INTEGRATING PHOTOVOLTAIC AND STORAGE SYSTEMS ON DISTRIBUTION FEEDERS

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ABSTRACT

Combined installations of solar photovoltaics (PV) and energy storage devices are increasingly being considered, both to combat the intermittent nature of PV, and to provide additional services to the grid. This work details the integration of one such system. The impacts of installing a distributed PV and storage system under various feeder conditions, locations, and control strategies are examined. The results provide an indication of where best to locate the system, how to control it, and what additional services it can provide to the local feeder.

INTRODUCTION

The integration of renewable energy resources has been widely acknowledged as a critical step towards reducing greenhouse gas emissions and the consequent rise in global temperatures. Accordingly, many renewable resources have emerged not only at the transmission level of the power system, but also at the distribution level. Solar PV systems look set to become the most common form of distributed generation that distribution systems will encounter, both in the form of small-scale customer PV, as well as larger scale utility installations. Having generation located close to the load has the potential to be advantageous in a number of ways, however, the emergence of distributed PV also presents some challenges for distribution systems. In particular, the variability of solar generation as well as the non-coincident peaks of solar generation and load may lead to distribution systems being pushed outside of their safe operating limits. One solution to this is to install energy storage alongside PV installations, however, it is important to coordinate the operation of the PV and storage systems.

The work in this paper details a demonstration project which examines the integration of a new 5 MW utility scale PV plant, as well as a 10 MW energy storage system, to an existing group of distribution feeders. The main objective for the storage is to participate in a frequency regulation market service. There are four potential locations where the combined PV and storage system can be connected. Preliminary analysis will investigate the feeder impacts of installing the combined PV and storage at each of the potential locations, particularly when the storage is participating in frequency regulation (primary objective for storage operation in this study). The analysis will provide a baseline for determining the limiting factors of the feeders and the control that may be required to mitigate negative impacts. Additional storage control objectives such as solar shifting and voltage support are also examined to assess the potential for the storage to provide a secondary service to the feeders.

SYSTEM AND MODEL

Distribution feeders and PV/storage system

The distribution system under examination consists of a substation that feeds three feeders as well as an open bay. The voltage level of the feeders is 34.5 kV with the peak load being 40 MW. A one-line diagram of the feeders is shown in Figure 1 below where the substation is shown by the black marker.

Figure 1 One-line diagram of test distribution system

A combined PV and storage system is being installed at the site shown in Figure 1. This system consists of a 5 MW PV plant and a 10 MW/10 MWh storage device. The site where the system will be located has been decided, however there are four potential connection points, one on each of the feeders as well as one at the open bay. These are marked in green in Figure 1. The primary function of the storage is to provide a service to the bulk system by participating in a fast frequency regulation scheme. This scheme requires the storage to be able to ramp up and down within 1 second, with a signal being sent every 4 seconds. Therefore, the first step is to determine the feeder impacts of the storage ramping in response to the frequency regulation signal, at each of the four potential locations.

Modelling

The distribution system shown in Figure 1 has been modelled in EPRI's OpenDSS distribution system modelling software [1]. This software is capable of modelling all of the elements that are present on distribution feeders such as transformers, capacitors, and load tap changers (LTC), as well as their respective control modes. There are also explicit PV and storage models which are taken advantage of for the purposes of this work.

ANALYSIS

Uncontrolled Operation

Ramping Impacts

Actual load and solar data for these feeders is utilised within the model, as well as the signal data for the frequency regulation. All of this data was analysed to find worst case scenarios for ramping. Worst case ramping scenarios are defined as storage ramping up charging during high load and low solar output, and storage ramping up discharging during low load and high solar output. From the frequency data, realistic worst case ramping scenarios were chosen, however, these did not represent the absolute worst case ramp which could occur. The absolute worst case for ramping would be going from the storage discharging at 10 MW and the PV generating 5 MW to the storage charging at 10 MW and the PV not generating at peak load, and vice versa at minimum load. Therefore, a scenario is generated to analyse this absolute worst case. The daily profiles for storage and PV for this worst case scenario are shown in Figure 2, where the second subfigure shows a zoomed in version of the profile. The combination of these profiles is a ramp of 25 MW (15 MW generating to 10 MW consuming as described previously) between each time step for the duration of the day.

