamma_{idt} \le \frac{u_{idt} - u_{id(t-1)} + 1}{2} \qquad \forall i \in \mathrm{E}, \forall d, \forall t \qquad (7)$$

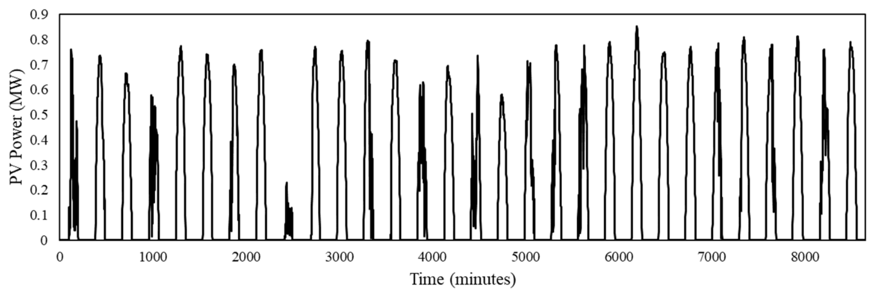
$$C_{idt} = C_{id(t-1)} - P_{idt}^{ch} \tau - \frac{P_{idt}^{dch} \tau}{\eta_i} \qquad \forall i \in \mathrm{E}, \forall d, \forall t \qquad (8)$$

$$(1 - D_i) C_{i}^{R} \le C_{idt} \le C_{i}^{R} \qquad \forall i \in \mathrm{E}, \forall d, \forall t \qquad (9)$$

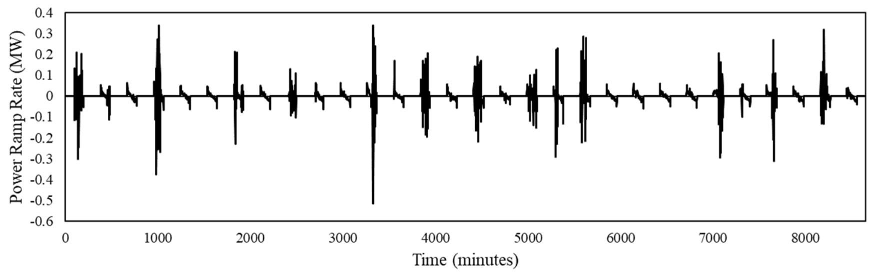
The BESS power (P_{idt}^{B}) given in (2) is the summation of the BESS charging power (P_{idt}^{ch}) and discharging power (P_{idt}^{dch}) at each time period (4). The charging and discharging power of the installed BESS are modeled using (5)-(6). The binary variable u indicates the BESS operation state, that is the BESS is discharging when u=1 and either charging or in idle state when u=0, thus it is ensured that the BESS does not charge and discharge at the same time period. This binary variable is used in (7) to indicate the BESS cycle completion, i.e., BESS charging/discharging cycle is completed when the value of γ_{idt} is 1. The stored energy within the BESS at each time period (C_{idt}) is defined as the stored energy at the previous time period minus the BESS charging/discharging power (8). The value of τ in (8) depends on the considered time periods. It must be noted how the BESS charging/discharging power are defined in (6) and (7), which will result in a negative value for BESS charging power and positive value for the BESS discharging power. Keeping this in mind, the stored energy within the BESS will increase if the BESS is charging and decrease if the BESS is discharging. In general, the stored energy within the BESS is limited by the maximum and minimum values, normally provided by the BESS manufacturer, to protect the BESS from excessive charging and discharging conditions. These limits are different from one BESS technology to another. In this work, it is assumed that the BESS can be charged up to its rated capacity and can be discharged up to an allowable depth of discharge value (D) decided based on the considered BESS technology (9).

