Reliability/cost Evaluation on Power System connected with Wind Power for the Reserve Estimation

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Abstract: - Wind power is ideally a renewable energy with no fuel cost, but has a risk to reduce reliability of the whole system because of uncertainty of the output. If the reserve of the system is increased, the reliability of the system may be improved. However, the cost would be increased. Therefore the reserve needs to be estimated considering the trade-off between reliability and economic aspects. This paper suggests a methodology to estimate the appropriate reserve, when wind power is connected to the power system. As a case study, when wind power is connected to power system of Korea, the effects on reliability and economic aspects according to various reserve capacity is evaluated at HLII level and the appropriate reserve is determined.

Key-Words: - Wind Power, Reserve Estimation, Reliability Evaluation, Reliability Cost, Operation Cost

1 Introduction

Wind power penetration to the conventional power system has increased globally. The reasons on the increase of wind power penetration are as follows; Due to the environmental problems and the exhaustion of fossil fuel, the eco-friendly and renewable resources have been more important. And the grid parity, the point at which the cost to produce renewable energy becomes equal to generating cost of the conventional energy, has been achieved as the related techniques are improved. Furthermore, the government regulatory and policies such as RPS, have encouraged the wind power penetration. The achievement of grid parity among them means that economic feasibility of wind power is reasonable [1]. However, wind power may have negative impacts on the system in respect of reliability. Therefore, for stable operation of power system, economic/reliability evaluation has to be performed comprehensively on the whole power system.

In power system, the generated power has to be same with the load changed in real time. So, for stable supply of power, the power system has to have the sufficient reserve capability and to control the output of generators. However, wind power has the variable and intermittent output, and the accurate forecast of them is also difficult because wind speed has a high uncertainty. Therefore, when wind power is connected to the grid, the determining the appropriate reserve capacity is very important issue. The scale of reserve capacity affects to both reliability and economic respects. There is the trade-off relationship between reliability and economic [3], [4]. That is, the more reserve capacity helps the power system to be more reliable, but requires more cost. So, the reserve capacity for wind power penetration is determined considering effects on both reliability and economic aspects [2].

In this paper, a methodology is suggested to evaluate effects of wind power penetration on the power system in terms of reliability cost and total generation cost, which represent reliability and economic aspects respectively. Also, a method to determine an appropriate reserve capacity is suggested [5].

2 Methodologies for Estimating Appropriate Reserve

In this paper, an operating cost includes the generation cost and the reserve cost which is a potential cost. The penetration of wind power may reduce the generation cost since the generated power from wind power plant can cover the same power generated from conventional power plant.

And if the reserve cost is defined as multiplication of the reserve capacity with a marginal cost of power system, the wind power may reduce the system marginal cost. as the result, the reserve cost may be also reduced. In reliability aspect, wind power may increase the load curtailment under the condition that power system has the same reserve capacity at before/after penetration of wind power. The load curtailment, which means power not supplied due to the fault of generators or transmission lines, can be considered through converted to reliability cost. Therefore, wind power may increase the reliability cost.

The following **Fig. 1** shows a basic concept related with these facts.

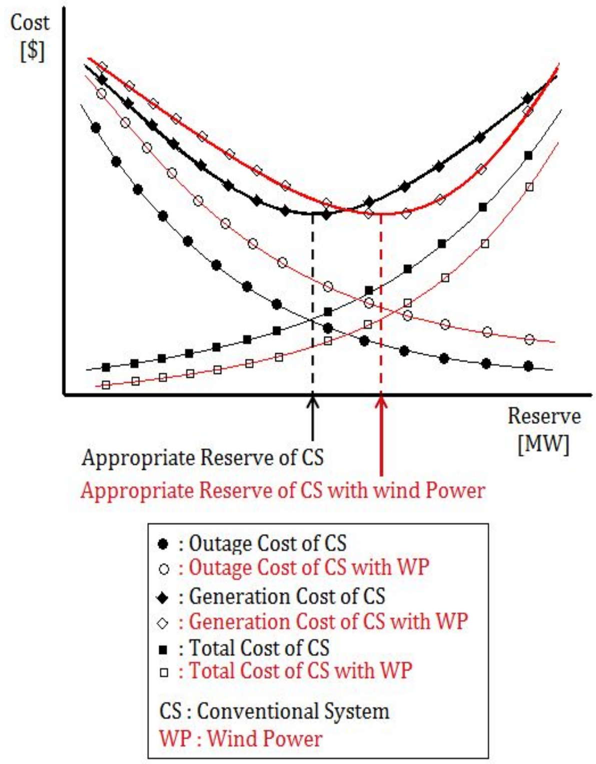

Fig. 1 Estimating appropriate reserves considering wind power

First, in case that wind power is not connected, the reliability cost and operating cost of the existing power system are represented by curve according to the reserve capacity. As the result, the appropriate reserve capacity for conventional system may be selected at point that minimizes the sum of the operation cost and the reliability cost. When wind power is connected to the grid, the curve of operation cost would be lower, and the curve of reliability cost would be higher. As the result, the new reserve capacity would be selected.

2.1 Evaluation of Operating Cost

The operating cost is calculated by sum of the generation cost and the reserve cost, according to the reserve capacity. At any reserve capacity, the generation cost is calculated considering the probability of output of wind power as follows; the output of wind power is divided into a few states. And the probability of each state is calculated using wind speed distribution. The generation cost of generators included in each reserve state, is calculated. And then, the expected cost considering all of states of wind power output is calculated by summation of all values which is obtained multiplying the generation cost and the probability of each state. This is represented by the following equation.

$$Gn.C^n(r) = \sum_{i \in In-serviced} a_i (G_i^n(r))^2 + b_i G_i^n(r) + c_i \quad (1)$$

$$Gn.C(r) = \sum_{\forall n} Gn.C^n(r) \times P_w^n \quad (2)$$

where r represents the reserve states. $G_i^n(r)$ is the output of i-th generator included in r-th reserve state at n-th wind power state. a_i, b_i, c_i are constants of generation cost of i-th generator. $Gn.C^n(r)$ is total generation cost at n-th state of wind power output. P_w^n represents the probability of n-th state of wind power.

2.2 Evaluation of Reliability Cost

If one or more of generators or transmission lines are failed, the load not supplied from generators occurs, which is defined as an outage capacity. At this situation, the load curtailment, that is the same with the outage capacity, has to be performed for balance between supply and demand and can be evaluated through converted to reliability cost using the composite customer damage function (CCDF),as follows;

$$E(Ot.Cap^n(r)) = \sum_{\forall f} LC^n(f,r) \times P(f) \quad (3)$$

$$Ot.C(r) = \left\{ \sum_{\forall n} \left(E(Ot.Cap^n(r)) \right) \times P_w^n \right\} \times CCDF \quad (4)$$

where, f represents the failure states, and $P(f)$ is the probability of failure states. $LC^n(f,r)$ is the load curtailment at f-th failure state, r-th reserve state, n-th wind power output state. $Ot.Cap^n(r)$ is the outage capacity at r-th reserve state, n-th wind power output state, and $\boldsymbol{Ot.C(r)}$ is the outage cost at r-th reserve state.

At HLII, one or more faults of generators or transmission lines may be considered simultaneously. Therefore, failure states can be modelled depending on these faults, and then the load curtailment at each failure state can be calculated through the optimal power flow. Considering the probability of failure states and the wind power output state, the load curtailment is calculated according to the reserve capacity.

2.3 Procedure on Determining the Appropriate Reserve Capacity

The following **Fig. 2** represents procedure on determining the appropriate reserve capacity using the operating cost and the reserve cost. The procedure is performed in case with no wind power at first, and then is performed similarly in case with wind power.

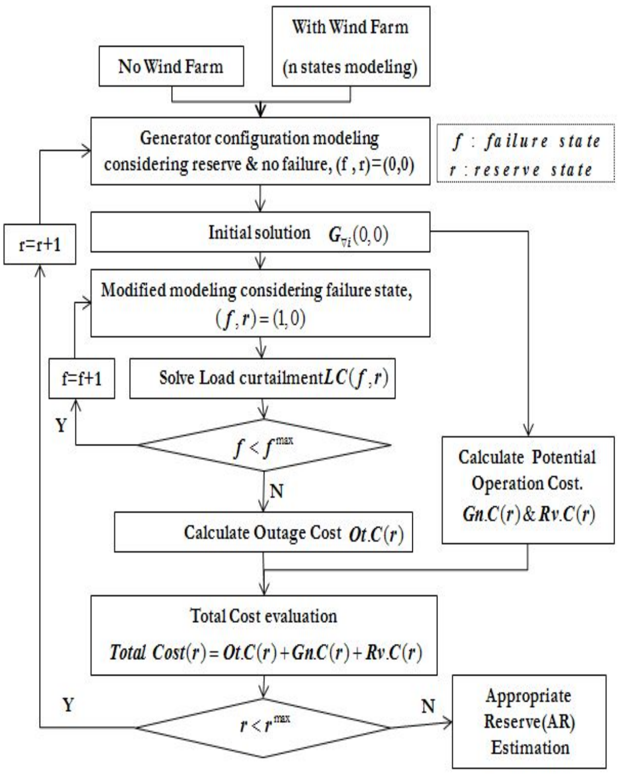

Fig. 2 Flowchart for estimation of AR

At first, the procedure is performed to select the reserve for conventional system with no wind power. Configuration of generators is modelled at no-failure state depending on reserve state, and then an initial solution is calculated to obtain an operating cost at the reserve state through an optimal power flow. The objective function in this stage is to minimize the quadratic generating cost on sum of the load and the reserve capacity. Constraints are considered with generating capacity, reserve capacity, power flow capacity on transmission lines and equivalence between supply and demand. The objective function and constraints are as follows;

Objective)

$$\min\{\sum_{\forall i} \boldsymbol{a}_i(\boldsymbol{G}_i(0,\boldsymbol{r})+\boldsymbol{Rv}_i(0,\boldsymbol{r}))^2+\boldsymbol{b}_i(\boldsymbol{G}_i(0,\boldsymbol{r})+\boldsymbol{Rv}_i(0,\boldsymbol{r}))+\boldsymbol{c}_i\} \quad (5)$$

Constraints)

$$\begin{aligned}
&\boldsymbol{L}_i = \boldsymbol{G}_i(0,\boldsymbol{r}) + \sum_{\substack{\forall j \\ j\neq i}} \boldsymbol{Pf}_{j-i}(0,\boldsymbol{r}) \\
&\boldsymbol{G}_i^{\min} \le \boldsymbol{G}_i(0,\boldsymbol{r}) + \boldsymbol{Rv}_i(0,\boldsymbol{r}) \le \boldsymbol{G.C}_i \\
&\boldsymbol{T.Rv}(\boldsymbol{r}) + \sum_{\forall i} \boldsymbol{L}_i = \sum_{\forall i} (\boldsymbol{G}_i(0,\boldsymbol{r}) + \boldsymbol{Rv}_i(0,\boldsymbol{r})) \qquad (6) \\
&\boldsymbol{T.Rv}(\boldsymbol{r}) = \sum_{\forall i} \boldsymbol{Rv}_i(0,\boldsymbol{r}) \\
&\left|\boldsymbol{Pf}_{j-i}(0,\boldsymbol{r})\right| \le \boldsymbol{T.C}_{j-i}
\end{aligned}$$

where, $\boldsymbol{L_i}$ is the i-th load. $\boldsymbol{Rv}_i$ is the i-th reserve capacity and $\boldsymbol{T.Rv}$ is total reserve capacity. $\boldsymbol{Pf}_{i-j}$ is power flow on i-j line and $\boldsymbol{T.C}_{i-j}$ is transfer capacity of line i-j.

Through the optimal power flow, the following results are obtained.

$$\boldsymbol{G}_i(0,\boldsymbol{r}),\ \ \boldsymbol{Rv}_i(0,\boldsymbol{r})$$

$$\boldsymbol{Gn.C}(0,\boldsymbol{r}) = \sum \boldsymbol{a}_i \boldsymbol{G}_i^2(0,\boldsymbol{r}) + \boldsymbol{b}_i \boldsymbol{G}_i(0,\boldsymbol{r}) + \boldsymbol{c}_i \qquad (7)$$

$$\boldsymbol{Rv.C}(0,\boldsymbol{r}) = \boldsymbol{SMP}(0,\boldsymbol{r}) \times \boldsymbol{T.Rv}(\boldsymbol{r}) \qquad (8)$$

Then, the modelling is modified depending on the failure state. The modified model is simulated to obtain load curtailment (LC) by the following optimal problem. The objective function is to minimize the curtailed load capacity. In equations for the objective function and constraints, it is assumed that bus i means fault bus, so load curtailment may occurs at the bus i, and if the failure is 'line i-j' fault, the bus i is selected as fault bus where $\boldsymbol{L}_i - \boldsymbol{G.C}_i$ may be bigger than the other bus in line i-j.

ISBN: 978-1-61804-131-9

The objective function and constraints are as follows;

Objective)

$$\min\{\boldsymbol{LC}(\boldsymbol{f},\boldsymbol{r}) = \boldsymbol{L}_i - \boldsymbol{G}_i(\boldsymbol{f},\boldsymbol{r}) - \sum_{\substack{\forall j \\ (j \neq i)}} \boldsymbol{Pf}_{j-i}(\boldsymbol{f},\boldsymbol{r})\} \qquad (9)$$

Constraints)

$$\begin{aligned}
&\underset{(j\neq i)}{\boldsymbol{L}_j} = \boldsymbol{G}_j(\boldsymbol{f},\boldsymbol{r}) - \sum_{\forall k} \boldsymbol{Pf}_{j-k}(\boldsymbol{f},\boldsymbol{r}) \\
&\boldsymbol{G}_i(0,\boldsymbol{r}) \le \boldsymbol{G}_i(\boldsymbol{f},\boldsymbol{r}) \le \begin{cases} \text{if a line failed} \\ \boldsymbol{G}_i(0,\boldsymbol{r}) + \boldsymbol{Rv}_i(\boldsymbol{r}) \\ \\ \text{if a generator failed} \\ \boldsymbol{G}_i(0,\boldsymbol{r}) + \boldsymbol{Rv}_i(\boldsymbol{r}) - \boldsymbol{F}.\boldsymbol{g}_i(\boldsymbol{f}) \end{cases} \qquad (10) \\
&\boldsymbol{G}_j^{\min} \le \boldsymbol{G}_j(\boldsymbol{f},\boldsymbol{r}) \le \boldsymbol{G}_j(0,\boldsymbol{r}) + \boldsymbol{Rv}_j(\boldsymbol{r}) \le \boldsymbol{G}.\boldsymbol{C}_j \quad , \ (j \neq i) \\
&0 \le \boldsymbol{Rv}_j(\boldsymbol{r}) \le \boldsymbol{Rv}_j^{\max}(\boldsymbol{r}) \\
&\left|\boldsymbol{Pf}_{j-i}(\boldsymbol{f},\boldsymbol{r})\right| \le \boldsymbol{T}.\boldsymbol{C}_{j-i}(\boldsymbol{f})
\end{aligned}$$

where i is the faulted bus, and j and k are non-faulted buses. $\boldsymbol{F}.\boldsymbol{g}_i$ represents the capacity of failed generator.

The above process is repeated until all failure states are considered. In each process, the load curtailment and the outage cost are calculated at the r-th reserve state as follows;

Output)

$$\boldsymbol{E}(\boldsymbol{Ot}.\boldsymbol{Cap}(\boldsymbol{r}))=\sum_{\forall f} \boldsymbol{LC}(\boldsymbol{f},\boldsymbol{r}) \times \boldsymbol{P}(\boldsymbol{f}) \qquad (11)$$

$$\boldsymbol{Ot}.\boldsymbol{C}(\boldsymbol{r}) = \left(\boldsymbol{E}(\boldsymbol{Ot}.\boldsymbol{Cap}(\boldsymbol{r}))\right) \times \boldsymbol{CCDF} \qquad (12)$$

where $\boldsymbol{Ot}.\boldsymbol{cap}$ means that the outage capacity which is the load curtailment considering all the faults and the probability of faults.

As final stage, total cost is calculated as the sum of the generation cost, reserve cost and outage cost at any reserve state, as follows;

$$\boldsymbol{T}.\boldsymbol{C}(\boldsymbol{r}) = \boldsymbol{Gn}.\boldsymbol{C}(\boldsymbol{r}) + \boldsymbol{Rv}.\boldsymbol{C}(\boldsymbol{r}) + \boldsymbol{Ot}.\boldsymbol{C}(\boldsymbol{r}) \qquad (13)$$

The process is repeated until all reserve states are considered. As the result, total costs are obtained according to the reserve capacities. Then the appropriate reserve capacity can be determined at point that minimizes the total cost.

In case that wind power is connected to power system, the following constraints are additionally included at each optimal problem.

Additional constraints for case including wind power)

$$\begin{aligned}
&\boldsymbol{G}_w(\boldsymbol{f},\boldsymbol{r}) = \boldsymbol{G}_w^{\ n} \\
&\sum_{\forall j} \boldsymbol{Pf}_{w-j}^{\ n} = \boldsymbol{G}_w^{\ n} \\
&\boldsymbol{Rv}_w(\boldsymbol{f},\boldsymbol{r}) = 0 \qquad (14) \\
&\sum_{\forall n} \boldsymbol{P}_w^{\boldsymbol{n}} = 1
\end{aligned}$$

where $\boldsymbol{w}$ is the bus connected with wind power. $\boldsymbol{G}_w^{\boldsymbol{n}}$ is wind power at n-th state of wind power output and $\boldsymbol{P}_w^{\boldsymbol{n}}$ is the probability of n-th state of wind power output

Also, the results are modified to reflect states of wind power output as follows;

Modified result equations)

$$\begin{aligned}
&\boldsymbol{Gn}.\boldsymbol{C}(0,\boldsymbol{r}) = \sum_{\forall n} \boldsymbol{Gn}.\boldsymbol{C}^n(0,\boldsymbol{r}) \times \boldsymbol{P}_w^n \\
&\boldsymbol{Rv}.\boldsymbol{C}(0,\boldsymbol{r}) = \sum_{\forall n} \boldsymbol{Rv}.\boldsymbol{C}^n(0,\boldsymbol{r}) \times \boldsymbol{P}_w^n \\
&\boldsymbol{E}(\boldsymbol{Ot}.\boldsymbol{Cap}^n(\boldsymbol{r}))=\sum_{\forall f} \boldsymbol{LC}^n(\boldsymbol{f},\boldsymbol{r}) \times \boldsymbol{P}(\boldsymbol{f}) \qquad (15) \\
&\boldsymbol{Ot}.\boldsymbol{C}(\boldsymbol{r}) = \left\{\sum_{\forall n}\left(\boldsymbol{E}(\boldsymbol{Ot}.\boldsymbol{Cap}^n(\boldsymbol{r}))\right) \times \boldsymbol{P}_w^n\right\} \times \boldsymbol{CCDF}
\end{aligned}$$

where CCDF is a composite customer damage function.

In case of connecting wind power, the appropriate reserve capacity can be determined at point that minimizes a sum of the operating cost and the reliability cost.

3 CASE STUDY

The case study is performed on the simplified power system in Korea. 154, 345 and 765kV among Branches of the grid were only considered. And the whole power system were separated to 13 areas, so the simulated system composited 13-buses system. These are shown in **Fig. 3**. The measured load is about 75,645MW. Finally, the capacity of connected wind power is 500MW. Wind power output modelled using a characteristic of wind power output and a wind speed data which is actual data obtained at the southwest coast in Korea.

Table. 1 States of wind power output

State	Output[%]	Wind Speed[m/s]	Probability[%]
1	0	0~3.5	33.70
2	0~20	3.5~7.2	42.10
3	20~40	7.2~8.5	8.49
4	40~60	8.5~9.5	5.03
5	60~80	9.5~10.5, 18.0~25.0	3.79
6	80~100	10.5~18.0	6.88

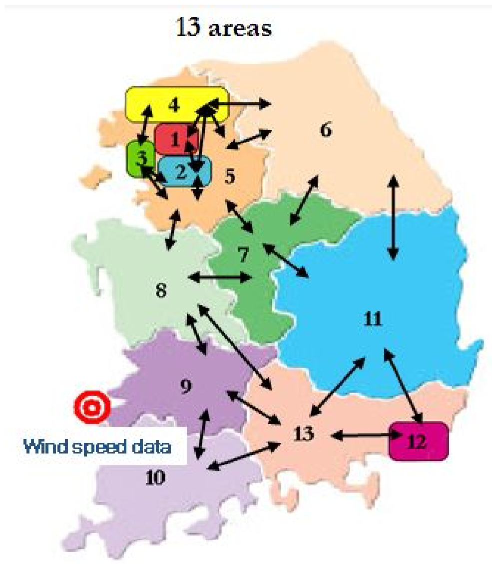

Fig. 3 the simplified power system of Korea

(13-bus system)

Optimal problems are solved through an optimal power flows simulation of PSS/E and a numerical analysis.

Only one of faults of the transmission lines and generators is considered simultaneously in each failure state.

According to reserve which is represented as ratio of reserve capacity to total load, the expected outage capacity is calculated as follows.;

Table. 2 Expected outage capacity

Reserve [%]	Conventional System (CS) [MW]	CS with wind power [MW]
10.6	9,256.3	11,342.7
11.0	9,412.0	11,186.9
12.6	10,080.9	10,517.2
13.0	10,240.8	10,357.2
15.0	5,157.6	5,338.0
15.7	5,158.2	5,339.0
17.1	5,140.0	5,320.0
17.7	5,140.0	5,320.0

As the reserve of the system is increased, the expected outage capacity decreases in both conventional system and system with wind power. It shows a general result that more reserve keep the system more reliable. However, the system with wind power is higher than the conventional system.

The result of outage cost calculation using the previous result and the system marginal cost is shown in **Table 3**.

Table. 3 Outage cost

Reserve [%]	Conventional System (CS) [$]	CS with wind power [$]
10.6	1,703.0	1,824.3
11.0	1,702.7	1,822.8
12.6	1,641.5	1,691.5
13.0	1,647.0	1,704.3
15.0	829.6	864.3
15.7	823.2	858.7
17.1	820.0	863.1
17.7	818.6	861.7

Also, the calculation result of potential operating cost is shown in the following **Table. 4**.

Table. 4 Operating cost

Reserve [%]	Conventional System (CS) [$]	CS with wind power [$]
10.6	2,929.1	2,912.4
11.0	2,929.2	2,941.2
12.6	2,958.7	2,941.3
13.0	2,958.8	2,985.3
15.0	2,985.5	2,985.5
15.7	3,011.9	2,985.5
17.1	3,013.0	3,012.0
17.7	3,013.3	3,011.7

As the reserve of the system increases, the potential operation cost increases. The reasons are that if a scale of generator configuration is increased to secure the reserve, the generation cost becomes higher, and the reserve cost is increased as the capacity increase.

ISBN: 978-1-61804-131-9

As the final result, the total cost is shown in the following **Table. 5**.

Table. 5 Total cost with variation of reserve

Reserve [%]	Conventional System (CS) [$]	CS with wind power [$]
10.6	4,632.1	4,736.7
11.0	4,631.9	4,746.0
12.6	4,600.2	4,632.8
13.0	4,605.8	4,689.6
15.0	3815.1	3,849.8
15.7	3,835.1	3,844.2
17.1	3,834.0	3,875.1
17.7	3,831.9	3,873.4

Each curve of total cost, which is the sum of outage cost and potential operation cost, has the smallest point. It indicates the appropriate reserve (AR) of each system. In case of conventional system, a 15.0% is selected as the appropriate reserve, while in second case, 15.7% is selected. As shown in **Fig. 4**, the appropriate reserve, the smallest point in each curve, moved to the right slightly after wind power penetration. It means penetration of wind power brought increase of reserves to the whole system.

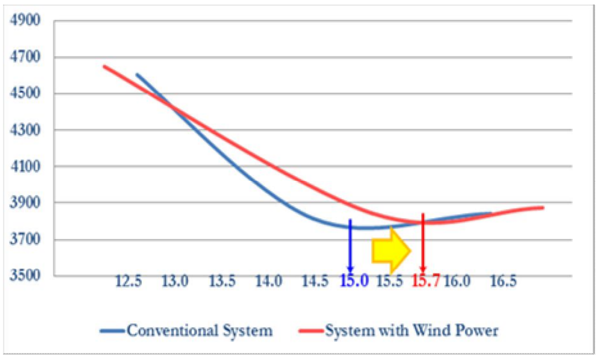

Fig. 4 Total cost curves of the systems

4 CONCLUSION

This paper suggested the methodology to determine the appropriate reserve capacity of the power system considering reliability and economic aspects. When wind power plant is connected, a sufficient reserve capacity is prepared to meet the equivalence between supply and demand of electrical power. Therefore, the reserve capacity should be determined considering uncertainty of wind power output caused by wind speed.

In this paper, the effects of connecting wind power are evaluated in respect costs which are the potential generation cost and the reliability cost. Wind power may reduce the operating cost, but increase the reliability cost. So, to consider this trade-off relationship between the operating cost and the reliability cost, the appropriate reserve capacity is determined at point to minimize the total cost which is a sum of the costs.

To illustrate the suggested methodology, the case study is performed on simplified power system in Korea. When a large size of wind power is connected to power system, the appropriate reserve capacity can be determined for a stable operation of power system considering the reliability and economic simultaneously. In conclusion, the suggested methodology can be useful reference to planning the transmission expansion and operating power system, if the related studies would be performed and improved.

ACKNOWLEDGMENT

This research was supported by a grant (CTI C-01) from Construction Technology Innovation Program funded by Ministry of Land, Transport and Maritime Affairs of Korean government.

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