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Quantifying Reserve Demands due to Increasing Wind Power Penetration

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Abstract-- With wind power penetration increasing in many systems worldwide, operational issues are beginning to emerge due to the uncertain nature of wind power. One of these issues is the provision of reserve for system security. To analyse this, one must consider generator outage rates, system load forecast errors and wind power forecast errors in such a way as to directly relate the system reserve level to the security of the system. In this paper a new methodology is proposed for the analysis and provision of system reserve levels. The methodology considers the provision of both reserve (on-line) and replacement reserve (off-line). The proposed methodology is then applied to the IEEE reliability test system incorporating other influencing factors like wind farm size and numbers and forecast periods. Results illustrate the impact increasing wind power penetration has on reserve.

Index Terms-- Forecasting, power generation faults, power system security, wind power generation.

I. INTRODUCTION

Wind power's variable nature gives rise to much discussion on the impact of large quantities of wind on conventional systems. It is widely believed that large wind penetrations would put an increased burden on system operations and ancillary services [1]. Quantifying this increased burden however has proved to be difficult.

In [2] the author discusses the modification of unit commitment, economic dispatch, and frequency controls when wind generation capacity is significant and attempts to determine a wind power penetration constraint based on a worst case wind generation change due to a thunderstorm. The author however does not consider the possible benefit forecasting may play in the system operation. Söder [3] considers wind speed and load forecasts errors and ramp rates of conventional thermal units to determine system reserve margins in the wind-hydro-thermal interconnected Swedish electricity system. The author considers the correlation of wind speed forecasts within a region and between different regions and links the reserve levels to a probability of too low a frequency due to load and wind fluctuations. Unlike other

systems the Swedish system has a need for a reserve pool for frequency control separate to that of the reserve allocated for generator and transmission line trips under a NORDEL group agreement [3]. Dany [4] attempts to quantify the technical consequences of high wind penetrations in terms of primary, secondary and long-term reserve as they apply to the interconnected German power system and suggests it will cause a substantial change in the demand for certain types of reserve. Interestingly the author also suggests a need for negative secondary reserve to avoid a surplus of power when wind farms produce a large unforecasted increase in power production. O'Dwyer *et al.* [5], assess the extent to which wind energy would be technically feasible and economically attractive on the isolated Irish electricity system. They analyse environmental and economic impacts along with capacity and frequency control issues from a 1990 perspective. However, like [2] it fails to consider the contribution that forecasting may have on the provision of frequency control reserve.

In this paper a methodology is proposed that will quantify the reserve needs of a system with wind in such a way as to directly relate it to a system reliability criterion. It considers both load and wind forecast errors along with generator outage rates. The approach also allows the impact of various factors such as numbers of wind farms and forecast period to be assessed in terms of their impact on reserve levels.

II. METHODOLOGY

During each hour of the year the total system demand has to be met with a corresponding level of generation, either from wind generation or conventional generation. Since the possibility exists of generation outages and unforecasted load and wind power fluctuations the system must carry an adequate level of reserve to meet such generation shortfalls. The level of reserve for the system which is deemed to be adequate will depend on a certain system reliability criterion. Here an hourly approach is taken, the results of which can easily be seen in a reliability criterion defined over a year.

A. Reliability criterion

There are many different reliability criteria used in power systems analysis, Expected Energy Not Served (EENS), Loss of Load Probability (LOLP) etc. Probably the most commonly used criterion is the Loss Of Load Expectation (LOLE), which is a statistical measure of the likelihood of failure, and unlike EENS it does not quantify the extent that supply fails to meet demand. LOLE is usually defined by how many hours load is shed per year. The Irish system aims to operate with a LOLE

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of 8 hours per year [6]. In this paper the criterion is defined as being the number of load shedding incidents tolerated per year (1), and can be thought of as the LOLE divided by the mean time that load is shed for. Here the definition of a load shedding incident is an incident when there is not enough reserve to meet a generation shortfall.

