A Study on Adequate Level of Generation Reserve Margin Based on Stochastic Evaluation of Operational Cost with Large Penetration of Photovoltaic Generations

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Abstract – Photovoltaic generation (PV) systems are growing as one of renewable energy resources in the world from their merits of low greenhouse effect gas exhaust and less fossil fuel consumption. However, PV output widely varies depending on the insolation condition and is uncontrollable. When huge amount of PV systems are interconnected to a grid, the supply and demand balancing, one of the most important and fundamental power system operations, might become more difficult. In such situation, PV output forecast should be taken in to account in the unit commitment process and/or the online balancing operation. Particularly, the generation reserves should be set aside so that the PV output fluctuation and PV output forecast error can be compensated. From this viewpoint, this paper proposes an operational cost evaluation method considering the probabilistic feature of forecast error. Furthermore, a method for estimating the adequate reserve required for large PV installations is presented.

Keywords: Economic load dispatch, Forecast error, Photovoltaic generation, Unit commitment

1. Introduction

Installation of photovoltaic generation (PV) system is growing in the world due to its environmental merits and sustainability. For example, in Japan, the amount of PV installed was 2.627GW by 2009 [1]. The Japanese government set a notional policy for cumulative PV installation to 28GW by 2020 and 56GW by 2030 [2]. The world top-ranking countries in cumulative PV installation are Germany (5.340GW by 2008) and Spain (3.354GW by 2008) followed by Japan.

Generally, PV output widely varies depending on the insolation condition and is uncontrollable. That is, penetration of PV systems would enlarge the uncertainty in system operation and control, and as a result, deterioration in power quality such as frequency excursion and/or voltage deviation may happen in the future. In order to accept massive PV installations, adequate level of operational margin should be procured. Generally, a power system operator plans the generation unit commitment (daily start-up and/or shut-down schedule of generation unit) to minimize the total generation cost based on the forecasted system demand. In this planning process, a certain amount of reserve margin for demand forecast error and/or unexpected events is set aside. When very large amount of PV systems are installed in the future, the PV output forecast should be also considered in the planning process. Particularly, the generation reserve should be set aside so that the PV output fluctuation and forecast error can be compensated. However, procurement of generation reserve requires additional cost. The adequate level of generation reserve should be discussed considering the trade-off between cost and performance. Reference [4] proposed a stochastic unit commitment method considering large penetration of wind power generation. This method can also find an adequate generation reserve. However, the method proposed in [4] has to treat huge number of scenarios; implementation is difficult from the computation time perspective.

From this viewpoint, this paper proposes a method to evaluate operational cost under the specified reserve level considering the probabilistic feature of PV output forecast error. Furthermore, a method for estimating the adequate reserve required for large PV installations is presented in this paper.

The following part of this paper is organized as follows. In chapter 2, the stochastic evaluation of operational cost under the specified reserve level considering the probabilistic feature of PV output forecast error. Furthermore, a method for estimating the adequate reserve required for large PV installations is presented in this paper.

In chapter 2, the stochastic evaluation of operational cost under the specified reserve level is proposed. In chapter 3, the procedure to estimate the adequate level of generation reserve margin is explained with some numerical case studies. In chapter 4, the validity of scenario generation process employed in chapter 3 is quantitatively ascertained. Finally, conclusion and remarks are given in chapter 5.
2. Stochastic Evaluation of Operational Cost

In this section, a method for stochastic evaluation of operational cost is proposed. The proposed evaluation method consists of two stages reflecting the actual generation scheduling and system operation.

2.1 Scheduling Basic Unit Commitment

In the first stage, called Stage1 in this paper, the unit commitment and the generation dispatch are determined so that the total operational cost can be minimized with meeting the forecasted net load (= system demand forecast – PV output forecast). In other words, the Stage1 corresponds to a day-ahead generation scheduling. The Stage1 can be recognized as a mixed integer programming (MIP) problem and formulated as equations (1) - (11).

