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Study on Reserve Requirement for Wind Power Penetration based on the Cost/Reliability Analysis

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Abstract – As the introduction of wind power is steadily increasing, negative effects of wind power become more important. To operate a power system more reliable, the system operator needs to recognize the maximum required capacity of available generators for a certain period. For recognizing the maximum capacity, this paper proposes a methodology to determine an optimal reserve requirement considering wind power, for the certain period in the mid-term perspective. As wind speed is predicted earlier, the difference of the forecasted and the actual wind speed becomes greater. All possible forecast errors should be considered in determining optimal reserve, and they are represented explicitly by the proposed matrix form in this paper. In addition, impacts of the generator failure are also analyzed using the matrix form. Through three main stages which are the scheduling, contingency and evaluation stages, costs associated with power generation, reserve procurement and the usage, and the reliability cost are calculated. The optimal reserve requirement is determined so as to minimize the sum of these costs based on the cost/reliability analysis. In case study, it is performed to analyze the impact of wind power penetration on the reserve requirement, and how major factors affect it.

Keywords: Wind power uncertainty, Reserve requirement, Scheduling stage, Contingency stage, Cost/Reliability analysis

1. Introduction

The growth of wind power in recent years poses challenges to power system planners and operators [1]. The integration of wind power can lead to the reduction of an operating cost by zero fuel cost of wind power [2], but it can also lead to negative effects such as the decline of system reliability and stability by irregular and less predictable wind power [3, 5]. As the penetration of wind power is steadily increasing, the negative effects become more critical, and it is tried to solve them by securing more reserve [3, 6]. In order to determine an appropriate reserve capacity for coping with undesired situations caused by the uncertainty of wind power, many methodologies have been studied based on a probabilistic approach. These methodologies evaluate and utilize the probability of that available generators and wind power do not meet the system load for a given period [7, 8]. However, there are somewhat differences according to whether the assessment focuses on the one or both respects of the reliability and economic depending on the purpose and target period [8, 9]; short-term system operation and long-term system planning.

In the short-term system operation perspective, the typical objective is to operate a power system economically for a short period (usually, one or more days) while securing the balancing between the system load and power, so that the assessment is performed in both the reliability and economic aspects. Conventionally, the capacity margin is defined as total generation capacity minus the system load represented by probabilistic measure [7], and it can be also regarded as the maximum reserve capacity. More reserve capacity can improve the reliability but degrade the economics. Therefore, an optimal requirement of reserve capacity should be determined so as to minimize the sum of the reliability cost and costs related to power generation and reserve capacity [7]. In case that the output of wind turbines is included in the generation capacity, the uncertainty of wind power should be taken into account. Many studies have focused on modeling the uncertain wind power, and the probabilistic wind power model containing the forecast error of wind power is combined with the forecast error of the system load and the capacity of failed generators. As a result, the capacity margin model reflecting wind power is obtained [10-14]. Since wind speed is forecasted from hour-ahead up to day-ahead in timeframe of short-term, the wind speed prediction can be regarded as relatively accurate. However, when establishing the operating plan for a longer period, a few months, the accuracy of the wind speed prediction would decline further. The existing wind power models may not be enough to reflect the uncertainty of wind power for the expanded period. To remedy it, an output of wind power is divided into several states based on the probabilistic distribution, and then all possible wind power errors which

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are defined as the difference between the forecasted and the actual wind power, are represented and considered by the explicit matrix proposed in this paper.

In the long-term planning perspective, it should be verified that available generators would be able to accommodate reliably the system load expected for some years in the future [7]. Therefore, the assessment focuses mainly on the reliability evaluation with the risk indices such as EENS (Expected Energy Not Served), LOLE (Loss of Load Expectation) and LOLP (Loss of Load Probability), in contrast in the short-term case where both reliability and economics are interested. If risk indices are not satisfied within the specific maximum acceptable level, then the expansion planning for reserve procurement or new generators should be studied to improve the system risk. In the long term perspective, it is interested more in simulating the fluctuation of wind power than modeling wind power with the forecast error. In order to represent the periodically fluctuating wind power, wind speed series are generated stochastically for some months or years, by applying the chronological Monte-Carlo Simulation [9] or by applying the universal generation function [8]. In [8, 9], the risk indices for several reserve capacities are calculated, and it is discussed that which reserve capacity is more proper for satisfying the predefined reliability criterion. However, determining explicitly an optimal reserve capacity is more useful for power system to be operated more reliable.

