EVALUATION OF WIND ENERGY SOURCES INFLUENCE ON COMPOSITE GENERATION AND TRANSMISSION SYSTEMS RELIABILITY

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Abstract – This paper presents some results of studies performed to evaluate the impact of using wind energy based generation on power systems composite reliability evaluation. The reliability evaluation is based on non-sequential Monte Carlo simulation for consideration of both generation and transmission systems failure events. The stochastic models for the conventional generation units and the transmission elements are the two state or multiple states Markov models, usually adopted in reliability studies. For the wind energy based generation units, a special model is developed based on a combination of the wind velocity characteristic and the multiple power output levels associated with the velocity of the wind turbine. Three different impact studies is performed: wind generation penetration degree, wind generation farm location and a comparison with other energy sources. The test system used is the IEEE RTS-79 modified to include the representation of the wind plants. The results obtained allow for the quantitative and qualitative analysis of wind generation influence on composite system reliability for several generation level and connection point scenarios.

Keywords: Composite Reliability Evaluation, Wind Energy Systems, Statistical Clustering Technique, Monte Carlo Simulation.

1 INTRODUCTION

A significant increase in the use of renewable energy sources for power system generation expansion is being observed all over the world in the last years. A number of strategic and commercial issues combined are responsible for this increasingly interest, mainly [1]:

- Pollutant gazes emission reduction;
- Energy sources matrix diversification;
- Electric sector deregulation and competition policy;
- Reduced construction time and capital cost of smaller plants;
- Increase in energetic efficiency and rational use of energy;
- Need for expansion of the generation system;
- Availability of modular generation plants ;
- Transmission costs reduction by allocation of generation closer to the load.

In Brazil, particularly, government programs stimulate the investment in generation plants based on alternative energy, such as biomass, wind energy, photovoltaic energy, etc. Renewable sources, however, tend to have smaller energy density when compared to fossil fuels and, for that reason, the plants are smaller and geographically more distributed. The wind farms, in addition, need to be located in places with a favorable wind pattern and the smaller ones are, in general, connected to distribution and sub-transmission systems. They are not centrally dispatched by the Independent System Operator but, instead, by the Independent Producers according to the availability and the velocity of the wind. The large uncertainty present in wind farms generation influences strongly on power systems reliability.

This paper presents some results of studies performed to evaluate the impact of using wind energy based generation on power systems composite reliability evaluation. The reliability evaluation is based on non-sequential Monte Carlo simulation for consideration of both generation and transmission systems failure events. The stochastic models for the conventional generation units and the transmission elements are the two state or multiple states Markov models, usually adopted in reliability studies. For the wind energy based generation units, however, a special model was developed based on a combination of the wind velocity characteristic and the multiple power output levels associated with the velocity of the wind turbine.

The hourly based wind velocity curve is aggregated into a number of discrete wind velocity levels by the application of statistical clustering techniques [2]. The technique applied identifies the more significant velocity classes in the curve and represent the entire curve in terms of these hierarchically clustered wind levels and their transitions to other levels. This is done in order to translate all possible wind velocity values into a statistically representative and feasible number of levels for analysis. The clustered wind characteristic will provide different power generation levels according to the wind - power generation characteristic of the wind turbine. Therefore, the wind energy based generation unit is represented by a multiple states Markov model with transition rates and limiting state probabilities derived from the wind characteristic for the farm location region.

Three different studies were performed in order to evaluate the impact on composite reliability of the following aspects: wind generation penetration degree, wind generation farm location and a comparison with other energy sources. The test system used in the studies is the IEEE RTS-79 modified to include the representation of the wind plants. In the first study, wind generation penetration is considered as 10%, 5% and 0.03% of the total generation capacity of the system, the last being the actual penetration scenario of wind generation in Brazil. In the second study, the wind plant is located at generation and at load buses in order to analyze the impact of the proximity to the load on the overall system reliability. In the third study, wind generation is compared with two distinct types of thermal generation, conventional and nuclear, in terms of reliability influence. The results obtained allow for the quantitative and qualitative analysis of wind generation influence on composite system reliability for several generation level and connection point scenarios.

