July 2001 • NREL/CP-500-30490

Conference Paper

A Chronological Reliability Model to Assess Operating Reserve Allocation to Wind Power Plants

Preprint

M.R. Milligan

To be presented at the 2001 European Wind Energy Conference
Copenhagen, Denmark
July 2–6, 2001

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

A CHRONOLOGICAL RELIABILITY MODEL TO ASSESS OPERATING RESERVE ALLOCATION TO WIND POWER PLANTS

Michael R. Milligan
National Wind Technology Center
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
USA
milligan@nrel.gov
Phone: +1-303-384-6927
Fax: +1-303-384-6901

As the use of wind power plants increases worldwide, it is important to understand the effect these power sources have on the operations of the grid. This paper focuses on the operating reserve impact of wind power plants. Many probabilistic methods have been applied to power system analysis, and some of these are the basis of reliability analysis. This paper builds on a probabilistic technique to allocate the operating reserve burden among power plants in the grid. The method was originally posed by Strbac and Kirschen [1] and uses an allocation that prorates the reserve burden based on expected energy not delivered. Extending this method to include wind power plants allows the reserve burden to be allocated among different plants using the same method, yet incorporates information about the intermittent nature of wind power plants.
Keywords: Reliability, Utility Integration, Ancillary Services

1 INTRODUCTION

To maintain a reliable supply of electricity, provisions must be made to ensure a reasonable level of backup generation, or operating reserves, that can quickly be tapped to respond to a system emergency. The units typically used for this type of service are either quick-start generators, such as combustion turbines, or the unloaded portion of a plant that is already synchronized and running at a level less than full capacity.

As electricity markets move away from the regulated monopoly model and towards some form of competition, there is increasing interest in how to assess charges for ancillary services. These services include the provision of reserves and other functions necessary for the reliable operation of the electrical supply system. The level of reserve is typically determined by an entity with a systemwide perspective, such as a power pool or other control area. The benefit of this approach is that the principle of diversity can be used to reduce the overall operating reserve requirement in a large pool. This diversity principle is really based on probabilistic analysis, which allows for determining the probability that various combinations of generating units would fail simultaneously. The electric utility industry has used reliability modeling for many years to obtain such information.

Recent work by Strbac and Kirschen [1] includes a method to allocate the cost of providing reserve to the generating plants within a control area. The reserve level allocated to each plant is a function of both the plant's capacity and forced-outage rate. Generating plants with a poor availability record are encouraged to improve because in so doing they could reduce their costs. Generating plants with a high reliability level are rewarded by a relatively low reserve payment. The method also distinguishes between large and small plants, which is important because the former have a larger impact on system reliability than the latter. The reserve cost borne by the generating companies is assumed to be passed forward to the consumer.

Utilities sometimes presume that for each mega-watt (MW) of wind capacity installed on their system, there must be 1 MW of backup. This assumption ignores the principle of diversity, and is contrary to the way that reserve requirements are calculated for conventional generation. The result is that the wind plant is unfairly penalized, and consumers face higher costs than necessary.

The Strbac-Kirschen (SK) method appears to be ideal for assessing the reserve allocation to wind power plants. Because of the intermittent nature of wind; however such plants may have very low mechanical forced outage rates, but still generate at a relatively low annual capacity factor compared to conventional base-load generators.

The purpose of this paper is to adapt the chronological reliability calculation so that the intermittency of the wind power plant can be taken into account in the reliability calculation for the generating system. The next step is to apply the SK model of reserve allocation to the wind power plant. Using this approach, all generators are evaluated on the same basis, and the technique benefits from a substantial body of reliability analysis. The capacity and availability rates of each generator are the primary determinants of composite generator reliability. This model takes these issues in to account.

This paper outlines the SK model, and provides a short description of a chronological reliability assessment that can be used with wind plants. Following these model descriptions, the chronological method will be adapted to include the SK reserve allocation method. Finally, an example will be used to calculate the reserve allocation based on a real system and a hypothetical wind plant that is based on real wind data.

2 RESERVES AND THE STRBAC-KIRSCHEN MODEL

The SK model is based on well-known probabilistic assessments of reliability. There are several ways that reliability can be measured. Perhaps the most common reliability statistic is the loss of load probability (LOLP), which can be calculated for any time period. For a given hour, the LOLP quantifies the probability that the generating capacity will not be sufficient to supply the demand for electricity. Over time, the probabilistic assessment of reliability can be converted into an energy measure. Given the hourly values of LOLP and load, we can calculate the expected energy not served (ENS), which is simply the sum of the capacity shortfalls (weighted by their probabilities) over one month. Similarly, we can calculate the ENS for any other time period, although for most reliability studies it is not appropriate for time intervals exceeding one year.

