7-11-2016

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Citation Details

R. B. Bass, J. Carr, J. Aguilar and K. Whitener, "Determining the Power and Energy Capacities of a Battery Energy Storage System to Accommodate High Photovoltaic Penetration on a Distribution Feeder," in IEEE Power and Energy Technology Systems Journal, vol. 3, no. 3, pp. 119-127, Sept. 2016.

Received 24 December 2015; revised 15 April 2016; accepted 24 June 2016. Date of publication 11 July 2016; date of current version 16 September 2016.

Digital Object Identifier 10.1109/JPETS.2016.2586072

Determining the Power and Energy Capacities of a Battery Energy Storage System to Accommodate High Photovoltaic Penetration on a Distribution Feeder

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ABSTRACT The integration of distributed energy generation systems has begun to impact the operation of distribution feeders within the balancing areas of numerous electrical utilities. Battery energy storage systems may be used to facilitate greater integration of renewable energy generation. This paper describes a method for determining the power and energy capacities a battery energy storage system would need in order to accommodate a particular photovoltaic penetration level within a distribution feeder, or conversely, the amount of photovoltaic that could be installed on a feeder with a minimal investment in power and energy battery energy storage system (BESS) capacities. This method determines the BESS capacities required to compensate both intra-hour and inter-hour load and photovoltaic fluctuations to achieve a flat feeder power profile. By managing the feeder power, the voltage drop along the length of feeder may be managed, thereby mitigating the voltage fluctuation induced by the stochastic nature of both renewables generation and load. Doing so facilitates system benefits, such as conservation voltage reduction, fewer operations of load tap changers, and voltage regulators, and allows for deferment of capital expenditures.

INDEX TERMS Battery energy storage systems, firming, photovoltaic (PV) integration, shaping.

I. INTRODUCTION

THE purpose of this paper is to describe and demonstrate a method for determining the power (MW) and energy (MWh) capacities required of a battery energy storage system (BESS) in order to accommodate a particular photovoltaic (PV) penetration level on a distribution feeder. This method involves using a BESS s-domain plant model and a PI (proportional-integral) compensator, feeder load data, and local insolation data to determine the BESS MW and MWh capacities required to provide both firming (intra-hour compensation) and shaping (inter-hour) on a distribution feeder in response to both photovoltaic (PV) and load fluctuations.

This method is applicable to any distribution feeder, so long as relevant load and insolation data are available. The results presented in this report are unique to the Oxford-Rural feeder, part of Portland General Electric's (PGE) distribution network in Salem, Oregon (despite it's name, the feeder is not in a rural area). The Oxford-Rural feeder has an average daily maximum load of 2.94 MW. It was found that a BESS with 0.61 MW of power capacity and 2.4 MWh of energy capacity would be able to achieve a flat feeder profile with 35% PV penetration on this feeder. Other feeders will present different load curves and be subject to different insolation profiles. As such the BESS capacity recommendations will differ from feeder to feeder. It is expected though that the general behaviour of the results are extensible to other feeders. The general trend will be consistent; there is likely an ideal level of PV penetration, perhaps 25% to 35%, where BESS capacity requirements are minimal.

Capital costs for BESS have declined significantly over the past several years. There are few up-to-date figures for the costs of BESS within the academic literature. However, Nykvist and Nilsson compiled capital cost data from both academic and non-academic sources to develop an understanding of recent cost trends [1]. These data are specific to Li-ion electric vehicle battery packs, rather than utility BESS. However, the EV market is a significant driver of battery costs and Li-ion technologies are often used for utility BESS. The consensus Nykvist and Nilsson report is that Li-ion capital costs will continue to decline, settling asymptotically within the \$150-\$300/kWh price range by 2025. As such, we can expect an increasing rate of adoption of BESS for utility applications.

II. BACKGROUND

BESS are capable of providing a number of ancillary services, including frequency regulation, economic arbitrage, voltage regulation or reactive power (VAr) support, and the firming and shaping of power. In 2013, PGE commissioned its Salem Smart Power Project (SSPP), which features a 5 MW, 1.25 MWh lithium ion BESS. Since its commissioning, the SSPP has helped establish the value of integrating BESS into distribution feeders. The system was used to demonstrate the concept of a high reliability zone by providing power between the moment of an outage and when back-up internal combustion engines come on line. While successful, the system is not currently utilized in this way. The SSPP has also demonstrated extremely rapid response to frequency events, responding in approximately seven seconds, with full 5 MW output within 30 seconds. PGE, and many other utilities, would like to know if systems like the SSPP may be used to facilitate greater integration of renewable energy generation within their balancing area. The objective of this research is to develop a method for evaluating the MW and MWh capacities of a BESS to increase the penetration level of photovoltaic generation within a distribution feeder.

Many research groups have investigated how BESS may be used to integrate renewables within distribution feeders, particularly those subject to high penetration levels of PV generation. Several groups have analyzed BESS distributed along the length of a feeder, mixed in with distributed PV or integrated directly with PV systems. Jackson, *et al.* model the effects of various penetration levels of PV systems within distribution feeders and how PV impacts may be mitigated with BESS that are distributed along the length of the feeder [2]. Jayasekara, *et al.* investigated the impact of co-located PV and storage distributed throughout a feeder [3]. They use a power management tool to direct these distributed storage systems to regulate both the feeder voltage profile and peak shaving. Tant, *et al.* propose using a multiobjective optimization method for a BESS installed within a residential distribution feeder experiencing over-voltage problems, with a single BESS located strategically along the feeder, not at the substation. The BESS helps mitigate power quality issues while simultaneously allowing for deferment of distribution asset upgrades [4]. Mardira, *et al.* investigated the impact on peak demand that distributed residential PV has on the load profile of customers on a distribution feeder, both with and without integrated BESS. They found that the aggregated load profile of customers with both PV and BESS is characterized by reductions in both average and peak load while the aggregated load profiles of customers with just PV experienced a reduction only in average load [5]. Alam, *et al.* use an inverter ramp-rate control algorithm and BESS to manage voltage ramp rates induced by cloud coverage within weak distribution feeders [6], [7]. BESS and PV are co-located at multiple points along the length of the feeder. Pandya and Aware propose managing distribution feeder voltage profiles using a D-STATCOM and BESS, co-located with BESS. The D-STATCOM and BESS provide reactive and real power, respectively, which are used to manage the feeder voltage profile [8].

Other researchers have analyzed the economic and asset management impacts BESS have on distribution feeders. Kleinberg, *et al.* analyze the economic consequences energy storage has on distribution feeders impacted by PV generation [9]. Nagarajan and Ayyanar use convex optimization to calculate the optimal charge/discharge cycling of a BESS in order to minimize feeder transformer losses as well as BESS life-cycle costs through economic arbitrage of energy price within a distribution feeder subject to PV-induced power fluctuations [10].

Gaztañaga, *et al.* demonstrate how the stochastic generation of PV may be compensated through coupling with BESS. They use BESS to compensate PV at the plant, rather than addressing a feeder profile. Theirs is an approach well-suited for large PV generation plants rather than feeders with multiple distributed load and subject to high penetration of distributed PV [11].

This paper differs from these approaches in three ways. One, this method manages the feeder voltage by controlling the net power coming out of the feeder: load minus PV generation plus/minus BESS power. It is variations in the net load, calculated as the feeder load minus PV generation, that result in voltage drops along the feeder that affect feeder voltage profiles. Voltage is a service sold to utility customers, guaranteed to be within $\pm 5\%$. Deviations in voltage outside of these bounds can result in stalling of induction machines, unintended tripping of relays, or excessive tap changes within load tap changers and voltage regulators. And, rapid changes in voltage cause flicker in lighting systems and disrupt customer operations that require high quality power, such as data centers [12]. It is the *net load* against which the BESS was used to provide firming and shaping of the feeder power profile.

Two, a procedure was developed by which the MW and MWh BESS capacities may be determined, given a particular penetration level of PV on the feeder, in order to achieve this flat feeder power profile. Alternatively, the approach can be used to determine the possible PV penetration within a feeder that may be achieved with a minimal investment in MW and MWh capacities.

And three, this new approach is realizable using the functionality available within industry-standard contol systems, specifically programmable logic controllers (PLCs). PLCs are used to provide outer-loop control for BESS, and controls engineers are familiar with using the toolboxes provided for PLCs to build complex control systems. For instance, PLCs provide PI control loop feedback code blocks and PI coefficient tuning tools. A practical approach for BESS management must be realizable using the capabilities of PLCs, the controller of choice for utility-scale BESS.

III. METHODOLOGY

Developing a clear depiction of the firming and shaping capabilities of a BESS requires developing representative data models of the load, PV generation and desired feeder profile. After developing these data models, the MW and MWh requirements are determined for each specific seasonal and PV configuration.

To characterize seasonal discrepancies in both load and PV insolation throughout the year, data were gathered from representative days near the equinoxes and solstices. Load data come from the Oxford-Rural feeder. PV data came from two sources. Five-minute data came from a solar insolation monitoring site at the SSPP. One-second data, used to model cloud effects, came from an insolation monitoring station on Oahu, Hawai'i.

A. BESS s-DOMAIN MODEL

In order to determine the MW and MWh capacity requirements for a BESS to compensate PV and load fluctuations, a 2^{nd}-order s-domain BESS plant model was developed, to which could be applied test data. Plant output was controlled using a simple negative feedback control loop with a PI compensator, Fig. 1. The PI compensator was tuned to

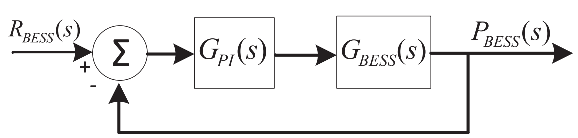

FIGURE 1. Feedback control loop for the BESS.

control the plant transient response and eliminate steady-state step response error. This proved sufficient to demonstrate that the BESS can provide firming against PV- and load-induced power fluctuations.

To develop the model, the BESS at PGE's SSPP was subjected to both frequency response testing and step response testing. Results from these tests were then used to derive the parameters of a 2^{nd}-order transfer function.

For the frequency response testing, the BESS was subjected to a sinusoidal reference power signal

$$p(t) = 600 + 500 \sin(2\pi t/T)\, kW \tag{1}$$

with T ranging from 0.5 seconds to 15 seconds. The magnitude and phase angle of the controlled output were measured with respect to the reference input. A 2^{nd}-order transfer function was then derived that best fit these phase and magnitude data points.

For step response testing, the BESS was subjected to both increment (*inc*) and decrement (*dec*) reference power steps of 100 kW, 500 kW, 1000 kW and 1500 kW. Overshoot, rise time and settling time were measured, and from these measurements, two 2^{nd}-order transfer functions were derived, one from the *inc* tests and another from the *dec* tests. This was done in case the BESS response to *inc* commands differed from *dec* commands [13], [14]. A slight variation was observed, but not significant enough to justify using anything more complicated than a single 2^{nd}-order model.

These two transfer functions were compared with the one derived from the frequency response testing. All three were found to be very similar, so the average of the three was taken as the representative BESS plant model. For the general 2^{nd}-order transfer function

$$G_{BESS}(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{2}$$

$\xi = 0.76$ is used for the dampening coefficient and $\omega_n = 0.245$ as the undamped natural frequency.

The proportional and integral compensator gain settings were tuned to $K_P = 0.39$ and $K_I = 0.06$, given the general form of a PI compensator

$$G_{PI}(s) = K_P + \frac{K_I}{s}. \tag{3}$$

B. PV DATA

Two sources of PV data were used: PV data from a University of Oregon Solar Radiation Monitoring Laboratory station located at the SSPP and PV data from an irradiance monitoring station on Oahu, Hawai'I [15], [16]. The Oahu data have a sampling rate of one sample per second. The Salem PV data have a much slower sampling rate of one sample per five minutes. Because the sampling rate of the Salem PV data is not fast enough to represent rapid fluctuations such as cloud events, the Oahu PV data were used in combination with the Salem data to provide this level of detail.

The Salem PV data were used to develop a PV envelope, which is important for determining the gross behaviour of solar irradiance over a typical day. Then the Oahu data were superposed atop the Salem data in order to represent rapid fluctuations in PV output. The assumption is that these fluctuations are less geographically dependent than the envelope profile, but they are still important enough to include in the PV data model in order to help determine proper BESS MW and MWh capacities for a particular feeder.

To combine the two PV data sources, the Oahu data were superposed onto the Salem PV data over the period that the Salem irradiance data showed deviations from the ideal PV irradiance envelope. As such, detailed one second data were overlaid onto the PV envelope only on portions of the envelope where there was known to be fluctuations. For the Oahu data, a lower envelope curve was determined using a PV envelope function.[1] The cloud-induced fluctuations were then isolated by taking the difference between the actual PV data and the PV envelope, as shown in Fig. 2, which was then normalized.

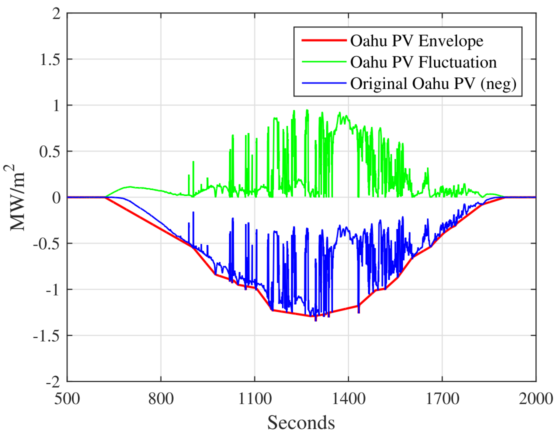

FIGURE 2. **Oahu data provide the necessary one-second sampling rate needed to represent rapid PV fluctuations. To extract these fluctuations, an ideal PV envelope was calculated. This envelope was then subtracted from the data, leaving behind only the fluctuations.**

The envelope function was also applied to the Salem PV data, which is also normalized. The span of fluctuation of the Salem PV data for each season was determined by comparing the original Salem PV data with the Salem PV envelope. The Oahu data were then superposed over the Salem envelope, with the centers of fluctuations aligned. The fluctuation span, as well as the time of day that the fluctuation occurred, varied by season.

C. COMBINATION OF LOAD AND PV PENETRATION

Developing a feeder load profile involved normalization of the load data from the Oxford-Rural feeder. To normalize these data, a nominal feeder load was determined by obtaining an *average daily maximum* from the feeder data. The maximum load for each day over a period of one year was determined; the average daily maximum is the average of all these maxima. For the Oxford-Rural feeder, this average daily maximum was determined to be 2.94 MVA.