The expansion of conventional generators becomes limited due to various reasons and instead the penetration of wind power is actively developed. In this situation, the operating plan such as the maintenance schedule for conventional generators or the reserve procurement plan should be established more carefully over a few months, quarters or a year. In the mid-term system planning perspective, it is important to recognize the maximum generation capacity required for a certain target period, which occurs usually at peak load during the period. System operators should prepare available generators to meet the required capacity [8, 9].

This paper proposes a methodology to determine the optimal reserve requirement in the aspect of mid-term. It can contribute for system operators to identify the maximum required capacity that needs to be secured from available generators. Undesired situations caused by wind power error as well as the generator failures [9, 16], are expressed and treated using the explicit matrix form. Using the matrix form, several costs are calculated through three main stages and then the optimal reserve requirement is determined so as to minimize the sum of the costs, based on the cost/reliability analysis.

2. Impact of Wind Power on Reserve Requirement

When large-scale wind power is introduced into power system, it influences the strategy of unit commitment (UC) and economic dispatch (ED) [4]. To illustrate the influence of wind power, examples of the UC and ED for situations caused by the uncertainty of wind power are shown in Fig. 1, where *Gen*1 to *Rv*7 are allocated in ascending order of their power generation and reserve procurement costs, respectively.

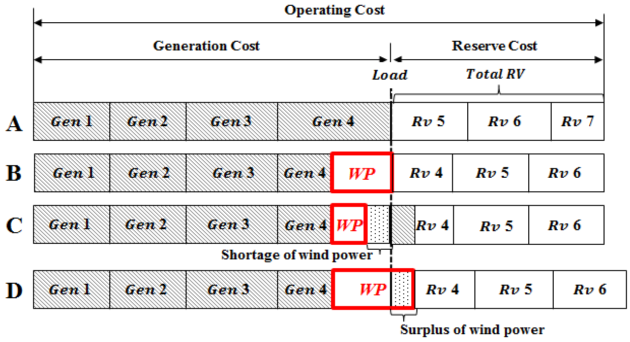

Fig. 1. Impacts of wind power penetration on UC and ED

Fig. 1A shows the case without wind power, where the shaded area indicates power assigned to conventional generators to satisfy the system load and the remaining area indicates a specific reserve requirement.

When a predicted output of wind power is considered in the UC and ED, it can replace a portion of Gen4, as shown in 1B because the generation cost of wind power is assumed to be zero in this paper [13]. The replaced power of Gen4 can take a role of reserve as Rv4 and push the most expensive Rv7 out of the reserve requirement area. Compared with 1A, 1B indicates that wind power can reduce not only the generation cost but also the reserve cost [5]. However, owing to the uncertainty of wind power, an actual wind power output may be different than the predicted value. Figs. 1C and 1D represent situations in which the actual output of wind power is less or greater than the predicted value, respectively. In 1C compared with 1B, a portion of Rv4 is used to cover a power shortage by wind power. As a result, an operating cost is increased and reliability is aggravated because some of available reserve prepared for the unexpected situation is used [15]. In 1D, a power surplus from wind power may replace some of the scheduled power or the prepared reserve, but the surplus is assumed to spilled out in this paper [12], and thus it seems that case 1D is similar to case 1B. However, if there are some errors in the forecasted load or failure of generators, the surplus of wind power could be used to cover them in preference to using reserve. As a result, it can contribute to enhance reliability of the entire system. To focus mainly on these impacts of wind power, however, the uncertainty of system load is not taken into account in this paper.

In the typical cost/reliability analysis, increasing reserve improves reliability, and thus the reliability cost is reduced. However, more reserve results in an increase of an operating cost, which consists of costs for generating power and preparing reserve. Therefore, an optimal reserve

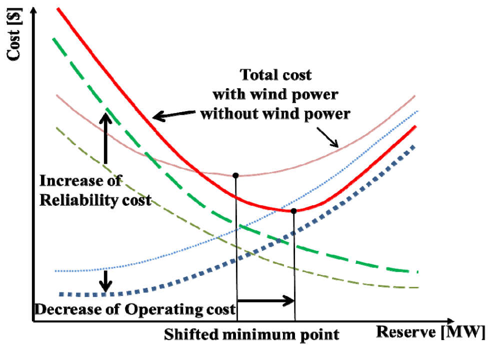

Fig. 2. Typical Cost/Reliability curve according to reserve

capacity is determined to the point where the sum of the two costs is minimized, as shown in Fig. 2 [10, 16]. If wind power is introduced into a power system, it can significantly save the operating cost, while increasing the reliability cost due to uncertain wind power. As a result, the minimum point would be shifted to the right, and more reserve is required for cost optimization.