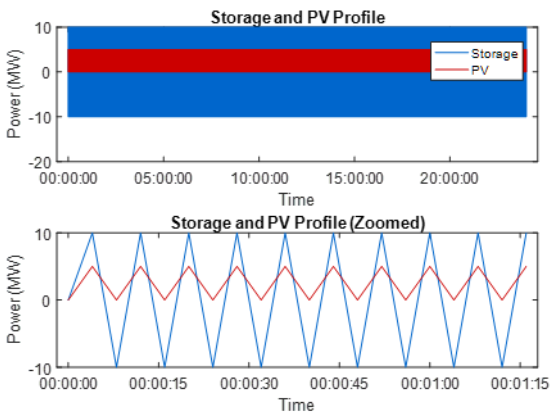

Figure 2 Storage and PV profile for worst case ramping

Figure 3 and Figure 4 show the resulting substation voltages for the peak and minimum load day respectively. Results are shown for adding the combined PV and storage system at all four of the potential connection points shown in Figure 1. The first subfigures show the voltage throughout the day while the second subfigures show a zoomed in version highlighting the largest voltage ramp. It is clear that even the worst case ramping does not push the substation voltage outside the ANSI limits of 0.95 pu and 1.05 pu. The largest voltage drop resulting from a 25 MW ramp seen at 15:28 in Figure 3 is 0.005 pu, while the largest voltage increase seen at 15:36 in Figure 4 is 0.001 pu. The substation voltages are almost identical regardless of location, therefore, it is feasible to connect the system to any of the four potential connection locations. It should also be noted that no voltage violations are recorded anywhere on the feeder, and the LTC taps do not reach the maximum or minimum values. There are also no equipment overloads. These results indicate that installing this PV and storage system and participating in the frequency regulation service will not result in any adverse impacts to the feeder.

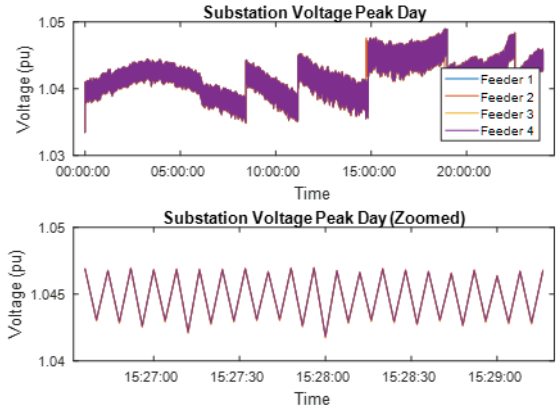

Figure 3 Substation voltages for worst case ramping on peak load day

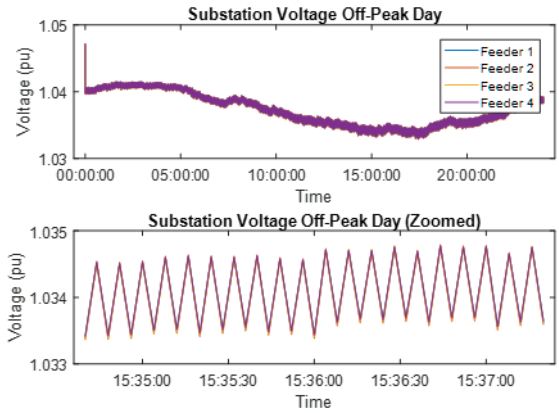

Figure 4 Substation voltages for worst case ramping on minimum load day

Storage Capacity Impacts

The second part of the impacts analysis determines whether the battery has sufficient capability to participate in the frequency regulation service. In order to analyse this, the frequency signal data is examined to find worst case capacity days. Three representative days are chosen: a maximum charging day, which is the day when the

charging energy minus the discharging energy is largest; a maximum discharging day when the discharging energy minus the charging energy is largest; and a maximum variation day which is the day with the largest standard deviation of charging/discharging. It is assumed that the battery is full at the beginning of the day. Figure 5-Figure 7 below show the frequency signal and actual dispatch as well as the storage state of charge for each of these three days. The times when the red series is visible without the blue series underneath indicate times that the storage was requested but not dispatched due to capacity limitations. These capacity limitations are evident in the state of charge plots, either by the state of charge being at the maximum value of 10 MWh, or the minimum value of 2 MWh (battery has a reserve value of 20%). This shows that without some additional control the storage may not have the capacity to meet the frequency regulation requirement at all times.

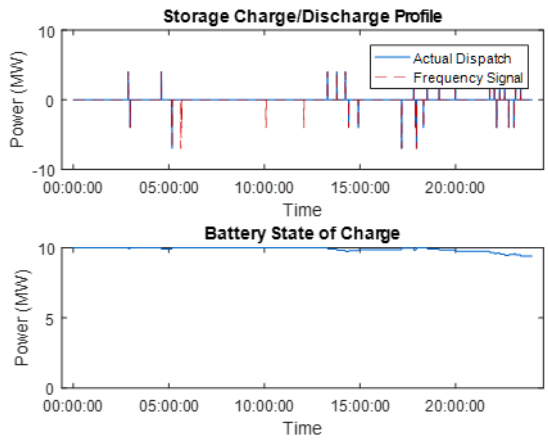

Figure 5 Storage dispatch and state of charge for maximum charge day

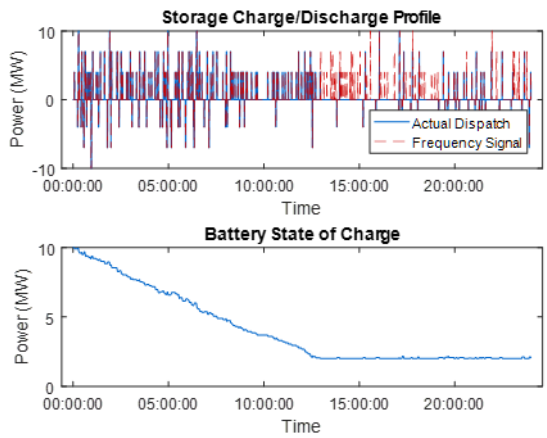

Figure 6 Storage dispatch and state of charge for maximum discharge day

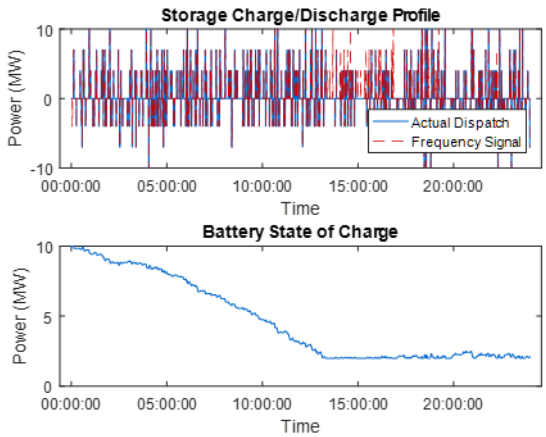

Figure 7 Storage dispatch and state of charge for maximum variation day

Controlled Operation

Control for storage capacity availability

Following on from the results shown in the previous section, storage control is implemented to ensure there is adequate battery capacity when frequency regulation is required. The control states that if the battery state of charge is higher than 9 MWh, the battery should discharge at 10 MW, and if the battery state of charge is lower than 4 MWh, the battery should charge at 10 MW. The results of the controlled operation for each of the three test days are shown in Figure 8-Figure 10. It is clear that there are no times when the frequency signal is requested and not dispatched, and there are now times when frequency regulation is not required that the storage is dispatching. This is indicated by the blue series that doesn't have the red series overlayed. These are times that the storage is operating due to the control. The second sub-figure in Figure 8-Figure 10 show the battery state of charge is kept within the 1 MWh and 9 MWh limits imposed by the control.

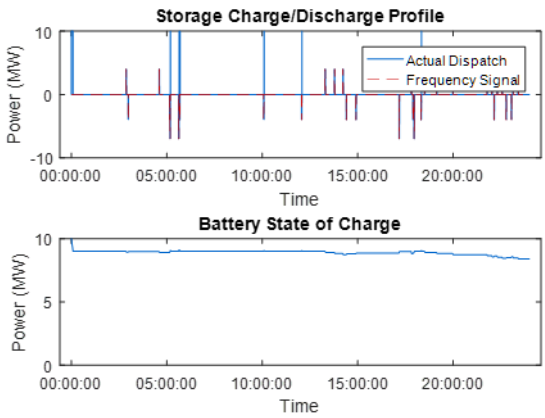

Figure 8 Controlled storage dispatch and state of charge for maximum charge day

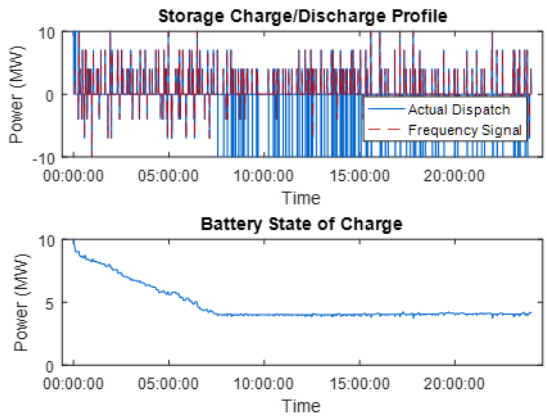

Figure 9 Controlled storage dispatch and state of charge for maximum discharge day

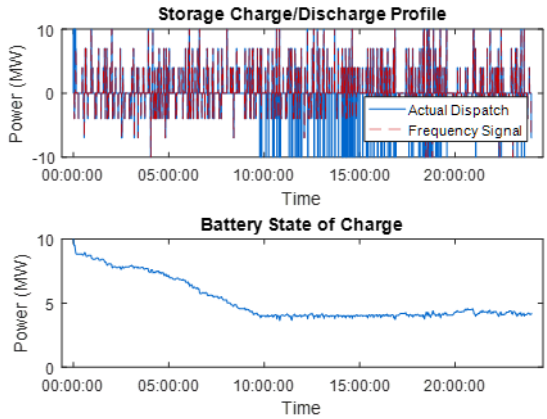

Figure 10 Controlled storage dispatch and state of charge for maximum variation day

Solar Shifting

Another control function that is examined is solar shifting. The idea behind solar shifting is to charge the battery during the day when the PV plant is generating large amounts of power, and to discharge that stored energy later in the day when load is high, thus flattening out the daily feeder profile. Two different scenarios are analysed for solar shifting, solar shifting on a day when there is no frequency regulation requirement and solar shifting on a day when there is substantial frequency regulation requirement, namely the maximum variation day as discussed in the previous section. Data for the minimum load day is utilised for this analysis and the battery state of charge at the beginning of the day is 50%. The control instructs the battery to charge at times when the PV is generating, the power through the substation transformer is less than 18 MW, and the battery is not in use for frequency regulation. It controls the battery to discharge at times when the power through the substation transformer is greater than 22 MW and the battery is not in use for frequency regulation. The values of 18 MW and 22 MW are illustrative and can be modified based on the feeder requirements. The charge rate is the difference between the current substation power and target (18 MW or 22 MW). It is assumed that the battery capacity control from the previous section is also in place for the day that frequency regulation is required.

The resulting daily feeder profile for the solar shifting control on a day without any frequency regulation requirement is shown in Figure 11, and is compared to the feeder profile without any storage control. The corresponding storage charge/discharge profile and state of charge are shown in Figure 12. It can be seen that the storage charges up early in the day when the PV is producing power and the load is low, and subsequently discharges power later in the day to reduce the peak load.

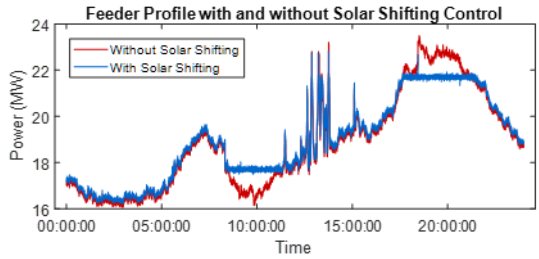

Figure 11 Feeder profile with and without solar shifting on day with no frequency regulation requirement

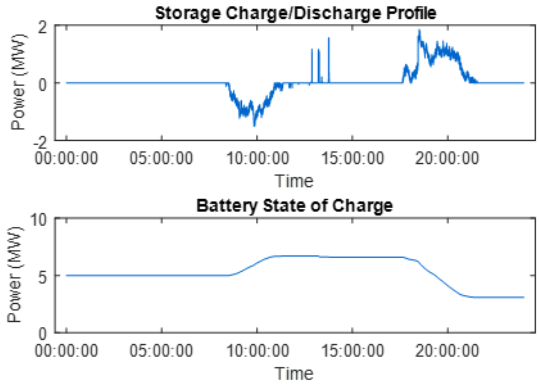

Figure 12 Controlled storage dispatch and state of charge for solar shifting on day with no frequency regulation requirement

The same results for the day with high frequency regulation requirement are shown in Figure 13 and Figure 14. It can be seen that during the times when the frequency regulation is not required and the PV is generating or the load is high, the battery is charging and discharging to perform the solar shifting objective. The battery state of charge results show that the battery capacity control is also being required, as the battery hits the state of charge limit of 4 MWh. This can also be observed in the charge/discharge profile, where there is a significant level of charging, particularly in the evening when the battery needs to discharge as part of the solar shifting objective to keep the state of charge above 4 MWh. These results indicate that although the battery is capable of performing a solar shifting objective, it may not be advisable to do so on a day when there the frequency regulation requirement is significant.