$$\text{Incidents / Year} = \frac{\text{LOLE}}{\text{MeanSheddingPeriod}} \quad (1)$$

B. Generator Outages

The generator outages are dealt with in an hourly fashion. They are defined as the probability of a generator tripping out in an hour period, P_{trip} . This is assumed to be the same for all hours and can be related to the Forced Outage Rate (FOR) and Mean Time To Repair (MTTR) as

$$P_{\text{trip}} = \frac{\text{FOR}}{\text{MTTR}} \quad (2)$$

C. Load Forecast Model

Like any forecast, load forecasts have an error associated with them. In general this error can be said to increase as the forecast period increases, but this increase may be quite small due to the repetitive nature of the daily system load curve. The load forecast error can be modeled as a Gaussian stochastic variable with a mean of zero and a standard deviation of $\sigma_{\text{Load},h}$ for a forecast period of h hours ahead.

D. Wind Power Forecast Errors

Like load forecast errors, wind forecast errors also increase as the forecast period increases. This increasing nature may be more significant in wind power forecasting than in load forecasting as wind power outputs are not as cyclic or repetitive in nature as load levels. Forecast errors between wind farms may also be correlated depending on the forecasting period and technique. Like load forecast errors wind forecast errors may be modeled as a Gaussian stochastic variable with a mean of zero and a standard deviation of $\sigma_{\text{WP},h}$ for a forecast period of h hours ahead.

E. Total System Forecast Error

While the possibility of forecast error correlation has been considered, there is however little research investigating the nature of such correlations. It is for this reason that the forecast errors between farms and between wind power and load are assumed to be uncorrelated in this paper.

To enable the uncertainty of the system to be integrated easily into the calculations the wind power and load forecast errors are combined to give the total system error. There is assumed to be no correlation between the wind power and the load forecast errors. Therefore total system forecast error for h hours ahead can be modeled as a Gaussian stochastic variable with mean of zero and standard deviation as given in (3).

$$\sigma_{\text{Total},h} = \sqrt{\sigma_{\text{WP},h}^2 + \sigma_{\text{Load},h}^2} \quad (3)$$

F. Reserve Allocation

The method adopted in this paper considers two types of system reserve.

1. Reserve that is called upon to make up any shortfall due to unforecasted wind/load variations and/or a generator trip. Due to the hourly approach adopted here the time frame of how fast this reserve can react is not considered. Here it is simply called reserve.
2. Replacement reserve is defined as the amount of reserve the system operator must be capable of putting in place during a set period after the generator trip in order to restore the reserve level.

The technique calculates how much reserve the system needs but it does not consider how the reserve is to be provided. The reserve levels need to be allocated every hour in such a way as to correspond to the probability of having a load shedding incident in that hour. The sum of all these probabilities over a whole year will then correspond to the reliability criterion as defined in (1). For each hour the reserve level can be related to the probability of shedding load by considering the probability of an unforecasted wind/load fluctuation and/or a generator trip being greater than the amount of system reserve. See Fig. 1. The relationship between the reserve level and the probability of shedding load in any given hour is given in (4).

$$P_{\text{LoadShed}} = \left[1 - \Phi \left(\frac{R_{\text{System}}}{\sigma_{\text{Total},h}} \right) \right] + \sum_{m=1}^M P_{\text{trip}_m} \left[1 - \Phi \left(\frac{R_{\text{system}} - X_m}{\sigma_{\text{Total},h}} \right) \right] \quad (4)$$

where

R_{System} = reserve level

X_m = power from generator m from the set of M generators

P_{trip_m} = probability of trip of generator m

$\Phi(x)$ = normalised Gaussian distribution function

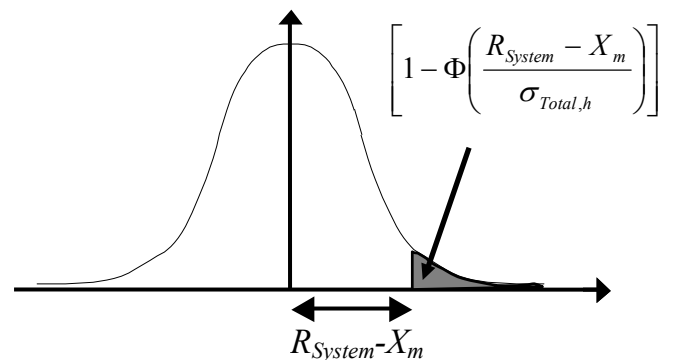


Fig. 1. Gaussian distribution of total system forecast error h hours ahead. Gray area corresponds to the probability of having a forecast error greater than the system reserve level minus the power from generator m .

The reserve level that corresponds to a certain probability of load shedding is found by using a Gauss-Newton algorithm with a mixed quadratic and cubic line search procedure in MATLAB.

When considering the reliability criterion over the whole year some assumptions are made.

1. The probability of shedding load in any hour is the same for all hours of normal operation. This is illustrated in Fig. 2 by P_{LSBASE} .
2. The reliability of the system after a generator trip is restored in a linear fashion over a predefined number of hours. The hours until reliability was restored was decided to be 4 hours [7]. See Fig. 2.

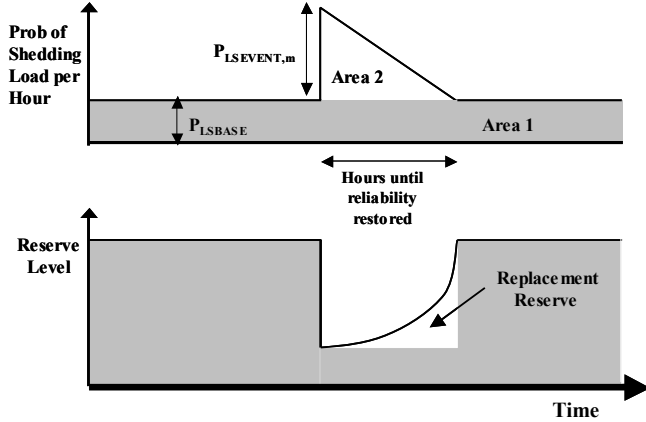


Fig. 2. Illustrative plots of probability of load shedding and spinning reserve level against time during a generator trip.

The probability of load shedding during normal hours of operation P_{LSBASE} sets the level of spinning reserve which in turn determines $P_{LSEVENT,m}$, the load shedding probability above that of the base level after the trip of generator m and the overall reliability criterion can be thought of as the sum of Area 1 and all the Area 2 triangles over the year Fig.2. One can see that the variable P_{LSBASE} determines all other variables in the system. Using this piece of information one can find the reserve requirements of the system by searching the solution space varying P_{LSBASE} between its lower bound of zero and its upper bound of $\frac{\text{Incidents} / \text{Year}}{8760}$. See Fig.3.

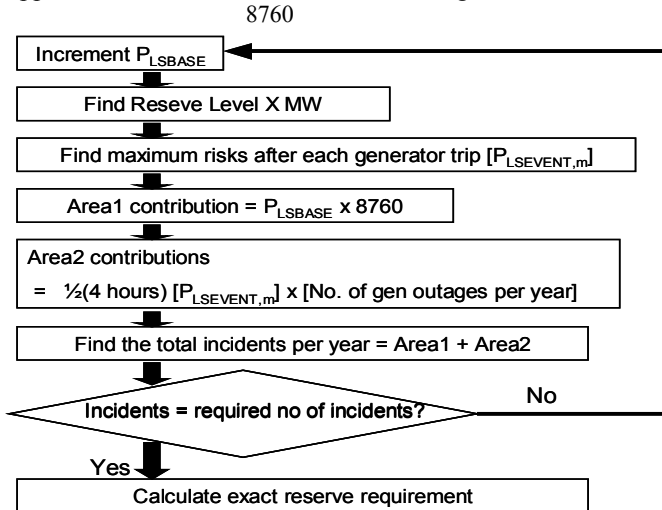


Fig. 3. Calculation flow chart.

G. Forecast period

In a real system scheduling decisions for a certain hour have to be made at various times before that hour based on the best possible information at that time. These decisions are influenced by units' minimum start up and shut down times, ramp rates and generation output limits etc. To reflect the need to plan the system reserve levels a certain time in advance a simplification was made and a forecast period was introduced. Here the forecast period is defined to be the number of hours between each time the system is rescheduled. It is assumed that the wind and load forecasts are received at hour zero, the system is then planned for the next forecast period to meet the net load plus the reserve requirements until new forecasts are received and the system is planned again for the next forecast period.

III. IEEE RELIABILITY TEST SYSTEM

The technique above was applied to the IEEE reliability test system [8]. In order to avoid scheduling and economic dispatch algorithms the load of the test system was assumed to be the same for all hours.

A. System Load

Since the technique just quantifies how much reserve is needed and not where this reserve should come from, the load level was taken to be the total generating capacity of the system, 3405 MW [8]. The load forecast error was assumed to be the same for all hours, with a mean of zero and a standard deviation of 80 MW.

B. Generating Units

Table 1 shows the reliability information of the units and their maximum capacities at which they are assumed to be operating [8].

TABLE I
GENERATING UNIT RELIABILITY DATA

Unit Size (MW)	Number of Units	FOR	Prob. of Trip per Hour
12	5	0.02	0.0003333
20	4	0.1	0.002
50	6	0.01	0.0005
76	4	0.02	0.0005
100	3	0.04	0.0008
155	4	0.04	0.001
197	3	0.05	0.001
350	1	0.08	0.0008
400	2	0.12	0.0008

C. Wind Power and Forecasting

In [9] the performance of the Prediktor wind power forecasting tool is evaluated. It finds that the forecast error increases with increasing forecast horizon and that in general the persistence forecasting method yields more accurate forecasts for a forecast horizon up to 3 hours whereas the Prediktor method is more accurate from 3 hours upwards. Here it is assumed that the forecast error is not sensitive to the actual output of the farm itself. The forecast error per unit

installed capacity based on the results of [9] is shown in Fig. 4 with the persistence method being employed for a forecast horizon up to 3 hours and the Prediktor method being used from 3 hours upwards. For this initial study, it was assumed that wind capacity neither contributes to nor reduces the reliability of the system in terms of generation trips.

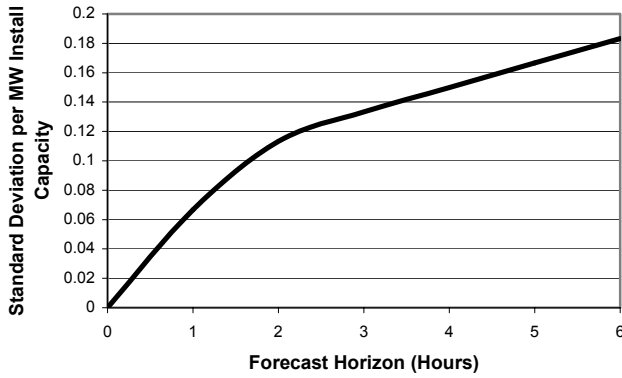


Fig. 4. Plot of standard deviation in the wind power forecast error per unit installed capacity versus the forecast horizon.

IV. RESULTS

Fig. 5 shows the probability of load shedding and the reserve level for the IEEE test system during the trip of a 400 MW unit at hour 7. This is similar to the illustrative plot in Fig 2. The installed wind capacity is 920 MW, corresponding to 27% of the installed capacity and is located in 5 farms. The system reliability criterion is 2 incidents per year and the forecast period is 6 hours.

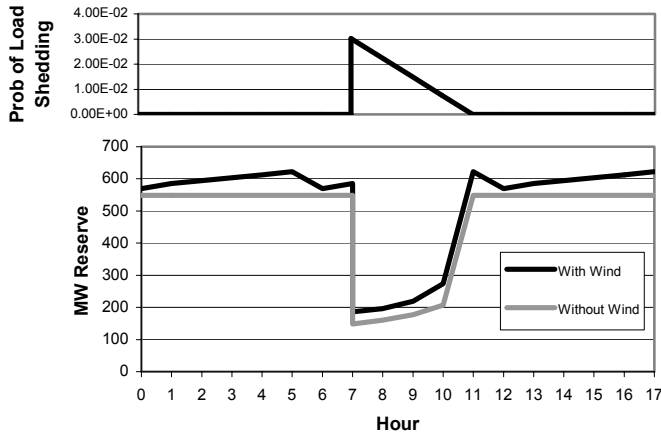


Fig. 5. System reserve plot for case with wind and without wind during the trip of a 400 MW unit.

It is assumed that the forecast is received and the system is scheduled at hours 0, 6 and 12. The increasing need for reserve can be clearly seen as the hour gets further away from the forecast hour. The average reserve needed per hour to meet the reliability criterion is 598 MW in the case with wind and is 548 MW in the case without wind. Wind also causes an increase in the replacement reserve capability. In the case without wind the replacement reserve capacity need over 4

hours is simply the size of the largest unit, 400 MW. While in the case with wind the replacement reserve needed over 4 hours is 436 MW, this is greater than the size of the largest unit due to the increasing uncertainty in the wind over the 4 hour period.

Fig. 6 shows the average reserve needed per hour as a function of the reliability criterion. It illustrates the concept that is widely accepted, that the more reliable a system has to be the more reserve it must carry.

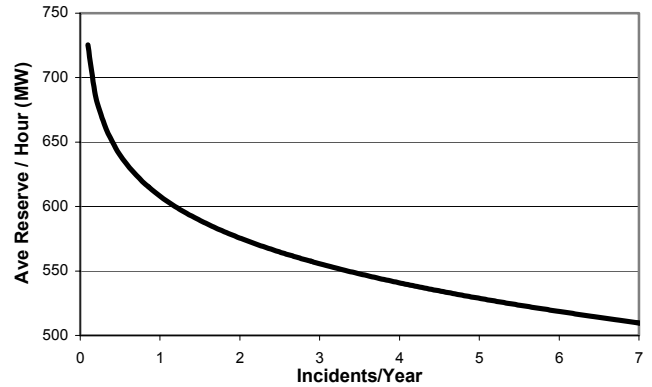


Fig. 6. Plot of average reserve per hour versus the number of incidents tolerated per year. System operated with 920 MW of installed wind capacity, in 5 farms with forecast period of 3 hours.

The results presented in Fig. 7 show that as installed wind capacity increases the system must either carry more reserve or tolerate an increase in the number load shedding incidents tolerated a year.

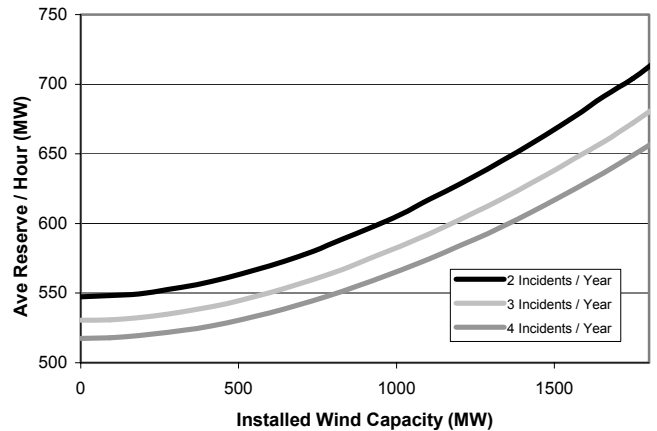


Fig. 7. Plot of average reserve operation versus increasing wind power penetration for 2, 3 and 4 load shedding incident per year. System operated with 920 MW of installed wind capacity in 5 farms with a forecast period of 6 hours ahead.

Fig. 8 shows the benefits of having the installed wind capacity divided up into numerous farms. This is due to the wind forecast error comprising of smaller and more numerous uncorrelated forecast errors. The incremental benefit decreases as the number of farms increases.