2 COMPOSITE RELIABILITY

The main objective of power systems composed reliability evaluation is to evaluate the system adequacy in order to satisfy the electric power demand at the main load points. For this purpose, it is considered the possibility of failures at both generation and transmission systems components [3]. Monte Carlo Simulation (MCS) is widely used in composite systems reliability evaluation, due to its flexibility to incorporate precise components models and operative conditions, allied to the possibility to represent complex phenomena and a great number of severe events. The composite reliability evaluation consists of the calculation of several adequacy indices, such as the Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Expected Energy Not Supplied (EENS), Loss of Load Frequency (LOLF), Loss of Load Duration (LOLD), etc., using the stochastic model of the power system operation. The conceptual algorithm for this evaluation using the non-sequential MCS, in which the system state space X is randomly sampled, is as follows.

1. *Select an operating scenario* $\underline{x} \in X$ *corresponding to a load level, components availability, operation conditions, etc.*
2. *Calculate the value of an evaluation function* $F(\underline{x})$ *which quantifies the effect of violations in the operating limits in this specific scenario. Corrective actions such as generation re-scheduling, load shedding minimization, etc., can be included in this evaluation.*
3. *Update the expected value of the reliability indices based on the result obtained in step 2.*
4. *If the accuracy of the estimates is acceptable, terminate the process. Otherwise, return to step 1.*

Step 1 of the previous algorithm consists of obtaining a sample of a random vector $\underline{x} = (x_1, x_2, \ldots, x_n)$, where x_i is the state of the i-th of the m components of the system (generators, circuits, loads, etc). This vector corresponds to an operating scenario and is obtained by sampling the probability distributions of the components operating states, using a random number generator algorithm.

In step 2 of the previous algorithm, it is necessary to simulate the operating condition of the system in the respective sampled state, in order to determine if the demand can be satisfied without operating restriction violations. The simulation requires the solution of a contingency analysis problem and, in some cases, of an optimal load flow problem to assess the generation re-scheduling and the minimum load shedding.

The indices calculated in step 3 correspond to the expectation estimate of different evaluation functions, obtained for a sample whose size is the number of analyzed state.

3 WIND GENERATION MODELING

One of the greatest challenges to the implementation of wind generation in large scale at an electric power system is related with the energy source: the wind. Despite its advantages, such as being abundant, clean, renewable and, in principal, available at many places, the wind also presents some important disadvantages. First of them, it can be cited the low energetic density, which in practice means that it's necessary a lot of wind to generate a small quantity of energy. Other important disadvantage is that it cannot be stored. However, the most important factor for this work is its intermittent supply. No other energetic source used in large scale has intermittency as significant as the wind. The combination of all these characteristics constitutes a potential problem to power systems reliability, since it cannot be guaranteed how much energy will be generated and when it will be generated.

Power generation from a wind plant depends on the presence of wind. A simplified approach for obtaining the stochastic model of the wind generation availability can be based only in the wind availability. In that sense, it is necessary that different generation levels, related with different wind velocities, are extracted from the data of a chronological wind velocity curve. The basic idea in this approach is to model a wind generation plant as a multiple state stochastic model.

It is usual to model a generation plant as a two states Markov model: operative and repair. That means that, for reliability purposes, it is operative and generating its nominal power, or it is in repair. For a multiple states Markov modeled plant, there are different power generation levels that correspond to intermediate operating levels regarding its nominal power. For each of these levels, the model contains information that allows to estimate the plant availability.

The biggest problem for the adaptation of this model to characterize the multiple generation states of a wind plant is to find a way to transform a wind velocity curve into different generation levels.

3.1 Wind Model

The reliability indices calculated for a wind plant should incorporate the effects of the wind variation, whose behavior influences directly in the generation availability. The influence of wind variation are expressed by frequency, duration and magnitude of different power supply levels (velocities). Since the load power supply failures depend on these factors, it is important that the reliability evaluation take into consideration the wind curve behavior along the analysis period. This can be done by designing a wind stochastic model that represents the frequency and duration of the considered wind levels.

One way to reduce the number of levels to be analyzed is to use statistical grouping techniques, also known as clustering techniques, to identify representative wind levels [2]. Given n wind levels which should be aggregate into m classes (clusters), the problem consists of selecting the best partition of the data set into m classes so as to optimize a specified function, which can be the sum of the squares of the distances between levels and the average of the respective classes, for example. The solution methods that do not assume hypotheses about the probability distribution in focus are the most adequate for this application. They are based on hierarchical clustering techniques and are able to deal with large values of n. These methods use a distances matrix between any pairs of clusters (initially, each level of the wind curve corresponds to a possible cluster). In each stage of the hierarchical method, the nearest values are grouped to each other, the distances matrix is updated, and the process is repeated until it results in m classes.

