A CHRONOLOGICAL COMPOSITE SYSTEM ADEQUACY ASSESSMENT CONSIDERING NON-DISPATHABLE RENEWABLE ENERGY SOURCES AND THEIR INTEGRATION STRATEGIES

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Abstract – Many studies addressing the effect of wind power integration strategies on the system adequacy assessment have been made, only concerning the generation point of view and usually disregarding the effect of the transmission network. On the other hand, studies considering the transmission network usually have ignored the effect of wind power integration strategies, focusing only on capturing the time dependent nature of this type of renewable energy source. Therefore, this work presents a chronological Monte Carlo simulation approach that assesses the system adequacy of composite systems (generation and transmission) considering non-dispatchable and dispatchable renewable energy production (wind and hydro, respectively). Case studies involving the IEEE-RTS 79 and modified versions of this system are presented and discussed as didactic examples.

Keywords: Composite Power System Reliability, Sequential Monte Carlo Simulation, Renewable Energy Sources

1 INTRODUCTION

Power system operators, especially in thermal-dominated generation systems, are cautious on meeting a large fraction of system load with wind power since, unlike conventional production, wind generators are not easily able to perform load following. Furthermore, the contribution for system stability in case of perturbations is an evolving issue justifying in many cases a policy of some precaution, especially when there is no fault ride-through capability. As a conservative measure, wind power curtailment to accommodate a more stable set of generating units in the hourly dispatch became a usual strategy adopted by power system operators. Strategies to coordinate wind and hydro generating units through pumping schemes have been explored by utilities to improve system performance and the efficient use of renewable energy, since wind energy can be stored in terms of water in hydro reservoirs for further use [1].

Many studies addressing the effect of wind power integration strategies on the system adequacy assessment have been made [2-5], basically regarding the security of supply point of view, and disregarding the effect of the transmission network. In fact, the security of supply assessment is one of the first concerns linked to the package of measures needed to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change [6]. On the other hand, studies considering the transmission network usually have ignored the effect of wind power integration strategies, focusing mainly on capturing the time dependent nature of this type of renewable energy source [7-8]. Renewable energy source is defined as any energy resource naturally regenerated over a short time scale that is derived directly from the sun (such as solar thermal and photovoltaic), indirectly from the sun (such as wind, hydropower and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and ocean energy) [9].

Recently, a discussion involving the transmission system to accommodate wind energy production have been proposed on several forums, mainly focusing on the current power system debate involving wind versus nuclear technologies. In general, the previous discussion is supported by deterministic perceptions of the system operators and planners. In fact, deterministic evaluation have simple implementation and easy understanding, assessment and judgment by operators and planners in relation to severe conditions like replace a large thermal unit by several small wind turbines. Unfortunately, the perception of many engineers that past experience in addition to some known critical situations is enough to assess system risk conditions is not valid, essentially because past experience with renewable sources like wind power is very limited. However, the principles of some deterministic standards (e.g. “N-1” criterion) must be recognized as attractive.

From the planning point of view, probabilistic based approaches have very attractive characteristics for transmission system evaluation. Methodologies based on probability concepts can be extremely useful in assessing the performance of power systems [10]. They have been successfully applied to many areas including generation and transmission capacity planning, operating reserve assessment, distribution systems etc. This paper will present a chronological Monte Carlo simulation approach that assesses the system adequacy of composite systems (generation and transmission) considering non-dispatchable and dispatchable renewable energy production (wind and hydro). Furthermore, operation strategies to maximize wind power integration are discussed along with the system adequacy assessment. Case studies involving the IEEE-RTS 79 and modified versions of this system are presented and discussed as didactic examples.

