CHRONOLOGICAL EVALUATION OF THE BENEFIT OF STORAGE SYSTEMS ON WIND GENERATION RELIABILITY

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ABSTRACT

In systems with predominant wind generation, it becomes necessary to use some energy storage system to avoid load shedding due to energy unavailability. This work analyzes the effect of battery systems in generation reliability indexes using chronological Monte Carlo simulation. For this purpose, it considers the batteries power output time series as an extra generation source that is combined with the wind generation to mitigate its variability. The batteries efficiency along their life cycles is also represented. In order to evaluate the effectiveness of using battery storage systems to increase the system reliability, this study compares the reliability indexes without and with different amount of batteries, taking into consideration different charge/discharge power rates. It also analyses the indexes by varying the number of wind turbines in the power plant and the indexes sensibility as a function of the generating unit capacity and failure rates.

1 INTRODUCTION

The use of renewable energy resources has been extensively studied and implemented in order to reduce the negative impacts that classical sources, as large hydro generation and thermal fossil fuel based generation, have on the environment.

The development of reliable control techniques and mechanical components made wind power plants implementation a problem mainly related to power generation reliability. With the increasing participation of this kind of energy resource on electric power systems, the power oscillations due to the wind behavior cannot be neglected anymore.

In the case of systems based predominantly on intermittent sources, like solar and wind, the reliability of generation may be insufficient with many periods of lack of power supply. Figure 1 shows the behavior of a wind generation power output versus a load curve in a range of three days. There is potential load shedding when the demand is higher than the power supply, corresponding to the shaded area in the figure.

Such occurrences can be mitigated with the use of energy storage systems, which can also save energy in periods when the load is lower than the supply. This may involve several discharging/charging cycles. Nowadays it is feasible to implement high-energy storage systems, but since they involve expensive investments, it is necessary to calculate the necessary storage system capacity to meet the required reliability level.

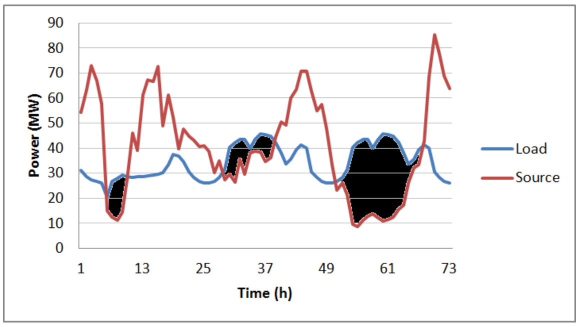

Figure 1 Wind generation power output and load curves.

The reliability study of power systems may be done through analytical and stochastic methods. While in analytical methods the time variation of the wind cannot be accurately evaluated, it is possible to consider both wind and load time series when using the chronological Monte Carlo Simulation (MCS).

In order to evaluate wind generation availability, it is necessary to represent the wind variation but also the reliability of the components of the wind plant [1]. The four main components that provoke failures on wind plants are the blades, the gearbox, the electrical generator and the control system, in which the electronic converter is allocated. The sum of the four failure rates represents the total failure rate of the wind turbine-generator system. The components reliability and their typical failure rates (λ) and mean time to failure (MTTF) are discussed in [2], and Table 1 shows an extract of wind turbine failure rates according to their nominal capacity.

Table 1 Failure rates according to wind power capacity.

Group I (~ 300 kW)	1 failure / year
Group II (~ 500 kW)	2 failure / year
Group III (>= 1 MW)	3 failure / year

This paper evaluates the influence of the storage system on wind generation availability taking into consideration events that occur in an hourly time basis. Monte Carlo chronological simulation studies are presented to evaluate the effect of using battery time series in a system based on wind generation as the only power source.

The studies have been performed using the *RelSim* simulation program [3] for wind time series and forecasted load data of two wind power plants in the southern region of Brazil. The results of the sensitivity analysis taking into consideration different battery characteristics help to determine the better battery storage system that is necessary to achieve the required reliability indexes.

2 EFFECT OF CONTROL SYSTEM ON RELIABILITY

The chaotic nature of wind speed implies a specific approach to the wind turbine control. Depending on the application, the active power can be kept constant [4], as well as the output power can be controlled to be maximum, thus adopting a Maximum Power Tracking (MPT) strategy.

