# *Allocation of battery energy storage systems (BESS) to mitigate FIDVR in the Con Edison Transmission Systems*

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***Abstract*—Fault-Induced Delayed Voltage Recovery (FIDVR) is an unexpected time delay in the recovery of voltage to its nominal value following the normal clearing of a fault. Typically, the delay can last seconds to tens of seconds, which has attracted attention as a significant issue in power systems. Inverter-based renewables such as battery energy storage systems (BESS) show the potential to provide voltage support during FIDVR events. This paper studies the optimal allocation of BESS to mitigate FIDVR in Con Edison of New York, including the BESS control strategy, BESS size, and BESS locations. The study is carried on by means of computer simulations in Siemens PTI software PSS/e.**

***Keywords—Fault-Induced Delayed Voltage Recovery (FIDVR), battery energy storage systems (BESS) , PSS/e* simulation**

## I. Introduction

Fault-Induced Delayed Voltage Recovery (FIDVR) is a phenomenon when the power system voltage remains at a substantially reduced level several seconds after a transmission fault is cleared [1]. FIDVR is caused by the widespread installing of residential single-phase induction motors, such as AC conditioners [2]. In the system with large load proportion and constant torque characteristics of single-phase induction motor, when the system voltage drops to a lower value under fault conditions, the motor stalls [3][4]. These types of low inertia motors absorb a large amount of reactive power from the grid under low voltage conditions. The current consumed by these motors under such stall or locked rotor conditions is 5-6 times of their steady-state current. Therefore, the system voltage remains in the reduced state for a long time until the thermal protection trips the single-phase motor load. Once the motor is removed from the system, the system voltage will gradually recover. During a FIDVR event, it may take up to 30 seconds for the system voltage to return to normal. The consequences of FIDVR events may be voltage collapse and multiple cascading events on the power system[5].

With the increasing integration of inverter-based renewables, e.g., battery energy storage systems, winds and solar PVs, it is feasible to use these inverters' fast reactive power modulation capability to provide voltage support during FIDVR events. Battery energy storage systems (BESS) is one of the energy storage technologies that has been widely adopted in the current power industry in the U.S. A BESS equipped with a suitably inverter can perform both active power control and reactive power control. This allows a BESS to provide reactive power to support the system voltage during FIDVR events.

There are multiple literatures studied on mitigating FIDVR with inverter-based devices. For example, ref. [6]-[8] presented control strategies for STATCOM, energy storage systems to alleviate FIDVR. However, these studies carried out simulations with small systems, such as the IEEE 13 or 57 example bus system. In practice, the system is relatively much larger, which may affect the FIDVR mitigation result.

ConEdison of New York operates one of the world's largest energy delivery systems. Recently, they experienced a few FIDVR events and expected several BESS to be installed in its system. In this paper, simulations are carried out with the ConEdison of New York PSS/e model, which consists of almost 90,000 buses. Different battery energy storage systems (BESS) control strategy, size, locations are tested to understand the allocation of BESS to mitigate FIDVR in the ConEdison Transmission Systems.

This paper is organized as follows: In Section II, different 3-phase short circuit fault locations are simulated to find a more obvious FIDVR event for the following simulation. In Section III, Based on this event, different reactive power control options are all tested to design a control strategy for the BESS to mitigate FIDVR. Sensitivity studies are carried out to find the optimal parameters under each control options. In Section IV, simulations with different BESS sizes are also carried out. Since Con Edison is more interested in the voltage at 5 second after fault is cleared ($t_{fault}$+5s), this study calculated the voltage improvement with the help of BESS being installed at $t_{fault}$. Section V tests the effect of BESS distribution for different bus voltage levels and BESS sizes. Section VI summaries the finding in this study.

## II. The Con Edison of New York PSS/e model with different fault locations

Fault location affects the FIDVR voltage response. In this subsection, the 3-phase short-circuit fault is applied to different buses. According the Con Edison of New York