Reserves are provided on a systemwide basis, not an individual unit basis, to provide backup in case of generator failure or unexpected load increases. Operating reserve is the excess available capacity, and can be divided into spinning (unloaded, online capacity that is synchronized) and non-spinning (capacity that can be started and loaded within about 10-15 minutes). As pointed out in Ilíc et al. [2], probabilistic methods are used to help determine whether or not new capacity should be built, whereas operational rules for providing reserves are often based on the N-1 security criterion. The N-1 criterion requires that a sufficient reserve be maintained to cover the largest single contingency, i.e., protecting against a failure of the largest generating unit. There is no direct relationship between reserve levels calculated by the SK and N-1 methods. Milligan [3] and Ilíc point out that reserve management is one component of risk management. As restructuring continues to unfold, the use of probabilistic techniques and other risk-management activities will become much more widespread.

The SK approach does not attempt to determine what the proper level of reserves should be. Instead, it allows for a calculation to allocate the reserve burden to all power plants in the system. It is important to distinguish between the *allocation* of a systemwide reserve burden to all generators, and calculating reserves that should be supplied to *support* a particular generator. Reserves are, and have always been, assessed on a systemwide basis, and there are no accepted methods for assigning a reserve requirement to a specific power plant. The SK approach can be applied to the N-1 security criterion or to a more sophisticated calculation of the reserve level based on probabilistic methods.

Because the failure of a large power plant has a more prominent effect on supply than that of a small plant, large plants should be responsible for more of the reserve costs than small plants. Similarly, a plant with a relatively high failure rate should bear a larger burden of the reserve cost allocation than a more reliable unit. The SK procedure takes both of these factors into account because the allocation of the reserve burden is prorated based on each plant’s fraction of total ENS.

3 CHRONOLOGICAL RELIABILITY ANALYSIS OF WIND POWER PLANTS

Milligan [4] developed a model for calculating LOLP for systems with wind power plants. The distinguishing feature of this model is that it simultaneously considers the stochastic nature of the wind resource and the variation in wind power. This model is chronological, and can therefore calculate system LOLP every hour.

Before running this model, the analyst chooses an appropriate time period to use in calculating the wind power frequency distribution. This time period is called the *sliding window period*, and is normally a period consistent with the unit-commitment time frame or other appropriate period. For highly diurnal wind sites, the number of hours in the window might be small, e.g., 2 or 3, with the ability to group hours from adjacent days. For example, we might choose a sliding window of 2 hours over a 3-day period. As the algorithm proceeds, we would consider 10:00–11:00 on Monday, Tuesday, and Wednesday in the same window. For sites that do not exhibit significant diurnal characteristics, it might be more appropriate to select a moving window of 6 hours, which is approximately the time frame in which unit commitment decisions are made for slow-start power plants. Other appropriate window sizes can also be chosen. Once the window size has been selected, the model can be used to calculate an effective forced outage rate for the wind plant (EFORW). This rate is based on wind availability rather than mechanical failure rates.

To do the chronological reliability calculation, the model proceeds by stepping one hour at a time through the chronological data. After the capacity outage table is populated with data from the conventional power plants, the hourly wind capacity and wind plant effective forced outage rate (see [4] for details) are convolved into the capacity table. Because the sliding window provides information about the probabilities of various wind output levels, the system LOLP does account for the stochastic nature of the wind power plant. We therefore obtain hourly system LOLP estimates, which can be analyzed as needed.

4 ADAPTION OF THE RESERVE MODEL FOR WIND POWER PLANTS

The SK reserve allocation technique can be incorporated with the chronological reliability model so that we can obtain probabilistic estimates of the reserve burden for a wind plant. This technique is attractive for a number of reasons. First, the basic method is built upon well-established and well-known probabilistic techniques used in power system analysis for many years. Conventional reliability models already do many of the required calculations, and could be easily adapted to handle the chronological reliability calculations and SK technique for wind power plants. Second, this approach is based on the size of the power plant, both in absolute terms and in relation to the remainder of the system. Large power plants pose larger risks, and accordingly pick up a larger reserve burden. Wind plants that are large relative to the system would also receive larger reserve burdens than smaller wind plants. Third, the method rewards plants with predictable output and few outages. A wind plant with a very high capacity factor would therefore shoulder a smaller portion of the reserve burden than one with a very low capacity factor. An extension to this model would consider the effect of accurate wind forecasts, which would result in a smaller reserve burden than for a wind plant with inaccurate forecasts. Finally, this is a transparent method appropriate for all power plants. Because the important influences of capacity and availability are included in the calculation, every power plant is treated in an equitable way.