The MPT approach may provoke non-acceptable oscillations on power systems due to periods with more generation than load. For that reason, systems with energy source predominantly intermittent requires energy storage during the exceeding periods to prevent power cuts during the deficit periods.

A control method is presented in [5] that provides active power above the MPT output power during 10s in order to help the system restoration after a frequency disturbance. After the overproduction period, the wind turbine needs a subproduction period to recover the normal operation state. The whole process demands just a few minutes.

The power converters have to control the line frequency, the line voltage and the active power provided by the wind turbine. Furthermore, it must keep the system operating even during an a.c fault or line de-energization. The protection controls are fundamental to maintain the integrity of mechanical and electrical components of the wind generation system. For example, the "crowbar" protection downs the current to zero during an a.c short-circuit, protecting the generation system. Some types of crowbar protection are presented in [5]. So, based on these control performances, and also considering a decoupling between the grid state and the wind turbine state, it is possible to make stochastic analyses based on independent processes.

Wind time series use to be discretized according to the application. The order of magnitude can be seconds, minutes, hours, days or months. In the case of transient studies as the mentioned protection control method, the wind time series must be discretized in seconds at least. In the other hand, on reliability studies, the time series use to have magnitude of minutes or hours. It makes the effect of the transient control system negligible.

3 STORAGE SYSTEM

3.1 Storage System type

The protection against transient events demands low storage capacity from the wind generation system. However, for power oscillations due to wind variations, or even for turning off because of wind gusts, it is necessary a storage system with compatible capacity to provide energy to the loads of the system. The types of storage systems are listed and compared in [6] and [7].

Events with duration of 20s that affect wind turbine generation, as short-circuits and voltage and frequency oscillations, demand only conventional capacitors and inductors or supercapacitors in some cases to be the energy reserve. In the case of strong wind gusts that take some minutes, some dedicated storage system as SMES (Superconducting Magnetic Energy Storage), flow batteries, or sodium-sulfur (NaS) batteries, are required. For NaS batteries and SMES, there are storage systems with high capacity available, above 100 MW. So, this paper considers the particular case of NaS batteries in the simulation studies due to its capacity to attend the system magnitude and also, its high efficiency to operate during some hours.

3.2 Battery Time Series

The use of storage system in chronological Monte Carlo simulation demands a time series of power output from the battery. So, for each time step, it is necessary to determine the difference between the power produced by the wind plant and the load demand, called the surplus power $\mathrm{SP_t}$, that is obtained from the respective time series as [8]:

$$\mathrm{SP_t} = \mathrm{P_{gen_t}} - \mathrm{P_{load_t}} \qquad (1)$$

were $\mathrm{P_{gen_t}}$ is the power produced and $\mathrm{P_{load_t}}$ is load demand at time step *t*.

Ideally, this would be the power to be supplied by/to the battery at each time step. However, the battery time series is not composed only by the differences in (1). The $\mathrm{SP_t}$ value must be delayed to the next time step and is limited by the minimum and maximum energy amount that the battery is capable to store. In addition, an efficiency index of η=90%, associated with NaS batteries, is considered to adjust the SP value. So, each time step of the battery series can be obtained by (2), in a similar way as described in [8]:

$$\mathrm{B_{t+1}} = \begin{cases} \mathrm{B_{min}}, & \eta\mathrm{SP_t} + \mathrm{B_t} < \mathrm{B_{min}} \\ \eta\mathrm{SP_t} + \mathrm{B_t}, & \mathrm{B_{min}} \le \eta\mathrm{SP_t} + \mathrm{B_t} \le \mathrm{B_{max}} \\ \mathrm{B_{max}}, & \eta\mathrm{SP_t} + \mathrm{B_t} > \mathrm{B_{min}} \end{cases} \qquad (2)$$

where $\mathrm{B_t}$ and $\mathrm{B_{t+1}}$ are the calculated battery power available at time step *t* and *t*+1, respectively, and $\mathrm{B_{min}}$ and $\mathrm{B_{max}}$ are the minimum and maximum battery storage capacities, respectively.

In order to include the battery time series into the MCS, an element equivalent to a generating unit that produces that time series is considered. The inferior storage limit $\mathrm{B_{min}}$ is set to zero, even though real batteries use to have a minimum charge level different from zero in order to preserve its time life.