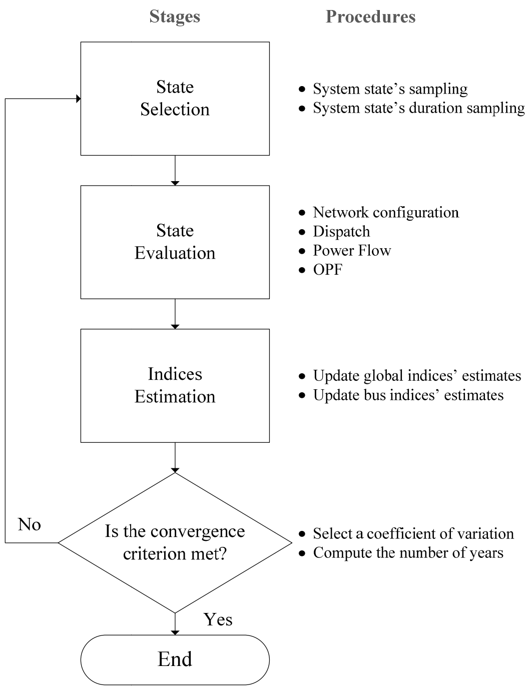

Figure 1: Sequential Monte Carlo Stages and Procedures.

2 PROPOSED METHODOLOGY

New computational models and tools have been developed in order to deal with the great number of new variables that come from renewable sources, particularly of wind power, since they are the most popular source of green electricity. This impressive growth of the wind power production has consequently caused new transmission system demands, mainly increasing interconnections among electric areas and utilities. In order to deal with these new demands, the proposed methodology is based on sequential Monte Carlo simulation (SMCS) [11-12]. It is a suitable methodology that allows assessing power system's reliability considering not only failures of generating units preserving time dependences, but also failures of the transmission network's components such as transmission lines and transformers. The structure of the proposed methodology is composed of four stages, as depicted in Figure 1, which are consecutively executed until convergence is reached [11]. Each of those stages is composed of several procedures necessary to accomplish each stage's task. The next sections will discuss the component model applied on each stage.

2.1 Sequential Monte Carlo Simulation

The reliability assessment of real large power systems by SMCS is known for being a very expensive computational evaluation. Moreover, to analyze the sampled states, heavy computational tools such as optimal power flows are intensively used [11]. However, SMCS makes it possible to use a wide range of detailed models, including non-Markovian representations for generation and transmission equipment, correlated sequential load models, and others.

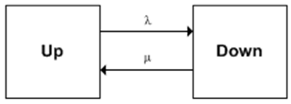

Figure 2: Two State Model.

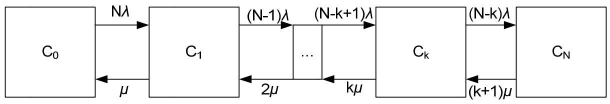

Figure 3: Multi State Model.

The operation history of system states, for a simulation period *T*, is based on stochastic models of the components and on the load model. All about SMCS can be found in [11].

2.2 Generation Representation

In order to determine the capacity of a generating unit in a given state, two characteristics have to be considered:

- The failure/repair cycle stochastic model,
- The capacity time-dependent model.

The first characteristic is related to the stochastic behavior of generating units, which define its up/down cycle during the simulation process. The second characteristic is linked with the representation of the time dependent characteristics of the capacity of some generating units. In fact, the capacity of some generating units are hourly, weekly, monthly and/or even yearly dependent. Therefore, to properly model this behavior, the theoretical maximum capacity has to be affected by the corresponding time-varying characteristic. The time-varying characteristic is captured by means of hourly/monthly series with probabilities associated obtained for several years.

2.2.1 Conventional Generation

Conventional generating units are all of those which convert the thermal energy contained in fossil fuels or in the atomic nucleus to electricity via a thermodynamic process. The failure/repair cycle of this type of generators is represented by a two-state model, whose transitions follow an exponential probability distribution, like depicted in Figure 2. When in up-state, a conventional generator is able to produce its maximum capacity; conversely, in the down-state, the generator's capacity is zero.

2.2.2 Hydro Generation

Hydro generators are those which convert the potential energy of the water to electricity. Like conventional generators, the failure/repair cycle of this type of generators is also represented by a two-state model, (see Figure 2) whose transitions follow an exponential probability distribution. Unlike conventional generators, the capacity time-dependent model is more complex since hydro generators power output depends both on the levels of water stored on the reservoirs and on the river flow [13, 14]. As a preliminary approach, hydrological series that capture a proportional relation between the total water stored at a given reservoir and the total power produced by the corresponding hydro generator in a given month is defined, based on volume historical data. In this case, each sampled year is classified following a historical hydrological condition [13, 14].

2.2.3 Unconventional Generation

Unconventional generation can be classified as wind power, solar thermal or photovoltaic, some types of biomass, and so on. Particularly, this paper is focusing wind power production on several discussions. Therefore, wind generators are those which convert wind energy to electricity. Taking advantage of the fact that wind generators within wind farms traditionally are equal, a multi-state Markov model is used (see Figure 3) to represent the failure/repair cycle of the aggregation of equal wind generators. This stochastic cycle follows an exponential probability distribution. Similar to the capacity time-dependent model of hydro generators, the maximum capacity of the states is multiplied by a value extracted from the wind farm hourly wind series [13, 14]. These series are constructed based on observations throughout many years and relate the total power output of wind farm with the hour of the year. Despite having a probabilistic nature, they are used as input parameters, similar to the hydrological series. When a sampled year begins a new wind regime is sampled.

2.3 Transformers and Transmission Lines Representation

Both transmission lines and transformers failure/repair cycle is modeled by a two-state model, whose transitions follow an exponential probability distribution. It is assumed that their maximum capacity is not altered through time.

2.4 Load

The load is modeled using a sequential representation containing as many steps as hours in the year. In addition, each bus has its own hourly load profile in percentage of its peak load. Each hourly load percentage is obtained by dividing the peak load of that hour by the peak load of that year. The SMCS follows chronologically the loads steps as the simulation advances through time.

2.5 Network Configuration

The network configuration procedure is based on a list search method [15]. This method assumes the network is described by a node/branch representation, being nodes the buses of the transmission network and branches the transmission lines and transformers. All nodes are numbered and each branch connects two nodes. The main objective is to identify the connectivity among nodes and to determine how many electric islands there are and the nodes/branches they enclose.

2.6 Operation Model and Remedial Actions

Remedial actions follow a sequence of evaluations according to the operational procedure commonly used to define an optimal dispatch. From the adequacy point of view, first is proposed a merit order to the generating units in order to meet the hourly load requirement. Second, a Power Flow (PF) analysis is performed in order to check transmission and transformers limits, and if necessary an Optimal Power Flow (OPF) also is performed in order to achieve a suitable dispatch solution. Therefore, the remedial action module can be described in three main evaluations, as follows.

2.6.1 Dispatch Order Strategies

The objective of this procedure is to allocate the load to the available generating units taking into account restrictions associated to each generator. In this case, it can follow a merit order strategy or a proportional strategy. In the merit order strategy the generators with a higher merit are preferably dispatched with its full capacity rather than the generators with lower merit. This strategy is as follows:

a) Find the next available generator with the highest merit that has not yet been dispatched,
b) Dispatch the generator with its full capacity, considering its maximum/minimum technical limits,
c) Update the remaining load, and if all load has been allocated, end the procedure; otherwise go to step a).

In the proportional strategy, a generator is dispatched with an amount of load proportional to its generation capacity and the total available generation capacity. This strategy is as follows:

$$P_i = \frac{(\overline{P}_i - \underline{P}_i)}{\sum_{i=1}^{N}(\overline{P}_i - \underline{P}_i)} \times \left(L - \sum_{i=1}^{N} \underline{P}_i\right) + \underline{P}_i \qquad (1)$$

where, N is the subset of all generating units to be dispatched, P_i is the amount of the load L allocated to generator i; $\overline{P}_i$ is the technical maximum of generator i; $\underline{P}_i$ is the technical minimum of generator i; and L is the load value.

2.6.2 DC PF

The DC PF task consists in determining if there are transmission lines or transformers operating outside their operational limits. A linearized representation of the PF equations is adopted so that instead of numerical methods direct mathematical methods can be used.