3. Methodology to Determine Reserve Requirement

This paper suggests a methodology to determine an optimal reserve requirement, RV^{Opt}, for a certain period with the mid-term perspective, when large-scale wind power is introduced. The methodology is performed through three stages; scheduling, contingency and evaluation stages [13, 14]. In the scheduling stage, a generation schedule is established to satisfy both the system load and a specific reserve requirement, RV, through the UC and ED process considering the predicted wind power. In the contingency stage, the schedule is revised to resolve the imbalance between power and load that occurs according to the failure of generators or the difference between the predicted wind power in the scheduling stage and an actual output in the contingency stage. Finally, in the evaluation stage, the total cost for RV is calculated with the results of the previous two stages.

3.1 Wind power error matrix

States of wind power output and their probabilities can be represented by the discrete distribution, using the historical data [8], as shown in Eqs. (1) and (2), respectively.

$$\mathbf{P^W} = [p_1^w, \ldots, p_k^w, \ldots, p_{NW}^w], \quad p_k^w = (k-1)\cdot\frac{P^{w,\,Max}}{NW-1} \tag{1}$$

$$\mathbf{Pr^W} = [pr_1^w, \ldots, pr_s^w, \ldots, pr_{NW}^w] \tag{2}$$

where, p_k^w is an output at k-th wind power state, $P^{w,Max}$ is the maximum wind power output, and NW is the number of wind power states.

Wind power errors, er^w is defined as the differences between each wind power state considered at the scheduling and contingency stages, and it can be represented by the following matrix form.

$$\mathbf{Er^W} = [er^w(s,c)\,|\,p_c^w - p_s^w,\ 1 \le s,c \le NW] \\ = \begin{bmatrix} p_1^w - p_1^w & p_2^w - p_1^w & \cdots & p_{NW}^w - p_1^w \\ p_1^w - p_2^w & p_2^w - p_2^w & \cdots & p_{NW}^w - p_2^w \\ \vdots & \vdots & \ddots & \vdots \\ p_1^w - p_{NW}^w & p_2^w - p_{NW}^w & \cdots & p_{NW}^w - p_{NW}^w \end{bmatrix} \tag{3}$$

where, (s,c) is the ordered pair to represent the s-th and c-th wind power states at scheduling and contingency stages, respectively. Because diagonal elements in $\mathbf{Er^W}$ indicate the situation that two wind power states are identical, the elements are zero. Elements of the upper triangular matrix have positive values because $p_c^w > p_s^w$, and are regarded as the wind power surplus. On the contrary, elements of the lower triangular are negative and are regarded as the wind power shortage.

The probability matrix for all wind power errors is obtained by Eq. (4).

$$\mathbf{Pr^{Er}} = \left(\mathbf{Pr^W}\right)^T \times \mathbf{Pr^W} \tag{4}$$

3.2 Scheduling stage

For simplicity, it is assumed that the UC and ED process is performed based on the merit order rule, and the cost of conventional generators is modeled as the piecewise-linear function consisting of several segments [11, 13]. The objective of the scheduling stage is to minimize the sum of costs for generating power and preparing reserve while satisfying the system load as well as a specific reserve requirement, RV. When s-th wind power state is considered as the predicted one, the operating cost, $Cost_s^{SCH}$ is calculated by Eq. (5).

$$Cost_s^{SCH} = \sum_{n=1}^{NG}\left\{\sum_{m=1}^{NS_n}\left(GC_n^m \cdot p_{n,s}^m + RC_n^m \cdot rv_{n,s}^m\right) + SU_n \times \mu_{n,s}\right\} \tag{5}$$

where, NG is the number of generators, NS_n is the number of cost segments of the n-th generator, $p_{n,s}^m$ is power at the m-th segment of the n-th generator, $P_{n,s}$ is the total power of the n-th generator, GC_n^m is the power generation cost at the m-th segment of the n-th generator and $GC_n^{m-1} < GC_n^m$, $\mu_{n,s}$ is a state variable which has 1 or 0 depending on whether the n-th generator participates in the generation schedule, $rv_{n,s}^m$ is the reserve capacity at the m-th segment of the n-th generator, RC_n^m is the cost for preparing the reserve capacity and $RC_n^{m-1} < RC_n^m$, SU_n is the start-up cost of the n-th generator, and L^P is the peak load for a certain period.

While resolving the objective function, the following constraints are taken into account.