4 SIMULATION RESULTS

4.1 System Description

The simulation was performed using the *RelSim* program [3], which evaluates power systems reliability using either chronological MCS or state sampling MCS. The program supports the representation of wind, solar, river inflows and load time series and can perform composite and generation system reliability evaluations.

The generating system reliability evaluation does not consider the transmission or distribution system that connects source and load, and the generation availability and the load at the analyzed period are compared. The system failure states correspond to those where the available generation, composed by the wind power output and the batteries power supply, are lower than the load.

In order to emphasize the wind generation behavior, the power generation considered in the studied system is compound only by wind plants. Two power plants of 75 wind turbines of 1 MW each with different wind time series are considered. The wind time series were extracted from [9]. The wind turbine-generator system failure rates and mean time to repair were taken from [1] and are summarized in Table 2. The peak load is 48 MW and it is represented by a time series with an average value of 32.18 MW.

Table 2 Wind turbine-generator system reliability parameters.

Failure rate	Mean time to repair
4/year or 0,000455/hour	90 hours

The battery supply time series, obtained through the process described in (2), is then added to the wind generation time series. The storage failure was not considered, what means that its failure rate was set to zero.

4.2 Indexes Without Batteries

Table 3 shows the LOLP (Loss of Load Probability), LOLE (Loss of Load Expectation) and EPNS (Expected Power Not Supplied) indexes without considering any energy storage. It can be seen that these indexes are quite high, meaning a very low reliability. The Expected Available Wind Energy (EAWE) 449,587 MWh without considering failures of the turbine-generator system. This implies in a Capacity Factor of 34,20%, which becomes even smaller when the failures are considered.

Table 3 Reliability indexes for the system without storage.

LOLP	LOLE (h)	EPNS (MW)
0.3835	3361	7.136

If the system had more generation units, with more than 150 MW installed capacity, it is reasonable to affirm that the reliability would increase. Figure 2 shows the reduction of LOLE index as the installed capacity increases. It can be seen, however, that beyond certain amount (1000 MW in this case), the increase in the installed capacity does not reduce the LOLE index significantly, and there is a saturation around 500 h/year no matter the capacity has been doubled.

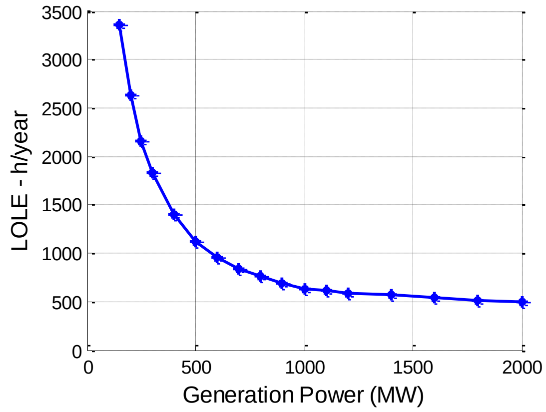

Figure 2 LOLE as a function of wind installed capacity (no storage).

4.3 Indexes Variation with the Battery Size and Charge/Discharge Rate

Since the battery supply time series are hourly based, the surplus power (SP) not used at each time step can be considered as being stored to be used at the next time step. This way, B_{t+1} can be calculated directly in MWh. However, this value does not necessarily correspond to the value that can be supplied by the battery at t+1, because there are maximum and minimum limits for charging and discharging in a short period of 1 hour.

The effect of the charge and discharge rate was evaluated for three different battery sizes (values of B_{max}): 500 MWh, 1000 MWh e 2000 MWh. For each battery size, the LOLE index was calculated for different charge/discharge capabilities per hour, varying from 10 MW to 60 MW. Figure 3 shows the results.

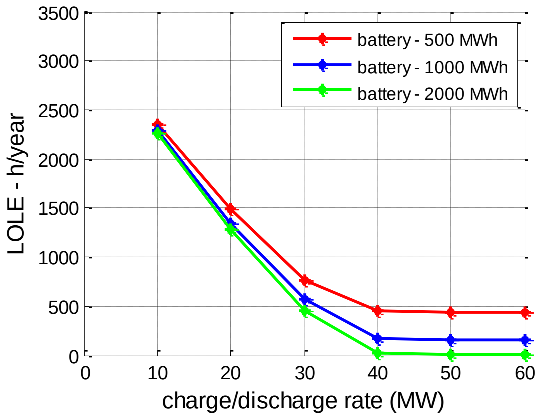

Figure 3 LOLE variation for different energy storage configurations.