The chronological reliability model uses the hourly LOLP information and forced outage rates to calculate ENS for each generator in the system. Once this has been done, it is possible to perform the SK calculation to determine the reserve allocation to the various power plants. Although the SK model was originally applied to longer time periods, such as one year, we can adapt the approach to account for hourly fluctuations in wind power output by applying the SK algorithm chronologically.

The chronological reliability model assumes a relatively high level of ignorance concerning the amount of wind power output during a window period. Within any given period, the model assumes that whenever hourly output is less than the maximum during the period, the difference should be counted toward ENS. Although that is probably not a realistic assumption, we include these model runs as worst-case scenarios (called the "Basic ENS" results below). A more realistic approach is to use deviations from the statistically expected level of wind power output during the window as ENS, and to compare these model runs (called the "Average ENS" method) with the extreme case. This follows the analysis in Chan et al. [5]. Extensions to this work that are not considered here might include the simulation of various forecasting techniques, perhaps with Monte Carlo sampling over a large number of model runs. This would make it possible to calculate probability distributions of the ENS and reserve obligation of the wind plant.

5 RESULTS

We applied the model to load and generator data from Minnesota. The level of required operating reserve was set to 7% of load for the example, but could be calculated in a number of other ways, as appropriate. The wind site used for these simulations is a composite site identified in a geographic dispersion study by Milligan and Artig [6]. Under the most extreme assumptions, the maximum reserve allocation to the wind plant is just over 20% of the wind plant rated capacity. As shown by Figure 1, this level of reserve obligation only lasts for a short period of time, declining to an annual average of

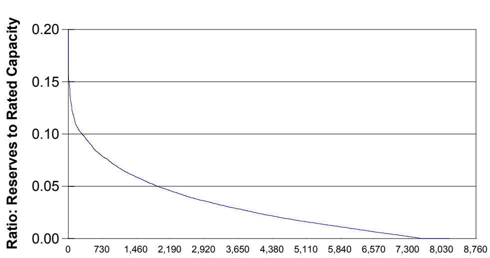

Figure 1: Basic ENS method for calculating reserves

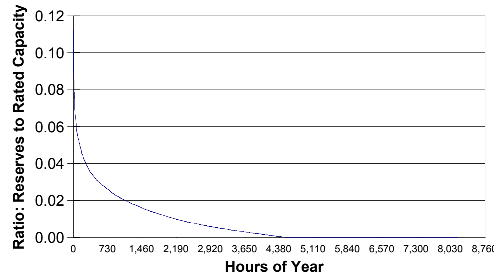

Figure 2: Average ENS method for calculating reserves

just over 3% of rated capacity over the year. When we use the more realistic Average ENS modeling approach, Figure 2 shows that the maximum reserve requirement is just over 11% of the rated capacity of the wind plant, averaging less than 1% over the year.

Figure 3 shows the hourly wind power output and reserve allocation, calculated by the Basic ENS method, for the winter peak month, January. The graph shows that in periods during high wind power variability at high output levels, the reserve allocation is relatively high. Conversely, during periods of variability at lower output levels, reserve requirements are reduced.

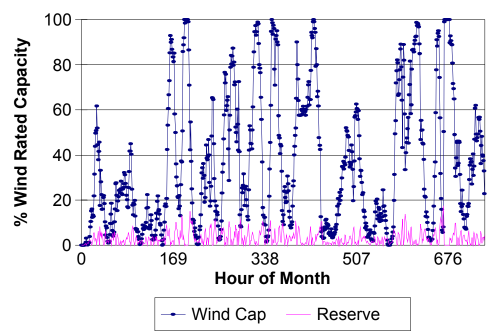

Figure 3: January basic ENS method

Figure 4 shows the same information for the Average method. The reserve level is about one-half of the level calculated by the Basic ENS method, but the overall direction of variation is similar.

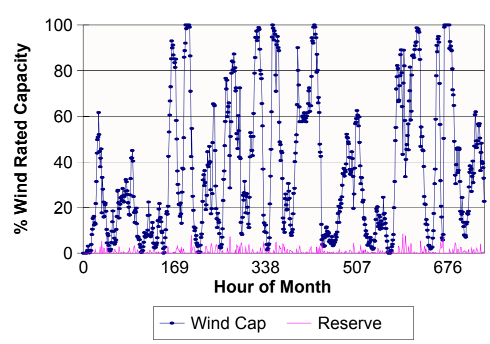

Figure 4: January average ENS method

The analysis presented here is, no doubt, not the final word on reserves and wind power plants. However, a couple of important points can be made. Using the highest reserve level from the most pessimistic modeling approach, we find that the reserve burden of the wind plant is 20% of its rated capacity, averaging about 3% throughout the year. This pessimistic approach is based on counting less-than-full wind output towards ENS, which is not realistic. The Average ENS method considers deviations from average wind output during the moving window time period, which is a much more reasonable assumption. Using this more realistic approach, we find that the maximum reserves ratio for this wind plant is just over 11% of rated capacity, and averages about 1% throughout the year. It should be noted that these results are based on a particular combination of conventional generators and wind regimes, and would be expected to differ with other systems. It is also important to emphasize that the method described in this paper is built on an extensive history of reliability analysis, which is well known and broadly applied. Any reasonable method for calculating a reserve allocation for a wind (or any other) plant should build upon existing methods and techniques.