- Power balance constraint;

$$\sum_{n=1}^{NG}\left(\sum_{m=1}^{NS_n} p_{n,s}^{m}\right)=\sum_{n=1}^{NG} P_{n,s}=L^{P}-p_{s}^{w} \tag{6}$$

- Reserve requirement constraint;

$$\sum_{n=1}^{NG}\sum_{m=1}^{NS_n} rv_{n,s}^{m}=RV \tag{7}$$

- Generator upper/lower limits;

$$P_{n}^{Min}\le\sum_{m=1}^{NS_n} p_{n,s}^{m}\le P_{n}^{Max} \tag{8}$$

- Reserve upper/lower limits;

$$\begin{aligned} &P_{n}^{Min}\le\sum_{m=1}^{NS_n} rv_{n,s}^{m}\le P_{n}^{Max}, && \text{if } u_{n,s}=0\\ &0\le\sum_{m=1}^{NS_n} rv_{n,s}^{m}\le (P_{n}^{Max}-P_{n,s}), && \text{if, } u_{n,s}=1 \end{aligned} \tag{9}$$

For all wind power states, operating costs are calculated, and then expressed by a column vector, $\mathbf{Cost^{SCH}}$. The expected operating cost is calculated by Eq. (10).

$$Cost^{SCH}=\mathbf{Pr^{W}}\times\mathbf{Cost^{SCH}} \tag{10}$$

3.3 Contingency stage

Contingency states by the generator failure are expressed by $f(i,j)$ based on the *N*-2 contingency rule, where *i* and *j* are number of the failed generators. The probability of a failure state, $f(i,j)$, can be expressed as follows [7].

$$pr_{f(i,j)}=U_i\cdot U_j\cdot\prod_{\forall k\notin i,j}(1-U_k) \tag{11}$$

where, U_i is the unavailability of the *i*-th generator that is participated in the previous generation schedule, and in order to consider the *N*-1 contingency rule as well, U_i is assumed to be excluded in Eq. (11) when *i* is 0.

The power outage at $f(i,j)$ is defined as the sum of amounts of power assigned to the failed generators. Because power assigned to generators is already determined at the scheduling stage, the power outage is calculated based on the result of the scheduling stage. The power outage matrix, $\mathbf{PO_f}$ at $f(i,j)$ is defined by Eq. (12).

$$\mathbf{PO_f}=\left[po_{f(i,j)}(s,\mathrm{c})\,|\,P_{i,s}+P_{j,s}\right] \tag{12}$$

where, all elements in each row are identical because they are not affected by the wind power state considered at the contingency stage.

The power imbalance, $\mathbf{PI_f}$ which contains wind power errors and the power outage at $f(i,j)$, is expressed as

$$\mathbf{PI_f}=\mathbf{Er^{W}}-\mathbf{PO_f} \tag{13}$$

where, negative power imbalance is covered by some of the prepared reserve. However, if a generator having a reserve capacity is failed, then an actual available reserve is reduced as much as the reserve capacity assigned to the failed generator. Therefore, the available reserve at $f(i,j)$ can be expressed by the following net reserve matrix, $\mathbf{RV_f^{NET}}$.

$$\mathbf{RV_f^{NET}}=\left[rv_{f(i,j)}^{net}(s,c)\,|\,RV-\sum_{k\in i,j}^{NG}\sum_{m=1}^{NS_n} rv_{k,s}^{m}\right] \tag{14}$$

The net power outage matrix, $\mathbf{PO_f^{NET}}$ can be expressed as

$$\mathbf{PO_f^{NET}}=\mathbf{PI_f}+\mathbf{RV_f^{NET}} \tag{15}$$

Negative elements in the $\mathbf{PO_f^{NET}}$ mean an amount of the load not met even by the prepared reserve and they are assorted into the loss of load matrix, $\mathbf{LOL_f}$.

$$\mathbf{LOL_f}=\left[lol_f(s,c)\,|\,po_f^{net}(s,c)<0\right] \tag{16}$$

Alternately, positive elements in the $\mathbf{PO_f^{NET}}$ may contain the wind power surplus, $\mathbf{SW_f}$ as well as the remaining reserve, $\mathbf{RV_f^{NET}}$ after being used for power imbalance.

$$\mathbf{PO_f^{NET}}-\mathbf{LOL_f}=\mathbf{SW_f}+\mathbf{RV_f^{REM}} \tag{17}$$

where, the right side represents the positive elements. Because the power surplus is regardless of RV, the power surplus can be simply obtained as the positive element in the $\mathbf{PO_f^{NET}}$ calculated at zero reserve requirement, $RV=0$. The wind power surplus can be expressed by Eq. (18).