The use of batteries promoted a significant reduction in the LOLE index. The index reduced from 3361.20 h (without batteries) to less than 2500 h (about 26%) for the smallest charge/discharge rate cases. For the smallest battery size, the LOLE was reduced to less than 500 h (85% reduction) for higher charge/discharge rate values, while for the largest sized one it can reach almost zero.

It can also be noted that for charge/discharge rates bigger than the peak load value (48 MW), the power output of the battery system does not reduce the LOLE index. Comparing the results of Figure 3 with those of Figure 2, it can be noticed that the increase in the power capacity and charge/discharge rate of the batteries implies in a faster reduction of the LOLE index than the one promoted by the increase in the wind power capacity.

4.4 Indexes Variation with Failure Rate and Number of Wind Turbines

The capacity and the number of wind turbines both can affect the reliability indexes. Figure 4 shows the EPNS obtained by varying the capacity of each turbine (0.3, 0.5, 1, 2 and 10 MW) but maintaining the total power of 150MW, and the same failure rate of Table 2. The battery considered has a charge/discharge rate of 30MW.

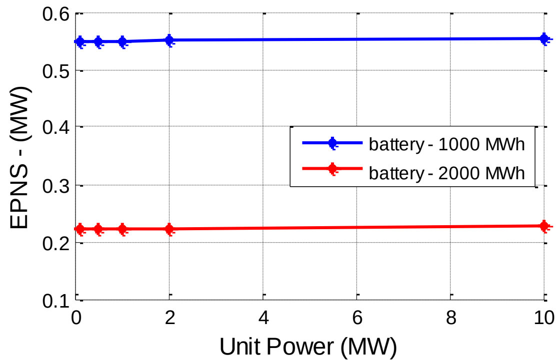

Figure 4 EPNS varying number and power of units - same failure rate.

The use of batteries promoted a significant reduction in the EPNS index. The index reduced from 7.136 MW (without batteries) to about 0.550 MW (93% reduction) with the smallest battery size and to about 0.210 MW (97% reduction) with the largest one. It can also be observed that there is a small increase in the index as the capacity of the turbines increases due to the reduction in the dispersion of the generating units.

Another analysis was conducted considering the failure rates of Table 1 according to the capacity size of the units. Figure 5 show the EPNS obtained for units of 0.3, 0.5 and 1 MW each, with the same total power of 150MW.

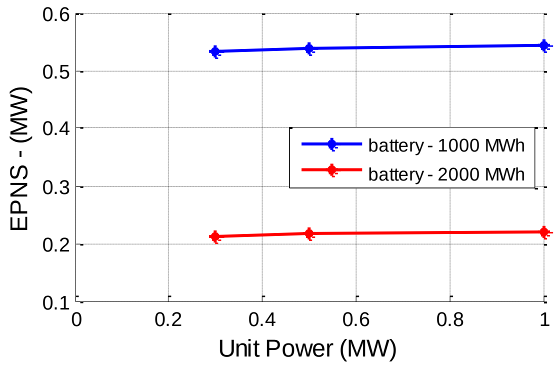

Figure 5 EPNS varying number and power units - different failure rates.

The use of smaller failure rates for the smaller units produced a slight reduction in the EPNS index when compared to those of Figure 4. It can also be observed that the increase in the failure rates as the wind turbine capacities increase does not produce a significant deviation in the EPNS index, due to the large number of turbines in the power plants (varies from 500 to 150).

5 CONCLUSIONS

The increase of wind power installed capacity does not reduce the reliability indexes as significantly as it might be expected. The increase of the storage system capacity is more significant in decreasing the indexes. Therefore, the use of storage systems is a fundamental strategy to reduce the overall risk of power unavailability. The required storage capacity and characteristics of a given system can be designed if the reliability constraints are known. From a certain amount of battery capacity, no load shedding occurs. The charge and discharge rate influences significantly on the reliability indexes. However, the number of units at a wind power plant and their failure rates does not influence the reliability indexes so significantly.

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