3. NUMERICAL RESULTS

The proposed model is tested on a 1 MW solar PV unit. The solar PV power data are retrieved from [11] with a 5-minute time resolution. Figure 2 shows the PV power profile for one month and the associated ramp rate values. As can be seen, the solar PV power profile changes from one day to another. Most of the presented days, however, show a typical solar PV power profile that is associated with small ramp rate variation as illustrated in Figure 2(b). For these days, a small BESS is sufficient to control the variations and maintain the power sent to the grid within the required ramp rate limit. Due to weather changes, the PV profile at certain days exhibits a rapid change, resulting in high ramp rate variations. In this case, a large BESS is needed to either absorb or produce the difference between the PV output power and the power that should be sent to the grid in order to satisfy the grid operator ramp rate limit.



(a)



(b)

Figure 2: Solar PV power and the associated ramp rate

In this work, two BESS technologies with different characteristic and capital costs, as shown in Table 1, are utilized to control the solar PV ramp rate. An 8% interest rate and a 10-year lifetime are assumed to calculate the annualized capital costs.

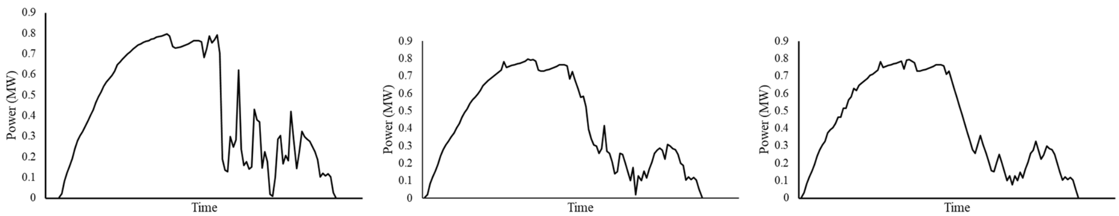
Table 1: BESS Technologies Characteristics

BESS Technology	Power Rating Cost ($/kW)	Energy Rating Cost ($/kWh)	Depth of Discharge (%)	Round Trip Efficiency (%)
Lead acid	600	400	70	75
Li-ion	1300	800	90	95

The ramp rate limit is assumed to be 0.05 MW (i.e., 5% of PV rated power). The optimal size for the installed BESS units along with the corresponding annualized investment cost are calculated as in Table 2. The overall investment cost is found to be $36,475/year. Figure 3 shows PV power, output power after using lead acid battery for large ramp rate control, and the output power after using Li-ion battery for small ramp rate control. Besides the difference in the installed size, it is noticed that the lead acid battery performs around 66% fewer cycles than the Li-ion battery (2136 cycles/year for lead acid and 6312 cycles/year for Li-ion). Table 3 shows how many times in a year the ramp rates value has exceeded a given percentage of the solar PV rated power ramp rate values. It can be seen that large ramp rates (i.e., >15%) are mitigated using lead acid battery. After mitigating large ramp rates, the Li-ion battery is used to control the small ramp rates (i.e., <10%) to satisfy the grid ramp rate limit.

Table 2: Numerical Simulation Results

BESS Technology	**Optimal Power Rating (KW)**	**Optimal Energy Rating (KWh)**	**Investment Cost ($/year)**
Lead acid	205	96	24,048.6
Li-ion	58	10	12,426.6



(a) (b) (c)

Figure 3: (a) PV power, (b) output power after using lead acid battery for large variation control, (c) output power after using Li-ion for small variation control (i.e., power transferred to the grid)

Table 3: Ramp Rate Analysis

Ramp Rate Percentage	**No. of violations**		
	in original Solar PV	**after using BESS 1**	**after using BESS 2**
5	2040	1104	0
10	828	12	0
15	444	0	0
20	228	0	0

4. CONCLUSION

A coordinated sizing method was proposed in this paper to determine the optimal size for two different BESS technologies that are installed to control solar PV ramp rate. The BESS technology with lower lifecycle and capital cost was selected to control the large solar PV ramp rate while the BESS technology with higher lifecycle and capital cost was used to control the small solar PV ramp rate. This way, the overall investment cost is reduced compared to using only one BESS to perform PV ramp rate control application. The results obtained from numerical simulations showed that the proposed method was able to determine the optimal size of both BESS technologies while at the same time satisfying the ramp rate limit imposed by the grid operator.

ACKNOWLEDGEMENT

This work is supported in part by US NSF Grant 1429093.

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