Both the normalized load data and the normalized PV data were scaled using this average daily maximum. The PV data were then subtracted from the load data, giving the *net load* on the system, $p_{net}(t)$. Seasonal models were developed for a range of PV penetration levels on the Oxford-Rural feeder

$$p_{net}(t) = p_{load}(t) - p_{PV}(t). \tag{4}$$

D. DESIRED FEEDER PROFILE

A flat feeder profile was chosen, meaning the feeder power would be constant throughout the day. When loading exceeds the desired feeder profile, the BESS modulates output as an additional generation resource to balance the load. When feeder load falls below the desired feeder profile, the BESS provides extra load, drawing power from the feeder in proportion to the error.

We chose to use a flat feeder profile in order to get a sense of the upper bounds for the BESS MW and MWh capacities that would be required to provide both firming and shaping in response to load and PV fluctuations. The flat profile is the worst-case scenario; in order to achieve a flat profile, a large amount of energy must be stored during low-demand and/or high PV generation periods, then discharged during high demand and/or low PV generation periods. So the flat feeder profile is most challenging for shaping, but importantly, it illustrates that any profile can be attained. Consider, a smooth feeder profile could be defined, one whereby the feeder output was smoothed using an integration function, which would reduce the MW and MWh capacities required of the BESS. By using a flat profile however, we get an understanding of the maximum MW and MWh capacities that would be required of a BESS.

The desired feeder profile was calculated using the average of the net load for a representative day in a season. This straight-line average represents the ideal target value at which the gross energy consumed on the feeder would equal the gross energy produced. The role of the BESS is to charge and discharge in proportion to the error in order to balance these stochastic load and generation profiles against the constant desired feeder profile. If chosen well, the desired feeder profile balances the charging requirements with the discharging requirements.

The difference between the desired feeder profile and the net load determines the BESS reference signal, which is fed into the BESS s-domain plant model

$$r_{BESS}(t) = p_{DFP} - p_{net}(t). \tag{5}$$

The BESS output power, $p_{BESS}(t)$, is then determined by applying the BESS reference signal to the plant model, Fig. 1.

$$P_{BESS}(s) = \frac{R_{BESS}(s)}{1 + G_{PI}(s)\, G_{BESS}(s)} \tag{6}$$

where $P_{BESS}(s)$ is the Laplace transform of $p_{BESS}(t)$.

The controlled output signal closely follows the reference signal, which indicates that the BESS is able to accommodate the PV and load fluctuations. Plots showing the feeder load, PV generation, net load, desired feeder profile, and BESS reference signal are shown in Fig. 3. Application of linear control theory ensures the algorithm may be readily implemented within the outer loop PLC of a BESS.

E. MW AND MWh CAPACITY REQUIREMENTS

The MW capacity for a BESS was obtained by calculating the maximum of the absolute value of the BESS reference signal curve. This also equals the maximum difference between

[1] "Envelope1.1," Mathworks File Exchange. [Online]. Available: https://www.mathworks.com/matlabcentral/fileexchange/3142-envelope1-1

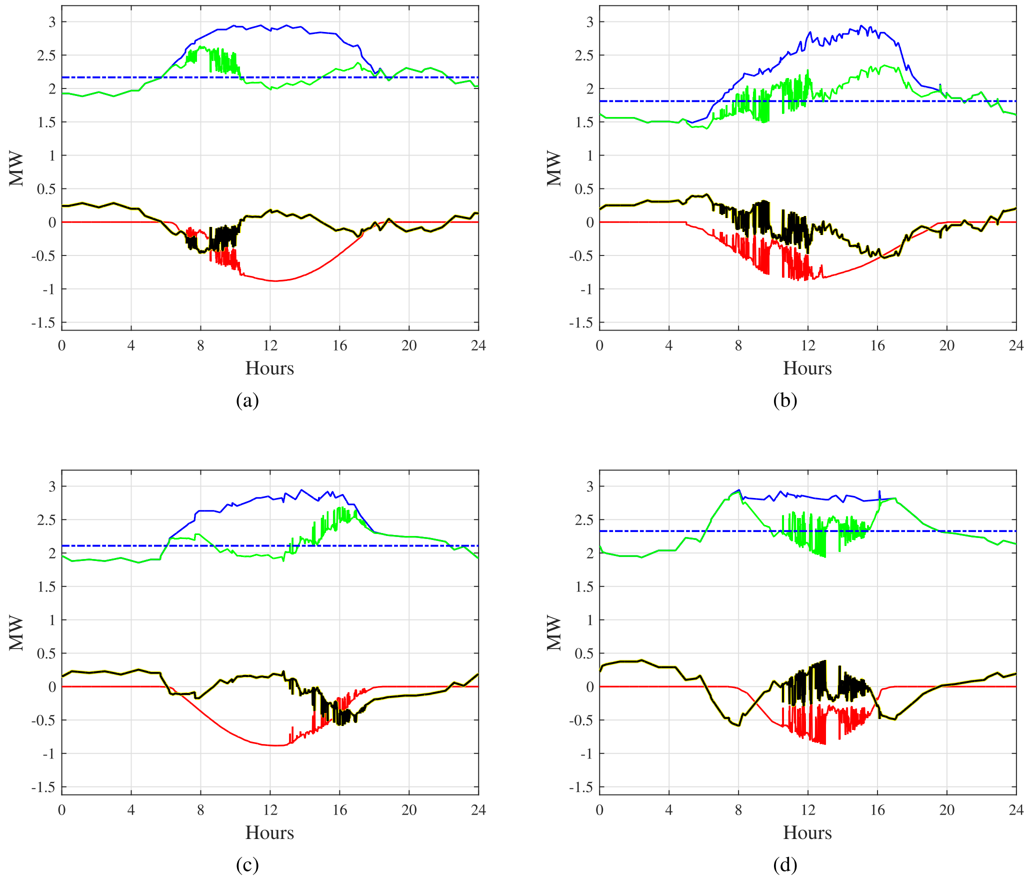

FIGURE 3. Shown are load, PV, and BESS power profiles for sample days from each of the four seasons. There is 30% PV penetration in all cases. Key: load (blue), PV (red), net load (green), desired feeder profile (DFP, dash blue), BESS reference input signal (yellow), and BESS response (black). (a) Spring. (b) Summer. (c) Fall. (d) Winter.

the summed load and PV data and the desired feeder profile, and it represents the MW requirement for the BESS to accommodate a given load and PV penetration. The MW capacity requirement is dependent on the desired feeder profile, seasonal loading, seasonal PV generation and percent PV penetration.

The MWh capacity for a BESS was determined by integrating the BESS reference signal curve. The peak MWh value from this curve indicates the required BESS MWh capacity. The MWh capacity also depends on the desired feeder profile, seasonal loading, seasonal PV profile and percent PV penetration. As such, a variety of seasonal scenarios must be examined in order to determine both the MW and MWh capacities required for a particular penetration level of PV and a particular desired feeder profile.

IV. ANALYSIS AND RESULTS

Using the method described, the desired feeder profile was evaluated with respect to different seasonal load and PV profiles on the Oxford-Rural feeder. Examining the various seasons provides an overview of the BESS response to loading and solar integration throughout the year.

The PV penetration was varied over a range of 10% to 50% of the feeder size, in increments of 5%. This variance in PV nameplate capacity provided a means for analyzing the necessary MW and MWh requirements for the BESS under differing amounts of renewable penetration. All of these test cases were scaled to a base line feeder size of 2.94 MVA, the average daily maximum for the Oxford-Rural feeder.

A. SEASONAL VARIANCE

For this analysis, the PV penetration level is held constant at 30%. The desired feeder profile (DFP) varies seasonally, as each seasonal DFP depends on both the load and the PV insolation characteristic of the season. From these analyses is developed an understanding of the required MW and MWh capacities for the BESS as a function of seasonal variations. Results are summarized on Table 1.

1) SPRING

Fig. 3(a) shows the spring 30% PV profile, red line. The loading on the feeder, blue line, peaks at 2.9 MW. The net loading, green line, is the difference between the PV and feeder load. The DFP, at 2.2 MVA, is the straight dashed blue line about which the net loading is centered. The yellow line shows the required BESS reference input signal required to balance the net loading against the DFP. Note that at 30% PV penetration, there is not a great difference between the net

TABLE 1. Given the variation in the seasonal data and the PV nameplate percentage of feeder size, this table depicts the needed MW and MWh capacities for a BESS to accommodate the different target feeder profiles given 30% PV penetration on the feeder.

30% PV Nameplate

Spring			**Summer**		
DFP [MW]	**MW Cap**	**MWh Cap**	**DFP [MW]**	**MW Cap**	**MWh Cap**
2.2	0.47	1.8	1.8	0.54	2.5
Fall			**Winter**		
DFP [MW]	**MW Cap**	**MWh Cap**	**DFP [MW]**	**MW Cap**	**MWh Cap**
2.1	0.59	2.0	2.3	0.58	2.4

loading and the DFP, and as a result the required BESS MW and MWh capacities are relatively low.

2) SUMMER

The summer 30% PV profile, Fig. 3(b), reveals a greater variation between the net load and the DFP than that of the spring profile. The summer DFP is lower, 1.8 MVA, with the net loading having multiple oscillations about the DFP. From this figure, it can be seen that the BESS would need to accommodate renewable integration to a greater extent than that of the spring profile; ie. the MW and MWh BESS capacity requirements are higher in the summer than they are in the spring.

3) FALL

Within the fall 30% PV profile, Fig. 3(c), the DFP (2.1 MVA) appears suitable for the majority of the day, but due to a decrease in PV generation from 15:00 onwards while loading is still high, the net loading increases, thereby requiring higher MW and MWh capacities for the BESS.

4) WINTER

For the winter 30% PV profile, Fig. 3(d), the BESS must accommodate two load net peaks; only during midday is PV generation sufficient to decrease the net loading on the feeder. As such, MW and MWh capacities for the BESS are high, though slightly less than those for summer.

As shown in Table 1, the DFP varied slightly between seasons; the DFP was approximately 2 MVA throughout the year. The results show that the spring season did require the least amount of BESS compensation, given the 30% PV penetration, with a total MW requirement of 0.47 MW and a MWh requirement of 1.8 MWh. While spring was the definitive low point in regards to the amount of required BESS capacity, fall required the greatest amount of MW capacity, and summer needed the greatest amount of MWh capacity. In order to achieve flat desired feeder profiles all year round, given 30% PV penetration on the feeder, a BESS would need to have capacities of 0.59 MW and 2.5 MWh, as dictated by the seasonal load and PV generation during fall and summer, respectively.

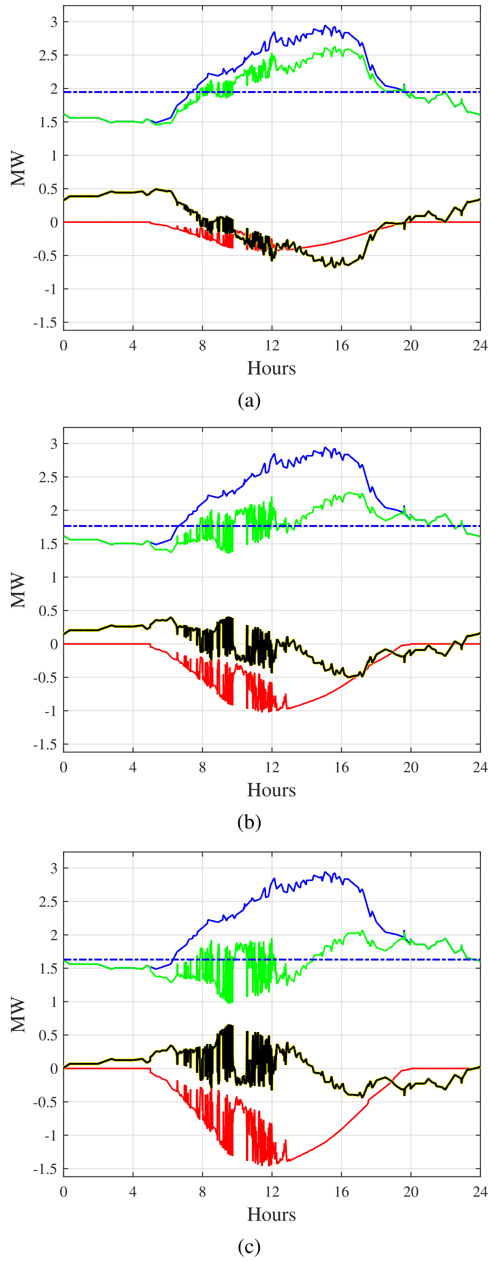

FIGURE 4. Shown are load, PV, and BESS power profiles for several PV penetration levels, 15%, 35%, and 50%. Season is the same for all cases, summer. Key: load (blue), PV (red), net load (green), desired feeder profile (DFP, dash blue), BESS reference input signal (yellow), and BESS response (black). (a) 15% PV penetration. (b) 35% PV penetration. (c) 50% PV penetration.

The results within Table 1 do affirm typical seasonal characteristics, as winter and summer typically have an increase in load due to more drastic weather conditions. Observing the reference signal more thoroughly for each season, one can see that the required MW and MWh BESS capacities are related to the net loading, the difference between the load and PV generation. As the net load approaches the desired feeder profile of the system, there is less need for BESS compensation. This is a result of the feeder load and renew-

TABLE 2. This table provides the seasonal MW and MWh capacities (Cap) requirements for the various PV penetration levels, indicated as percentages of the feeder size. These data are plotted in Fig. 5(a) and 5(b).