A chronological wind levels curve aggregated in m distinct classes can be represented through an individualized multiple states Markov model. The wind curve analysis allows to obtain all the necessary information necessary for the model of m individualized states, such as: probability, frequency and average duration of each level, frequency in which the wind levels transit to superior or inferior levels, etc. The basic parameters obtained by this analysis that will be used in the multiple state models are the transition rates between the different wind levels, calculated as:

$$\lambda_{ij} = \frac{\text{no. of transition from level } i \text{ to } j}{\text{total time spent in level } i} \quad (1)$$

Figure 1 shows an example of a wind states transition diagram for a hypothetical wind curve.

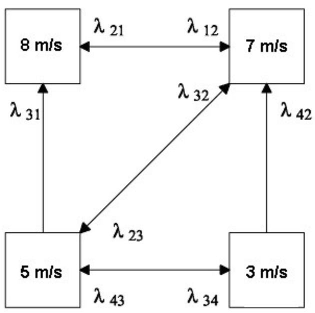

Figure 1: Wind States Transition Diagram

3.2 Power Generation Model

Through the hierarchical cluster grouping technique, the chronological wind curve is transformed into a discretized curve with a reduced number of wind levels and then the wind states transition diagram is derived from the curve, as previously described. Each wind level or state is associated with a generation level, with the respective states transition rates and average duration times. The values of these wind levels are given not only by the wind speed itself, but also by the quantity of data available and the number of classes chosen to accomplish the clustering. In this way, the wind generation is modeled through a multiple states Markov model, based on the stochastic behavior of the wind at the plant installation region.

The power generated by a wind turbine, in Watts, is given by the equation [1]:

$$P = \tfrac{1}{2} C_p \rho V^3 A \quad (2)$$

where C_p is the power coefficient, ρ is the air density [kg/m^3], V is the wind velocity [m/s] and A is the area covered by the blades [m^2]. The power coefficient characteristic varies with the rotor project done by the turbine manufacturer and with the relative speed between the rotor and the wind. With the objective of turning the analysis of the reliability influence more general, it was not included any particular model of the wind turbine. In that sense, the stochastic model adopted for the power generation was the same model of the wind, what implies in considering the generation levels proportional to wind velocities. Although the power generation values obtained with this simplification are not exact, the variation in p.u., the average duration and the transition rates of the power generation levels are correctly represented.

4 RESULTS

In this work, studies were performed to evaluate the impact of the use of wind generation in the composite reliability of an electric power system. For that purpose, three case studies were chosen in order to observe different characteristics and behaviors of the system: wind generation penetration degree, wind generation farm location and a comparison with other energy sources. The base system used to calculate the influence on the reliability indices is the RTS-79. The indices were calculated by non-sequential Monte Carlo Simulation with an uncertainty level of $\beta \leq 5\%$.

4.1 Wind Generation Model

The wind curve used in this work was obtained in [4] and is relative to the Desert Ridge station, located near the city of Phoenix, Arizona State, USA. Desert Ridge is located in 518 meters of altitude, latitude 33° 44' 00'' N and longitude 111° 58' 00'' approximately. Although very complete, the used data are not the ideal for this kind of study, since they are meteorological data and not specific for energy generation. These data were used because of the great difficulty that exists in obtaining actual wind measures for energy generation. This difficulty is due to economical reasons, mainly associated with the high cost of wind potential measurement together with the commercial value of this information.

From the daily and hourly measures available for 2002, 2003 and 2004 years, the daily data were used for obtaining the wind curve grouped into 6 wind levels. The clustering into only 6 levels was made due to the limitation of maximum number of states of the multiple states model implemented in the computational tool used (the program NH2®, developed by CEPEL – Electrical Energy Research Center of Brazil [5]). Figure 2 shows the original curve and the curve grouped into 6 wind levels, where the speed of 1.0 p.u. = 3.979 m/s.

