RENEWABLE ENERGY INTEGRATION STUDY ON MULTI-STATES PREDICTIVE SIMULATION IN RELIABILITY EVALUATION OF POWER SYSTEM

NGHIÊN CỨU TÍCH HỢP NĂNG LƯỢNG TÁI TẠO BẰNG MÔ PHỎNG PHỎNG ĐOÁN ĐA TẦNG KHI ĐÁNH GIÁ ĐỘ TIN CẬY HỆ THỐNG ĐIỆN

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ABSTRACT

Reliability of Power System research has a long history. The topic includes three levels: the first relates to generation facilities, the second refers to the integration of generation and transmission, the third one refers to the complete system including distribution system. The first level is a basic step for the next level, still being interested, especially on researches on the renewable energy sources integration. Monte-Carlo simulation is used to describe the power state of traditional generations, wind turbines and the hourly load of the power system. In particular, the 2055MW wind turbine is simulated in four states. The reliability test power system IEEE-RTS version 1979 was used to verify the simulation method. Four scenarios of the share of wind power were tested: 0.2%, 2.4%, 3.6%, 4.8%. Each scenario was simulated respectively with different load levels. The results show that the reliability is slightly changed when the share of wind power is negligible (0.2%). However, the reliability changes dramatically only with 2.4% of the share of wind power. The greater the wind power integration, the lower the reliability when considering the results of the other scenarios. This paper also shows a significant increase in the loss of load expectancy (LOLE) as the annual peak load increases of 100MW.

Keywords: *Reliability, power system, wind turbine integration, Monte-Carlo simulation, IEEE-RTS.*

TÓM TẮT

Nghiên cứu độ tin cậy hệ thống điện đã có lịch sử lâu đời. Chủ đề này thường bao gồm ba cấp độ: cấp độ thứ nhất liên quan đến phần nguồn điện, cấp độ thứ hai để cập đến sự tích hợp của các nguồn điện trong lưới điện truyền tải, cấp độ thứ ba để cập đến hệ thống hoàn chỉnh bao gồm cả hệ thống phân phối điện. Cấp độ đầu tiên là bước cơ bản cho cấp độ tiếp theo, vẫn đang được quan tâm, đặc biệt là các nghiên cứu về tích hợp các nguồn năng lượng tái tạo. Mô phỏng Monte-Carlo được sử dụng để mô tả trạng thái công suất của các nguồn truyền thống, tuabin gió và phụ tải theo giờ của hệ thống điện. Trong nghiên cứu này, một hệ thống tuabin gió công suất 2055MW được mô phỏng ở bốn trạng thái phát điện. Mô hình thử nghiệm độ tin cậy IEEE-RTS phiên bản 1979 được sử dụng để xác minh phương pháp mô phỏng. Bốn kịch bản về tỷ trọng điện gió đã được thử nghiệm: 0,2%; 2,4%; 3,6%; 4,8%. Mỗi kịch bản được mô phỏng tương ứng với các mức phụ tải khác nhau. Kết quả cho thấy độ tin cậy có chút thay đổi khi tỷ trọng điện gió không đáng kể (0,2%). Tuy nhiên, độ tin cậy chỉ thay đổi đáng kể với 2,4% thâm nhập công suất điện gió. Sự tích hợp công suất điện gió càng lớn thì độ tin cậy càng thấp khi xem xét kết quả của các kịch bản khác. Bài báo này cũng cho thấy sự gia tăng đáng kể trong chỉ số kỳ vọng mất tải (LOLE) khi phụ tải đỉnh hàng năm tăng 100MW.

Từ khóa: *Độ tin cậy, hệ thống điện, tích hợp tuabin gió, mô phỏng Monte-Carlo, IEEE-RTS.*

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1. INTRODUCTION

The reliability of the power system has been strongly studied since the 1970s. Roy Billinton's team could be considered as a comprehensive foundation for researches in this domain due to the publication of several books and articles. The Institute of electrical and electronics engineers (IEEE) then assembled researches of Reliability of Power system in states from 1971 to 2002 [1-6]. Some basic assessment criteria became common in most publications: the loss of load probability (LOLP), the loss of load expectancy (LOLE), the loss of energy expectancy (LOEE), the frequency and duration (F&D). Almost scientific publications about the Reliability of Power System assembled by IEEE use a sample system for comparison, called IEEE-RTS [7]. This system was published firstly in 1979 then it was expanded in 1986 [8] and 1999 [9]. In addition, Billinton and his colleagues developed a smaller system testing called by RBTS [10] for training and exploration of the fundamentals of power system reliability.

The recent publications no longer focus on the reliability with only conventional power sources such as coal, oil, natural gas and hydropower, but instead experiment with renewable energy sources such as wind or solar power. The above-mentioned researches on reliability assessment were studied early and started by Billinton, Allan's research teams and the other teams with the integration of wind power [11-16]. It has continued to be published so far [17, 18].