There are a number of ways to apply this approach in practice, depending on the structure of the power markets and operating practices of the control area. First, this method can be used in a planning context to determine what share of operating reserve would be reasonably assigned to a wind plant. Second, electricity markets could use this approach to guide operational decisions. For example, at the beginning of the sliding-window period, the wind forecast can be used to establish reserve burdens. At the end of the period, settlement can be carried out based on deviations from the forecast. Further work is needed to help quantify the effect of accurate wind forecasting on the operating reserve allocation to wind power plants.

It is also relevant to consider the related issue of regulation requirements of a wind plant. Hudson et al. [7] find that regulation as a percentage of rated capacity is just below 11%, declining to about 6% for larger wind installations. This work used 1-second data from Lake Benton II in Minnesota, aggregated to 2 minutes. Application of the SK model to operating reserve assessment and the Hudson, Kirby, and Wan results indicate that both reserve and regulation requirements for wind power plants are on the order of about 10% or less of the wind plant rated capacity.

6 CONCLUSIONS

The method of assessing the portion of system reserve that can be allocated to wind power plants presented in this paper is built upon well-known and widely accepted reliability analysis. Even a pessimistic application of this method shows that the proportion of reserve allocated to the wind plant is 20% of rated capacity for a very small number of hours, declining to an average of about 3% for the year. A more plausible analysis is based on deviations from mean wind generation during the sliding window period, and effectively cuts the maximum reserve ratio in half, with about 1% average over the year.

Further refinements of this technique could include the application of wind forecasting to this basic model, or a Sequential Monte Carlo analysis of the reserve ratio based on more than one year of wind data.

7 REFERENCES

1. Strbac, G., and Kirschen, D., *Who Should Pay for Reserve?* Electricity Journal, 2000. **13**(8): p. 32-37.
2. Ilíc, M., Arce, J., Yoon, Y., Fumagalli, E, *Assessing Reliability as the Electric Power Industry Restructures.* Electricity Journal, 2001. **14**(2): p. 55-67.
3. Milligan, M. *Factors Relevant to Incorporating Wind Power Plants into the Generating Mix in Restructured Electricity Markets*. in *Proceedings of the 24th International Conference of the International Association for Energy Economics*. 2001. Houston, TX: IAEE.
4. Milligan, M. *A Sliding Window Technique for Calculating System LOLP Contributions of Wind Power Plants*. in *Proceedings of the Windpower 2001 Conference*. 2001. Washington, D.C.: American Wind Energy Association. NREL/CP-500-30363.
5. Chan, S.M., Powell, D.C., Yoshimura, M., Curtice, D.H., *Operations Requirements of Utilities with Wind Power Generation.* IEEE PES, 1983. **PAS-102**(9): p. 2850-2860.
6. Milligan, M., Artig, R. *Optimal Site Selection and Sizing of Distributed Utility-Scale Wind Power Plants*. in *Proceedings of the International Conference of the International Association for Energy Economics*. 1998. Quebec: IAEE. NREL/CP-500-24312.
7. Hudson, R., Kirby, B., and Wan, Y. *Regulation Requirements for Wind Generation Facilities*. in *Proceedings of the Windpower 2001 Conference*. 2001. Washington, D.C.: American Wind Energy Association.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
July 2001

3. REPORT TYPE AND DATES COVERED
Conference paper

4. TITLE AND SUBTITLE
A Chronological Reliability Model to Assess Operating Reserve Allocation to Wind Power Plants

5. FUNDING NUMBERS
WER13230

6. AUTHOR(S)
Michael R. Milligan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-500-30490

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
As the use of wind power plants increases worldwide, it is important to understand the effect these power sources have on the operations of the grid. This paper focuses on the operating reserve impact of wind power plants. Many probabilistic methods have been applied to power system analysis, and some of these are the basis of reliability analysis. This paper builds on a probabilistic technique to allocate the operating reserve burden among power plants in the grid. The method was originally posed by Strbac and Kirschen [1] and uses an allocation that prorates the reserve burden based on expected energy not delivered. Extending this method to include wind power plants allows the reserve burden to be allocated among different plants using the same method, yet incorporates information about the intermittent nature of wind power plants.

14. SUBJECT TERMS
wind energy; reliability; utility integration; ancillary services

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL