

The Sizing of Battery Energy Storage for the Mitigation of Slow and Fast Fluctuations in Rooftop Solar PV Output

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Abstract— Highly penetrated rooftop solar photo-voltaic (PV) units might cause both slow and fast voltage fluctuations in the connected low voltage (LV) distribution feeder due to random variations in solar PV power output, in addition to the variations in load demand. These fluctuations in voltage can be mitigated with the use of distributed energy storage systems integrated in solar PV units. A novel methodology to determine the optimum sizing of a Battery Energy Storage System (BESS) for the simultaneous mitigation of fast and slow voltage fluctuations has been proposed in this paper. The proposed method is simulated on a practical distribution feeder in NSW, Australia. The simulation results show that the optimum sizing and optimum operating parameters can be obtained for various fast and slow PV output variations.

Index Terms—Battery Storage, Low Voltage Distribution Network, Solar PV, Voltage Regulation, Voltage Fluctuations

I. INTRODUCTION

Grid-connected solar Photo Voltaic (PV) applications have gained more attention with the increasing popularity of household rooftop PV units, particularly in Australia. However, grid-connected PV units create certain challenges due to the uncertainty of power generation and the dynamic nature of load.

Integrating Energy Storage Systems (ESS) with PV units can assure that the uncertainty of the generation is minimized or eliminated, and the addition of ESS allows the intermittent PV generation to provide supply and demand balance despite the varying nature of the sun irradiation and the load demand. The integration of ESS with rooftop PV units will also provide value added benefits by being able to reduce energy costs, improving power quality and increasing reliability [1, 2].

A strategy for peak load shaving to utilize the available capacity of a plug-in electric vehicle (PEV) is discussed in [3]; which mainly focuses on utilizing the balanced energy stored in the BESS of PEV to improve the voltage profile, which does not prioritize the voltage regulation. The sizing of BESS based on peak load shaving has been investigated in [4, 5]; reduction in the energy bill has been the main criteria for sizing. The sizing of BESS based on load shifting while considering energy cost has been explored in [6, 7]. However,

none of above literature [3-7] discusses about the voltage regulation using BESS considering both fast and slow fluctuations.

The work presented in this paper focuses on the sizing of BESS integrated with solar PV unit for regulating voltage profile, when the system is faced with both slow and fast fluctuations. The sizing of BESS will be determined based on the real time varying solar PV output and the varying residential load demand, leading to fast (due to cloud passing causing high ramp rate PV output) and slow voltage variations (due to varying sun irradiation during the day). The sizing of BESS will be based on the; (i) ability to mitigate both fast and slow fluctuation in the voltage profile, (ii) ability to maintain the charging/discharging rates of the BESS to be within the manufacturer specification, (iii) fully utilize the capacity of BESS with a 10% margin to mitigate unexpected variations in voltage profile, (iv) ability to assure SoC of the BESS at the end of the day is same as the initial SoC at the start of the same day. As per the Australian Standard AS 60038 for Standard Voltages, the rooftop solar PV output should be at 230V at the Point of Common Coupling (PCC) in single phase line-to-neutral with a tolerance of +10% and -6% [8]. Maximum charge/discharge rate of the BESS based on physical limitations of lead acid BESS is C/3 (Capacity hour rate) according to manufacturer specifications.

Trial simulations on a practical distribution feeder in NSW have been carried out with various BESS sizes to test the proposed strategy.

II. THE PROPOSED STRATEGY FOR SIZING OF BESS TO REGULATE VOLTAGE AT PCC

The conceptual block diagram of a typical BESS integrated with a rooftop solar PV system, which will be studied in this work, is presented in Fig. 1.

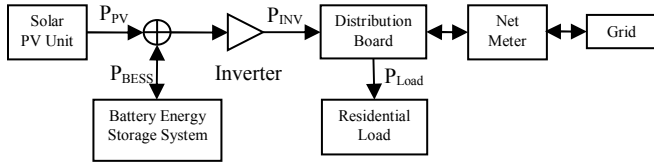


Fig. 1: Conceptual Diagram of the solar PV unit with BESS

Without the BESS, when the inverter output (P_{INV}) is higher than the residential load (around noon time), the excess energy will flow into the power system leading to voltage rise, which may cause the voltage to exceed the upper limit of the Australian standard 60038. However, with the BESS, the excess energy can be stored temporarily in the BESS for use in the evening to support the voltage (to avoid voltage at PCC eluding the lower limit of the Australian standard 60038) during the evening peak load period.

A. Modelling Solar PV Inverter

Fig. 1 shows that the power output of the solar PV inverter, P_{INV} is a combination of the raw power output of solar PV, P_{PV} and the power output of BESS, P_{BESS} , although to take into account the efficiency of the inverter, P_{INV} needs to be multiplied by the inverter efficiency, η_{INV} . Therefore, the rooftop solar PV system used in this work can be modeled as below:

$$P_{INV} = \eta_{INV} \times (P_{PV} + P_{BESS}) \quad (1)$$

η_{INV} is usually provided in the manufacturer datasheet for the specific inverter. For simplicity, in this study, the inverter efficiency η_{INV} will be considered to be at unity.

B. Modelling Battery Energy Storage System(BESS)

The mitigation of both fast fluctuations and slow fluctuations in the power output of solar PV inverter (P_{INV}) will be considered for the modeling of the BESS. The lead acid BESS is used in this work.

1) Modeling of BESS to mitigate fast fluctuations in solar inverter output

The fast fluctuations in the solar PV inverter output occur due to sudden cloud passing over the rooftop solar PV unit causing sudden drops in the solar PV output leading to fast fluctuations in the voltage profile. In our proposal, the magnitude of the maximum rate of change of the solar PV inverter output ($\frac{dP_{INV}}{dt}$) will be maintained at a specified rate of change, defined in this paper as $EINV$, to mitigate the fast fluctuations.

Depending on the rate of change of the actual PV output (RPV), initially the specified rate of change of the solar PV inverter output (EINV) will be set as below:

$$EINV = \begin{cases} EINV_{max}, & \text{if } RPV > 0 \\ EINV_{min}, & \text{if } RPV < 0 \\ 0, & \text{if } RPV = 0 \end{cases} \quad (2)$$

In this way, P_{INV} is controlled to be between $EINV_{min}$ and $EINV_{max}$. In this paper, the value of

$EINV_{min}$ of -5 watts/s and $EINV_{max}$ of 5 watts/s is used for simulations; although this value can be changed by the user.

After the selection of $EINV$, the rate of change of the BESS power output, $\frac{dP_{BESS_FF}}{dt}(t)$ can be calculated as below:

$$\frac{dP_{BESS_FF}}{dt}(t) = \begin{cases} 0, & \text{if } |RPV| \leq |EINV| \\ EINV - RPV, & \text{otherwise} \end{cases} \quad (3)$$

The rate of change of the BESS power output ($\frac{dP_{BESS_FF}}{dt}$) is zero when the absolute value of the rate of change of the raw solar PV output (RPV) is equal to or lower than the absolute value of the specified $EINV$. Accordingly, BESS is idle at this moment; it is not charged or discharged. Otherwise, the rate of change of BESS power output ($\frac{dP_{BESS_FF}}{dt}$) will be the difference between $EINV$ and RPV to mitigate fast fluctuations.

2) Modeling of BESS to mitigate the slow fluctuations in solar inverter output

Slow fluctuations in the solar PV inverter output occur due to relatively slow variations of the solar PV inverter output (due to the variation in the sun irradiation) and the load demand causing slow fluctuations in the voltage profile.

To mitigate this, the BESS will be charged in the mid-day when there is excess solar PV generation, and discharged in the evening when there is no solar PV generation but higher residential load. The real time selection of the rate of change of charge/discharge current ($\frac{di_{BESS}}{dt}(t)$) of BESS is crucial for the voltage control as we want to maximise the use of the limited storage.

The improvement in the voltage (ΔV) is related to the rate of change of charge/discharge current of BESS ($\frac{di_{BESS}}{dt}(t)$). For example, if the improvement in voltage is 0.1 pu when $\frac{di_{BESS}}{dt}(t)$ is 20 A/h, it will be higher when $\frac{di_{BESS}}{dt}(t)$ is 30 A/h, and it will be lower when $\frac{di_{BESS}}{dt}(t)$ is 10 A/h.

Similarly, the time (T) it takes to fully charge or discharge the battery capacity, C , (within its specified depth of discharge) is inversely related to $\frac{di_{BESS}}{dt}(t)$. The higher $\frac{di_{BESS}}{dt}(t)$, the faster it takes to charge or discharge the battery capacity (within its specified depth of discharge) and vice versa.

Because of the limited capacity of the battery, it is desirable to ensure that the full capacity of the battery is used during charging/discharging. For example, if the rate of change of battery charging is too high, the battery will be fully charged to its full capacity while there is still excess PV generation, and therefore voltage rise will still occur. Similarly, if the rate of battery charging is too low, at the end of the duration of the voltage rise, the battery is not fully charged and hence we have not maximized the use of the battery capacity.

In our proposal, the selection of $\frac{di_{BESS}}{dt}(t)$ is based on the voltage at the point of common coupling (PCC). When the voltage at PCC deviates more from the operating voltage boundary, the rate of change of charge/discharge is higher,

and when it deviates less from the operating voltage boundary, the rate of change of charge/discharge is lower. This has been expressed as below:

$$\frac{di_{BESS}}{dt}(t) = \begin{cases} 0, & \text{if } V_L < V_{PCC} < V_H \\ A_1, & \text{if } (V_H) < V_{PCC} < (V_H + B_1) \\ A_2, & \text{if } (V_H + B_1) < V_{PCC} < (V_H + B_1 + B_2) \\ A_3, & \text{if } (V_H + B_1 + B_2) < V_{PCC} \\ C_1, & \text{if } (V_L - D_1) < V_{PCC} < (V_L) \\ C_2, & \text{if } (V_L - D_1 - D_2) < V_{PCC} < (V_L - D_1) \\ C_3, & \text{if } V_{PCC} < (V_L - D_1 - D_2) \end{cases} \quad (4)$$

Where, the rates of change of charging are; $A_1 < A_2 < A_3$ and the rates of change of discharging are; $C_1 < C_2 < C_3$. Trial simulations will be performed with different values for A_1 - A_3 , B_1 , B_2 , C_1 - C_3 , D_1 and D_2 to identify the most suitable set of values with different BESS capacities in the process to determine the optimum BESS capacity and parameters.

Fig. 2 illustrates the methodology for the selection of parameters. The voltage severity level decision parameters B_1 , B_2 and D_1 , D_2 are determined based on the initial voltage profile. The voltage profile, which lies outside the operating voltage range, is divided into sections based on the deviation from operating voltage range. However, the number of sections and the size of a section can be different for each case study. During our work, we have divided the voltage profile into three section for charging and three sections for discharging. Once B_1 , B_2 and D_1 , D_2 are determined, parameter values A_1 , A_2 , A_3 , C_1 , C_2 and C_3 can be determined as the energy stored during charging to be discharged totally at the end of discharging period of BESS (Eq.5).

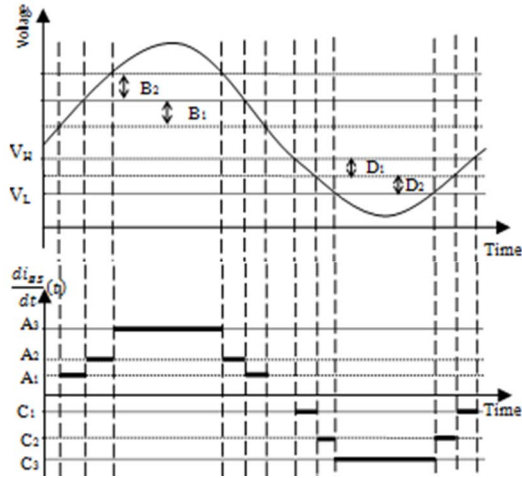


Fig. 2. Methodology for the selection of parameters A_1 , A_2 , A_3 , B_1 , B_2 , C_1 , C_2 , C_3 , D_1 and D_2

$$(A_1 \times \Delta T_1) + (A_2 \times \Delta T_2) + (A_3 \times \Delta T_3) = (C_1 \times \Delta t_1) + (C_2 \times \Delta t_2) + (C_3 \times \Delta t_3) \quad (5)$$