V. DISCUSSION

This technique can quantify how much reserve a system should carry to correspond to a certain reliability criterion over a year. It does not consider from which units the reserve is to be provided but rather determines the level of reserve that is needed. It was assumed here that the wind farm power forecast errors are uncorrelated; in reality it is likely that this is not the case. The influence of these correlations would depend on the forecasting technique used and its effect on the reserve level may be quite significant. Fig. 7 shows that as the penetration of wind power increases the system will become less reliable unless reserve levels are increased. Table 2 highlights the important influence that the size of wind farms and the forecast period has on the level of reserve. The forecast period reflects the need to plan the system a certain period in advance. A system with relatively inflexible plant will have to make its commitment decisions well in advance of the actual hour of operation. This may cause an over commitment of plant as the wind power penetration increases and suggests that more flexible plant may be suited to systems with increasing wind penetration.

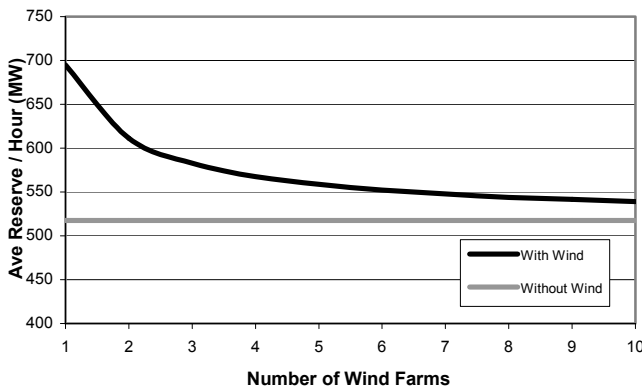


Fig. 8. Plot of average reserve per hour versus the number of wind farms. System operated with 920 MW of installed wind capacity with a forecast period of 6 hours and a reliability criterion of 4 load shedding incidents per year.

As seen in Fig 4, the error in the wind forecast increases as the forecast period increases. This results in an increased need for reserve as the forecast period increases, as can be seen in Fig.9.

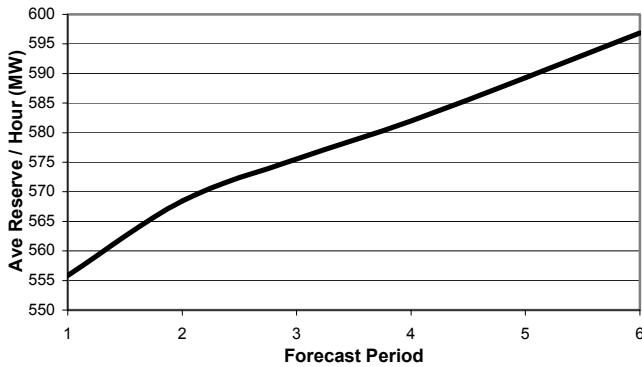


Fig. 9. Plot of average reserve needed per hour versus forecast period. System operated with 920 MW of installed wind capacity in 5 farms with a reliability criterion of 2 incidents per year.

Table 2 below highlights the importance that the forecast period and the number of farms can play in accommodating increased levels of reserve on the system.

TABLE II
SYSTEM SCENARIOS

Scenario	Installed Wind Capacity	Reserve (MW)	No. Farms	Forecast Period (Hours)	Incidents per Year
1	368	569	2	6	2
2	2208	569	10	1	2
3	2208	569	2	6	104

Scenario 1 shows that a system with 569 MW of reserve can accommodate 368 MW of installed wind capacity in 2 farms with a forecast period 6 hours and operate with 2 load shedding incident per year. Scenario 2 shows that for the same amount of reserve the system can take 2208 MW of installed wind capacity without decreasing the reliability of the system if it was in 10 farms and the system forecast period was 1 hour. Scenario 3 shows that the same amount of wind would cause 104 load shedding incidents per year if no alterations were made to the farm sizes or forecast period of scenario 1.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

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