$$\mathbf{SW_f}=\left[sw_f(s,c)\,|\,po_f^{net}(s,c)>0,\ RV=0\right] \tag{18}$$

Once $\mathbf{SW_f}$ is obtained, the remaining reserve can be also derived from positive elements in $\mathbf{PO_f^{NET}}$ by Eq. (19).

$$\mathbf{RV_f^{REM}}=\mathbf{PO_f^{NET}}-\mathbf{LOL_f}-\mathbf{SW_f} \tag{19}$$

Reserve used for resolving power imbalance can be obtained by excluding the remaining reserve from the available reserve.

$$\mathbf{RV_f^{USE}}=\mathbf{RV_f^{NET}}-\mathbf{RV_f^{REM}} \tag{20}$$

3.4 Evaluation stage

As a result of the contingency stage, $\mathbf{LOL_f}$ and

$\mathbf{RV}_\mathbf{f}^{\mathbf{USE}}$ have been obtained for all failure states. The expected loss of load matrix, $\mathbf{LOL}$ for all failure states is

$$\mathbf{LOL} = \sum_{\forall f} \left(\mathbf{LOL}_\mathbf{f} \cdot pr_f \right) \tag{21}$$

Then, the expected value of loss of load, LOL for all of the ordered pairs, (s,c) is calculated by multiplying a row vector, $\mathbf{Pr}^\mathbf{W}$ and the expected loss of load matrix, $\mathbf{LOL}$, as shown in Eq. (22).

$$LOL = \mathbf{Pr}^\mathbf{W} \cdot \mathbf{LOL} \cdot \left(\mathbf{Pr}^\mathbf{W} \right)^T \tag{22}$$

Assuming that the reliability cost is proportional to LOL, the reliability cost is [15]

$$Cost^{REL} = VOLL \cdot LOL \tag{23}$$

where, $VOLL$ $[\$/\mathrm{MW}]$ is the value of load loss.

Compared with Eq. (5), an additional cost may occur owing to using reserve, which corresponds to the difference between the power generation cost and reserve procurement cost [12]. If a generator with only reserve capacity starts to operate for the first time, its start-up cost is also included in the additional cost. At $f(i,j)$, the additional cost by using reserve can be represented as follows;

$$\mathbf{Cost}_\mathbf{f}^\mathbf{RV} = \left[cost_f^{rv}(s,c) \right], \quad (1 \le \mathrm{s,c} \le NW)$$

$$cost_f^{rv}(s,c) = \sum_{n=1}^{NG} \left\{ \sum_{m=1}^{NS_n} \left((GC_n^m - RC_n^m) \cdot rv_{n,f}^m \right) + SU_n \cdot (1-\mu_{n,s}) \right\} \tag{24}$$

Then, the expected additional cost for the reserve usage is calculated reflecting all failure and wind power states, as in Eq. (25).

$$Cost_f^{RV} = \mathbf{Pr}^\mathbf{W} \cdot \left\{ \sum_{\forall f} \mathbf{Cost}_\mathbf{f}^\mathbf{RV} \cdot pr_f \right\} \cdot \left(\mathbf{Pr}^\mathbf{W} \right)^T \tag{25}$$

Finally, the total cost is expressed by Eq. (26), which is the sum of costs for the generation schedule and the used reserve, and the reliability cost. The optimal reserve requirement, RV^{Opt}, is determined so as to minimize the total cost.

$$\min_{RV} \left\{ Cost^{TOTAL} = Cost^{SCH} + Cost^{RV} + Cost^{REL} \right\} \tag{26}$$

The entire procedure for determining RV^{Opt} is presented as the following flowchart.

Based on the trade-off relationship between cost and reliability, the proposed methodology is conducted while varying RV with an appropriate increment. A brief description for the flowchart is as follows.