The last two decades have seen a huge application of the Monte-Carlo technique. This technique became step by step an important component in the reliability assessment and plays a key role in a wide range of scientific articles. This method is used in many software systems intended for energy systems [19]. In contrast to other techniques, Monte-Carlo can reduce execution time and avoid problems with big data in large systems. The reliability assessment based on the Monte-Carlo simulation usually consists of the following steps [20]: creation of power system states [21]; minimization of power shortage in each states and calculation of reliability indices.

In this paper, the Monte-Carlo Simulation was chosen to perform the LOLE calculation to investigate the first level of power system reliability assessment including a significant share of wind power on the total power capacity. Therefore, the content of this paper includes the following sections:

Introduction: A general introduction of the power system reliability research and the content included in this paper.

Materials and Methods: The IEEE-RTS test system is used for this research, particular emphasis on the Monte-Carlo simulation model of conventional power sources and hourly load. The data of a wind turbine was also described for using in different scenarios with the integration of wind power. Several scenarios for wind power integration are proposed for research.

Multi-states Monte-Carlo Simulation of a wind turbine: An introduction to Monte-Carlo simulation of multi-states of a wind turbine, three and four states, was used in this study.

Results and Discussion: Results and discussion are presented. This includes obtaining results as verifying the accuracy of the simulation method for the IEEE-RTS test system and the effect of wind power on the reliability of the power source as the share of wind power increases.

Conclusions: Summarizing the results of the research and proposing future research focus.

2. RESEARCH METHOD

2.1. IEEE-RTS test system

2.1.1. Single line Schematic of IEEE-RTS version 1979

This test system consists of 11 conventional power plants (coal, oil, nuclear, natural gas and hydropower) with 33 generation units (generators) from 12 to 400MW. The transmission system consists of 38 lines connecting the load and the source at both 138kV and 230kV. Since this research focuses on the reliability of the power sources, the several parameters (substation configuration, distribution system configuration, interconnections with other systems, protective relay configurations, load/generation forecasting) are not mentioned in the following descriptions.

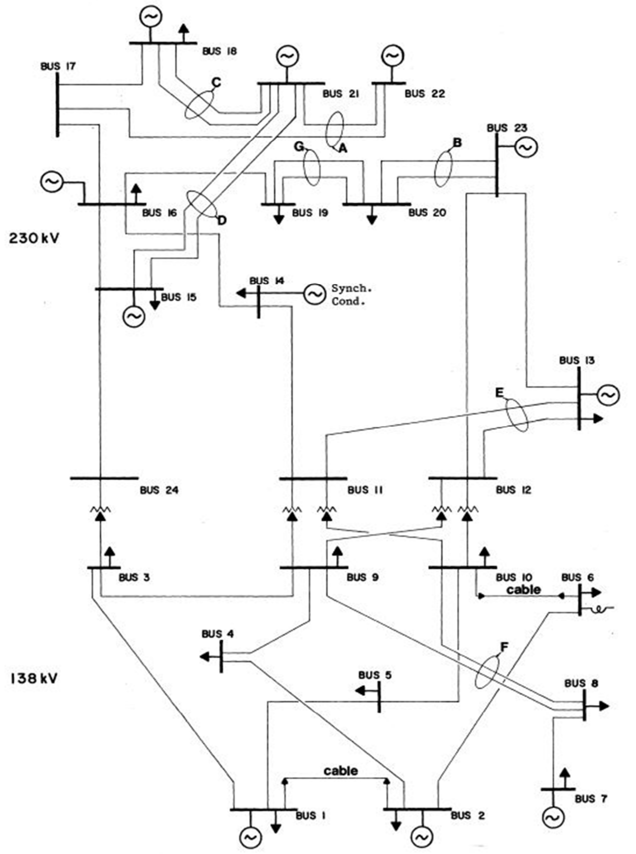

Fig. 1. Experimental apparatus and louver equipment

2.1.2. Model of Load

There are two ways of input data: direct data of hourly load value or indirect data through the correlation with peak loads. IEEE-RTS uses an indirect way. In this way, the hourly load is calculated by correlation with the daily peak, daily peak load is calculated by correlation with the weekly peak, weekly peak load is calculated by correlation with the annual peak. So, changing the annual peak (2850MW in the original scenario of IEEE-RTS) will allow checking the load regimes to perform the growing load researches. Load model of IEEE-RTS is shown in Table 1, Table 2 and Table 3.

