Optimal Placement and Control of BESS for a Distribution System Integrated with PV systems

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Abstract – Recently, photovoltaic generation (PV) has attracted a great attention as one of green power generations. Accordingly, a large amount of PV systems will be installed in residential areas in the coming years. In such a scenario, reverse power flow caused by PV in feeders may cause some problems such as voltage rise over upper limits in the distribution line, and the reverse power flow into the distribution substation. Battery energy storage system (BESS) is a promising option to solve the above both problems at the same time. However, the effect of BESS depends on location of BESS. Therefore, it is necessary to consider an appropriate location in the residential distribution system to install BESS to obtain an optimal effect. This paper investigates an optimal placement pattern of BESS in the residential distribution system with certain patterns of PV installation. It has been made clear that the obtained results can determine the best placement pattern of BESS with the minimum required BESS capacity and power loss.

Keywords: Battery energy storage system (BESS), Distribution system, Photovoltaic generation (PV) system, Reverse power flow, Voltage rise.

1. Introduction

Recently, distributed power generations from renewable energy sources such as photovoltaic generation (PV) and wind power generation have attracted a great attention from viewpoints of environmental issue and energy security. Usually, PV systems are installed on the roofs of houses in residential areas. Due to much investment associated with PV installation, it is preferable to put the PV systems in new houses. As a result, a large amount of PVs may be connected to one area whereas may not to others.

When a large amount of PVs are connected to the residential distribution system, many operational problems could occur under the present control scheme of power system. It is essential to establish a new distribution control schemes, capable of handling mass introduction of PV.

Battery energy storage system (BESS) is a promising option to solve certain PV created problems. This paper investigates an effective placement and a control scheme of BESS which mitigates the problems of reverse power flow caused by PV in distribution system.

2. Distribution System

2.1 Problems caused by reverse power flow

In a distribution line with lots of PV installed, reverse power flow could occur under certain conditions, so the direction of power flow could be time dependent. In this paper, two operational problems caused by the reverse power flow are considered.

If this situation occurs, either the PV power output has to be reduced or the PV system has to be disconnected from the grid.

The first issue associated with reverse power flow is that distribution line voltage could exceed the operational limit. The voltage of distribution line has to be maintained within predetermined range in order to supply quality power all the way down to receiving ends. The reverse power flow caused by PV will increase the line voltage, which may rise over the limit. The conceptual diagram depicting this problem is shown in Fig.1.

Secondly, the reverse power flow from the distribution line into distribution substation will sometimes occur when the total PV output exceeds the total demand of loads connected to the all feeders supplied by a distribution transformer as shown in Fig.2. Such reverse power flow could result in protection failures or damages to the present power system.
Fig. 1. Voltage limit violation of the distribution line.

Fig. 2. Reverse power flow into distribution substation.

2.2 Distribution system model

These problems will become serious in residential areas, because a great amount of PV systems are expected to be installed on roofs of residential houses. In this paper, a main feeder model based on Electric Technology Research Association’s residential distribution system model in [1] is used as the system model for the study. This model is shown in Fig.3.

Fig. 4 shows daily active and reactive power demand changes for a typical residential distribution line under the heavy and light load conditions in [2]. The tap position of pole transformer at each node on the main feeder model is determined by the line’s voltage profile under the heavy load condition. In order to ensure analysis of system under the severest condition of reverse power flow caused by PV, the light load condition is considered in the simulation.

Fig. 4. Daily load curves of a residential distribution line.

2.3 PV system

PV system in the residential distribution system has many installation patterns. In this paper, the ratio of the total PV capacity to the installation capacity, 3000kVA, of the distribution line is defined as PV penetration ratio. In addition, 3 cases of PV installation patterns are considered: nearly uniform installation along the distribution line, high concentrated installation near the far end of the line, and high concentrated installation near the close end of the line.

These cases are illustrated in Fig.5.

Fig. 5. PV installation patterns.

Fig. 6 shows PV power output during a sunny day. Since the severest condition of reverse power flow occurs when the PV output is maximum, a sunny day has been selected.
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for this study.

Fig. 6. PV power output (per capacity).

It is possible to control the PV output power and its power factor with power conditioning system in PV system itself. However, when some PVs have to reduce their generation to control the reverse power flow, the PV owners lose the opportunity to sell the surplus PV power. This disadvantage could be location dependent and could lead to a social problem. An appropriate placement of BESS is required due to their high cost. Moreover, it is necessary to explore possible placement of BESS which requires neither the active power control nor reactive power control to address the reverse power flow issue under the worst case operation.

2.4 BESS

This paper investigates effective placement of BESS in the residential distribution system with the specified patterns of PV installation. In this study, 3 installation patterns of BESS, shown in Fig.7, will be examined in terms of the control performances.

pattern A: BESS is uniformly distributed to each PV pattern B: BESS is installed at the middle of the line pattern C: BESS is installed at the end of the line

Fig. 7. Patterns of BESS placement.

The line voltage and the active power flow can be controlled by charging BESS with the surplus PV output power during the daytime, and discharging this accumulated energy during the night time. The charging and discharging of the BESS should be equal for a given day in order to ensure sustainable operation of the BESS as shown in Fig.8. Otherwise the stored energy level of the BESS could reach extreme and fail to produce expected effects. In other words, carryover energy of the BESS should be zero for the sustainable operation.

Fig. 8. The state of BESS in a day.