(objective function)
\[
\min TC_1 = \sum_{t=1}^{T} \sum_{b=1}^{B} \left[ F_{b,t}(P_{b,t}) + ST_b \left(1 - u_{b,t-1}\right)\right] u_{b,t} \tag{1}
\]

(supply and demand balancing)
\[
\sum_{b=1}^{B} P_{b,t} = d_t - \delta_t \tag{3}
\]

(generation capacity limits)
\[
P_{b,t} + r_{b,t}^{up} \leq P_{b,t}^{max} u_{b,t} \tag{4}
\]

(ramp rate limits)
\[
P_{b,t} - P_{b,t-1} \leq \left(1 - u_{b,t-1}\right) P_{b,t}^{max} + \text{ramp}_{b} \tag{6}
\]

(required reserve constraints)
\[
\sum_{b=1}^{B} r_{b,t}^{up} \geq R_t \tag{10}
\]

Where \( TC_1 \) is total cost [JPY], \( T \) is total scheduling duration [h], \( B \) is total number of thermal units, \( F_{b,t} \) is fuel cost of unit \( b \) at time \( t \) [JPY], \( P_{b,t} \) is generation output of unit \( b \) at time \( t \), \( a_b \), \( b_b \), and \( c_b \) are coefficients of fuel cost of unit \( b \), \( ST_b \) is start-up cost of unit \( b \) [JPY], \( u_{b,t} \) is a binary variable representing the state of unit \( b \) at time \( t \) (1:running, 0:stopped), \( d_t \) and \( \delta_t \) are forecasted system demand and PV output at time \( t \) [MW], \( P_{b,t}^{max} \) and \( P_{b,t}^{min} \) are maximum and minimum output of unit \( b \) [MW], \( r_{b,t}^{up} \) and \( r_{b,t}^{de} \) are upper and lower reserve provided by unit \( b \) at time \( t \) [MW], ramp\(_b\) is available ramp rate [MW], \( R_t \) is required reserve in the whole system at time \( t \) [MW].

In order to solve the above MIP, this paper employs the relaxation method approach proposed in [5].

2.2 Evaluation of Operational Cost Considering Net Load Scenarios

In the second stage, called Stage2, expected total operational cost is evaluated considering the variation of net load from the forecasted value. The detailed calculation procedure is as follows. First, the scenarios which represent net load forecast errors are generated (details are explained in 2.3). Then, the operational cost consists of fuel cost, interruption cost and PV disconnection cost under each forecast error scenario is evaluated by solving the following economic load dispatch (ELD) problem.

(objective function)
\[
\min OC_{2,\omega} = \sum_{t=1}^{T} \sum_{b=1}^{B} \left[ F_{b,t}(P_{b,t}) + \alpha I_{b,t} + \beta S_{b,t}\right] \tag{12}
\]

(supply and demand balancing)
\[
\sum_{b=1}^{B} P_{b,t} + I_{b,t} - S_{b,t} = d_t - \delta_t + \theta_{b,t} \tag{13}
\]

Where, \( \omega \) identifies the scenario considered, \( OC_{2,\omega} \) is the operational cost for the scenario \( \omega \) [JPY], \( \alpha \) and \( \beta \) are unit costs for interruption cost and PV disconnection [JPY/MWh], \( I_{b,t} \) and \( S_{b,t} \) are the amount of interrupted load and disconnected PV at time \( t \) [MW], \( \theta_{b,t} \) is the net load forecast error at time \( t \) under the scenario \( \omega \) [MW]. In addition to equations (12) and (13), constraints shown in equations (4) - (7) are also considered.

The generation dispatch obtained from the above optimization problem corresponds to the system operation of the day with assumed forecast error scenario; therefore, start-up and shut-down schedule of generators (\( u_{b,t} \)) should be fixed in the above optimization.

The expected total operational cost (\( TC_2 \)) is calculated as a weighted average of \( OC_{2,\omega} \) and start-up cost as shown in equation (14).
\[
TC_2 = \sum_{t=1}^{T} \sum_{b=1}^{B} \left[ ST_b \left(1 - u_{b,t-1}\right) u_{b,t}\right] + \sum_{b=1}^{B} p_{b} OC_{2,\omega} \tag{14}
\]
Where, $\Omega$ is total number of scenarios generated, $p_\omega$ is the occurrence probability of scenario $\omega$.