Where, $\Delta T_1, \Delta T_2, \Delta T_3$ are charging durations with the rates change of charging A_1 , A_2 , A_3 respectively and $\Delta t_1, \Delta t_2, \Delta t_3$ are discharging durations with the rates of change of discharging B_1 , B_2 , B_3 respectively. Initially, the simulation will be performed with A_1 as the lowest rate of change of charging and A_3 as the highest rate of change of charging; C_1

as the lowest rate of change of discharging and C_3 as the highest rate of change of discharging within the physical constraints of BESS. During the simulations, the results will be analysed if the voltage profile is maintained within the operating voltage range after applying the proposed voltage control method. The BESS capacity will be increased if the highest rate of change of charging (A_3) or the highest rate of change of discharging (C_3) are not capable to support the voltage control. Also, the BESS capacity will be decreased if the lowest rate of change of charging (A_1) or the lowest rate of change of discharging (C_1) are capable of supporting voltage, but the utilization of BESS capacity is less.

The rate of change of the charge/discharge power output of BESS for the voltage control ($\frac{dP_{BESS SF}}{dt}(t)$) can be calculated using (6).

$$\frac{dP_{BESS SF}}{dt}(t) = \frac{\frac{di_{BESS}}{dt}(t)}{3600} \times V_{BS} \quad (6)$$

Where, $\frac{di_{BESS}}{dt}(t)$ is the rate of change of charge/discharge current of the 12V lead acid battery in A/h, and $V_{BS}(t)$ is the Battery Voltage in V, obtained from the interpolation in the battery characteristic curves as discussed in [9].

3) Modeling of BESS to mitigate both fast and slow fluctuations in voltage profile

Even though $\frac{dP_{BESS FF}}{dt}(t)$ and $\frac{dP_{BESS SF}}{dt}(t)$ are determined separately for the mitigation of the fast and slow fluctuations, both can be integrated to form $\frac{dP_{BESS T}}{dt}(t)$ to charge or discharge the BESS for voltage control. In this paper, we have separated the two, to show more clearly the outcome of each of the proposed strategy.

The power output of BESS, $P_{BESS}(t)$ for voltage control is determined based on the BESS power output at the previous instance ($P_{BESS}(t-T)$) and the rate of change of charge or discharge of BESS power output for the current instance as below:

$$P_{BESS}(t) = \begin{cases} 0, & |RPV| \leq |ENV| \\ P_{BESS}(t-T) + \frac{dP_{BESS T}}{dt}(t) * (t - (t-T)), & \text{otherwise} \end{cases} \quad (7)$$

Proper measures should be taken to avoid overcharging the BESS during the charging/discharging periods. Hence, the BESS State of Charge (SoC) will be maintained between 20-100% during the entire control operation. The initial SoC of the BESS must be sufficient to mitigate the fast fluctuations that occur prior to the start of BESS charging for the slow fluctuations in mid-day. In addition, the capacity of BESS must be sufficient to control voltage during the entire period.

III. CASE STUDIES

Feeder data for a section of the practical MV/LV network (Fig. 3) in NSW, Australia is used to demonstrate the effectiveness of the proposed method described in Section II.

Fig. 3 shows a small low-voltage feeder connected to MV/LV network, which is derived from a practical system in New South Wales, Australia. The system consists of a

11kV/400V transformer and 16 LV buses. Each LV bus is connected to a household with a 5kW rooftop solar PV and a BESS installed.

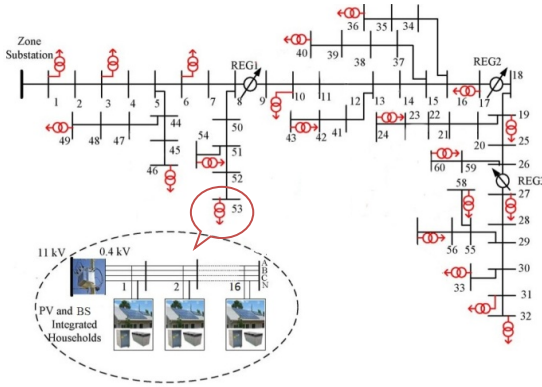


Fig. 3: The practical MV/LV network used for simulations

Various BESS capacities are considered during the initial simulations to identify the optimum capacity and the optimum operation. The voltage control strategy associated with the fast fluctuations is to maintain the magnitude of the maximum rate of change of the solar PV inverter output ($\frac{dP_{INV}}{dt}$) at 5 Watts/s. The voltage control strategy associated with slow fluctuations is to select the optimum parameter values for $A_1, A_2, A_3, B_1, B_2, C_1, C_2, C_3, D_1$ and D_2 on the initial voltage level. The minimum value of SoC used was 20% and the maximum value of the SoC used was 100% for all the trial simulations. Also for the test feeder used in this study, the lower voltage limit, V_L and the higher voltage limit, V_H are set according to the Australian Standard, AS60038 as 0.94 pu and 1.1 pu, respectively.