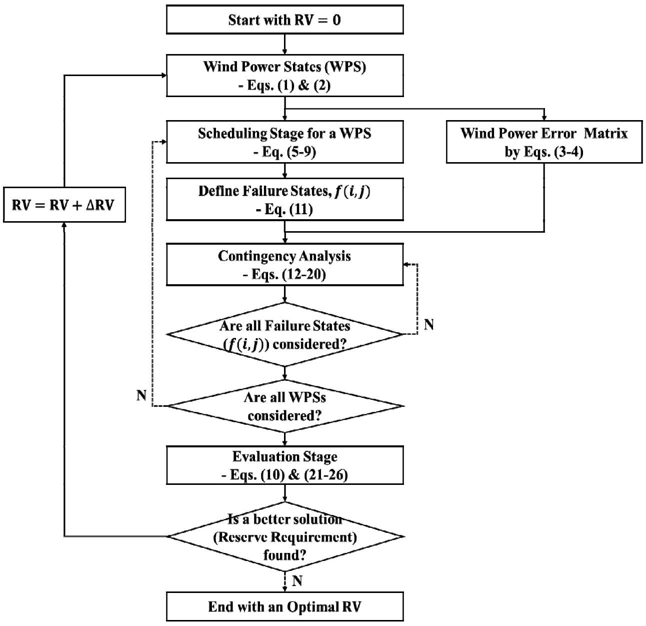

Fig. 3. Flowchart for the proposed Methodology

Step 1. Using historical data of wind speed data for a certain period, wind power states, $\mathbf{P}^\mathbf{W}$ and their probability, $\mathbf{Pr}^\mathbf{W}$ are defined. Then, the wind power error matrix, $\mathbf{Er}^\mathbf{W}$ is also defined.

Step 2. Under a specific wind power state at the scheduling stage, the UC and ED process is conducted with the objective function of Eq. (5) and constraints such as Eqs. (6-9).

Step 3. Based on the result of Step2, all possible failure states, $f(i,j)$ are defined. And then, at the contingency stage, the analysis for a failure state is performed through Eqs. (12-20), in order to obtain $\mathbf{LOL}_\mathbf{f}$, $\mathbf{RV}_\mathbf{f}^\mathbf{NET}$ and so on.

Step 4. Step2 and Step3 are performed iteratively for all wind power states and failure states, respectively.

Step 5. The expected value of the total cost for a specific reserve (RV) is calculated by Eqs. (10) and (21-26).

Step 6. If a present reserve requirement (RV) improves the result than the previous one, then the reserve requirement for the next iteration is increased by an appropriate increment. This iterative process is performed until a better solution is no longer found.

4. Case Study

The system for case study consists of 58 conventional generators and 100 wind turbines. The total capacity is 6510 MW, and detailed data is shown in Table 1. The cost related to conventional generators is modeled as a piecewise-linear function with three segments, and the cost for preparing the reserve is assumed to be 20~40% of

Table 1. Basic data of conventional generators

Type	no. of Units	Individual Capacity [MW]	Generation Cost [$/MW]		
			1st Seg.	2nd Seg.	3rd Seg.
Hydro	6	50	0	0	0
Nuclear	4	400	3.6	4.5	5.4
Coal_1	2	350	27.6	34.5	41.4
Coal_2	8	150	37.2	46.5	55.8
Coal_3	8	75	50.8	63.5	76.2
Gas_1	6	100	114	142.5	171
Oil_1	6	200	123	153.75	184.5
Gas_2	10	15	155.6	194.5	233.4
Oil_2	8	20	178.8	223.5	268.2

Table 2. Reliability data of conventional generators

Type	Availability	*FOR*
Hydro	0.9900	0.0100
Nuclear	0.8800	0.1200
Coal_1	0.9200	0.0800
Coal_2	0.9600	0.0400
Coal_3	0.9800	0.0200
Gas_1	0.9600	0.0400
Oil_1	0.9500	0.0500
Gas_2	0.9800	0.0200
Oil_2	0.9000	0.1000

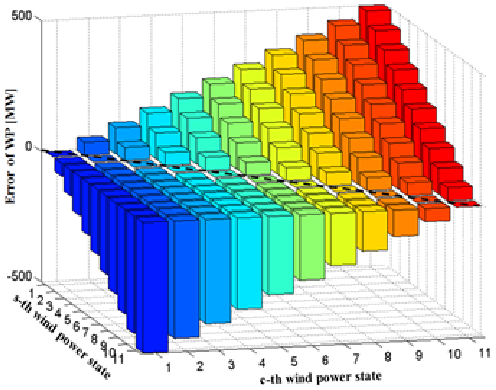

Fig. 4. Wind power error matrix ($\mathbf{Er}^{\mathrm{W}}$)

the corresponding generation cost according to types of generators [13]. Data for the availability and FOR (Forced Outage Rate) of conventional generators are shown in Table 2 [17].

Wind power consists of 5 MW x 100 WTs, so that the total capacity of wind power is 500 MW, which accounts for approximately 7.13% of the entire system. Wind power distribution is modeled as eleven wind power states, and the wind power error matrix, $\mathbf{Er}^{\mathrm{W}}$ is depicted in Fig. 4. If a scheduled generator has failed, the entire graph of $\mathbf{Er}^{\mathrm{W}}$ would be shifted down by the amount equivalent to power assigned to the failed generator.