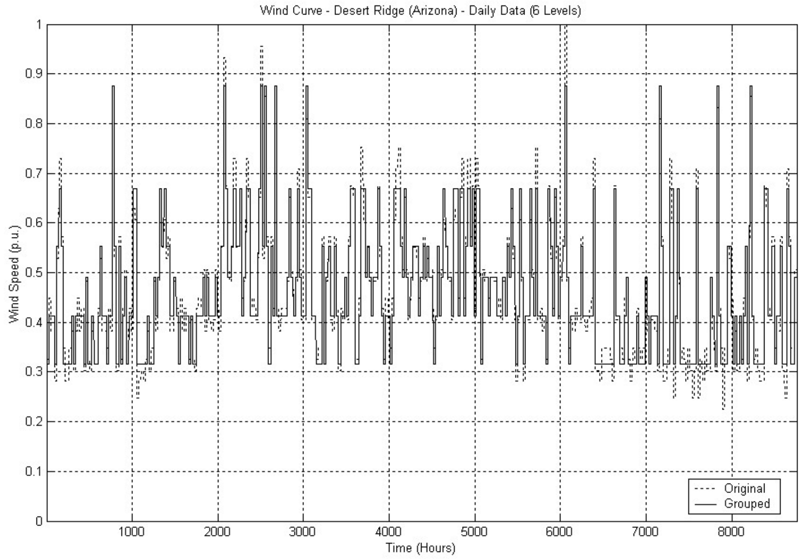

Figure 2: Wind Curve – Desert Ridge (Arizona) – Daily Data – Original Curve and Grouped into 6 Levels

The 6 states stochastic model of the wind generation, obtained from the curve grouped into 6 wind levels, is shown in Figure 3.

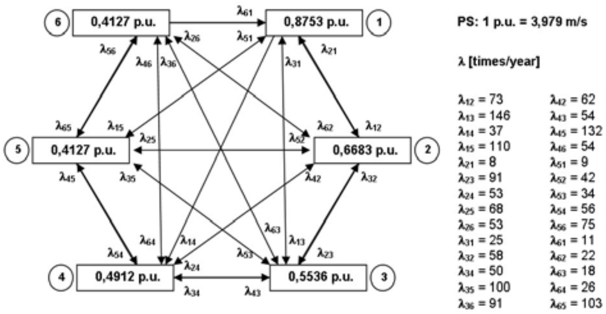

Figure 3: States Transition Diagram of the Wind Generation

4.2 *Penetration Study*

The penetration study of wind generation aims to establish the magnitude of its impact in the system reliability indices. Three cases were considered. In case A, it was considered an installed wind generation capacity of 374 MW, about 10% of the total power installed in the system. In case B, the value of this capacity was 5% of the total power (176 MW). In case C, it was considered a penetration level similar to the current scenario of the Brazilian electric system: 1,1 MW, approximately 0,03% of the installed power, which is the percentage of wind generation present nowadays in Brazil, according to ANEEL's Data - Brazilian National Agency of Electric Energy [6]. Tables 1, 2 and 3 present the estimate of some system reliability indices, per area and per bus, respectively.

Indices	Cases			
	RTS-79	A (10%)	B (5%)	C (0.03%)
LOLP [%]	0.0109	0.0051	0.0080	0.0107
LOLE [h/year]	96.236	44.970	70.411	93.582
EENS [MWh/year]	14700.84	5762.43	9876.01	14923.61
LOLF [/year]	47.077	21.726	32.513	44.969
LOLD [hours]	2.04	2.07	2.16	2.08

Table 1: Reliability indices of the system (Penetration)

	Cases			
Area 1 (138 kV)				
Indices	RTS-79	A (10%)	B (5%)	C (0.03%)
LOLP	0.0109	0.0051	0.0080	0.0107
EENS	7136.93	2831.71	4821.57	7181.19
LOLF	47.077	21.694	32.513	44.9691
LOLD	2.04	2.07	2.17	2.08
Area 2 (230 kV)				
Indices	RTS-79	A (10%)	B (5%)	C (0.03%)
LOLP	0.0099	0.0040	0.0068	0.0097
EENS	7563.91	2930.71	5054.44	7742.42
LOLF	44.408	19.230	29.763	42.825
LOLD	1.95	1.83	2.01	1.98

Table 2: Reliability indices per area (Penetration)

	Cases			
Bus 6 (Area 1)				
Indices	RTS-79	A (10%)	B (5%)	C (0.03%)
LOLP	0.0107	0.0048	0.0075	0.0103
EENS	911.29	400.41	615.50	851.12
LOLF	45.913	20.656	31.102	43.912
LOLD	2.05	2.05	2.13	2.06
Bus 18 (Area 2)				
Indices	RTS-79	A (10%)	B (5%)	C (0.03%)
LOLP	0.0098	0.0040	0.0068	0.0096
EENS	1647.6	639.52	1101.1	1688.4
LOLF	44.092	18.918	29.516	42.381
LOLD	1.95	1.84	2.01	1.99

Table 3: Reliability indices per bus (Penetration)

Comparing RTS-79 and Cases A, B and C, it is generally observed a successive improvement of the system reliability indices as the penetration of the extra generation increases. Similar improvement can be noted when analyzed the area and bus indices, where an improvement of the reliability indices of Area 1 and its buses occurs even the wind plant being located in Bus 18 of Area 2.

However, when comparing Case C with RTS-79, a negative impact is observed in some reliability indices (EENS and LOLD). The reason of the worsening of these indices can be related to the low capacity factor of the wind plant. In a small proportion to the total and with a low capacity factor, the total energy generated by wind generation may not be enough to cover the periods in which it is not available. In this way, it is possible that the introduction of a small amount of this type of generation makes the system less reliable. However, more detailed studies are necessary to ratify these affirmatives.

4.3 Location Study

The location study of wind generation aims to verify the influence of the installation point proximity to the load centers on system reliability. For that purpose, two cases were considered, both with 10% of penetration. In case A, already described, the wind plant was located at a bus that originally contained generation and load (Bus 18). In case D, the wind plant was located in a bus that originally contained only load (Bus 6), chosen because it was one of the most fragile points of the system. This was done in order to determine benefits and prejudices of placing the wind generation near to the consumption centers.

Tables 4, 5 and 6 present the estimate of the system reliability indices, per area and per bus, respectively.

Indices	Cases		
	RTS-79	A (Bus 18)	D (Bus 6)
LOLP [%]	0.0109	0,0051	0,0040
LOLE [h/year]	96.236	44,969	35,314
EENS [MWh/year]	14700.84	5762,42	5282,91
LOLF [/year]	47.077	21,726	18,702
LOLD [hours]	2.04	2,07	1,89

Table 4: Reliability indices of the system (Location)

Comparing RTS-79 with cases A and D, we can affirm that, in general, all reliability indices improved when the generation location was changed from bus 18, which already had generation and load, to bus 6, which only contained load.

	Cases		
Area 1 (138 kV)			
Indices	RTS-79	A (Bus 18)	D (Bus 6)
LOLP	0.0109	0.0051	0.0040
EENS	7136.93	2831.71	2538.19
LOLF	47.077	21.694	18.694
LOLD	2.04	2.07	1.89
Area 2 (230 kV)			
Indices	RTS-79	A (Bus 18)	D (Bus 6)
LOLP	0.0099	0.0040	0.0037
EENS	7563.91	2930.70	2744.72
LOLF	44.408	19.229	17.516
LOLD	1.95	1.83	1.86

Table 5: Reliability indices per area (Location)

	Cases		
Bus 6 (Area 1)			
Indices	RTS-79	A (Bus 18)	D (Bus 6)
LOLP	0.0107	0.0048	0.0037
EENS	911.29	400.41	248.98
LOLF	45.913	20.656	17.529
LOLD	2.05	2.05	1.85
Bus 18 (Area 2)			
Indices	RTS-79	A (Bus 18)	D (Bus 6)
LOLP	0.0098	0.0039	0.0037
EENS	1647.6	639.5	598.2
LOLF	44.092	18.918	17.386
LOLD	1.95	1.84	1.86

Table 6: Reliability indices per bus (Location)

Comparing the reliability indices of each of the areas separately with the general indices of the system, it can be seen that the indices of the system are very similar to the ones of Area 1 (138 kV), which is the more fragile area of the system.

Analyzing the indices per area, it is observed that the location of the wind plant at a load bus (Bus 6) brings more benefits to the areas and to the system than enlarging the generation capacity of a generation bus (Bus 18). The same can be observed if compared the indices per bus. The study indicates that the benefits for the reliability are larger if the additional generation is located closer to the load center. The introduction of the generation in bus 6 brings benefits not only to the bus itself and Area 1, but also improves the reliability of bus 18 and Area 2. These results demonstrate a whole system benefit provided by the introduction of the wind generation at a single bus.