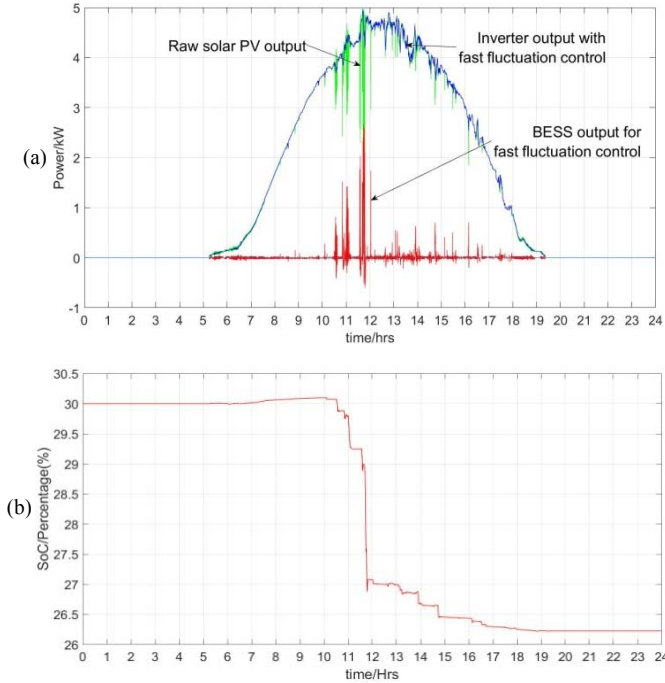


Fig. 4: (a) Solar PV output, BESS power output and Inverter power output for fast fluctuation control (b) Variation of BESS SOC in 22-31% SoC range

Initially, 250 Ah BESS was considered for simulations. The initial SoC level was assumed as 30% of the full BESS capacity.

Fig. 4(a) illustrates the variation of raw solar PV output, BESS power output for fast fluctuation control and inverter output with fast fluctuation control over the selected 24hr time duration. The fast fluctuations with high ramp rates occur between 10am to noon due to cloud passing. Moreover, fairly large isolated ramping events have occurred from 12.30 pm to 4 pm. The compensation provided by the BESS for the mitigation of fast fluctuations has successfully smoothed the solar PV inverter output. Fig. 4(b) illustrates the SoC variation during the mitigation of fast fluctuations in the solar PV output. A solar PV output drop of 2.77kW occurs around 11:30 am lasting for 20 sec. The mitigation of this event lasts around 800 sec. with the BESS losing 4.74% of its SoC. Fig 4(b) shows that about 8% of the full capacity of BESS is used for the fast fluctuation control during entire 24hr period. Few frequent but smaller fluctuations occur around 12.30 pm to 4:30 pm, which have caused continuous drop in the SoC level of the BESS. With sufficient initial storage available in the 250Ah battery, fast fluctuations can be mitigated without any interruption.

A. Comparison on the mitigation of fast fluctuations in the solar PV output using various BESS sizes

The initial SoC level must assure that sufficient energy is stored in the BESS to facilitate the mitigation of fast fluctuations which can occur anytime without reaching the minimum allowed SoC level (which is 20%) of BESS. Based on the results with 250 Ah BESS, the initial SoC level of 35% was used for simulations with 200Ah and 150 Ah BESS, 40% with 120 Ah BESS to ensure that there is sufficient capacity available for the mitigation of fast fluctuations. Fig. 5 illustrates the SoC variation for different BESS capacities for the mitigation of fast fluctuations in the solar PV output.

Accordingly, the variation of SoC is apparently similar in its behavior but different in how much the percentage of SoC is used. The BESS with 120 Ah used 16% of SoC when the BESS with 250 Ah used only 7.5% of SoC for fast fluctuation control. The BESS with 150 Ah and 200 Ah used 13% and 10% of SoC respectively. Accordingly, all the BESS capacities have reached 22-25% minimum SoC for fast fluctuation control within 24hr period which avoids the undercharging of the BESS without any interruption.

