Optimal Operation Strategy with using BESS and DGs in Distribution System

Masato Oshiro*, Akihiro Yoza†, Tomonobu Senjyu*, Atsushi Yona*, Toshihisa Funabashi** and Chul-Hwan Kim***

Abstract – This paper proposes a methodology for distribution system operation using battery energy storage system (BESS), interfaced inverter with DGs and existing voltage control devices. The proposed method decides the optimal operation schedule of each control device by optimal calculation. Optimal calculation uses a forecast information for a next day photovoltaic generator output and load demand. As a result, the proposed method achieves a voltage control for each of the node within the acceptable range, smoothing an interconnection point power flow and reducing of total distribution loss. The effectiveness of the proposed method is verified by using MATLAB.

Keywords: Distribution system, Distributed generator, Battery energy storage system, Interconnection point power flow

1. Control Objective

Since Japan aims for the achievement of the low carbon society, recently the use of renewable energy in the form of distributed generators (DGs) has increased. Renewable energy sources (RES) such as wind turbine generator and photovoltaic generator (PV) are getting attention worldwide according to the viewpoint of carbon dioxide is not exhausted and reproducible energy. However, DG using renewable energy is influenced by weather conditions. Therefore, maintaining the voltage in the distribution system within the statutory range becomes difficult. In addition, conventional distribution systems have been constructed without the consideration of DG connections. Consequently, some problems emerge due to the DG penetration. If large amount of DGs using renewable energy are connected to a distribution network, voltage deviations and fluctuations according to output power fluctuation of DGs become a significant problem which cannot be solved only by the tap changing of a load ratio control transformer (LRT) in the substation and step voltage regulators (SVRs), due to relatively slow behavior. As a countermeasure against this problem, some control methodologies which mainly use reactive power controllers such as additional reactive power compensators [1-3] or reactive power control of distributed generators [4-11], have been proposed. In particular, as methodologies for reactive power control of DGs, voltage control schemes based on centralized information such as voltage and power flow in the distribution system [4-6] and using information of adjacent DG [7] are proposed, while information of setting point of the control device is usually used for voltage control. However, these control methods are subjected to power factor control of DGs in spite of detriment for DG operators which arises from the reduction of active power output. On the other hand, interfaced inverters which are used for variable wind turbine generators and PV generators can control reactive power output independently within their capacity. Some methods [8, 9] utilize such strategy.

While, in order to solve the problems such as power quality loss, voltage and frequency fluctuation, operation method of BESS introduced to power system is proposed in [12]. Technologies for BESS of recent years are developed to achieve cost reduction, longer operating life and efficiency improvement, which are useful in electricity business. Therefore, by applying this technology is expected to improve some problem which is caused by the large amount of PV penetration and to achieve economic operation.

Centralized control methods and decentralized autonomous control methods have been proposed which utilize reactive power control function of PV generators [10, 11]. However, in these literature reverse power flow occurs
on daytime that the outputs are large. In addition, interconnection power flow is fluctuated considerably. In addition, interconnection power flow is fluctuated considerably, that is bad effect to the distribution system operator. Thus to improve and enhance for each power system level is necessary, because DG is also increasing in the future.

Therefore, this research aims to reduce interconnection point power flow fluctuation by introducing BESS to interconnection point to upper system. As proposed method, tap position control using existing voltage control devices, active power and reactive power control using BESS and DG are used. The proposed method performs cooperative control according to the optimal control references schedule of each device. The optimal control reference schedule is made by optimization calculation that the objective function is defined as the total distribution loss. Consequently the proposed method achieves voltage regulation within the acceptable range, interconnection point power flow smoothing and total distribution loss reduction.

2. Control Objective

This paper performs cooperative control between existing voltage control device, DG and BESS introduced to interconnection point. The proposed method aims to achieve voltage regulation within the acceptable range, interconnection point power flow smoothing and reduction of total distribution loss.

According to the Electricity Law in Japan, the statutory range of voltage at the residential consumer side is set up within $101 \pm 6 \text{ V}$. In the distribution systems, between pole transformer for 6.6 kV high-voltage distribution system and consumer side for 100 V system, when load is heavy, it occur up to 6.5 V voltage drop and when reverse power flows to the system from distributed generators, it occur up to 2 V voltage rise [16]. So the range of voltage at the residential consumer side is from $101.5 \text{ V} (0.967 \text{ pu})$ to $105 \text{ V} (1.0 \text{ pu})$. If we set tap of all the pole transformers at 6,600 V : 105 V, we should maintain voltage range within 6,380 V (0.967 pu) to 6,600 V (1.0 pu) in high-voltage distribution system. We define this range as the acceptable voltage range.