The probability matrix of $\mathbf{Er}^{\mathrm{W}}$ is depicted in Fig. 5, which is obtained using wind speed data with 5.60 m/s and 3.65 m/s as the average wind speed and standard deviation, respectively.

Table 3. Detailed results for Fig. 6.

Cases	w/o WP	with WP	
	I	II	III
RV [MW]	399	399	507
$Cost^{SCH}$ [$]	219,450	193,784	198,602
$Cost^{RV}$ [$]	7,003	12,670	13,678
$Cost^{REL}$ [$]	5,113	19,997	10,039
$Cost^{TOTAL}$ [$]	232,566	226,451	222,319

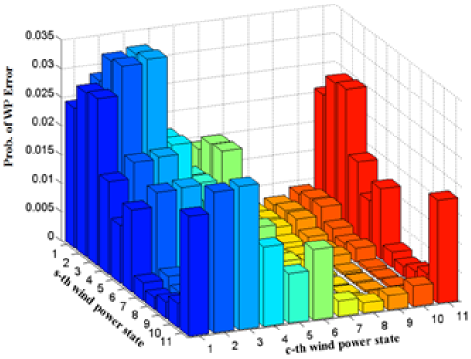

Fig. 5. Probability matrix for wind power error ($\mathbf{Pr}^{\mathrm{Er}}$)

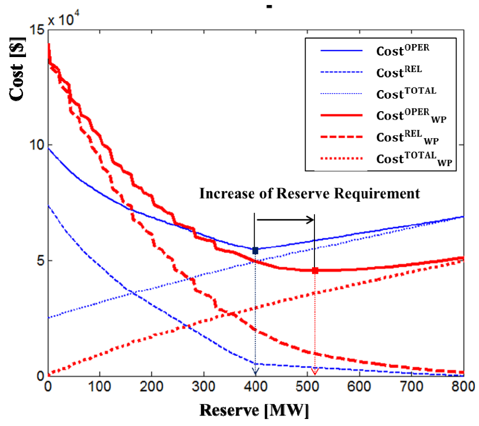

Fig. 6. Reserve requirements with/without wind power

Fig. 6 shows operating, reliability and total costs for the cases with/without wind power, when the system peak load is 4,900 MW for a certain period and $VOLL$ is assumed as \$1,000/MW. As seen in Fig. 6, RV^{Opt} is increased when wind power is penetrated. The operating cost in Fig. 6 is the sum of $Cost^{SCH}$ at the scheduling stage and $Cost^{RV}$ at the contingency stage, which are as defined in Eqs. (10) and (25), respectively. The numerical result is shown in Table 3.

Comparing Cases I and II for the same RV, 399 MW, Case II has a lower $Cost^{SCH}$ (-\$25,666) due to zero generation cost of wind power. However, it has more $Cost^{RV}$ (+\$5,667) and more $Cost^{REL}$ (+\$14,884) owing to the uncertainty of wind power. Comparing Cases II and III, more RV in case III can save the reliability cost much

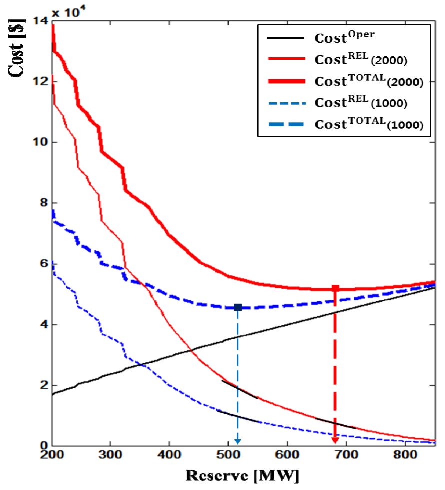

Fig. 7. Results of RV^{Opt} for two $VOLL$ values

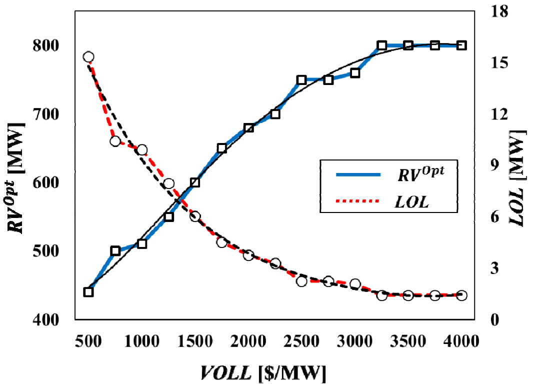

Fig. 8. Results of RV^{Opt} and LOL according to $VOLL$

more, though both $Cost^{SCH}$ and $Cost^{RV}$ are increased slightly. As a result, the total cost is decreased, and RV^{Opt} having the minimum total cost is shifted to 507 MW from 399 MW.