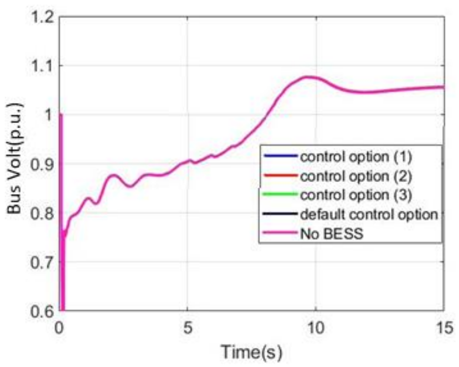
TABLE I. OPTIMAL PARAMETERS FOR CONTROL OPTIONS THAT HAVE GOOD VOLTAGE SUPPORT DURING FIDVR

| Control option number | | (1) | (2) | (3) |
|---|---|---|---|---|
| Control option | | Local coordinated V/Q control | Constant local Q control | Local (gen terminals) V control |
| Tuned parameters | $I_{qh1}$ (Upper limit on reactive current injection) | 1 | 1 | 1 |
| | $V_{ref0}$ (User defined reference) | 1.3 | 1.3 | 1.3 |
| | $V_{up}$(voltage above which reactive current injection logic is activated) | 1 | --- | --- |
| | $T_{rv}$ (voltage filter time constant) | 0.8 | --- | --- |
| | $K_{qv}$ (reactive current injection gain during over and undervoltage conditions) | 30 | --- | --- |
| | $K_{qi}$ (Reactive power regulator integral gain) | 0 | --- | --- |
| | $K_{vi}$ (Voltage regulator integral gain) | 10 | --- | --- |
| | $V_{dip}$ (low voltage threshold to activate reactive current injection logic) | 1 | --- | --- |

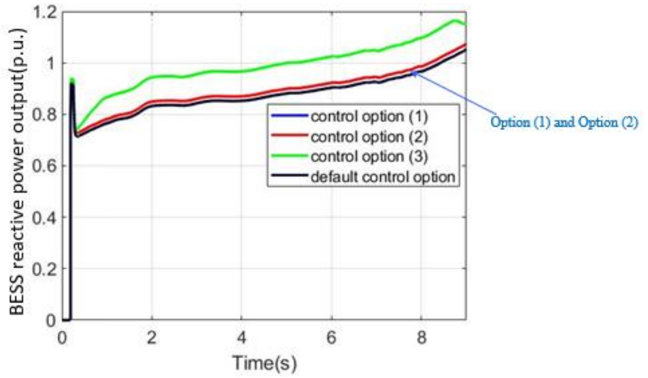
* "---" indicates that the parameter is the default value

TABLE II. THE POTENTIAL BUSES TO INSTALL A BESS BY CONEDISON3

| Location order | Stations | Buses |
|---|---|---|
| 1) | *Station G* | Double ring bus substation modeled in PSS/E as Bus_34[138kV] and Bus_46[138kV] |
| 2) | *Station E* | Modeled in PSS/E as Bus_84[138kV] |
| 3) | *Station A* | Double ring bus substation modeled in PSS/E as buses Bus_35[138kV]and Bus_49[138kV] |
| 4) | *Station R* | Double ring bus substation modeled in PSS/E as Bus_42[138kV] and Bus_43[138kV] |
| 5) | *Station_F* | Double ring bus substation modeled in PSS/E as buses Bus_44[345kV] and Bus_65[345kV] |
| 6) | *Station S* | Modeled in PSS/E as bus Bus_87[345kV] |
| 7) | *Station T* | Double ring bus substation modeled in PSS/E as buses Bus_85[138kV] and Bus_47[138kV] |




(a)

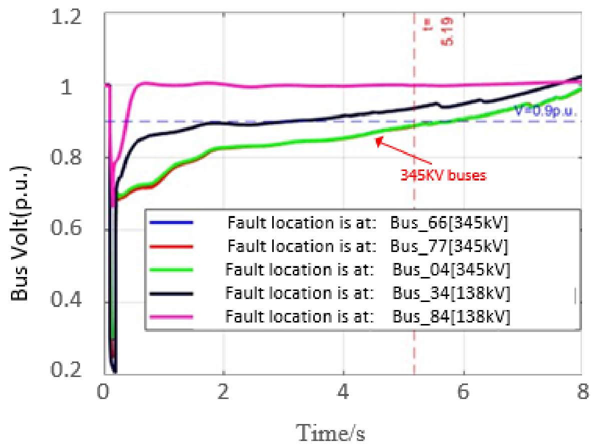



(b)

Fig. 1. Voltage (a) and BESS reactive power output (b) at bus Bus_66[345kV] when BESS is located at the bus Bus_84[345kV]

PSS/e model, buses that are associated with the top 2 largest loads for each voltage level are selected as the fault location candidatess as the below:

- Bus_77[345kV] for station transmission *Station_F*
- Bus_04[345kV] for station transmission *Station_W*
- Bus_34[138kV] for station transmission *Station_G*




- Bus_84[138kV] for station transmission *station E*

Con Edison recorded a real event that has an obvious FIDVR, which in the simulation system operated as: a 3-phase short-circuit fault happened at 0.1s at a 345kV bus Bus_66[345kV]. At 0.19s, fault is cleared and Bus_52[22kV]is disconnected.