### 2.3 Generation of Net Load Forecast Error Scenarios

This paper assumes that the demand and PV output forecast errors are normally distributed based on the central limit theorem. Also, the demand and PV output forecast errors are recognized as independent stochastic events. Therefore, the standard deviation of the net load forecast error at time $t$ ($\sigma_{nt}$) can be obtained by equation (15) [4].

$$\sigma_{nt} = \sqrt{\sigma_{dt}^2 + \sigma_{st}^2} \tag{15}$$

Where $\sigma_{dt}$ and $\sigma_{st}$ are the standard deviation of demand forecast error and PV output forecast error at time $t$, respectively.

From the practical point of view, the proposed operation cost evaluation procedure requires finite number of forecast error scenarios as noted in 2.2. In the proposed method, $N$ representative values are generated for each period from the assumed continuous probability density function (normal distribution) in the following steps. First, the probability density function is divided into the following $N$ sections;

$$\left\{\begin{array}{l}
\left(-\infty : -5 + \frac{10}{N} \sigma_{nt} \right] \\
\left(-5 + \frac{10}{N} \sigma_{nt} : -5 + 2 \times \frac{10}{N} \sigma_{nt} \right]
\end{array}\right. \ldots
\left[\begin{array}{l}
\left(-5 + (N-2) \frac{10}{N} \sigma_{nt} : -5 + (N-1) \frac{10}{N} \sigma_{nt} \right]
\left(-5 + (N-1) \frac{10}{N} \sigma_{nt} : \infty \right]
\end{array}\right. \tag{16}$$

Then, the median of each section is employed as a representative value. Fig. 1 shows an example of continuous probability density function and its representative values in case of $N=7$.

### 3. Adequate Reserve Level with Large PV Penetration

#### 3.1 Evaluation Method

The stochastic operational cost evaluation proposed in this paper can be used for designing an adequate level of generation reserve margin in a system with large PV penetration. Fig. 2 shows the flowchart of reserve evaluation. First, the net load forecast, the forecast error scenarios and unit data are prepared as input data. Then, Stage 1 and Stage 2 are iteratively calculated with increasing the required reserve $R_t$ by a certain step (1% of the net load forecast is employed in this paper). When the Stage 1 becomes infeasible for the specified reserve, iteration is terminated. Finally, $R_t$ resulting the minimum expected operational cost is recognized as the optimal level of reserve.

![Fig. 1. Proposed discretization of the normal probability distribution of the net load forecast error.](image)

![Fig. 2. Proposed generation reserve margin evaluation procedure.](image)
3.2 Case Study

Numerical example of reserve designing is explained in this section considering the power system supplying 539MW peak demand. The assumed generation composition is a 165MW nuclear power plant, five thermal power plants shown in Table 1 and 162MW PVs. In this case, the PV capacity accounts for about 30% of the peak demand assumed. That is, a power system with huge PV installation is assumed in this case study.

Demand forecast shown in Fig. 3 is assumed; it is generated based on the typical load curve of residential, industrial and commercial sectors in Japan [6] and their composition ratio in Hokkaido. In the following case studies, only from 7a.m. to 1p.m. is considered as evaluation duration because the effect of PV output becomes most severe during the day-time.

Fig. 4 shows the PV output forecast data applied in the case studies; it is made by multiplying the average insolation at 11 spots in Hokkaido [7] by the assumed PV capacity. The resultant net load forecast is shown in Fig. 5.

Standard deviation of demand and PV output forecast error are assumed to be 5% and 10% [8], respectively. Average of forecast error is assumed to be zero for both demand and PV output. In the scenario generation process, 5 representative values are prepared for each period (validity of this number is discussed in chapter 4). Fig. 6 shows the net load forecast (thick line) and the generated forecast scenarios.