2.6.3 DC OPF

If DC OPF task determines that transmission lines and/or transformers have operational limits violated a DC Optimal Power Flow (OPF) is performed. This task consists in enforcing the operational limits of the components by altering the buses' real power injected. Its objective is to minimize the total load curtailed, if there is the need of such corrective measure. The linear programming method used in the proposed methodology is based on Simplex algorithm. Two types of formulation for the DC OPF are implemented: the sparse formulation and the non-sparse formulation. The non-sparse formulation is based on the same set of equations of the sparse formulation. However, it takes advantage of the relationships between variables to form a condensed set of equations which enables a speed-up when solving the linear programming problem.

2.6.4 Aspects of Security Assessment

Based on the concept of must-run unit [16-18], a simple model to account for security of the system is proposed. It consists on considering that a fixed amount of load has always to be supplied by a given set of generating units, regardless of the hourly load variation [16-18]. It is assumed that these units are capable of guaranteeing the stability of the power system. In this model, stability is a board concept and does not refer to a specific stability problem: it is assumed that the set of generating units is capable of guarantee rotor stability, frequency stability and voltage stability as long as the fixed amount of load is supplied by them.

The dispatch of the fixed amount of load between the must-run units follows a proportional strategy, which was described in the previous section.

3 TEST SYSTEM DESCRIPTION

The original configuration of the IEEE-RTS 79 [19] consists of 32 generating units, 24 buses, 33 transmission lines, and 5 transformers. The installed capacity and annual peak load are equal to 3405 MW and 2850 MW, respectively. From the renewable point of view, there is only 8.8% of the installed capacity corresponding to 300 MW on hydro power plants, which can be considered renewable. On the other hand, 91.2% of the installed capacity comes from thermal power plants, which corresponds to 3105 MW divided into different thermal technologies. The load curve consists of 8760 hours, based on the original 8736 hourly load points of the IEEE-RTS 79. The extra 24 hours corresponds to the replication of the 28th day of February.

In order to highlight some specific effects that come from the renewable technologies on the IEEE-RTS 79, two major modifications are proposed. Firstly, it will be considered hydro power fluctuations for all hydro units resulting in a new configuration of this test system named IEEE-RTS 79 H. The second modification consists of increasing the total installed capacity from 3405 MW to 3805 MW, adding 400 MW of wind power on three different wind farms. Thus, the IEEE-RTS 79 will be renamed IEEE-RTS 79 HW. Moreover, during all studies carried out along the paper, several other configurations will be promoted. The aim is to increase the percentage of renewable and decrease the thermal participation, especially those linked to oil technologies.

As stated previously, one of the major modifications of the IEEE-RTS 79 HW is the fluctuation capacity on the hydro and wind power production, which makes it possible to consider seasonal hydro monthly effects and hourly wind variations. In order to consider hydro fluctuation, five historical hydro series are considered for the basin. Figure 4 shows the average monthly hydro fluctuation by each historical year.

From the wind power fluctuation point of view, three important aspects must be highlighted:

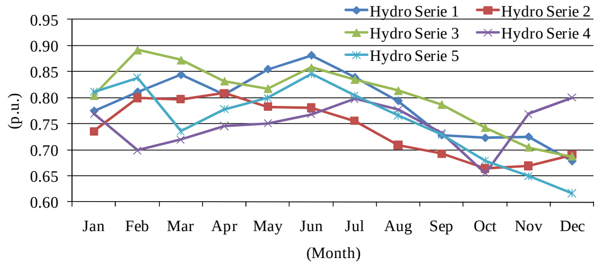

Figure 4: Hydro Monthly Variation.