PV Nameplate (% of Feeder Size)	SPRING DFP [MW]	SPRING MW Cap	SPRING MWhr Cap	SUMMER DFP [MW]	SUMMER MW Cap	SUMMER MWhr Cap	FALL DFP [MW]	FALL MW Cap	FALL MWhr Cap	WINTER DFP [MW]	WINTER MW Cap	WINTER MWhr Cap	Maximum MW Cap	Maximum MWhr Cap
10%	2.3	0.46	3.1	2.0	0.74	4.1	2.3	0.55	2.9	2.4	0.51	3.3	0.74	4.1
15%	2.3	0.45	2.5	2.0	0.68	3.7	2.2	0.55	2.4	2.4	0.52	3.0	0.68	3.7
20%	2.3	0.45	2.1	1.9	0.63	3.2	2.2	0.56	2.0	2.4	0.54	2.7	0.63	3.2
25%	2.2	0.45	1.7	1.9	0.57	2.9	2.2	0.58	1.9	2.4	0.56	2.5	0.58	2.9
30%	2.2	0.47	1.8	1.8	0.54	2.5	2.1	0.59	2.0	2.3	0.58	2.4	0.59	2.5
35%	2.1	0.49	1.9	1.8	0.50	2.3	2.1	0.61	2.1	2.3	0.60	2.4	0.61	2.4
40%	2.1	0.51	2.1	1.7	0.50	2.1	2.0	0.62	2.3	2.3	0.65	2.5	0.65	2.5
45%	2.0	0.54	2.4	1.7	0.59	2.1	2.0	0.64	2.6	2.3	0.77	2.6	0.77	2.6
50%	2.0	0.60	2.7	1.6	0.67	2.1	1.9	0.68	2.8	2.2	0.89	2.8	0.89	2.8

able penetration reaching a threshold point where the target and net loading are very similar. For this 30% PV penetration scenario, the spring case in Fig. 3(a) is an example of this threshold point being reached. With the exception of a slight peak at approximately 08:00, the rest of the day oscillates marginally about the DFP. In the winter case, Fig. 3(b), there are two peaks for the net loading, one around 08:00 and another around 17:00, with the additional time period from 24:00 to 06:00 also requiring excess BESS capacity.

B. PHOTOVOLTAIC PENETRATION

Choosing BESS capacities that provide firming and shaping services with minimal capital investment depends not only on the seasonal load and insolation characteristics but also on the PV penetration level within the feeder. The PV penetration is defined as a percentage of PV AC output to the average maximum feeder load. For the Oxford-Rural feeder example, this value is 2.94 MVA. For this analysis, the amount of PV penetration was varied from 5% to 50%. Note that for a given seasonal loading, the DFP varies as the PV penetration changes: the greater the penetration, the greater the load on the feeder was offset. So increased PV penetration results in a lower DFP.

Given seasonal load and PV insolation data and a DFP, a range of PV penetration levels were iterated through in order to establish a relationship between the PV penetration level and the MW and MWh capacities required of a BESS to achieve the DFP. Fig. 4(a) through 4(c) show the effects of PV penetration on the net loading, DFP, and BESS reference input for four different penetration levels in the summer case.

The plots in Fig. 4 show the result of increased PV penetration on the feeder. As PV penetration increases, the fluctuation of the net load around the DFP decreases, meaning less MW and MWh capacities are required of the BESS to support PV integration. This affect, however, is limited; beyond 40% penetration, additional MW and MWh capacities are required to support additional PV.

Table 2 shows the BESS MW and MWh capacities needed to accommodate various PV penetrations levels for each of the different seasonal scenarios. However, the required BESS MW and MWh capacities required to integrate PV depends

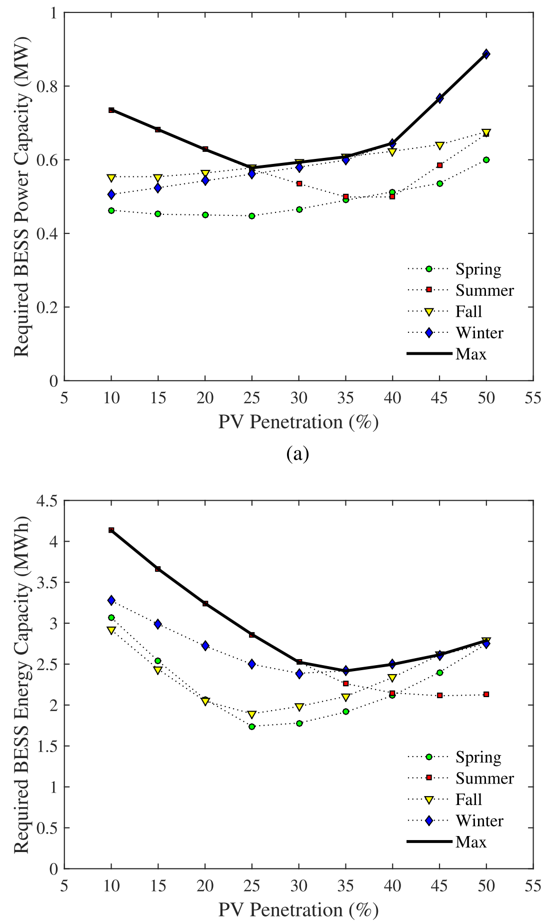

FIGURE 5. Shown are the MW and MWh BESS capacities versus PV penetration that are required to achieve a flat feeder profile for all seasons on the Oxford-Rural feeder. (a) Required BESS MW required versus percent PV penetration. (b) Required BESS MWh required versus percent PV penetration.

on the maximum values from all four seasons. These maxima are shown in the rightmost columns of Table 2.

