
Ryota Aihara*, Akihiko Yokoyama†, Fumitoshi Nomiyama** and Narifumi Kosugi**

Abstract - In recent years, a substantial amount of photovoltaic (PV) generations have been installed in Japanese power systems. However, the power output from the PV is random and intermittent in nature. As is known, the PV generation poses many challenges to the power system operation. To evaluate impact of the behavior of PV, we developed power supply reliability evaluation model considering a large penetration of PV generation into the power system. As a result, power supply reliability is getting worse as the PV penetration increases. To mitigate these issues, we proposed that pumped storage power plant (PSPP) is used to improve the reliability. This paper presents a fundamental study on the impact of the operation scheduling of PSPP taking into account the excess power caused by PV generations on the power supply reliability, which is evaluated by Monte Carlo simulation.

Keywords: Excess power problem, Monte carlo simulation, Photovoltaic, Power supply reliability, Pumped storage power plant

1. Introduction

The role of renewable energy resources is remarkable in Low Carbon Society. In recent years, a large amount of photovoltaic (PV) and wind power generations have been installed in power systems around the world. However, Japan is not an appropriate site to install a large amount of wind power generations. Therefore, the Japanese government aims at installing a large amount of PV in power system. Since the power output from the PV is random and intermittent in nature, the PV generation poses many challenges to the power system operation. PV cannot supply constant electric power output due to uncontrollable factors such as quantity of solar radiation. When the load demand is very small and at the same time the PV generates a large amount of power, the balance between power supply and demand cannot be maintained. This problem is called “excess power problem”. In addition to the excess power problem, it is also necessary to consider the intermittent and uncertain output characteristic of PV. Therefore, various kinds of counter measures have been considered when a substantial amount of PV generation is installed into a power system. Though the use of Battery Energy Storage System (BESS) could be considered as a solution of these issues, their high cost is preventing them from being considered as a solution in most situations. This paper proposes that Pumped Storage Power Plant (PSPP) is used effectively. PSPP is installed originally for load leveling within one day. The energy is stored in the form of water pumped up from a lower reservoir to an upper reservoir. The PSPP is usually operated as a generator in the daytime and a pump in the nighttime. A new operation scheduling of PSPP is proposed to solve these problems in this paper. It will be operated with the proposed pattern considering the excess power caused by PV generation. The effectiveness of the proposed method is shown by the simulation studies carried on IEEE Reliability 24-bus Test System (RTS) [1] during the period of 7 days.

2. Power Supply Reliability Evaluation Model

2.1 Reliability Evaluation Method

The flowchart of the proposed power supply reliability evaluation method is shown in Fig. 1. This paper considers a planning period of one week with one hour interval step. As depicted in Fig. 1, the first step is to determine the
Impact of Operational Scheduling of Pumped Storage Power Plant Considering Excess Power on...

generation scheduling for a one-week period based on the available data which include load demand, theoretical PV power output, PSPP operation pattern. The generation scheduling is obtained by solving an optimization problem which minimizes the power system operational cost. The problem is solved by means of Dynamic Programming (DP) as described in sub-section 2.2.

Next, Monte Carlo simulation is carried out to take into account the uncertainty associated with load demand, PV power output, and generator failure. During the simulation, if the power imbalance between supply and demand occurs, the power outputs of the thermal units are adjusted, and PSPP is operated to resolve such power imbalance. In case that the power balance cannot be resolved, this period is then regarded as supply interruption. Note that both supply shortage and surplus are regarded as supply interruption.

2.2 Generation Scheduling

As mentioned earlier, generation scheduling is found by solving an optimization problem in which the fuel cost is minimized. In this paper, it is assumed that nuclear and hydro power plants are always operated at the rated power output. As a result, only the fuel cost of thermal plants is considered here. The fuel cost of each thermal plant is given in (1).

\[ F^i = a^i P^2 + b^i P + c^i \]  

(1)

where \( a^i, b^i \) and \( c^i \) are fuel cost coefficients of each generator. \( P \) is power output of generator \( i \).

The optimization problem for a one-week period is then formulated as follows:

\[ \Phi = \sum_{i=1}^{N} \sum_{t=1}^{168} \{ u_i^t (F^i (P^i_t) + u_t^i (1-u_t^i)S^i) \} \]  

(2)

Subject to:

\[ L_t = \sum_{i=1}^{N} P^i_t + P_n + P_h + PV_t \]  

(3)

\[ P^i_{\min} \leq P^i_t \leq P^i_{\max} \]  

(4)

where \( \Phi \) is weekly total fuel cost of thermal power plants. \( N \) is the number of thermal power plants. \( P^i_t \) is power output of generator \( i \) at time \( t \). \( u_t^i \) is state variable of generator \( i \) at time \( t \): (1: committed 0: stopped). \( S^i \) is startup cost of generator \( i \). \( L_t \) is load demand at time \( t \). \( P_n \) is power output of nuclear power plant. \( P_h \) is power output of hydro power plant. \( PV_t \) is theoretical power output of \( PV \) at time \( t \). \( P^i_{\min} \) is minimum output of generator \( i \). \( P^i_{\max} \) is maximum output of generator \( i \).