Note that, in this case, a bus is disconnected at the time the fault is cleared in the real event. To make it comparable, a simulation that applies fault to Bus_66[345kV] is also carried out, while there is no bus being disconnected.

Fig.1 shows the bus voltage at bus Bus_18[138kV] when fault happens at different locations. It can be seen that more obvious FIDVR occurs when fault happens at 345kV buses. They are the worst among all the cases and is similar to each other. Therefore, the real event that was introduced above is selected as the simulation event for the following study.

## III. BESS CONTROL OPTIONS AND PARAMETERS

BESS models that are introduced by the WECC Renewable Energy Modeling Task Force have a variety of control options for real power control and reactive power

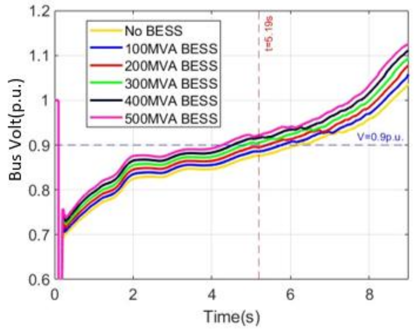



Fig. 3. Voltage at Bus_84[138kV] when a 100MVA BESS at Bus_84[138kV]

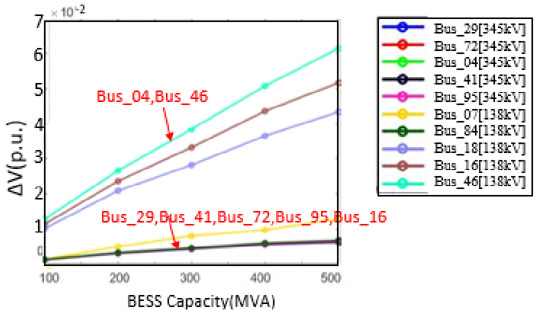



Fig. 4. Relationship between ΔV and the BESS capacity when BESS is at location 1)

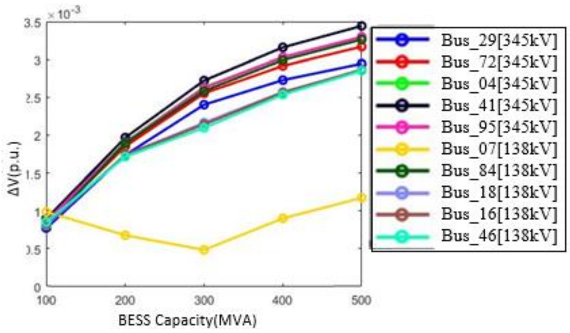



Fig. 5. Relationship between ΔV and the BESS capacity when BESS is at location 7)

control [11][12]. To support system voltage, the 8 reactive power control options are tested in Con Edison's model. Through simulations, we found the optimal parameter combinations for 3 control options that performs better than the default parameters. The optimal parameters for these 3 options are shown in Table I,where parameters that are not shown in this table are still the default values.

Fig.2 shows the bus voltage response and the BESS reactive power output. Since the control option (3) generates more reactive power among all the options, the rest of the simulations in this paper adopts the control option (3).

## IV. BESS CAPACITY IMPACT

Capacity is a factor that affects how BESS performs during FIDVR events. In this section, BESS with different capacities (ranges from 100MVA to 500MVA) are added to the 10 potential locations that are recommended by Con Edison's engineers listed in Table II. For example, Fig.3

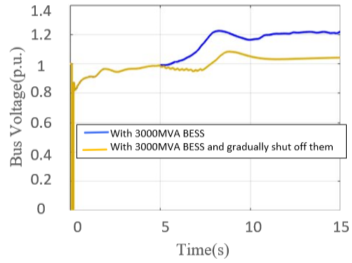



Fig. 6. Bus voltage before/after gradually reduce the total BESS capacity

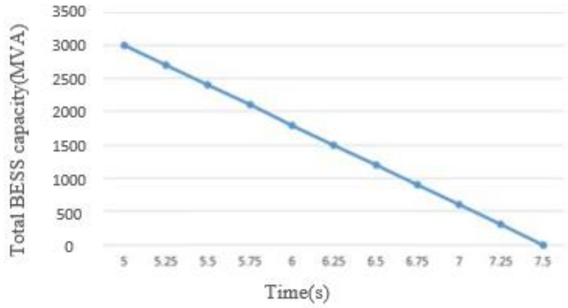



Fig. 7. Total BESS capacity.

shows the bus voltage at Bus_84[138kV] when different capacity BESS located at Bus_84[138kV]. some conclusions can be summarized for this case as the below:

- The voltage at $t_{fault}$+5s (i.e. 5.19s) increases with the BESS capacity.
- When BESS capacity increased to above 300MVA, the voltage at Bus_84[138kV] meet Con Edison's voltage response criteria, i.e. the voltage reaches 0.9p.u. at the 5s after the fault is cleared($t_{fault}$+5s).
- With each time the BESS capacity increases 100MVA, the voltage at $t_{fault}$+5s increases by 0.01p.u.

As indicated in the last conclusion above, with the increase of the BESS capacity by every 100MVA, the voltage at the $t_{fault}$+5s tends to increase by a certain value. In other words, there is a possibility that the increased voltage at the $t_{fault}$+5s to be linear to the increase of the BESS capacity.

Fig.4 shows the relationship between the delta voltage(ΔV) and the BESS capacity when BESS is at location 1) in Table II. The observation buses are the high voltage-level buses (345kV or 138kV) that Con Edison are interested in. The ΔV in this report is the voltage difference at $t_{fault}$+5s between the case when there is a BESS and there is no BESS. It can be seen that the curves in Fig.4 are almost straight lines, which means that the voltage increase is almost linear to the BESS capacity.

As an exception, the voltage responses at buses with generators connected are not always increases with the BESS capacity, as shown in Fig.5. With generators connected to the nearby buses, the bus voltage responses can be supported and multiplied.

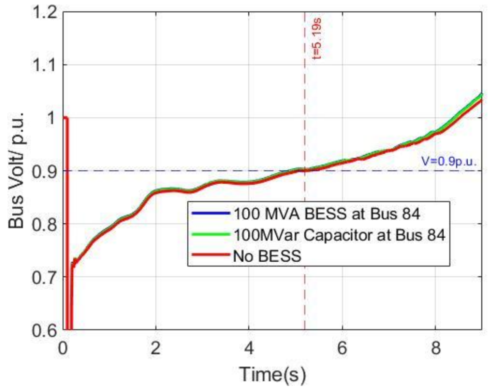



Fig. 8. Voltage at bus Bus_72[345kV] when a 100MVA BESS at Bus_84[138kV]

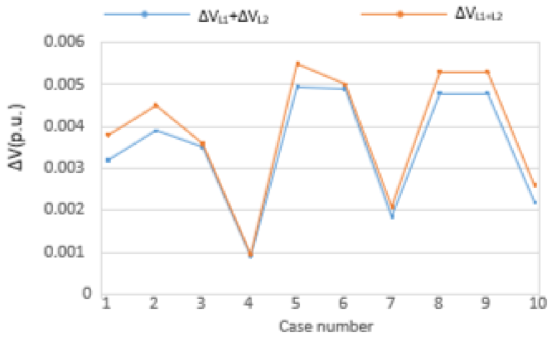



Fig. 9. ΔV when 100MVA are added to two different locations

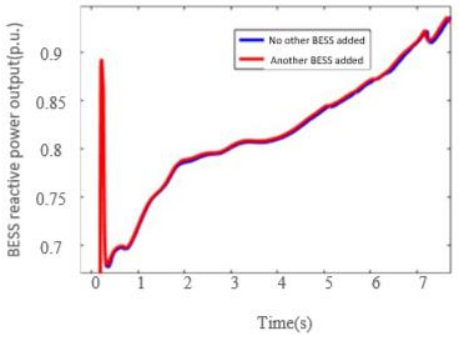



Fig. 10. the BESS at location Bus_34[345kV] outputs reactive power when there is/is not another BESS added to the system

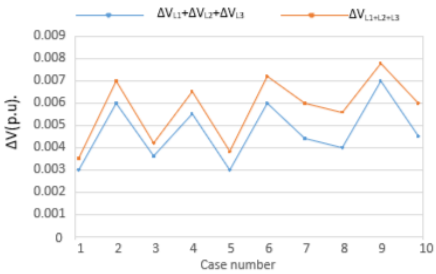



Fig. 11. ΔV when 100MVA BESS are added to three different locations

As can be seen from Fig.2, there are bus voltage overshoots after the fault clearance. The overshoots may be the result of the synchronous generation in the system but not be attributed to the inverters and batteries. However, the inverters can help with minimizing the overshooting, for example, by providing a much more controlled response, etc.

In practice, it is possible to implement a large-size BESS by deploying multiple small-size BESS. Therefore, a potential and easy way to mitigate the voltage overshoot is to gradually shut off BESS.

In this example case, assume that there multiple BESS being deployed at Bus_84[138kV] and the total BESS capacity is 3000MVA. The blue curve in Fig.6 shows the voltage at bus Bus_66[345kV].It can be seen that the voltage reaches 1.2p.u. in the steady state after the fault clearance. To mitigate the voltage overshoot, adjust the total BESS capacity by following Fig.7. This means that the total BESS capacity is reduced by shutting off 300MVA BESS every 0.25s starting from 5s.

The bus voltage after shutting off all the BESS is shown in the yellow curve of Fig.6. It can be seen that the steady-state voltage after fault clearance is mitigated to around 1.02 p.u..

## V. The Effect of the BESS Distribution

### A. *Deploy one BESS*

In this section, a 100MVA BESS and a 100MVar capacitor is deployed to the Bus_84[138kV], respectively, and the voltage responses of the following 10 buses are monitored : Bus_29[345kV], Bus_72[345kV], Bus_04[345kV], Bus_41[345kV], Bus_95[345kV], Bus_07[138kV], Bus_84[138kV], Bus_18[138kV], Bus_16[138kV], Bus_46[138kV].

Among all the tested cases, the voltage responses at different monitored buses do not have a significant difference. As Fig.8 shows, the voltage difference when there is a 100MVA BESS, 100Mvar Capacitor, and there is no BESS is marginal, which is within the PSSE modeling error. This indicates that the 100MW BESS provides as much as reactive powers that a 100MVar Capacitor can provide during fault. However, the voltage support to the Con Edison model is limited.

### B. *Deploy multiple BESS at different locations*

As discussed in Section IV, the ΔV tends to be linear to the BESS capacity when there is a BESS in the system. In this Section, multiple BESS are added to the system to calculate the voltage increase ΔV at $t_{fault}$+5s.

In Fig.9, the curve $\Delta V_{L1}+\Delta V_{L2}$ shows the ΔV at $t_{fault}$+5s when 100 MVA BESS are added to both the locations L1 and L2; $\Delta V_{L1}$ is the ΔV when a 100 MVA BESS is added to location L1, $\Delta V_{L2}$ is the ΔV when a 100MVA BESS is added to location L2. The tested locations are the BESS potential locations 1)~5) in Table II.

It can be seen from Fig.9 that $\Delta V_{L1+L2} \approx \Delta V_{L1}+\Delta V_{L2}$ for the tested cases. Take Case 1 as an example, Fig.10 shows the reactive power output of the BESS at Bus_34[345kV]. It can be seen from Fig.10 that, the BESS output similar reactive power when there is another BESS deployed in the system.

TABLE III. DEPLOY A 500MVA BESS AT BUS_07[138KV]

| Category | Bus Number | Voltage at $t_{fault}$+5s whenSBESS=500MVA/p.u. | Voltage at $t_{fault}$+5s whenSBESS=0/p.u. | Total P of the Trans station load /MW | Total Q of the Trans station load/MVar |
|---|---|---|---|---|---|
| A | *Bus_07* | 0.9498 | 0.8897 | 877.834 | 269.602 |
| A | *Bus_29* | 0.9092 | 0.9049 | 0 | 0 |
| A | *Bus_45* | 0.9089 | 0.9087 | 0 | 0 |
| A | *Bus_47* | 0.903 | 0.903 | 248.786 | 77.652 |
| A | *Bus_85* | 0.903 | 0.903 | 248.786 | 77.652 |
| B | *Bus_04* | 0.9015 | 0.8968 | 1007.133 | 373.574 |
| B | *Bus_48* | 0.9013 | 0.902 | 270.97 | 97.882 |
| B | *Bus_41* | 0.9006 | 0.8959 | 326.792 | 105.705 |
| B | *Bus_95* | 0.9001 | 0.8956 | 627.919 | 222.425 |
| C | *Bus_18* | 0.8824 | 0.8673 | 346.491 | 116.911 |
| C | *Bus_84* | 0.8807 | 0.8762 | 971.954 | 321.033 |
| C | *Bus_16* | 0.8670 | 0.8502 | 201.269 | 61.948 |
| C | *Bus_46* | 0.8546 | 0.836 | 1204.65 | 324.187 |

Similar results can be found from Fig.11 when 100MVA BESS are added to three different locations. It shows that there is $\Delta V_{L1+L2+L3} \approx \Delta V_{L1}+\Delta V_{L2}+\Delta V_{L3}$. Based on these two figures, it can be found that, distributing 100MVA BESS to different locations or one location will not make a significant difference on the voltage support.