Fig. 5(a) and 5(b) show plots of the data from Table 2. The thick black lines define the MW and MWh capacities required to accommodate various penetration levels of PV throughout the year. Those black lines derive from the maximum values from each of the seasonal plots. These lines can be used to determine the amount of MW and MWh capacities required to accommodate a particular penetration level of PV. On the other hand, the curves can be used to determine the possible penetration level of PV on a feeder - the possible PV penetration given the minimum amount of BESS capital investment. For the Oxford-Rural feeder, these data indicate a flat feeder profile can be achieved with a 30% PV penetration using a BESS with capacities of 0.59 MW and 2.5 MWh.

As shown in both Fig. 5(a) and 5(b), the required MW and MWh capacities are dictated by summer loading and generation conditions for low PV penetration levels, while winter conditions dictate the required capacities for high PV penetration levels. Fall conditions dictate MW capacities for mid-range penetration levels, 25-35%.

Note MW capacity requirements rise steeply as PV penetration levels exceed 40%, indicating an increasing challenge for integrating high penetration levels of PV. Note too the high MWh capacities required to integrate low levels of PV penetration; the wide variations between minimum and peak demand have not been tempered by sufficient PV generation on the feeder, indicating the benefits of shaping from PV integration are not fully realized until penetration levels reach 25 to 30%.

V. CONCLUSION

The objective of this research was to develop a method for determining the MW and MWh capacities a BESS would need in order to accommodate a particular PV penetration level on a distribution feeder; or, conversely, the amount of PV that could be installed on a feeder with a minimal investment in MW and MWh BESS capacities. An s-domain SSPP plant model was used, along with SSPP load data and local PV data, to demonstrate this method. The method determines the BESS MW and MWh capacities required to compensate against both intra-hour and inter-hour load and PV fluctuations, phenomena known as "firming" and "shaping," respectively.

To build seasonal data models, measured load data from PGE's Oxford-Rural Feeder and insolation data from a nearby solar insolation monitoring station were used. The Salem PV data are not very granular, sampled once every five minutes. This insolation data was augmented using highly granular data (one sample per second) from another insolation monitoring station. Adding these fluctuations allowed us to model rapid PV events, particularly cloud-effects, which in turn allowed us to better determine the MW and MWh BESS capacities needed to firm intra-hour PV events.

The developed method is applicable to distribution feeders, so long as the requisite load and insolation data are available. However, the results presented in this report are unique to the Oxford-Rural feeder. Other feeders will present different load curves and insolation profiles, and as such the BESS capacity recommendations will differ. The general trend of the results is expected to be found in other feeders; for every feeder, there is likely a "sweet spot" level of PV penetration, perhaps around 25% to 35%, where the BESS capacity requirements are minimal.

Findings indicate a BESS with 0.61 MW of power capacity and 2.4 MWh of energy capacity would be able to achieve a flat DFP with 35% PV penetration: 1.0 MW of the 2.94 MVA estimated as the average daily maximum load currently experienced on the Oxford-Rural feeder. Note that while the MW capacity of PGE's SSPP is more than sufficient to meet these power requirements, the SSPP's MWh capacity is too low, 1.25 MWh, to facilitate such high levels of penetration of PV on the Oxford-Rural feeder.

These results were obtained using a flat feeder profile, which we use to develop an understanding of the upper bounds for the BESS MW and MWh capacities required for firming and shaping load and PV fluctuations. The flat profile is the worst-case scenario, but it serves to illustrate that any profile can be attained. A smooth feeder profile is sufficient, so long as voltage fluctuations are not outside the ± 0.05 pu bound and dV/dt is not too extreme. The aim of our work is to develop a method for BESS sizing that can address feeders experiencing very high levels of PV penetration such that problems like the infamous Duck Curve can be mitigated.[2]

VI. FUTURE WORK

For this work, a simple, flat desired feeder profile (DFP) was used. With a flat DFP, customer voltages do not fluctuate as PV generation and loads change since the BESS makes up any difference between the net load and the flat DFP. It was hypothesize that other DFPs more closely shaped to approximate the net load would be able to facilitate the integration of high levels of PV penetration with less MW and MWh BESS capacities. These could be as simple as piecewise linear curves that roughly approximate the predicted daily loading or more complicated functions that specifically mitigate the Duck Curve. On-going work has focused on developing DFPs that provide firming, but much less shaping, by integrating the past 15 to 90 minutes of feeder power demand to provide a projection for future power demand on a minute-by-minute basis. Focusing on firming eliminates short-term fluctuations of customer voltage profiles, though intra-hour voltage fluctuations will still occur. But doing so does result in less required MW and MWh BESS capacities, particularly MWh.

VII. ACKNOWLEDGMENT

This work was a collaborative project between Portland State University and Portland General Electric.

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