To solve the optimization problem, Dynamic Programming (DP) [2] is used in this research. Since the unit commitment pattern has many combinations, the merit order method is used here. The merit order is determined by the fuel cost of generator at the rated output. The combination of committed generators is searched sequentially in ascending order of \( C^i \) described by (5).

\[ C^i = \frac{F^i(P^i_{\max})}{P^i_{\max}} \]  

(5)

For simplification, we are not concerned with the shutdown cost and the startup costs of all generators are assumed to be the same. The PV output is assumed to be theoretical in generation scheduling because power system operator cannot predict its output.
2.3 PSPP Operation Schedule

In PSPP, the energy is stored in upper reservoir in the form of water. Therefore, it should be operated within the capacity of the upper reservoir. The storage available in the upper reservoir of PSPP at the beginning and the end of simulation period is assumed to be a half of the full capacity of the upper reservoir because of the sustainable operation of the PSPP. The PSPP is usually operated as a generator in the daytime and a pump in the nighttime. This conventional pattern is named as "Pattern A" as shown in Fig. 2. On the other hand, the proposed pattern where the excess power from PV is absorbed by the PSPP in the daytime is identified as "Pattern B". "Pattern C" in Fig. 2 is a combination of Pattern A and Pattern B.

![Fig. 2. Power Output of PSPP.](image1)

In this paper, the amount of the stored water in the upper reservoir is considered as energy. It can be operated 6 to 8 hours continuously when the operation starts from the full capacity of the upper reservoir. Therefore, the capacity of the upper reservoir is assumed to be 7-hours operation of the rated power at generator mode.

In general, there are two types of PSPP, fixed speed one and adjustable speed one. The fixed speed PSPP cannot adjust the input power when it operates as a pump. The adjustable speed one can adjust the input power. It is coming into the limelight because of its adjustable characteristics in the pump mode. Therefore, the PSPP is assumed to be an adjustable speed PSPP in this paper. The capacity of the upper reservoir of the PSPP is shown in Fig. 3.

![Fig. 3. Capacity of the Upper Reservoir of PSPP.](image2)

2.4 Probabilistic Fluctuation Model

The load demand model with randomly fluctuating component is derived from (6). \( L_{dt} \) is load demand at time \( t \) considering probabilistic fluctuation. \( L_{gt} \) is load demand at time \( t \) given by the power system model and \( F \) is the random number based on the normal distribution where the average is 1 and the standard deviation is 3%.

\[
L_{dt} = L_{gt} \times F
\]  

(6)

The PV output fluctuation is also modeled with a randomly fluctuating component. It is described by (7).

\[
P_{V_{dt}} = P_{V_{gt}} \times F
\]  

(7)

where \( P_{V_{dt}} \) is PV output at time \( t \) considering probabilistic fluctuation, \( P_{V_{gt}} \) is PV output at time \( t \) given by the theoretical output and \( F \) is the random number based on the normal distribution considering weather changes shown in Table 1.

<table>
<thead>
<tr>
<th>Weather</th>
<th>Average</th>
<th>Standard Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunny</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Cloudy</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>Rainy</td>
<td>0.1</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The weather change is simply modeled at the probability of 1/3 at time \( t \). We assumed to be no relationship between before and after time \( t \). The theoretical PV outputs for three kinds of weathers are shown in Fig. 4.

![Fig. 4. PV output for each weathers.](image3)

The failure rate and restoration rate of a generator are given in (8). In (8), MTBF, is the Mean Time Between Failure of generator \( i \) and MTTR, is the Mean Time To Repair of generator \( i \).
\[ \lambda_i = \frac{1}{\text{MTBF}_i}, \quad \mu_i = \frac{1}{\text{MTTR}_i} \] (8)

If the generator failure occurs at time \( t \), the others generators are re-dispatched immediately. If imbalance of power supply and demand cannot be avoided by the re-dispatching, PSPP is operated immediately to avoid it. In the next time \( t+1 \), the remaining generators are committed to compensate for the unavailable generator. The failure generator is restored at the restoration rate \( \mu \) after time \( t+1 \).

2.5 Power Supply Reliability Calculation

The power supply reliability is evaluated through LOLP (Loss of Load Probability) index which can be computed from (9). \( \text{LOLP} \) is the total supply interruption period. \( C \) is the number of trial. \( \text{TIME} \) is the simulation period. The trial is repeated until LOLP converges to a steady value.

\[ \text{LOLP} = \frac{\text{LOSS}}{C \times \text{TIME}} \] (9)

3. Simulation Condition

3.1 Simulation Model

The simulation is conducted on the modified IEEE 24-bus Reliability Test System (RTS) with the generator data tabulated in Table 2. The system is modified by adding a 300MW PSPP in addition to the existing hydro power plants. This paper focuses on the generating system reliability evaluation, i.e. the failures associated with transmission networks are not considered.