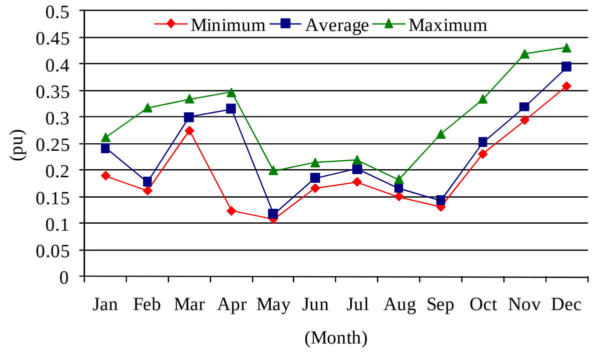

Figure 5: Wind Monthly Variation.

- First, it is linked to its availability,
- Second, it is linked to its variability,
- Third, it is linked to its forecasting properties.

For the purpose of this study, the wind power subsystem consists of 200 units of 2 MW, distributed among three different wind farms (60-bus 8, 60-bus 11 and 80-bus 19 turbines per bus-area respectively) with their own wind characteristics. Each wind farm is characterized by its own historical series (see Figure 5), on an hourly basis, referring to the average power produced by a wind generator and mainly representing the power fluctuation. Figure 5 gives an idea of the monthly available power in p.u., where the worst condition happens in May, with an average availability of 0.1 p.u. (~20 MW), and the best condition happens in December, with an average availability circa 0.43 p.u. (~172 MW). Another major concern on the IEEE-RTS 79 HW is linked to the aspects of security from the dispatch point of view. In this case, the four units of 155 MW, one unit of 350 MW and two units of 400 MW are considered must-run units [16].

4 APPLICATION RESULTS AND DISCUSSION

The first set of results aim at establishing a basis of comparison for the subsequent experiments using the different configurations of the IEEE-RTS 79 presented on the previous section. Table 1 presents the overall system indices of the standard configuration of the IEEE-RTS 79 test system and the IEEE-RTS 79 H test system that includes hydro capacity variation. All the system indices have a coefficient of variation lower than or equal to 5%.

The first conclusion is concerned with the validation of the sequential Monte Carlo simulation methodology presented on this paper.

Table 1: Validation Indices.

System ID	LOLE (h/yr)	EENS (MWh/yr)	LOLF (occ/yr)	LOLD (h/occ)
IEEE RTS 79	10.936	1345.54	2.293	4.769
IEEE RTS 79 [20]	10.483	-	2.265	4.728
IEEE RTS 79 H	25.010	3521.78	4.750	5.266

Table 2: Conventional Indices – Thermal Addition**.**

Nuclear Capacity (MW)	Maximum Energy (GWh/yr)	LOLE (h/yr)	EENS (MWh/yr)	LOLF (occ/yr)
400	3084.38	3.715	474.28	0.799

Table 3: Conventional Indices – Wind Addition.

Wind Capacity (MW)	Maximum Energy (GWh/yr)	LOLE (h/yr)	EENS (MWh/yr)	LOLF (occ/yr)
400	790.86	11.611	1476.30	2.371
800	1585.48	6.755	852.98	1.453
1200	2378.86	4.814	589.91	1.017
1400	2809.87	3.829	451.57	0.854
1500	3027.90	3.542	430.37	0.780
1600	3181.94	3.455	412.42	0.777

By comparing the LOLE, LOLF and LOLD indices presented on Table 1 with those obtained from [20] it can be concluded that the proposed methodology is in agreement with another accepted as reference in the literature. The second conclusion is related to the system indices obtained for the IEEE-RTS 79 H configuration. By modeling the hydro capacity fluctuation along time, the overall system indices came to be considerably penalized demonstrating that representing time-varying behavior of hydro units in reliability assessment studies is of the utmost importance even in power systems like IEEE-RTS 79 where the hydro capacity represents only 8.8% of the total installed capacity. Furthermore, the growth observed in each system indices is dissimilar for all indices, being the EENS the most penalized.

4.1 Discussion on the Integration of Intermittent Production in the Generation and Transmission System

An important issue, which has been an intense matter of discussion, is to determine the equivalence between wind and nuclear generators concerning the adequacy of the supply. To shed some light on this discussion two experiments were conducted: first, a run of the IEEE-RTS 79 H configuration with an extra 400 MW nuclear generator, with a MTTF = 1100 h and a MTTR = 150 h, at bus 19 was conducted; second, consecutive runs of the IEEE-RTS 79 HW configuration considering increasing wind generation capacities were carried on until the system reliability indices obtained overcome those of the previous experiment. In the latter experiment, all wind generators considered have capacities of 2 MW, with a MTTF = 1914.74 and a MTTR = 80. The total wind generation capacity is distributed proportionally by three wind farms placed at buses 8, 11 and 19 with a proportion of 30%, of 30% and of 40%, respectively. The first conclusion that can be derived from the

Table 4: Renewable Spill Indices – Thermal Addition.

Nuclear Capacity (MW)	LORE (h/yr)	Beta (%)	EENS (MWh/yr)	Beta (%)	LORF (occ/yr)	Beta (%)
400	6.56E-03	50.16	1.49	53.25	7.79E-04	44.71

Table 5: Renewable Spill Indices – Wind Addition.

Wind Capacity (MW)	LORE (h/yr)	Beta (%)	EENS (MWh/yr)	Beta (%)	LORF (occ/yr)	Beta (%)
400	3.07E-03	100	6.35E-01	100	4.73E-04	100
800	9.34E-04	100	1.76E-01	100	2.68E-04	100
1200	7.11E-03	56.29	1.27	59.87	1.79E-03	33.31
1400	0.559	3.22	6.54	8.81	0.337	3.07
1500	5.813	2.16	153.72	2.35	2.415	2.03
1600	16.711	1.68	712.04	1.88	5.791	1.62

results presented on Table 2 and on Table 3 is that only with 1500 MW of total wind capacity it is possible to overcome the LOLE index obtained considering 400 MW of nuclear capacity. Furthermore, if instead the LOLE index the EENS index or the LOLF index is considered, it is now necessary 1400 MW and 1600 MW of wind capacity, respectively. Hence, an unbiased comparison between both technologies demands establishing a rigorous and clear definition of what the measure of performance in terms of the adequacy of supply is. On the other hand, and mostly due to the intermittency of the primary energy resource and the failure/repair cycle the different technologies, 400 MW of wind capacity cannot produce the same amount of energy than 400 MW of nuclear capacity. In fact, from Table 2 and Table 3, the expected maximum energy that 400 MW of wind capacity is able to produce is 790.86 GWh/yr contrasting with the 3084.38 GWh/yr of 400 MW of nuclear capacity. This question is answered in Figure 6 created from the results presented on Table 2 and Table 3. This figure plots the variation of the LOLE as well as the variation of the expected maximum energy supplied with the variation of wind capacity. The dashed lines correspond to the LOLE and the expected maximum energy produced of 400 MW of nuclear capacity. From the analysis of this figure, at the value of wind capacity corresponding to an expected maximum energy equal to that of 400 MW of nuclear capacity, the LOLE is smaller than that of 400 MW of nuclear capacity. This means that, considering the expected maximum energy as performance measure, the wind overcomes nuclear. To this result contributes the both the facts that, contrarily to the nuclear capacity, the total wind capacity results from the aggregation of several units and that the wind capacity is dispersed throughout the transmission system and not concentrated at a single node, lessening the effect of transmission components' failure on system indices.

These two experiments were conducted favoring the use of renewable power sources so that it could be possible to detect the value of capacity from which the spill of renewable starts to be significant. In order to assess the expected hours per year as well as the frequency of occurrence of wind spill events the indices LORE and LORF, which are based on the ordinary LOLE and

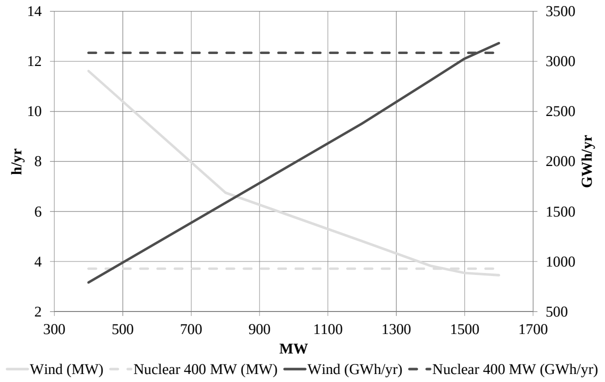

Figure 5: LOLE vs Expected Maximum Energy Produced.

Table 6: Conventional Indices.

Tech Min (% valley)	LOLE (h/yr)	Beta (%)	LOEE (MWh/yr)	Beta (%)	LOLF (occ/yr)	Beta (%)
100%	11.611	3.62	1476.30	5.00	2.371	2.90
75%	11.611	3.62	1476.30	5.00	2.371	2.90
50%	11.611	3.62	1476.30	5.00	2.371	2.90
25%	11.611	3.62	1476.30	5.00	2.371	2.90

Table 7: Insecure State Indices.

Tech Min (% valley)	LOLE (h/yr)	Beta (%)	EPNS (MW)	Beta (%)	LOLF (occ/yr)	Beta (%)
100%	47.459	2.51	9.32E-01	3.30	3.150	2.07
75%	16.269	4.32	1.78E-01	5.85	0.733	2.82
50%	4.799	5.42	1.37E-02	9.03	0.388	3.52
25%	3.216	5.31	4.07E-03	6.48	0.317	3.83

LOLF respectively, are proposed. As a result, Table 5 shows that from 1400 MW of wind capacity onwards the system cannot accommodate the total energy produced by the renewable and spilling events start to happen more frequently. As a result, Table 5 shows that from 1400 MW of wind capacity onwards the system cannot accommodate the total energy produced by the renewable and spilling events start to happen more frequently. This spill results from possible bottlenecks created within the network by the increase of generating capacity at given nodes and also by the fact that the load has not accompanied the growth of the wind capacity.

Furthermore, the results presented on Table 4 and on Table 5 also demonstrate that the bus where new units are connected influences the renewable spill indices. Indeed, despite the large coefficient of variation, it can be alleged that the renewable spill indices of 1200 MW of wind capacity are smaller than those of 400 MW of nuclear capacity. By adding a large generation capacity in some nodes, especially to those close to nodes with surplus of generation, bottlenecks in the network node can be created making impossible to use all the available renewable capacity.

4.2 Security Aspects of Generation and Transmission System

To investigate the influence of the must-run criterion on the adequacy of the system, several experiments were promoted using the IEEE-RTS 79 HW with 400 MW of wind capacity as test system and considering four different values to the amount of load that must be

Table 8: Renewable Spill Indices.

Tech Min (% valley)	LORE (h/yr)	Beta (%)	EENS (MWh/yr)	Beta (%)	LORF (occ/yr)	Beta (%)
100%	1110.656	0.65	125242.37	1.04	218.142	0.43
75%	97.803	2.05	4991.29	2.57	28.119	1.84
50%	3.07E-03	100	6.35E-01	100	4.73E-04	100
25%	3.07E-03	100	6.35E-01	100	4.73E-04	100

Table 9: Wind Spill Indices.

Tech Min (% valley)	LORE (h/yr)	Beta (%)	EENS (MWh/yr)	Beta (%)	LORF (occ/yr)	Beta (%)
100%	133.536	1.79	7479.33	2.24	37.383	1.65
75%	0.00	100	0.00	100	0.00	100
50%	0.00	100	0.00	100	0.00	100
25%	0.00	100	0.00	100	0.00	100

Table 10: Hydro Spill Indices.

Tech Min (% valley)	LORE (h/yr)	Beta (%)	EENS (MWh/yr)	Beta (%)	LORF (occ/yr)	Beta (%)
100%	1110.656	0.65	117763.04	0.98	218.142	0.43
75%	97.803	2.05	4991.29	2.57	28.119	1.84
50%	3.07E-03	100	6.35E-01	100	4.73E-04	100
25%	3.07E-03	100	6.35E-01	100	4.73E-04	100

supplied by the must-run units, which are: 100% of the valley load; 75% of the valley load; 50% of the valley load; and 25% of the valley load. It is also assumed that the must-run criterion is enforced when the maximum generating capacity of the must-run units is higher than or equal to the pre-established amount of load of the must-run criterion. A first conclusion that can be drawn from comparing results on Table 3 and on Table 6 is that, for this test system, adding the must-run criterion does not influence the loss of load indices. Likewise, the variation of the value of the amount of load of the must-run criterion does not alter the adequacy of the system. However, the same conclusion is not valid for the events where the load supplied by the must-run units is less than the load of the must-run criterion. These events are named insecure state events. They are characterized on Table 7 through indices which use the traditional nomenclature of the loss of load indices. In this case the LOLE corresponds to the expected number of insecure state events; the EPNS corresponds to the expected power by which the must-run units fail to supply the load of the must-run criterion; the LOLF relates to the frequency of occurrence of insecure state events. As the amount of load that must be supplied by the must-run units increases, the occurrence of insecure states also increases. An interesting result is that the expected power by which the must-run units fail to supply the load of the must-run criterion, as shown on Table 7, is small when compared to the capacity of the must-run units or even the value of the load of the must-run criterion. The amount of renewable spilled is influenced severely by the must-run criterion. As the value of the amount of load of the stability criterion increases, the amount of renewable energy spilled also increases, as shown on Table 8. Moreover, below 50% of the valley, there is almost no renewable spill. The fast rate of growth of the renewable spill indices presented on Table 8 is caused by the fact that when on valley hours almost all load is supplied by must run units resulting in a high number of renewable spill events and consequently in a high value of renewable energy spilled.

The renewable spill indices were also obtained for the two renewable technologies: hydro and wind. These indices are presented on Tables 8, 9 and 10. An interesting result is the fact that both LORE and LORF indices on Table 8 and 10 are equal. This means that every time there is a renewable spill event and a given amount of hydro energy is lost. Furthermore, as it is almost impossible to have no wind capacity on the system, when a renewable spill event happens it is very likely that it involves spilling of hydro energy. As a result, wind energy is not spilled without spilling hydro energy either. This is due to the dispatch order. After dispatching the must-run units, the remaining load is allocated, first among wind turbines until there is no wind capacity left and, afterwards, if there is any load remaining it is distributed among hydro units.

5 FINAL REMARKS

Renewable energy technologies will take a greater share of the electricity generation mix in order to minimize the dependence on oil and the emission of CO2. While contributions from renewable energy sources for electricity production is small, with the exception of hydro, their market penetration is growing at a much faster rate than any other conventional source.

More renewable power sources cause, however, an increase in the number of random variables and operation complexities in the system, mainly due to the fluctuating production levels of these sources and the needs for a flexible transmission system in order to distribute energy on system buses. Therefore, the determination of the required amount of system capacity to ensure an adequate supply becomes a very important aspect of generation and transmission expansion analyses.

This paper has evaluated the impact of different generation technologies, namely wind and thermal, on the adequacy of the generation and transmission system. It is demonstrated that the result of this evaluation depends strongly on the performance criterion adopted by system planner/operators. In order to shed some light on the power system debate about the differences between wind and nuclear system impact, some case studies were carried out where each technology presents advantages and disadvantages.

Based on the concept of must-run unit a simple model to account for the security of the system is proposed. This concept does not influence the assessment of conventional reliability indices. However, it is demonstrated that must-run criterion can start renewable spill events. Furthermore, it is also shown that the dispatch order influences the type of renewable spilled and its amount.

Further investigation will result on an enhanced model to account for the security of the system that can detect the amount of load that must-run units have to supply as a function of the type of units in the up state. Moreover, storing strategies of wind and hydro energy not used will be investigated aiming at determining its benefits regarding the adequacy of the system.

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