Next, in order to smooth interconnection point power flow and to give flexibility to distribution system operation, bandwidth is defined. In this research, bandwidth of interconnection point active power flow is defined as $\pm 0.1 \text{ pu} (500 \text{ kW})$ from average of a daily load curve. And interconnection point reactive power flow is defined as range that power factor is kept from 0.8 to 1.0. Interconnection point power flow is controlled basically by BESS introduced to interconnection point. The reactive power control system for DG which is assumed as PV is shown in Fig. 1. Active power output and reactive power output control system for BESS is shown in Fig. 2. Each interfaced inverter with DG introduced to the demand side controls reactive power output so that the node voltage $V$ follows the node voltage reference $V^*$. Active power and reactive power control system of BESS control active power and reactive power output so that the interconnection point power flow $P_f$ and $Q_f$ follows the interconnection point power flow reference $P^*_f$ and reactive power flow reference $Q^*_f$.

Above described control references are made by optimization calculation which includes the consideration of existing voltage control devices. In addition, the objective function is defined as total distribution loss, so the optimal control reference schedule achieves the reduction of total distribution loss.
In the guideline for DG connection to power system in Japan, there is a limitation for a power factor. However, if reactive power output of DG is controlled properly, that can contribute to reduce some voltage fluctuation. So, this paper is not considered about limitation for power factor. Besides, power factor control of DGs is proposed in spite of detriment for DG operators which arises from the reduction of active power output. On the other hand this paper supposes that reactive power output is controlled independently within rated capacity of interfaced inverter.

3. Control Method

In this chapter, how to make the control reference schedule and the using optimization calculation method are explained.

3.1 Control reference determination

As previously explained, this research aims to smooth interconnection point power flow and to regulate the voltage deviation. Additionally it aims to reduce total distribution loss by cooperative control for each device. Thus these aims can be described as optimization problem by following objective function and the constraints.

### Objective function

\[
\text{min } F(P_B, Q_B, Q_G, T) = \sum_i^n \sum_j^x P_{Li} \quad (1)
\]

### Constraints

\[
V_{\text{min}} \leq V_i \leq V_{\text{max}} \quad (2)
\]
\[
\sqrt{P_B^2 + Q_B^2} \leq S_B \quad (3)
\]
\[
C_{\text{min}} \leq C_B \leq C_{\text{max}} \quad (4)
\]
\[
C_{B24} \leq C_{B24} \leq C_{\text{max}} \quad (5)
\]
\[
\sqrt{P_G^2 + Q_G^2} \leq S_G \quad (6)
\]
\[
P_{f\text{min}} \leq P_f \leq P_{f\text{max}} \quad (7)
\]
\[
Q_{f\text{min}} \leq Q_f \leq Q_{f\text{max}} \quad (8)
\]
\[
T_{\text{min}} \leq T_k \leq T_{\text{max}} \quad (9)
\]

Where,

- \(n\): Total number of control reference changing
- \(x\): Total number of line
- \(P_B, Q_B\): Active power and reactive power output by BESS
- \(P_G, Q_G\): Active power and reactive power output by DG
- \(T\): Transformer ratio
- \(P_{Li}\): Distribution loss of line
- \(V_{ni}\): Node voltage of \(m\)-th node
- \(C_B\): State of charge for BESS
- \(C_{B24}\): State of charge for BESS at 12 am
- \(C_{\text{min}}, C_{\text{max}}\): Upper and lower bound of state of charge
- \(S_B\): Rated capacity of interfaced inverter with BESS
- \(S_G\): Rated capacity of interfaced inverter with DG
- \(P_f\): Interconnection point active power flow
- \(P_{f\text{min}}, P_{f\text{max}}\): Lower bound of interconnection point active power flow
- \(Q_f\): Interconnection point reactive power flow
- \(Q_{f\text{min}}, Q_{f\text{max}}\): Lower bound of interconnection point reactive power flow
- \(T_{\text{min}}, T_{\text{max}}\): Upper and lower bound of transformer ratio.

By defining the band width for interconnection point as equations (7) and (8), degree of freedom is given to control of distribution system. State of charge for BESS is operated between 20% and 80%. However it is undesirable that state of charge for BESS affects to operation of next day. Therefore, only state of charge at 12 pm is bounded between 40 and 60% as equation 5. By solving the above optimization problem using tabu search, optimal control reference schedule is determined.

3.2 Tabu Search Algorithm

TS algorithm is an extended local search algorithm. By introducing a memory system called tabu list to record the latest moves, TS algorithm can escape from the current local optimum by using tabu information. TS algorithm has advantages of high search efficiency of a local search algorithm and global search ability of an intelligent algorithm. The searching procedure of TS algorithm can be
described as follows and the flow chart is shown in Fig. 3.

1) The initial search origin is determined. The tabu list is formatted.
2) The neighborhood solutions around the origin are evaluated, and the best neighborhood solution, which is not recorded in the tabu list, is selected as the next origin. Here, the ±0.01pu of the tap position or the inverter output of battery energy storage system is considered as the neighborhood solutions. If the evaluated solution is better than the recorded best solution, the best solution is updated.
3) The earliest data in the tabu list are cleared and new evaluated solutions are recorded as latest data.
4) If the conditions of termination are satisfied, the search process is terminated. Otherwise, go to step 2.