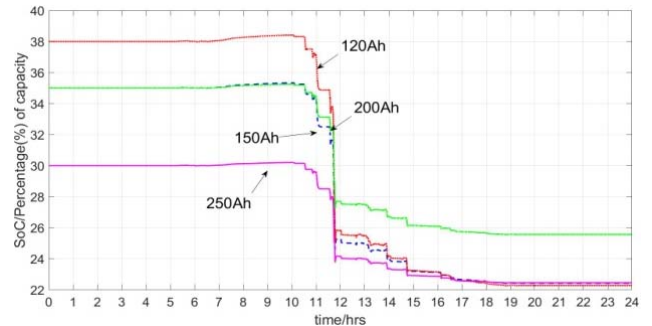


Fig. 5: Variation of Different BESS SOC in 22-40% SoC range

Next, the optimum sizing of the BESS will be decided based on the ability to provide the slow fluctuation control to comply with Australian Standard, AS60038 having selected initial SoC levels in this section.

B. Comparison on the mitigation of slow fluctuations in the voltage profile using various BESS sizes

The mitigation of the slow fluctuations in the voltage profile is performed as the methodology explained in Section II.B.2. The parameters used for slow fluctuation control with different BESS capacities are given in Table I for charging and Table II for discharging.

TABLE I. PARAMETER SELECTION FOR SLOW FLUCTUATION CONTROL DURING CHARGING

Capacity	B_1 (P.U)	B_2 (P.U)	A_1 (A/h)	A_2 (A/h)	A_3 (A/h)
250 Ah	0.004	0.004	12.5	25	50
200 Ah	0.004	0.004	12.5	25	50
150 Ah	0.004	0.004	12.5	25	46
120 Ah	0.004	0.004	12	24	40

TABLE II. PARAMETER SELECTION FOR SLOW FLUCTUATION CONTROL DURING DISCHARGING

Capacity	D_1 (P.U)	C_1 (A/h)	C_2 (A/h)
250 Ah	0.01	25	50
200 Ah	0.01	25	55
150 Ah	0.01	25	50
120 Ah	0.01	26	40

Several trial simulations were run for each BESS capacity to identify the optimum set of parameters to provide voltage control with the available capacity. Fig. 6 illustrates the improvement in voltage profile with the utilization of different BESS sizes. Selection of parameters A_1 - A_3 and C_1 - C_3 was based on the ability to maintain voltage profile within the operating voltage limit without overcharging or undercharging the BESS within the physical constraints of BESS.

The selection of the charge/discharge rates for all the BESS capacities were based on Eq.5. Also, the maximum charging/discharging rate did not exceed $C/3$ (capacity hour) rate to comply with the manufacturer specification of the lead acid BESS. According to Table II, BESS with 120 Ah charge and discharge at $C/3$ rate (40A/h) for voltage control, which is illustrated in Fig. 6(a) - Fig. 6(c). However, the 120 Ah BESS is not capable of maintaining the voltage profile within the operating limit according to the Australian Standard, AS60038. 150 Ah BESS discharge at $C/3$ rate (50A/h) and charge at $C/3.26$ rate (46A/h which is lesser than $C/3$) to maintain the voltage profile within the operating limits. Moreover, 200 Ah BESS discharge at $C/3.64$ rate (55A/h), charge at $C/5$ (50A/h) and 250 Ah BESS discharge, and charge at $C/5$ (50A/h) to maintain the voltage profile within operating limits. Accordingly, 150 Ah is the BESS to achieve voltage control according to Australian Standard, AS60038 while charging and/or discharging at the highest rate as per the manufacturer specification.

Fig. 6(d) illustrates the overall variation of SoC with the utilization of the different BESS sizes. Accordingly, 250 Ah, 200 Ah, 150 Ah and 120Ah BESS have reached 62%, 77%, 90% and 99% of SoC at the end of charging period. However,

the optimum sizing of BESS is the capacity which has the ability to maintain voltage profile within the operating voltage limit without overcharging or undercharging the BESS. Moreover, 10% margin of SoC will be allowed to meet any unexpected variations in voltage which can occur anytime.

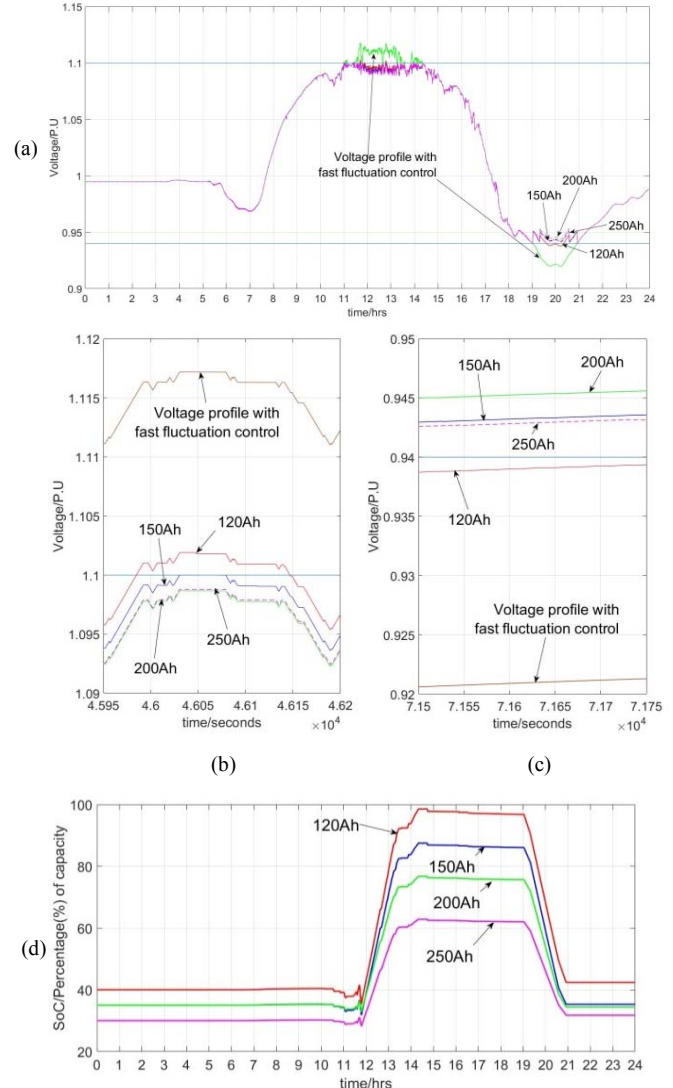


Fig. 6: (a) Improvement in voltage profile with different BESS capacities (b) Zoomed plot of (a) during charging 250 sec. period (c) Zoomed plot of (a) during discharging 250 sec. period (d) Overall SoC variation with different BESS capacities

Hence, 150 Ah BESS is the optimum size of the BESS to provide voltage control at Bus 16 in the system illustrated in Fig. 3 for the selected data set. The 150 Ah BESS can be charged up to 90% of SoC during charging with the maximum rate of $C/3.26$ (46 A/h) and will reach 35% of SoC (which is the initial SoC level as well) at the end of discharging period with the maximum discharging rate of $C/3$ (50 A/h). Accordingly, at the end of discharging period the BESS returns the SoC to its initial value for use in the next day.

IV. CONCLUSION

The optimum sizing and the optimum operating parameters for voltage control for BESS to mitigate the slow and fast fluctuations of solar PV output has been presented. Sufficient capacities for the mitigation of slow and fast voltage fluctuations have been determined through simulations using different BESS capacities. The fast voltage fluctuations have been mitigated by charging/discharging BESS to maintain the rate of change of the inverter output at a specified level. Slow fluctuations have been mitigated by charging BESS during mid-day and by discharging during the evening peak time. In addition, three charging/discharging rates for voltage control based on the severity level of voltage at PCC have been proposed. The sizing and the optimum operating parameters for the proposed method have been determined using a practical network in NSW. A BESS with a capacity of 150 Ah was identified as the optimum size for the voltage control strategy to mitigate the fast and slow voltage fluctuations. The sizing of the BESS is based on the minimum capacity to support voltage control during the 24hr period to maintain voltage profile within operating limit without exceeding physical limitations of the BESS while achieving the SoC at the end of the day similar to initial SoC.

V. ACKNOWLEDGEMENT

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