Table 1. Weekly Peak load in percent of annual peak

Week	Peak (%)	Week	Peak (%)
1	86.2	27	75.5
2	90.0	28	81.6
3	87.8	29	80.1
4	83.4	30	88.0
5	88.0	31	72.2
6	84.1	32	77.6
7	83.2	33	80.0

8	80.6	34	72.9
9	74.0	35	72.6
10	73.7	36	70.5
11	71.5	37	78.0
12	72.7	38	69.5
13	70.4	39	72.4
14	75.0	40	72.4
15	72.1	41	74.3
16	80.0	42	74.4
17	75.4	43	80.0
18	83.7	44	88.1
19	87.0	45	88.5
20	88.0	46	90.9
21	85.6	47	94.0
22	81.1	48	89.0
23	90.0	49	94.2
24	88.7	50	97.0
25	89.6	51	100.0
26	86.1	52	95.2

Table 2. Daily Peak load in percent of weekly peak

Day	Peak Load (%)
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

Table 3. Daily Peak load in percent of weekly peak

Hour	Winter weeks 1-8&44-52		Summer weeks 18-30		Spring/Fall Weeks 9-17&31-43	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
0-1	67	78	64	74	63	75
1-2	63	72	60	70	62	73
2-3	60	68	58	66	60	69
3-4	59	66	56	65	58	66
4-5	59	64	56	64	59	65
5-6	60	65	58	62	65	65
6-7	74	66	64	62	72	68
7-8	86	70	76	66	85	74
8-9	95	80	87	81	95	83
9-10	96	88	95	86	99	89
10-11	96	90	99	91	100	92
11-12	95	91	100	93	99	94
12-13	95	90	99	93	93	91
13-14	95	88	100	92	92	90
14-15	93	87	100	91	90	90
15-16	94	87	97	91	88	86
16-17	99	91	96	92	90	85
17-18	100	100	96	94	92	88
18-19	100	99	93	95	96	92
19-20	96	97	92	95	98	100
20-21	91	94	93	100	96	97
21-22	83	92	92	93	90	95
22-23	73	87	87	88	80	90
23-24	63	81	72	80	70	85

2.1.3. Model of Generating Units

Table 4. Generating Units Reliability Data

Unit Size (MW)	Number of units	FOR	MTTF (h)	MTTR (h)	Scheduled Maintenance (weeks/year)
12	5	0.02	2940	60	2
20	4	0.10	450	50	2
50	6	0.01	1980	20	2
76	4	0.02	1960	40	3
100	3	0.04	1200	50	3
155	4	0.04	960	40	4
197	3	0.05	950	50	4
350	1	0.08	1150	100	5
400	2	0.12	1100	120	6

In which:

MTTF: Mean Time to Failure; MTTR: Mean Time to Repair

FOR: Forced Outage Rate = MTTR/(MTTF+MTTR)

According to the above data, the total power capacity of the system is 3405MW. Table 4 shows both the FOR and Scheduled Maintenance. However, this research uses only the FOR for generating simulation. This neglect was also applied to the first level of reliability assessment that was published in the previous studies (Table 5 and Table 6).

Table 5. Results of various scenarios published by Roy Billinton and Li [22]

Reliability Index	Annual Peak (MW)			
	2750	2850	2950	3050
LOLE (h/year)	4.8516	9.3716	17.3696	30.7172

Table 6. Results of IEEE-RTS version 1979 scenarios with annual peak of 2850MW published by Ronald Normal Allan et al. [8]

Reliability Index		
Unit	Days/year	h/year
LOLE	1.36886	9.39418

2.2. Parameters of wind turbines

The multiple-state wind power model is simulated by fixing the number of states (4 states), therefore, it consists of 100%, 75%, 50% capacity of wind turbine (Table 7).

Table 7. Parameters of wind turbines for four states simulation

Parameters	Vci (m/s)	Vr (m/s)	Vco (m/s)	MTTF (100% Capacity) (h)	MTTF (75% Capacity) (h)	MTTF (50% Capacity) (h)	MTTR (h)	Pr (MW)
Value	3.5	14.5	25	300	250	200	40	2.055

2.3. Wind power integration scenarios

As described in the previous sections, the total generating capacity of the system is 3405MW; the annual peak is 2850MW; the conventional generating units have a minimum capacity of 12MW, the rated power of the wind turbine is 2055MW. With this data, the following scenarios are proposed for this study:

Wind scenario 1: Keeping the IEEE-RTS data and adding 4 turbines as a power plant of 4 generators. This scenario aims to verify that a small share of wind power will not affect the LOLE index. This scenario has the share of wind power of 0.2%.

Wind scenario 2: Assuming that the wind speed is the same across the entire terrain of the system. The power of each wind turbine is roughly calculated according to the wind velocity as described in Section 3. A sufficient number of wind turbines will be added to affect significantly the reliability (LOLE index). In this scenario, a unit of 12MW and 3 units of 50MW will be replaced by 80 wind turbines. As a result, the total generating power of the system retains approximately the initial power (3405MW). The annual peak rates from 2750MW to 3050MW are performed. This scenario has the share of wind power of 4.8%.

