Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Battery Storage System Sizing in Distribution Feeders with Distributed Photovoltaic Systems

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Abstract — **This paper presents a procedure for sizing a Battery Energy Storage System (BESS) for the purposed of shaving the peak demand of a residential distribution feeder. The BESS power and energy storage rating are determined from actual load demand data and desired level of peak reduction using the load following method. The impact of distributed photovoltaic (PV) power generation (to be installed by residential customers) on the feeder load curve, and on the BESS sizing is explored. It is determined that while PV installations have no impact on the BESS power rating, they reduce its energy storage capacity in proportion with the PV penetration level.**

Index Terms— **Battery Energy Storage System (BESS), load peak shaving, BESS sizing, distributed photovoltaic systems, peak demand.**

I. INTRODUCTION

Electric utility infrastructure costs are driven primarily by the need to serve the load during the peak demand period. Therefore, it is desirable to shave peak demand in order to defer generation, transmission and distribution equipment upgrades, and reduce or avoid the necessity to purchase much higher cost generation assets.

A common practical way to achieve a reduction in peak load is through demand-side management techniques such as direct load control of residential and commercial HVAC systems, and price responsive load control typically via a two-tiered time-of-use (TOU) rate. In addition, utility rate structures typically include charges tied to peak monthly demand of commercial and industrial customers.

Another alternative for utility load leveling is the application of battery energy storage systems (BESS) which has been known for quite some time [1]-[10]. In here, load leveling involves storing electric energy in a battery during the off-peak period, and extracting it during the peak period.

The rationale for the BESS scheme revolves around the fact that energy during the off-peak periods is cheaper and readily available; whereas, energy during the peak period of the day can be several times more expensive and sometimes hard to acquire.

In addition to load leveling, energy storage systems can provide a wide array of solutions to other key issues that affect the power system: These include, but not limited to, spinning reserves, frequency control, voltage regulation, relief of overloaded network components, capacity release, and the possibility of temporary islanding operations. Battery storage is also being used in conjunction with renewable energy resources (i.e., solar or wind) where they provide a means of converting these non-dispatchable and highly variables resources into dispatchable ones [11]-[13].

Although significant advances have been made in battery technology in terms of efficiency and life cycle over the past decade, their relatively high cost is hard to justify in many applications. For this reason, several reported BESS installations for the purpose of load leveling are considered as pilot projects that are partially of wholly funded by government entities. Nonetheless, the initial capital cost can be justified in case where the daily load profile creates a significant price difference between peak and off-peak load periods, and other factors such as deferral of equipment upgrade are taken into account.

Several studies have been reported on short-term scheduling of a given BESS to determine the hourly charge/discharge cycles for utility applications [5]-[6]. Others studies analyzed the combination of a PV array and a battery bank, both of which belong to a customer [11] or to the supplier [14]. This paper considers a real case where the sizing of a utility-owned BESS that is planned for installation at the substation end of a residential feeder is explored. The impact of future customer-owned distributed PV systems on the BESS sizing is also analyzed. A schematic of the system under study is shown in Figure 1 below where P_{grid}, $P_{load,}$ and P_{batt} respectively represent the grid power, the feeder load power, and the power generated by the battery system.

The paper content is as follows: First, the load demand of the feeder under study is examined during the past summer months. This is followed by sizing the BESS from the desired level of peak shaving by load following. Finally, the impact of distributed roof-mounted photovoltaic systems PV (soon to be

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978-1-4244-2235-7/09/$25.00 ©2009 IEEE

installed by individual customers) on the load curve and BESS power and energy ratings is quantified.

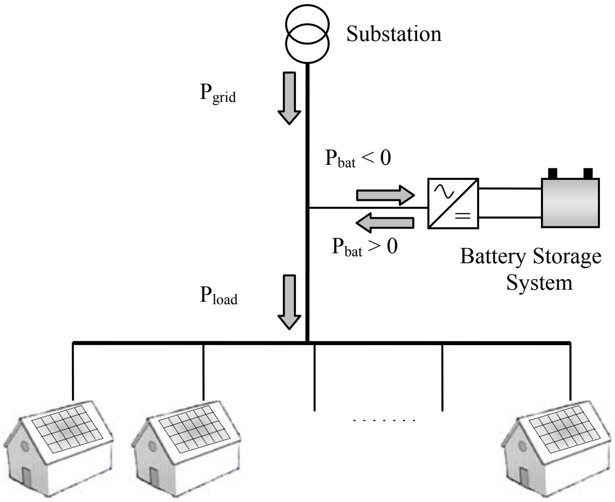

Figure 1: Feeder with Battery Energy Storage System and Residential Distributed PV Systems.