**Table 1. Parameters of distribution system**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line impedance at each section</td>
<td>0.04+j0.04pu</td>
</tr>
<tr>
<td>Power factor of each load</td>
<td>0.8</td>
</tr>
<tr>
<td>Rated capacity of PV node</td>
<td>0.08pu (400kW)</td>
</tr>
<tr>
<td>Rated capacity of interfaced inverter with PV</td>
<td>0.08pu (400kWh)</td>
</tr>
<tr>
<td>Rated capacity of BESS</td>
<td>5.0pu (25MWh)</td>
</tr>
<tr>
<td>Rated capacity of interfaced inverter with BESS</td>
<td>0.40pu (2MW)</td>
</tr>
</tbody>
</table>

**4. Simulation Result**

In this chapter, in order to indicate the effectiveness of the proposed method which is the cooperative control based on optimal reference schedule, the simulation is performed by using distribution system model shown in Fig. 4. In this model, we assume that DG continues to be introduced positively to the distribution system, so the ten nodes are connected to the DGs. Line impedances, power factor of load demand, rated capacity of the interfaced inverter with DG and BESS, rated capacity of PV and BESS for the distribution system model listed in Table 1, where the nominal capacity of distribution system and the nominal voltage are 5 MVA and 6.6 kV, respectively.

This research assumes that we can get high accuracy forecast information for PV output and load demand about next day. So the PV output is used 1h average of actual PV output shown in Fig. 5(a). Load demand is used the daily load curve shown in Fig. 5(b) and is assumed that the nodes from 11 to 24 are residential area, and from 31 to 35 are office area.
As simulation pattern, the simulation where PV, BESS and tap position control by using existing voltage control devices are not taken consideration is Case 1. The simulation where the cooperative control between the reactive power control by using DG and tap position control by using existing voltage control devices are performed is Case 2. The simulation where the cooperative control between the reactive power control by using DG, the active power and reactive power control by using BESS and the tap position control by using existing voltage control devices are performed is Case 3.

The simulation result for Case 1 is shown in Fig. 6. The Fig. 6(a) shows each node voltage, and the dashed line indicates the acceptable range. From this figure, we can confirm that the node voltage deviates from upper bound in the daytime and another times deviate from lower bound. Figs. 6(b) and (c) show the interconnection point active power flow and reactive power flow respectively. The interconnection point power flow is fluctuating substantially through a day. In addition the reverse power flow occurs in daytime because the PV output becomes large.

![Fig. 6. Simulation result for Case 1.](image)

The simulation result for Case 2 is shown in Fig. 7. Similarly to Case 1, Figs. 7(a) to (c) show the each node voltage and the interconnection point power flow. The voltage control within the acceptable range is achieved by...
cooperative control between the reactive power control by DG and the tap position control by existing voltage control devices. However, in this case there are no active power control devices available. So the fluctuation of interconnection point power flow is not improved. Figs. 7(d) and (e) show the reactive power output for DGs and the tap position for each transformer, respectively. In order to not reduce the PV output and to keep the output rated capacity of interfaced inverter with DG, the reactive power output for each DG in daytime is small. Therefore the reactive power output control performance is small in daytime. So the tap position is becoming low to keep the node voltage. When the active power is small, the reactive power output for DG contributes to reduce the total distribution loss.

Table 2. Total distribution loss with Case 2 and 3

<table>
<thead>
<tr>
<th></th>
<th>Total distribution loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2 (Compared method)</td>
<td>6,929 kWh</td>
</tr>
<tr>
<td>Case 3 (Proposed method)</td>
<td>4,879 kWh</td>
</tr>
</tbody>
</table>

The simulation result for Case 3 is shown in Fig. 8. Similarly to Case 2, Figs. 8(a) to (e) show the each node voltage, the interconnection point power flow, the reactive power output by interfaced inverter with DG and the tap position for each transformer. We can confirm that the node voltage is kept within the acceptable range. Because the BESS is introduced into this case, optimization calculation considers besides about interconnection point power flow smoothing. Consequently the interconnection point power flow is controlled within the band width as shown in Figs. 8(b) and (c), respectively. The active power output, reactive power output and state of charge for BESS are shown in Figs. 8(f) to (h). The rated capacity of interfaced inverter and BESS are set as achieve control within the band width. From figure (e), we can find that the BESS improves reverse power flow by charging the active power in daytime.
and discharges in another time. The interconnection point reactive power flow is improved by the reactive power control of DG and BESS.

Finally, the total distribution loss for Case 2 and Case 3 are described in Table 2. From this table, we can confirm that the proposed method (Case 3) is reduced about 30% compared to Case 2. In Case 3, because the active power and reactive power control of BESS are possible, the total distribution loss is being improved substantially.

5. Conclusion

In this paper, assuming DG continues to be introduced positively to distribution system, proposes introduction of BESS to upper system. In the proposed method, optimal schedule for each control device is prepared by using forecast information of next day. The simulation result was achieved reduction of the total distribution loss by defining the objective function as total distribution loss. Besides, node voltage control within the acceptable range and reduction of interconnection point fluctuation were achieved by using the optimal control reference schedule for each control device.

References


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