### *C. Deploy Large BESS at large load bus*

In this sub-section, BESS with large size is deployed at some load buses. According to Con Edison's system model, three locations are selected as the BESS location because they are associated with the transmission station that has the largest or the second-largest load: Bus_07[138kV], Bus_46[138kV], and Bus_95[345kV].

To be practical, different BESS capacities are chosen for different voltage level buses. To be specific, a 500MVA BESS are added for 138kV buses while a 1000MVA BESS are added for 345kV buses. Table 4~Table 6 shows the voltage at the buses that has the top 10 worst FIDVR voltage response when there is or is not a larger BESS for the 3 BESS locations listed above. The buses are classified into 3 categories as the below:

A. Meet the criteria even when there is no BESS (SBESS =0)

B. Can meet the criteria when there is a BESS (SBESS $\neq$0)

C. Not meet criteria when BESS capacity is either <= 500MVA for 138kV buses or <= 1000MVA for 345kV buses

In Table III, The buses that are colored in blue are the 138kV buses, while others are the 138kV buses. This table is ordered by the third column, which is the voltage at 5.19s when the larger BESS is added.

Based on the testing results, some conclusions are :

i. For the 138kV buses, the voltage at the $t_{fault}$+5s with BESS added decreases with its associated transmission station load. However, the buses Bus_18[138kV] and Bus_16[138kV] are special and probably because they are connected to some generator.

ii. There are 4 buses meet the voltage criteria even without a BESS being installed: Bus_29[345kV], Bus_45[138kV], Bus_85[138kV], Bus_47[138kV]

iii. There are 3 buses meet the voltage criteria with the help of installing BESS: Bus_04[345kV],Bus_41[345kV], Bus_95[345kV]

iv. Bus Bus_46[138kV] is associated with a large load, which prevents it from reaching the voltage response criteria for all the tested cases.

## VI. CONCLUSIONS

The analyses in this study designs a basic FIDVR controller and compare the control effects under different BESS locations for the Con Edison of New York PSS/e model.

FIDVR events were firstly replicated by applying a 3-phase short-circuit fault to several different buses, it is found that the fault at the 345kV buses leads to more obvious FIDVR. The BESS control effect was then tested under the most obvious FIDVR event suggested by Con Edison.

There are eight reactive power control options for BESS to support system voltage in the positive sequence models used in PSS/E. To find the optimal values, model parameters were adjusted in simulations. The results of that tuning are provided as well as descriptions of each parameter. Among these options, BESS outputs the most reactive power with the local V control. The tuned parameters are $I_{qh1}$=1 and $V_{ref0}$=1.3.

The BESS location and size affects the bus voltage responses. Several results are concluded in this report as below:

First, the deployment of BESS in the system could lead to bus voltage overshoot after a few seconds. This report discussed a potential way to minimize this overshoot, which is to gradually shut off the BESS. Other sophisticated ways to achieve this could be studied in the future.

Additionally, it is observed that the voltage change is linear to the BESS size for small BESS. Meanwhile, generators affect the voltage response for nearby buses. That is, the voltage response at buses can be supported and enlarged by the nearby generators.

Moreover, given the local configuration of the Con Edison system, the placement at 345 kV stations appears to provide more leverage for BESS responses than 138 kV stations.

The reactive power generated by a BESS does not have a significant difference regardless of whether there is another BESS in the system or not. That is, it does not matter if the BESS is distributed or aggregated in the system.

Finally, it is found that the larger the transmission station load is, the greater the voltage drop during a FIDVR event. That is, Local generation and lighter load help to alleviate the drop.

In conclusion, this study designs a control strategy for BESS to provide voltage support during FIDVR in Con Edison of New York. There are three interesting topics that remained and could be further studied in the future. The first topic would be how to design a control method that actively looks to dampen the response to mitigate the voltage overshoot response. Second, this report studied a large grid, future work could investigate using BESS for voltage support on microgrids. The last topic of interest is to predict the impact of future heat pump (building loads) and EV loads on FIDVR responses.

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