II. FEEDER LOAD CHARACTERISTICS

The local electric utility company imports a significant portion of the power demand from neighboring States during the hot summer period (June - September). In order to reduce peak demand, the company provides a choice for customers to participate in the Time Of Use (TOU) program in which the current energy rates are \$0.24/kWh during the peak hours (1:00-7:00 pm) and \$0.08/kWh for the rest of the time. In addition, it provides incentive for customers who allow their air conditioning systems to be controlled by the utility as needed during the above peak time window.

An experimental project is underway to install a BESS for load leveling purposes at the substation end of a relatively new feeder that is currently lightly loaded, and serves a growing residential area at the edge of town. The hourly real power demand of this feeder during the summer months of last year (2008) is shown in Figure 2 below. Note that a peak of $P_{load}^{\max}$ =1.46 MW occurred on July 8, and this coincided with the system peak demand for that year.

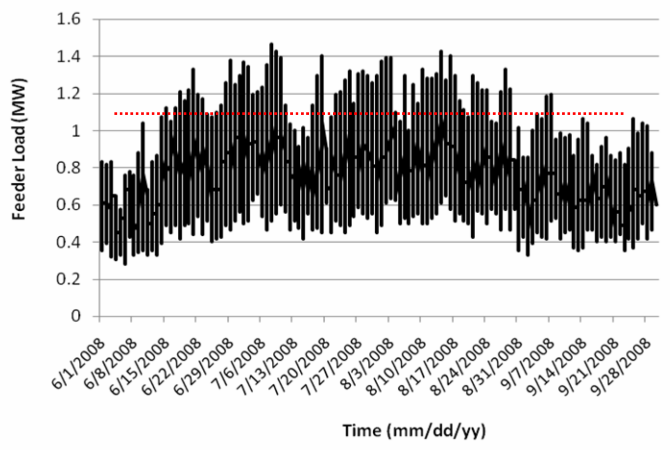

Fig. 2: Feeder Load during Peak Period (June-September).

Figure 3 shows the load duration curve corresponding to the 4-month long peak period. In here, 100% of the time represents 2,928 hours, or 122 days. For example, the feeder load exceeds 1 MW for 21% of the time (or 616 hours). The section that follows addresses the battery system sizing without considering the roof-mounted PV systems being installed by some individual customers.

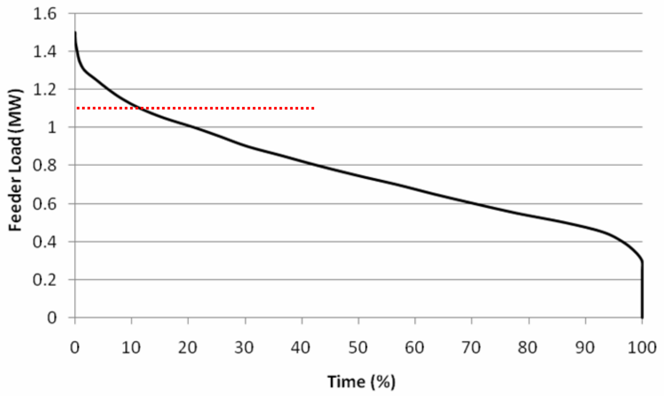

Fig. 3: Load Duration curve during peak period (June-September).

III. BATTERY STORAGE SYSTEM SIZING WITHOUT CONSIDERING PV PENETRATION

Sizing a suitable battery, in terms of its power and energy ratings, for shaving the peak demand hours depends primarily on the desired amount peak-shaving σ which is defined as a percentage of the maximum peak load, and available capital for the project: The amount of peak power shaving should be associated with the marginal cost of generating or importing electricity during the specified peak hours, while the cost of the battery system is largely associated with its energy storage rating (MWH) rather than the power rating (MW). Hence a small period of discharge is desired if all possible. Once the peak shaving is established, then the battery system is to supply a maximum net power of

$$P_{batt}^{\max} = \sigma\, P_{load}^{\max} \tag{1}$$

The BESS power rating P_{BESS} should include the battery losses during discharge as well as losses in the Power Conversion Unit (PCU). Let the overall system efficiency be denoted by η. Then,

$$P_{BESS} = P_{batt}^{\max} / \eta_d \tag{2}$$

The new grid power after battery installation becomes

$$P_{grid}^{\max} = P_{load}^{\max} - P_{batt}^{\max} = (1-\sigma) P_{laod}^{\max} \tag{3}$$

In this particular case under study, a shaving σ = 25% is desired. Hence, the BESS must provide a peak power of $P_{batt}^{\max}$ = 0.365 MW, which limits the grid power to $P_{grid}^{\max}$ = 1.095 MW. This latter value is indicated by a dotted red line in Figures 2 and 3. Assuming a discharge efficiency η_d = 90%, then the BESS power rating is P_{BESS} = 0.4 MW.