<table>
<thead>
<tr>
<th>Generator Group</th>
<th>Type</th>
<th>No. of Unit</th>
<th>Cap. of each Unit</th>
<th>Merit Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thermal (Oil)</td>
<td>5</td>
<td>12</td>
<td>22-26</td>
</tr>
<tr>
<td>2</td>
<td>Combustion Turbine</td>
<td>4</td>
<td>20</td>
<td>27-30</td>
</tr>
<tr>
<td>3</td>
<td>Hydro</td>
<td>4</td>
<td>50</td>
<td>3-6</td>
</tr>
<tr>
<td>4</td>
<td>Pumped Storage</td>
<td>1</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Thermal (Coal)</td>
<td>4</td>
<td>76</td>
<td>18-21</td>
</tr>
<tr>
<td>6</td>
<td>Thermal (Oil)</td>
<td>3</td>
<td>100</td>
<td>15-17</td>
</tr>
<tr>
<td>7</td>
<td>Thermal (Coal)</td>
<td>4</td>
<td>155</td>
<td>11-14</td>
</tr>
<tr>
<td>8</td>
<td>Thermal (Oil)</td>
<td>3</td>
<td>197</td>
<td>8-10</td>
</tr>
<tr>
<td>9</td>
<td>Thermal (Coal)</td>
<td>1</td>
<td>350</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>Nuclear</td>
<td>2</td>
<td>400</td>
<td>1-2</td>
</tr>
</tbody>
</table>

3.2 Simulation Condition

Figure 5 depicts three different load conditions for three seasons, i.e. summer (August), winter (February), and spring (May). Note that the load is highest in summer and lightest in spring. The system peak load is 3200 MW. In the simulation, the PV penetration is varied from 0 to 1000 MW with an increment step of 100 MW.

4. Simulation Result

4.1 Generation Schedule at PV Penetration 1000MW

The obtained generation scheduling for three PSPP operation patterns under two conditions, i.e. (1) weekday in summer where the load is highest, and (2) holidays in spring where the load is lightest, is given in Figs. 6-11. The Pattern A, B and C are the operating patterns of PSPP shown in Fig. 2. In summer where the load demand is the largest season, excess power does not occur.
4.2 LOLP Calculation

The calculated LOLPs for three seasons with three different PSPP operating patterns are shown in Figs. 12-14. The results show that the LOLP increases with the PV penetration for all PSPP operating patterns. This is mainly due to the PV output fluctuation. It is also found that the LOLPs for patterns B and C are smaller than the LOLP for pattern A. Also note that in a light load season, i.e. spring, and when the PV penetration is less than 200 MW, the LOLP obtained by using the proposed PSPP operation pattern is higher than that obtained by using the conventional pattern. This is basically due to the PSPP pumping power which further adds up the load during the daytime.
Impact of Operational Scheduling of Pumped Storage Power Plant Considering Excess Power on ...

5. Conclusion

This paper has highlighted some important issues related to the large penetration of PV into power systems. To solve these problems, we have proposed two operation patterns for PSPP and have evaluated their advantages and disadvantages. Through the simulation studies it has been found that the proposed new PSPP operation patterns are effective to improve the power system reliability in case of a large integration of PV into power system. In the future work, we will develop a new scheduling method for obtaining the optimal PSPP operation pattern that makes it possible to improve both reliability and operating cost.

References


Ryota Aihara (IEEJ Student Member) was born in Tokyo, Japan, on September 20, 1984. He received B.S. Eng from Sophia University, Tokyo, Japan in 2009. He is currently a master course student at The University of Tokyo, Japan.

Akihiko Yokoyama (IEEJ Member) was born in Osaka, Japan, on October 9, 1956. He received B.S., M.S. and Dr. Eng from The University of Tokyo, Tokyo, Japan in 1979, 1981 and 1984, respectively. He has been with Department of Electrical Engineering, The University of Tokyo since 1984 and currently a professor in charge of Power System Engineering. He is a member of IEEJ, IEEE and CIGRE.

Fumitoshi Nomiyama (IEEJ Member) was born in 1969. He received his B.Eng., M.Eng. degrees in electrical engineering from Doshisha University in 1992 and 1994 respectively. He joined Kyushu Electric Power Company Inc. in April 1994.

Narifumi Kosugi (IEEJ Member) was born in 1970. He received his B.Eng., M.Eng. degrees in electrical engineering from Osaka University in 1993 and 1995 respectively. He joined Kyushu Electric Power Company Inc. in April 1995.