Wind scenario 3: Similarly, the same concept of Wind scenario 2, two units of 20MW and 2 units of 50MW will be replaced by 60 wind turbines. This scenario has a share of wind power of 3.6 %.

Wind scenario 4: Similarly, the same concept of Wind scenario 2, a unit of 12MW, a unit of 20MW and a unit of 50MW will be replaced by 40 wind turbines. This scenario has a share of wind power of 2.4 %.

3. MULTI-STATES MONTE-CARLO SIMULATION OF A WIND TURBINE

The output power of a wind turbine is mainly affected by wind speed but also by some uncertain factors that relate to the technology. The power curve of the wind turbine is usually expressed in terms of wind speed (Fig. 2).

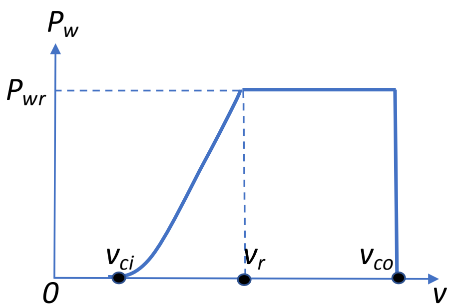

Fig. 2. The power curve of a wind turbine

In which:

- v_{ci}: Cut-in wind speed, at this point, the wind turbine starts spinning.

- v_r: Rated wind speed, theoretically, at this point, the wind turbine delivers the rated power.

- v_{co}: Cut-out wind speed, at this point, the wind turbine is recommended to stop spinning due to safety.

- P_{wr}: Rated power of the wind turbine.

We have known that, according to aerodynamic theories, the theoretical output power is proportional to the third power of wind speed according to the formula:

$$P_W(V) = 0.5 \times \rho \times A \times v^3 \quad (1)$$

In which, ρ is the air density, A is swept area of a wind turbine, v is the velocity or wind speed.

Shu Wang [23] directly utilized the full profile of wind speed to implement the study on the grid reliability. The real output power is calculated with some coefficients (C_p: performance coefficient; N_g: generator efficiency, N_b: gearbox and bearings efficiency) of efficiency according to the modified formula:

$$P_W(V) = 0.5 \times \rho \times A \times v^3 \times C_p \times N_g \times N_b \quad (2)$$

Tengran Sun [24] applied an ARMA model to forecast the wind speed. This ARMA model is very simple and etablished based on the ARMASA toolbox in MATLAB. It's can be seen in Equation 3:

$$\begin{aligned} v_t = {} & 1.1324v_{t-1} - 0.0707v_{t-2} - 0.0793v_{t-3} \\ & - 0.0401v_{t-4} + \varepsilon_t 0.3433\varepsilon_{t-1} \\ & - 0.1247\varepsilon_{t-2} - 0.0193\varepsilon_{t-3} \end{aligned} \quad (3)$$

Where, $\boldsymbol{\varepsilon_i}$ is the i[th] white noise error terms of moving average. The obtained data is then recalculated to simulate the output wind turbine power. As for processing time series data, Abdulaziz Almutairi [25] did not use the ARMA model but instead was the MCMC model which is the hybrid of Monte-Carlo and Markov Chain techniques. In contrast to the simplicity of ARMA model, the MCMC model is quite complicated with the big data.

However, there are several methods to simulate the wind turbine power depending on the operation of the wind turbine and the number of states to be simulated. The output power of the wind turbine, therefore, is usually expressed as the segmental formulas [26]:

$$P_W(V) = \begin{cases} 0 & (V < v_{ci}) \text{ or } (V > v_{co}) \\ \dfrac{P_{wr}}{{v_r}^3 - {v_{ci}}^3}(V^3 - {v_{ci}}^3) & (v_{ci} \le V \le v_r) \\ P_{wr} & (v_r < V \le v_{co}) \end{cases} \quad (4)$$

or [27, 28]:

$$P_W(V) = \begin{cases} 0 & (V < v_{ci}) \text{ or } (V > v_{co}) \\ \dfrac{P_{wr}}{v_r - v_{ci}}(V - v_{ci}) & (v_{ci} \le V \le v_r) \\ P_{wr} & (v_r < V \le v_{co}) \end{cases} \quad (5)$$

Therefore, based on measured wind speed data, it is possible to simulate the wind turbine's output power for the reliability research according to the three-step algorithm:

Step 1: Collecting and processing the wind speed data.

Step 2: Modeling the output power curve of a wind turbine by a function of wind speed.

Step 3: Determining the number of states of simulated wind turbine and dividing the calculated output power resulted from step 2 into these states.

In considering planning issues, the wind data (included the wind speed) is always required. So, in the step 2, the approximate formula of the output power based on the wind speed is described by [29]:

$$P_t = \begin{cases} 0 & 0 < v < v_{ci} \\ (A + B * v + C * v^2) * p_r & v_{ci} \le v < v_r \\ p_r & v_r \le v < v_{co} \\ 0 & v \ge v_{co} \end{cases} \tag{6}$$

In which, A, B and C coefficients are defined by a group of formulas:

$$\begin{cases} A = \dfrac{1}{(v_{ci} - v_r)^2}\left[v_{ci}(v_{ci} + v_r) - 4v_{ci}v_r\left(\dfrac{v_{ci} + v_r}{2v_r}\right)^3\right] \\ B = \dfrac{1}{(v_{ci} - v_r)^2}\left[\begin{matrix} 4(v_{ci} + v_r)\left(\dfrac{v_{ci} + v_r}{2v_r}\right)^3 \\ -(3v_{ci} + v_r) \end{matrix}\right] \\ C = \dfrac{1}{(v_{ci} - v_r)^2}\left[2 - 4\left(\dfrac{v_{ci} + v_r}{2v_r}\right)^3\right] \end{cases} \tag{7}$$

With this group of formulas, we obtain the actual output power corresponding the actual wind speed. Then, the formulas 8 and 9 are used to convert the output power into three and four states.

Three-states

$$P_d = \begin{cases} 0 & p_t < 0.25p_r \\ 0.5p_r & 0.25p_r \le p_t < 0.75p_r \\ P_r & p_t \ge 0.75p_r \end{cases} \tag{8}$$

Four-states

$$P_d = \begin{cases} 0 & p_t < 0.25p_r \\ 0.25p_r & 0.25p_r \le p_t < 0.5p_r \\ 0.5p_r & 0.5p_r \le p_t < 0.75p_r \\ p_r & p_t \ge 0.75p_r \end{cases} \tag{9}$$

Note that formula 7 is a shortened version of formula 8 which is derived from the publication of [21]. In which, P_d is the converted power, p_t is the actual power and p_r is the rated power of the wind turbine.

4. RESULTS AND DISCUSSION

4.1. Results on IEEE-RTS test with various load scenarios

In this test model, the load will be changed by changing the annual peak load. The annual peak load of 2750, 2850, 2950, 3050MW is used for performing. For each scenario, the simulation implements 4 times (corresponding to 1000, 2000, 5000, 10000 steps). For each simulation, the final result is the average value of three times of the same execution with the same number of steps. The simultaneous execution of multiple simulations allows choosing the optimal number of executions (taking into account the correlation between simulating time and simulating errors) to use for the scenarios integrated renewable power. The greater the amount of executions, the more the convergent point of simulation is closer to the real value. However, the references do not always refer to the total amount of execution and how the algorithm is programmed, so, it is quite difficult to compare results between this study and the references. The results of all test scenarios will be shown in Figures 3, 4, 5 and 6.

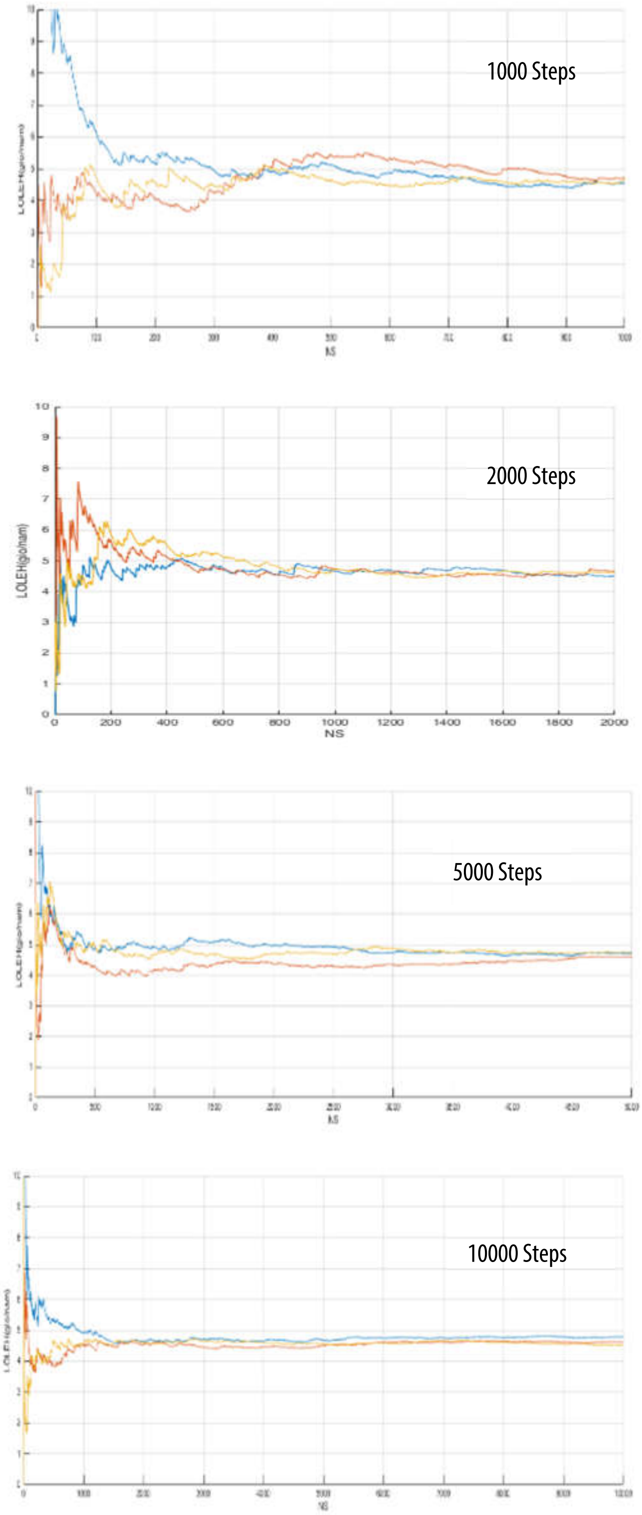

Fig. 3. Scenario corresponding to the annual peak of 2750MW. NS: Total amount of executions

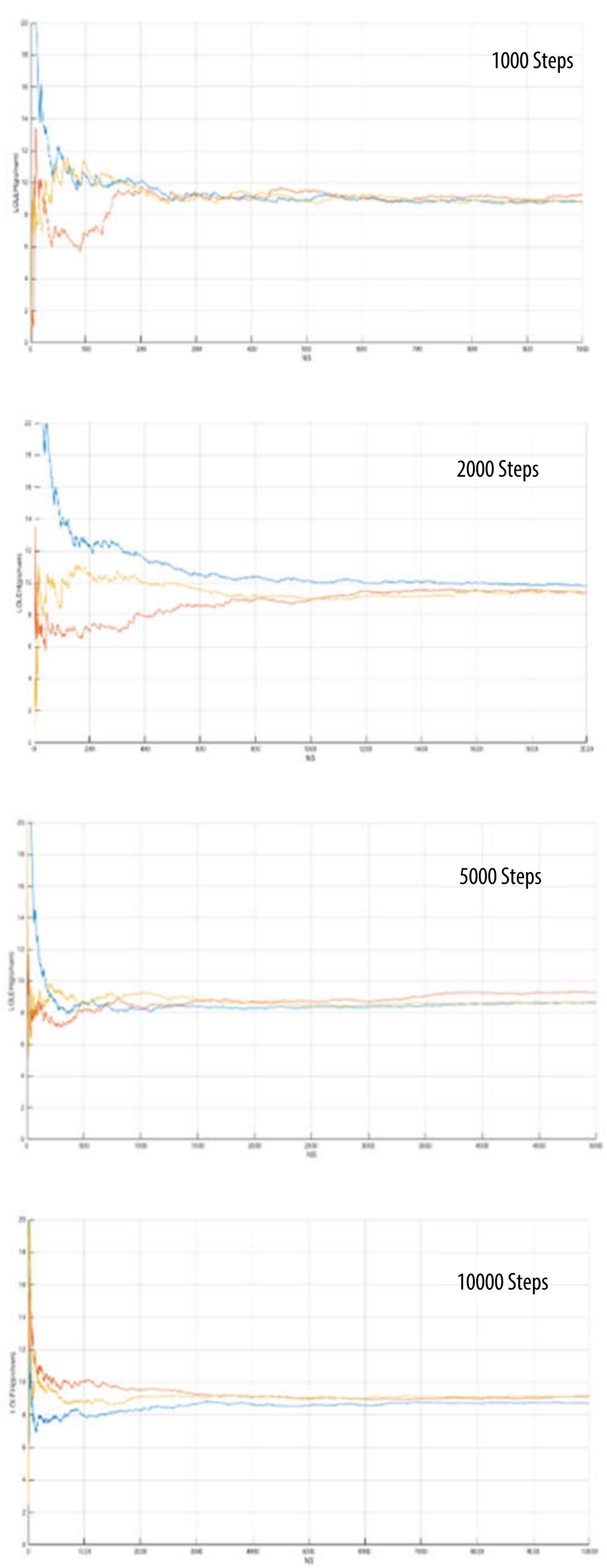

Fig. 4. Scenario corresponding to the annual peak of 2850MW. NS: Total amount of executions

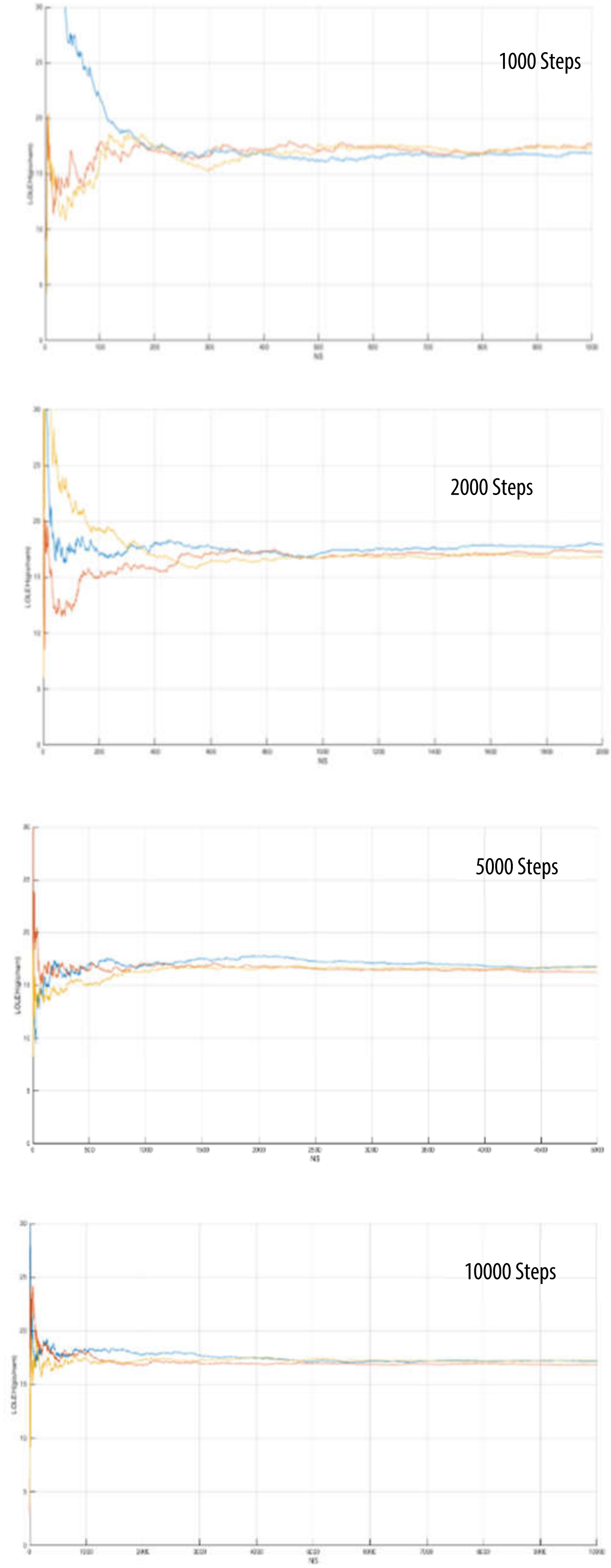

Fig. 5. Scenario corresponding to the annual peak of 2950MW. NS: Total amount of executions

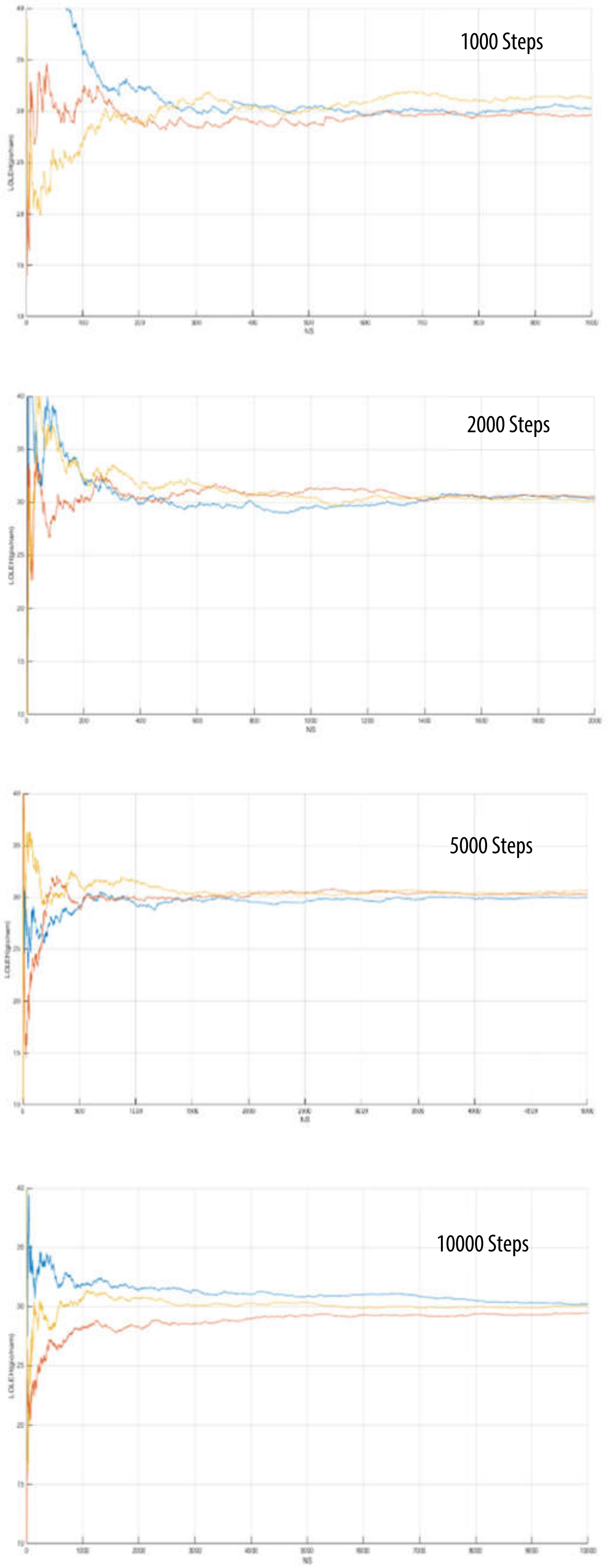

Fig. 6. Scenario corresponding to the annual peak of 3050MW. NS: Total amount of executions

On these figures, three lines on the graph illustrate the LOLEH values (LOLE with the hourly unit). The significant difference between the three lines confirms the need for multiple executions and the calculation of the average from the achieved results. What can be clearly seen in these figures is the variability of LOLEH before 1000 steps. The LOLEH is expected to remain steady after 2000 steps but this observation is not really true in case of 3050MW annual peak. This difference is due to the random function in MATLAB Software. The generating model depends completely on this function. These results are summarized in Table 8.

Table 8. Summary of the results from 4 testing scenarios

Scenario	2750 MW	2850 MW	2950 MW	3050 MW	2750 MW	2850 MW	2950 MW	3050 MW
NS	LOLEH (h/year)				Time of Simulation (s)			
1000	4.64	8.96	17.31	30.40	32.61	29.14	27.91	35.54
2000	4.58	9.55	17.35	30.35	62.01	52.08	50.17	60.39
5000	4.69	8.87	16.57	30.31	145.58	134.13	117.23	157.59
10000	4.64	8.99	17.08	29.90	234.40	230.27	298.92	282.08
Average	4.64	9.09	17.08	30.24				

By comparison with the references, the results can be shown in Table 9.

Table 9. Comparison between the simulated results and the sample tests

	LOLE (h/year)			
Annual Peak (MW)	2750	2850	2950	3050
Results	4.64	9.09	17.08	30.24
Billinton et al.	4.8516	9.3716	17.3696	30.7172
Allan et al.		9.39418		

Table 9 shows the similar LOLE values in all scenarios by comparing with the result of Billinton et al. The research of Allan et al. did not show the LOLE value at all annual peak but only in the scenario of 2950MW. However, this value is not significantly different from the result of this paper and of Billinton's publication. So, it could be seen that the algorithms are properly programmed and could be used for the integrated wind power studies in the next subsection. Because of the similarity between LOLEH of tests corresponding to 1000, 2000, 5000, 10000 steps, 5000 is selected for the number of simulation steps based on stable convergence and not too large execution time.

4.2. Reliability of the power source with the participation of wind turbines

Table 10. Comparison between three scenarios with the participation of wind turbines

Annual Peak (MW)	Wind scenario 2	Wind scenario 3	Wind scenario 4
2750	13.31	9.94	7.91
2850	24.32	18.92	14.75
2950	41.08	32.82	26.32
3050	70.01	56.81	45.43

As shown in the previous section, the results are based on simulation of 4 scenarios using the IEEE-RTS version 1979 with different annual peaks. Note that all LOLEH values are the average value of multiple re-executions. So, the results are given in Table 10.

It is easy to see that, although the share of wind power is not too big (smaller than 5%), it makes change so much more than the non-wind power (original scenario) or negligible wind (wind scenario 1) scenario. In each wind scenario, the LOLEH index increases sharply as the annual peak increases by 100MW (equivalent about 3.5% of the original annual peak: 2850MW). So, results suggest a hypothesis that when the annual peak is less than the total power capacity of the system then the wind power share of 0.2% is almost unaffected the LOLEH index. As the annual peak increases, there is a slight change in the LOLEH value. This hypothesis should be verified because this change is uncertain.

5. CONCLUSIONS

This research shows that when the share of wind power is negligible, the LOLEH index is almost unchanged. However, the greater the share of wind power, the lower the power reliability due to the increase of LOLEH value. In particular, the LOLEH value almost doubles as the annual peak increases 100MW (equivalent 3.5% of the original annual peak). The unreliability of wind power not only does not represent an irreversible disadvantage of this renewable energy source but also creates new studies that offer solutions to increase the reliability of the power system with renewable energy sources. One of the solutions to overcome this disadvantage is the construction of energy storage centers such as pumped-storage hydroelectric power plants or big storage battery system. These studies, therefore, are particularly important in trend using clean energy to replace fossil energy sources.

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