To determine the capacity or energy rating of the BESS, we first compute the daily energy demand that must be supplied the battery in order to keep the power flow from the substation side not to exceed the desired peak of 1.095 MW. This is achieved by simply determining the area between the load curve and horizontal red line in Figure 2 for each day *i* of the summer season:

$$E_{batt}^{i} = \int_{0}^{24} (P_{load}^{i} - P_{grid}^{\max})dt, \quad P_{load}^{i} \geq P_{grid}^{\max}. \tag{4}$$

The next step is to determine the maximum value of these daily energies to be injected by the BESS:

$$E_{batt}^{\max} = \max\{E_{batt}^{1}, E_{batt}^{2}, \ldots, E_{batt}^{n}\}, \tag{5}$$

where *n* is the number of days of the summer period. Finally, the BESS energy storage rating E_{BESS} is obtained by diving the result obtained in (5) by the discharge efficiency η_d and adding the minimum energy that must remain in the battery at all time (specified by the minimum State of Charge SOC_{min}) i.e.,

$$E_{BESS} = \frac{E_{batt}^{\max}}{\eta_d} + SOC^{\min} E_{batt}^{\max}, \tag{6}$$

In this study, Figure 4 shows the daily energy to be generated by the battery system according to Eqn. (4), with $n = 122$ days. It is clear that the storage system is required to supply a maximum amount of energy of $E_{batt}^{\max} = 2.12$ MWH. Once again, assuming a discharge efficiency $\eta_d = 90\%$, and letting the battery $SOC^{min} = 20\%$ leads to the BESS capacity rating $E_{BESS} \approx 2.75$ MWH.

One notes that the above BESS power and capacity ratings of 0.4 MW and 2.75 MWH were derived based on load following, i.e., battery power generation matches any load change in excess of the 1.095 MW threshold. This method is referred to as *power control* or *load following* since the demand controls the amount of power generated by the battery system. In this case, the battery system will operate at variable power for a total of 360 Hours or 12% of time. The operating time is also variable between 0 and 9 hours per day. Furthermore, it will operate at rated power for only two hours and only during the specific day where the maximum demand occurred (i.e., July 8).

The above method does not fully utilize this resource since the battery is utilized in only 63 days out of 122 days, and discharged only partially when used, except for the day of system peak. On the other hand, the method extends the life cycle as the depth of discharge (DOD) of batteries has a direct affect on their expected life. A more common way to operate the BESS is to supply constant power over a specific number of hours during the peak period. If this method were to be applied to the feeder under study, the capacity of the battery system would have to be upgraded by nearly 50% in order to achieve the desired level of peak shaving.

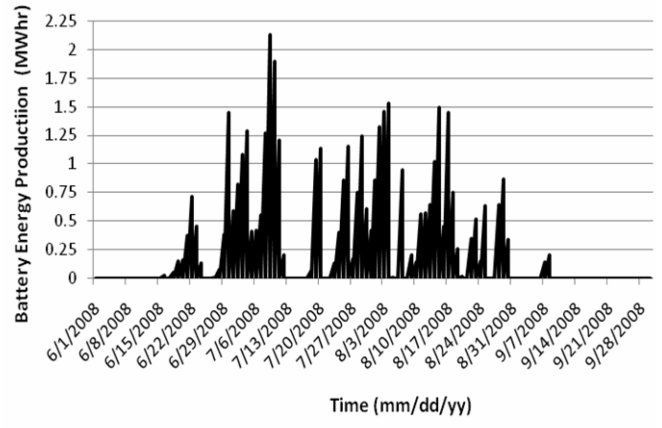

Fig. 4: Daily BESS Energy Generation.

Since the daily utility load experiences a low demand period during the early morning hours, this period is suitable for charging the battery. In this study, the BESS is to be recharged early the following morning (starting at 4:00 am), if it was partially discharged the previous day, in order to prepare for the next discharge cycle.

The resulting variation in power demand of the feeder load in combination with the BESS is shown in Figure 5 which illustrates the desired peak power shaving. The Figure also shows the daily minimum load is higher that the base case due to battery charging during the early morning hours.

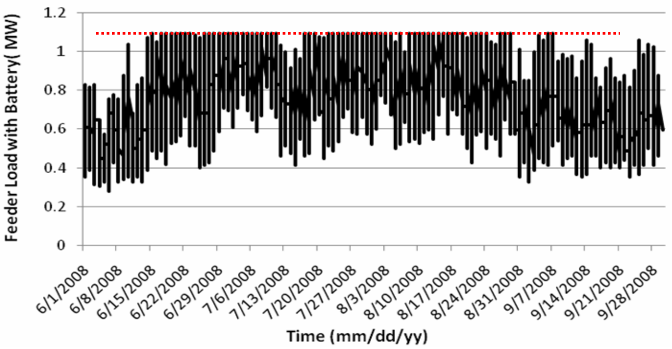

Fig. 5: Daily Grid Power Variation (after Battery Installation).

IV. DISTRIBUTED PV SYSTEM CHARACTERISTICS

Presently, only a handful of residential customers served by this particular feeder installed grid-interactive roof-mounted photovoltaic systems. However, the level of penetration of these systems is expected to rise sharply in the not too distant future. For example, one particular subdivision plans to install roof-integrated PV systems (averaging 2 kW per unit) in over 150 homes.

How will these system affect the peak load and hence battery sizing? The answer depends on the PV penetration level, orientation of the arrays, the coincidence level between the feeder peak and PV generation, and local weather conditions. Ideally, PV systems are oriented south (for all regions in the northern hemisphere) at a particular tilt angle in order to optimize the annual energy production. In reality, however, there are restrictions on roof tilt angle (most homes are built with a 22.5° roof tilt in the local area), and not all the roofs have suitable south-facing areas. Hence some installations will end up facing more south-east or south-west rather than south.

From the utility point of view, the west-facing PV systems are preferable since the system peak occurs in the late afternoon/early evening hours. To illustrate, Figure 6 shows the actual load curve of the day of peak demand on the feeder, and PV generation of a 2 kW system with 22.5° tilt angle for three orientations: east, south and west. Note that only the array facing west still produces some level of power during the peak demand hour of 6:00 pm.

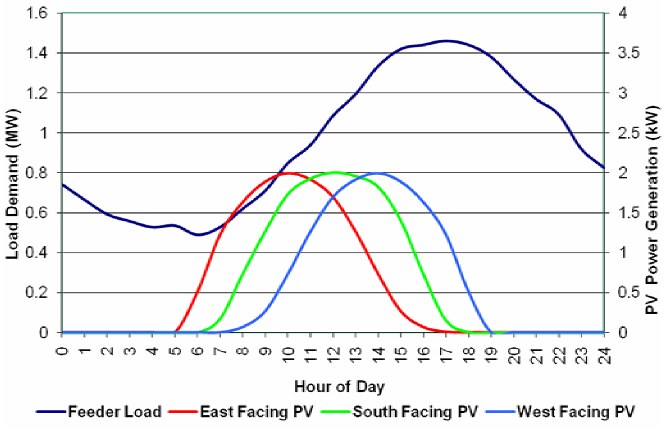

Fig. 6: PV Generation with Different Orientations and Load Curve.

Simulations were conducted with PV-DesignPro software to estimate the power generation from distributed PV systems at 20% penetration level and its impact of the feeder load curve. It is assumed that 150 systems (each rated at 2 KW) will soon be installed, and they all face south at 22.5° tilt angle. Past weather local weather data was used in the analysis. The resulting total hourly power production by these distributed PV systems is shown in Figure 7 below, and the modified feeder power variation is displayed in Figures 8.

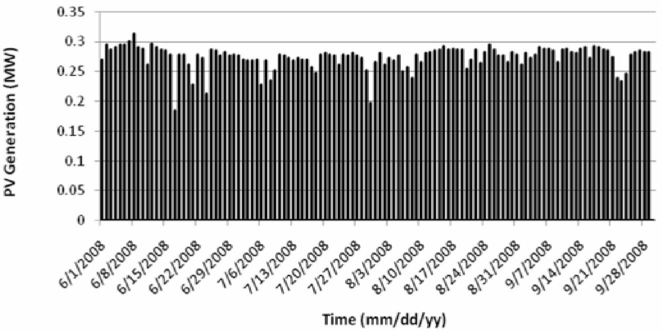

Fig. 7: Hourly PV Power Generation (20% Penetration Level).

Note that the peak power demand is reduced by a very small amount of just 3% (from 1.460 MW down to 1.415 MW). Consequently, PV systems that face south have little or no impact of the peak power demand in this particular region. On the other hand, these PV systems do contribute a significant amount of energy when considering the peak time windows. For example, the feeder load now exceeds 1 MW during 430 hours (i.e., 14.7% of the time). Without these PV systems, the feeder load exceeded the same amount of power during 616 hours (or 21% of the time) as indicated earlier – that's nearly 25% reduction. From Figure 7, west facing PV systems are expected have more significant reduction in both peak power and energy demand.