4.4 Generation Type Study

This study has the objective to evaluate advantages and disadvantages of choosing an energy source in detriment of another under the reliability perspective. The indices obtained based in wind energy were compared with other two cases where it was substituted by other types of generation. In case E, the wind plant was substituted by a nuclear plant (NTU) and, in case F, by a conventional thermal plant (THU), all with the same capacity. The thermal unit was modeled in 2 states, while the nuclear unit was modeled in 4 states. The modeling used for the thermal and nuclear plants were the ones defined in RTS-79.

Tables 7, 8 and 9 present the estimate of the system reliability indices, per area and per bus, respectively.

Indices	Cases			
	RTS-79	A (WIN)	E (NTU)	F (THU)
LOLP [%]	0.0109	0.0051	0.0029	0.0031
LOLE [h/year]	96.236	44.969	25.678	27.486
EENS [MWh/year]	14700.84	5762.42	2770.81	3000.48
LOLF [/year]	47.077	21.726	11.895	12.253
LOLD [hours]	2.04	2.07	2.19	2.24

Table 7: Reliability indices of the system (Generation Type)

	Cases			
Area 1 (138 kV)				
Indices	RTS-79	A (WIN)	E (NTU)	F (THU)
LOLP	0.0109	0.0051	0.0029	0.0031
EENS	7136.93	2831.71	1413.52	1526.16
LOLF	47.077	21.694	11.852	12.211
LOLD	2.04	2.07	2.16	2.24
Area 2 (230 kV)				
Indices	RTS-79	A (WIN)	E (NTU)	F (THU)
LOLP	0.0099	0.0040	0.0020	0.0021
EENS	7563.91	2930.71	1357.28	1474.33
LOLF	44.408	19.230	9.712	10.057
LOLD	1.95	1.83	1.79	1.86

Table 8: Reliability indices per area (Generation Type)

	Cases			
Bus 6 (Area 1)				
Indices	RTS-79	A (WIN)	E (NTU)	F (THU)
LOLP	0.0107	0.0048	0.0026	0.0028
EENS	911.29	400.41	234.01	248.46
LOLF	45.913	20.656	10.705	11.026
LOLD	2.05	2.05	2.16	2.23
Bus 18 (Area 2)				
Indices	RTS-79	A (WIN)	E (NTU)	F (THU)
LOLP	0.0098	0.0040	0.0019	0.0020
EENS	1647.6	639.52	293.03	318.11
LOLF	44.092	18.918	9.301	9.622
LOLD	1.95	1.84	1.81	1.87

Table 9: Reliability indices per bus (Generation Type)

For the three analyzed cases, it can be observed that the benefit to the system reliability of the use of generation based on conventional sources (nuclear and thermal) is superior to the use of alternative sources, like wind generation. Comparing Cases E and F, it can be observed that the reliability indices for the case with nuclear generation are better than the ones for conventional thermal. This is due to the existing models in RTS-79: the nuclear plant modeled in 4 states provides a superior capacity factor than the conventional thermal plant modeled in 2 states. In this case, the nuclear plant is less unavailable and therefore provides larger reliability to the system.

The observation of the reliability indices per area and per bus also confirms the analysis made above. The system becomes in fact more reliable if thermal and nuclear plants are used instead of wind generation. The results of this study indicate that, despite the benefits introduced by the generation based on alternative sources, the system reliability improvement provided by generation based on conventional sources is still superior. This occurs basically because of the random wind availability that, due to the great intermittency, makes the capacity factor of wind plants low when compared to thermal ones.

5 CONCLUSION

This paper presented the results of studies carried out in order to evaluate the impact of wind energy based generation on the system composite reliability. In a general sense, it can be concluded that wind generation may be interesting to electric system because it may increase its reliability. However, the benefits obtained with its utilization depend on different factors, such as: the primary energy source (wind) availability, the plant location and generation capacity with respect to the existing system capacity and topology, etc. Any reliability impact studies of wind generation should take into consideration all these characteristics in order to measure the benefit introduced regarding the installation and operation costs of this type of generation.

The presented results were calculated using an available computational tool and being, thus, restricted to the implemented stochastic models. Therefore, some simplifications needed to be introduced when representing the developed wind generation model in the tool, such as the maximum number of wind levels and the lack of representation of the power generation model of the wind turbine. However, these results are indicative, both qualitative and quantitatively, of the effects of wind generation in system composite reliability and can be immediately obtained from the computational tool adopted in the Brazilian Electric Sector.

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