3. OPF calculation

Under aforesaid conditions, the required BESS capacity can be determined. For each 24 hour time section, 1 hour duration, if any problems occur during a sunny day under the light load condition, the below OPF (Optimal Power Flow) calculation is performed. It is assumed that the voltage and the active/reactive power flows of the distribution line are monitored correctly. The BESS is assumed to be under a centralized control with communication network for issuing commands to the BESS either to supply or absorb the active power.

The range of line voltage to be maintained at the low voltage side of pole transformer is set to 103V to 106V. Because, in Japan, the receiving voltage of customers connected to low voltage feeder should be maintained in 101±6V, and the maximum voltage drop and rise along the actual low voltage feeder are estimated to be 8V and 1V respectively. Besides, the sending voltage at the substation depends on the line voltage profile without PV output. Actually, the sending voltage should be maintained considering the line voltage profile[3].

Generally, multiple 4 to 8 main feeders are connected to one distribution substation, so the reverse power flow into the substation will occur when the total PV output exceeds the total demand in all these lines. In this study, we assume much tighter constraint in reverse power flow which does not allow the reverse power flow on each feeder.

The required kW capacity of BESS is determined by selecting the maximum value among kW requirements.
obtained for all time sections by minimizing the objective function given by (1) at each time section. The corresponding kWh value is selected as required energy capacity. System energy loss, which is defined as the sum of distribution line loss at each time section and BESS charge-discharge energy loss (15% of the required BESS kWh capacity), is also calculated.

If carryover energy exists in BESS, it is concluded that BESS cannot resolve the problems in that situation.

\[
\text{Minimize} \quad \sum_{i \in N} P_{\text{BESS},i,t} \quad (1)
\]

\[
\text{Subject to} \quad I = Y V \left( P_{i,t} + j Q_{i,t} = I_{i,t} \bar{V}_{i,t} \right) \quad (i \in N) \quad (2)
\]

\[
\text{(Range of line voltage)} \quad V_{\text{min}} \leq V_{i,t} \leq V_{\text{max}} \quad (i \in N) \quad (3)
\]

\[
\text{(Direction of line power flow)} \quad P_{0,t} \geq 0 \quad (4)
\]

\(i, t\) : node number, time section number
\(N\) : set of all nodes
\(I, V\) : current vector, voltage vector
\(Y\) : admittance matrix
\(P_{i,t}, Q_{i,t}\) : active and reactive power
\(P_{\text{BESS},i,t}\) : active power of charging BESS
\(V_{i,t}\) : distribution line voltage
\(V_{\text{min}}, V_{\text{max}}\) : upper and lower limit of line voltage

4. Simulation results

The effectiveness of BESS placement to alleviate the reverse power flow problem was analyzed under 3 PV installation cases given in the previous chapter.

4.1 Case 1: PV nearly uniform installation

Fig. 9 shows the required BESS kW, kWh capacity and the system energy loss for 3 BESS patterns for different PV ratios in Case 1. In almost all situations, BESS is required for voltage control rather than for surplus power control with exception at PV ratio of 60-70% in pattern C. In other words, the reverse power flow will not occur when the line voltage is maintained within proper range.

Fig. 9(a) and 9(b) show that the kW and kWh requirements of BESS for pattern A are about 1.1 to 1.2 times as large as those for patterns B and C. Moreover, of the 3 patterns, the marginal PV penetration ratio increases in the order of pattern C, pattern B, and pattern A.

BESS charge-discharge energy loss is dominant compared with the distribution line loss in the system energy loss, so that the energy loss for pattern A is also about 1.2 times as large as those for patterns B and C.

4.2 Case 2: PV far-end installation

Fig. 10 shows the required BESS capacity and system energy loss (case1).
loss in Case 2. In all situations, the required BESS capacity for voltage control is quite larger than that for surplus power. Compared with Fig. 9(b), Fig. 10(b) shows that more than 1000kWh of the extra BESS capacity is needed for the same PV ratio and BESS placement. Especially, BESS connected to the middle point of the line is ineffective in controlling line voltage in this case, so that the required capacity for pattern B is much larger than those for the other patterns. Regarding the system energy loss, pattern A and C are superior to pattern B.

### 4.3 Case 3: PV close-end installation

**Fig. 11.** BESS capacity and system energy loss (case 3).

Fig. 11 shows the required BESS capacity and system energy loss in Case 3. In this case, BESSs of patterns B and C are mainly required for surplus power control rather than for voltage control. In contrast, BESS of pattern A is needed for voltage control, because the BESS's location is far from the point where the voltage exceeds the limit. In spite of the same amount of required BESS, the system energy loss of pattern B is less than that of pattern C. This is attributed to the difference in line voltage loss. The marginal PV penetration ratio of each BESS pattern is the same as that of case 1.

The maximum PV penetration ratio of each BESS pattern is also smaller than that in the previous case.
5. Conclusion

In this paper, the effectiveness of BESS placement patterns in the distribution line has been presented to address the problems caused by reverse power flow due to high penetration of PV. The required BESS capacities and the system energy losses for 3 BESS placement patterns were calculated under 3 PV installation cases. It can be said from the result that BESS should be placed at the end of the line in almost all cases to have better performance in terms of required capacity and system loss. When quite a large amount of PVs are installed in the system, however, BESS will suffer from non-zero carryover energy.

Since a lot of BESS will be installed in the future power system, the effective placement and control scheme of the BESS should be considered from the viewpoints of operation and economy. For this purpose more detailed studies are intended as the future work.

References


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