$\alpha$ and $\beta$ are respectively set to 200,000 and 0 JPY/MWh;

### Table 1. Specification of the generation units

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</thead>
<tbody>
<tr>
<td>Unit1</td>
<td>162</td>
<td>25</td>
<td>49500</td>
<td>2167</td>
<td>0.4378</td>
<td>99000</td>
<td>97</td>
</tr>
<tr>
<td>Unit2</td>
<td>80</td>
<td>20</td>
<td>40700</td>
<td>2449</td>
<td>0.7832</td>
<td>18700</td>
<td>48</td>
</tr>
<tr>
<td>Unit3</td>
<td>85</td>
<td>25</td>
<td>52800</td>
<td>3051</td>
<td>0.0869</td>
<td>28600</td>
<td>51</td>
</tr>
<tr>
<td>Unit4</td>
<td>55</td>
<td>10</td>
<td>72600</td>
<td>2851</td>
<td>0.4543</td>
<td>3300</td>
<td>33</td>
</tr>
<tr>
<td>Unit5</td>
<td>55</td>
<td>10</td>
<td>73150</td>
<td>3000</td>
<td>0.2442</td>
<td>3300</td>
<td>33</td>
</tr>
</tbody>
</table>
note that these values are not authorized values.

Fig. 7 shows the evaluated relationship between the procured reserve level and the expected total operational cost. On the other hand, as shown in Fig. 8, higher reserve level requires more units to be operated at lower efficiency; as a result, fuel cost increases. Trade-off between interruption cost and fuel cost dominates the most adequate reserve level. In this case study, the most adequate reserve level is from 2% to 16%.

4. Validity of Scenario Based Evaluation

As described in chapter 2, the proposed method discretizes the continuous probability density function of forecast error into $N$ representative values. The larger discretization resolution can express the original continuous probability density function more accurately; however, it requires larger number of scenarios and longer computation time. It is important to employ an appropriate discretization resolution considering accuracy of estimation and computation burden. For the reason mentioned above, the authors investigated the distribution

Fig. 8. Load dispatch decided in the Stage1.
of total operation cost calculated through Stage2 with different discretization resolutions \((N=3, 5, 7)\). Their computational time was also compared. The Monte Carlo simulation (MC) with 1 million sampling was also executed to obtain a reference result. In MC, the net load realized is generated from the normally distributed random number.

Table 2 summarizes the calculated expected total operation cost \((TC_2)\) and computation time. This summary reveals that all discretization resolutions result in almost same \(TC_2\), however, the computation time depends on the number of scenarios. For the reserve level design explained in chapter 3, the expected total cost should be evaluated iteratively; therefore, the MC might not be an appropriate approach from the computation time perspective.

Fig. 9 shows the histogram of total cost in the each case

### Table 2. Expected total cost and computation time

<table>
<thead>
<tr>
<th>(TC_2) [JPY]</th>
<th>The Number of Scenarios</th>
<th>Computation time [h]</th>
</tr>
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<tbody>
<tr>
<td>MC</td>
<td>3,250,852</td>
<td>1,000,000</td>
</tr>
<tr>
<td>(N = 7)</td>
<td>3,234,270</td>
<td>117,649</td>
</tr>
<tr>
<td>(N = 5)</td>
<td>3,239,691</td>
<td>15,625</td>
</tr>
<tr>
<td>(N = 3)</td>
<td>3,223,685</td>
<td>729</td>
</tr>
</tbody>
</table>

(width of class interval: 10,000[JPY]). From this result, it can be found that the histogram in the case of \(N=3\) is completely different from the one of MC; therefore, we can conclude that \(N \geq 5\) is preferred especially when we focus on the dispersion and/or value at risk (VaR) of total cost.

### 5. Conclusion

This paper proposed the stochastic method to evaluate total operational cost considering the large penetration of PV. Furthermore, this paper also proposes the method to design an adequate level of generation reserve margin. The proposed method contributes to the stable power system operation after further PV installation.

The remaining work is further improvement in computation time to handle longer scheduling duration. Furthermore, development of stochastic unit commitment which can consider the forecast error scenarios explicitly in the MIP is also our future work.
References


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