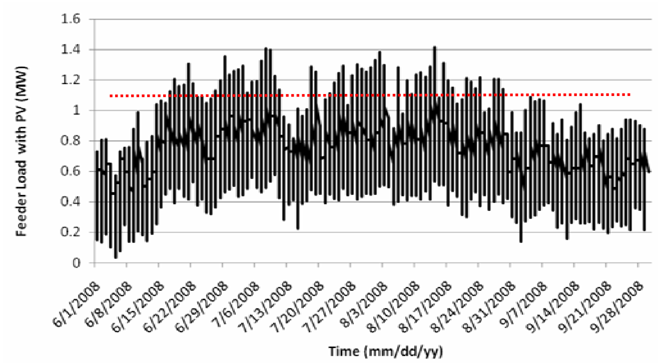

Fig. 8: Daily Grid Power Variation (after PV Installations).

V. IMPACT OF DISTRIBUTED PV ON BSS SIZING

As stated above, the south-facing PV systems have a negligible impact on the feeder maximum power demand. Hence in order to achieve the desired 25% reduction in peak shaving, the battery system power rating of 0.4 MW remains the same after the distributed PV installations. But the battery capacity rating should be reduced since these systems partially reduce the feeder energy demand during the peak time windows as noted above. To determine the new MWH rating of the BESS system, the same procedure outline in part III is performed on the modified hourly power demand displayed in Figure 8. The BESS daily energy production is displayed in Figure 9 below.

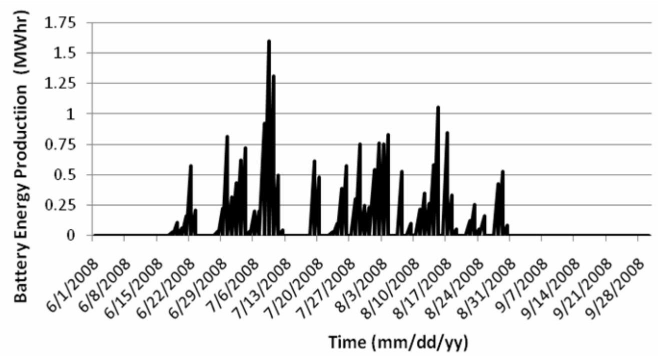

Fig. 9: Daily Battery Energy Generation (with 20% PV Penetration).

Note that the maximum energy production by the battery bank is now reduced to 1.59 MWH (that is a 25% reduction when compared to the value of 2.12 MWH prior to PV installation). Once gain, adding 10% of this energy to account for losses and 20% for satifying the minimum State-Of-Charge constraint results in an new BESS rating of nearly 0.4 MW/2MWH. If the original size of the BESS system is to be kept, then PV penetration will help maintain the battery bank at higher state of charge. The resulting stored capacity after peak shaving can then be used to reduce peak demand of adjacent feeder or as an additional spinning reserve. For comparison purposes, Figure 10 shows the modified feeder load duration curve after installing the PV and battery storage systems.

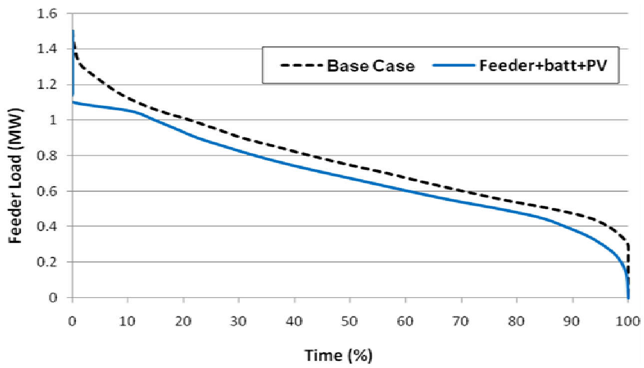

Fig. 10: Load Duration Curve after and Battery Installation.

VI. CONCLUSION

This paper presented a straight forward procedure for sizing a battery energy storage system for the purpose of shaving the peak demand of a residential power distribution feeder. The BESS power rating is obtained from the desired percentage of peak shaving and the feeder actual peak, while the capacity rating is derived from the daily maximum excess energy above the desired peak demand. The BESS is to be operated by following the load.

The impact of distributed PV systems (to be installed on the same feeder) on the BESS sizing was also analyzed numerically. As most PV systems will be south-facing, they have little or no impact on the BESS power rating. However, the installation of these systems assist in downsizing the energy storage rating of the BESS while achieving the same level of peak load shaving. The reduction in battery size depends on the level of penetration of the PV systems.

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