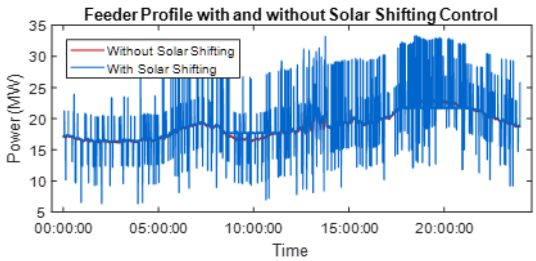

Figure 13 Feeder profile with and without solar shifting on maximum variation frequency regulation day

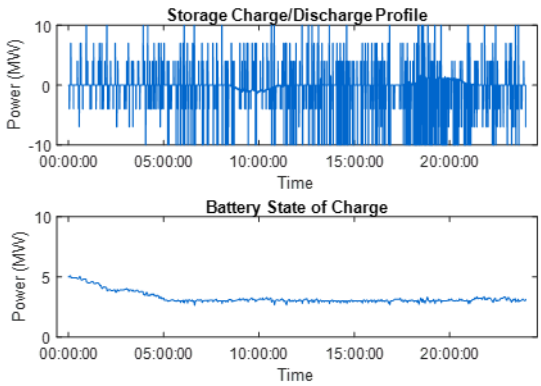

Figure 14 Controlled storage dispatch and state of charge for solar shifting on maximum variation frequency regulation day

Voltage Support

The final control function examines whether the storage can be used for voltage support. Voltage support is needed for a large customer connected to one of the feeders that experiences motor start problems due to voltage sags during faults. The analysis therefore consists of simulating faults on the two adjacent feeders as well as the HV side of the substation transformer in order to cause a voltage sag. The maximum amount of reactive power available from the storage (10 MVAr) is subsequently injected to the feeder in order to boost the voltage. Both a three-phase fault and a single-line to ground fault are simulated, however the results are similar, therefore only results for the single-line to ground fault are shown here, in Figure 15. The first two subfigures show the voltage for the large customer and the third shows the reactive power output of the storage. It should be noted that the reactive power output is three-phase, i.e. 3.33 MVAr is injected on each phase. The results show that although the reactive power injection from the storage can provide some voltage support, in this case it is not enough to bring it up from 0.88 pu to 0.9 pu during a fault, therefore it may not be prudent to depend on storage for voltage support for this customer during faults.

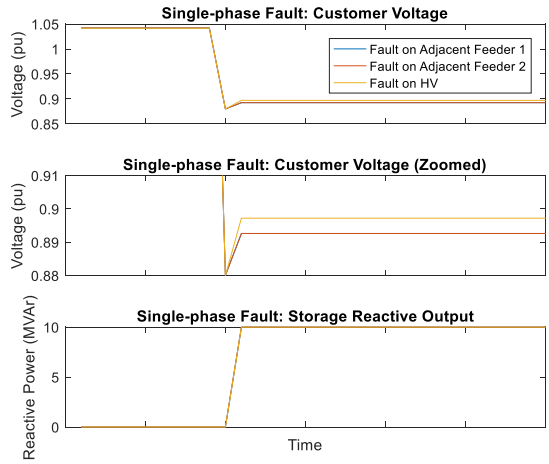

Figure 15 Customer voltage and storage reactive power during a fault

CONCLUSIONS

The work in this paper details the analysis for the integration of a combined PV and storage system to existing distribution feeders. The impact analysis shows that the system can be accommodated at any of the four potential connection locations without negatively impacting the feeders. Additionally, the worst case ramping that is possible with this PV and storage system participating in the primary frequency regulation objective, does not result in any feeder violations in terms of voltage or overloads. The capacity of the battery for participation in the frequency regulation objective was also analysed and it was shown that some control may be required to ensure capacity is available. This capacity control was tested, along with two other control objectives. The solar shifting control was shown to be effective, primarily when the storage is not operating to regulate frequency. Finally, the storage was shown to provide some level of voltage support during faults, but not enough to reliably mitigate the large customer's voltage issues.

REFERENCES

[1] OpenDSS, Electric Power Research Institute, [Online]. Available: http://sourceforge.net/projects/electricdss/.