Case IV applying $VOLL$ of $2,000/MW is compared with the previous Case III. Because only $VOLL$ is increased, the operating cost is not changed but the reliability cost is increased doubly, and thus the total cost is also increased. As a result, RV^{Opt} in Case IV is shifted to 680 MW from 507 MW.

For the sensitivity study of $VOLL$, several RV^{Opt} are determined varying the $VOLL$ values. Fig. 8 shows result of RV^{Opt} as well as LOL. It is natural that the reserve requirement is more required to further reduce LOL as $VOLL$ rises. However, a specific RV can still reduce LOL slightly more, but it may increase an operating cost more than it can reduce the reliability cost. As a result, the total cost at the specific RV is increased, and thus it is economic no longer. So, RV^{Opt} would be saturated according to increase of $VOLL$. As shown in Fig. 8, after $VOLL$ of $3,250/MW, it can be seen that RV^{Opt} and LOL at that time are saturated to about 800 MW, 1.43 MW, respectively. Consequently, it is important to choose an appropriate $VOLL$ when determining RV^{Opt}.

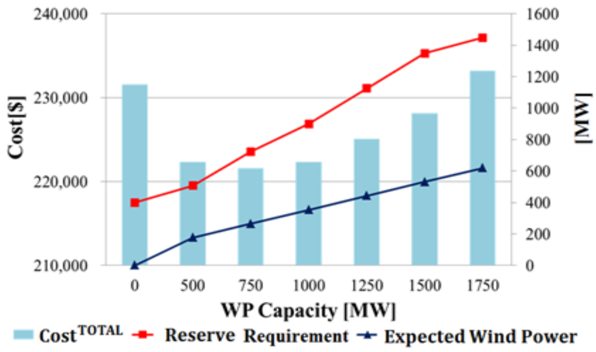

Fig. 9. RV^{Opt} for installed capacities of wind power

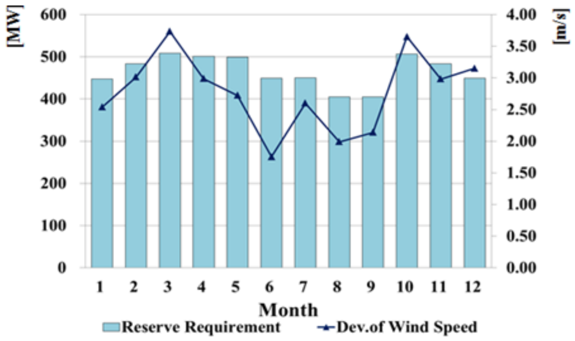

Fig. 10. RV^{Opt} according to wind speed deviations

Fig. 9 shows RV^{Opt} and expected wind power according to installed capacities of wind power. In Fig. 9, it can be seen that RV^{Opt} needs more than the expected output of wind power, as the installed capacity increases. This is because influences of the uncertainty of wind power becomes much greater. Nevertheless, it is observed that wind power can reduce the total cost, except of 1750 MW wind power that is considered as uneconomical.

Fig. 10 shows a result of RV^{Opt} according to deviations of monthly wind speed. If the deviation of wind power is increased, the off-diagonal elements of $\mathbf{Pr}^{\mathbf{Er}}$ depicted in Fig. 5 are increased, so that the corresponding negative elements of $\mathbf{Er}^{\mathbf{W}}$ in Fig. 4 may more significantly affect the system reliability as well as RV^{Opt}. It seems that the deviation of wind speed is one of the main factors for determining RV^{Opt}.

5. Conclusion

This paper proposes a methodology to evaluate the impact of high penetration of wind power, and to determine the maximum required capacity of available generators for a certain period in the mid-term perspective, that contains an optimal reserve capacity. Using a historical wind speed distribution data, all possible wind power errors are expressed explicitly in the proposed matrix form. All situations such as a power shortage and a power surplus caused by wind power and the generator failure are analyzed through the matrix form. The methodology is performed through main three stages. The costs for the generation, the procurement and usage of reserve, and the reliability cost caused by the negative power imbalance are calculated through scheduling and contingency stages. In the evaluation stage, the optimal reserve requirement is determined at the point where the total cost is minimized, based on the cost/reliability analysis. The results of case studies show how the optimal reserve requirement is changed when wind power is introduced, and how major factors affect the reserve requirement.

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