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Reliability of Power System with High Wind Penetration under Frequency Stability Constraint

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***Abstract*—This paper presents a new method to evaluate the reliability of a power system with high penetration of wind generation, considering the impact of not only the intermittence but also the low inertia characteristic of wind power. As wind generation gradually replaces conventional generation, the system stability and the reliability are negatively affected. Some of the measures employed to deal with the challenges resulting from increasing wind penetration include operating wind generators at lower levels than their available output and providing inertia so that wind generation is able to contribute to system frequency regulation. Apart from these measures, another factor that limits the amount of wind power that can be absorbed into the grid is the imposition of the frequency standard and this also affects the reliability of the system in the presence of wind penetration. The reliability evaluation approach proposed in this paper is developed using discrete convolution and implemented on an IEEE RTS-79 system with a suitable modification. Power system reliability with and without considering the impacts of wind intermittence and low inertia are compared to show the effectiveness of the proposed method.**

***Index Terms*—Frequency regulation, intermittence, inertia, penetration limit, reliability, wind generation.**

I. Introduction

MODELING of wind generation in power system reliability has been amply addressed in previous works, using both analytical and state sampling methods. In [1]–[3], the probabilistic models for wind power and their use in reliability studies of wind-integrated systems were investigated. In prior work, detailed probabilistic models of wind farms or wind turbines have been developed, which have considered different wind regimes, spatial wind speed correlation, wake effects [4]–[6], the correlation between turbine outputs [7], [8], and a large number of wind turbines [9]. A method to determine the equivalent capacity of a wind farm using Monte Carlo simulation is presented in [10]. State sampling has also been used to evaluate the reliability indexes of a wind farm [11], [12], and of the integrated system [13], [14]. Transmission constraints have also been taken into account when evaluating the reliability of a system with large-scale wind power [15].

However, the research reported in the literature does not simultaneously capture the effects of intermittency and low inertia on system reliability. As a variable and low inertia source of power, wind generation causes technical challenges such as the generation reserve requirement [16], frequency deviation [17], [18], transmission violation [19], [20] and voltage instability [21], [22]. The reduction in frequency response due to the increase of variable generation has been reported by the North American Electric Reliability Corporation (NERC), Electric Reliability Council of Texas (ERCOT) and Western Interconnect (WECC) [23]–[25]. These challenges limit the penetration level of wind generation. Only as much wind power should be injected as can be tolerated by the system while preserving stability. Therefore, the availability of wind generation in power system reliability modeling must be evaluated considering stability requirements.

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The work presented in this paper extends the prior art by adding the following contributions: (i) it proposes an improved reliability modeling of wind generation which considers the impacts of wind intermittence and low inertia; (ii) it presents a direct, analytical method, based on discrete convolution, to evaluate the system reliability in the presence of wind generation.

Due to the system stability requirement, the traditional reliability model of wind farms is modified. The improved reliability model is developed based on the following two criteria:

- The wind generators are required to operate below their available output power to ensure that they have the ability to provide reserve for frequency regulation [26], [27].
- Wind generation has low inertia, which negatively affects the stability of the system [17], [28]. Therefore, wind penetration is limited to ensure system frequency stability.

Since all of the available output power of wind generation cannot be accepted by the system, the reliability of the grid is affected.

The proposed approach is tested on the modified IEEE-RTS 79 system. The reliability indexes are calculated with and without the frequency stability constraint. The results show how the inclusion of the stability constraint impacts the system reliability.

The remainder of this paper is organized as follows. Section II explains the reliability model of a wind farm with impacts of the intermittence and low inertia characteristics of wind generation. The discrete convolution model for evaluating the reliability of power system with wind farms is shown in section III. Simulation results that compare the models with and without considering the effects of wind intermittence and low inertia are presented in section IV. In this section, some observations are also included to clarify the salient aspects of the contribution. Finally, section V provides some concluding remarks on the work presented.

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II. Reliability of the Integrated System Considering the Impacts of Intermittence and Low Inertia

The integrated system is modeled as a combination of multiple conventional generators and wind farms. The reliability of an integrated system is evaluated using the following 3 steps:

- Calculating the individual probabilities and frequency of all power outage states for each wind farm.
- Modeling the impacts of intermittence and low inertia of wind generation on the system frequency stability to modify the reliability indexes of wind farms.
- Calculating the reliability of the integrated system using discrete convolution under the stability constraints.

The details of each step are presented below.

A. Modeling of Wind Farm

1) Modeling of wind speed: To estimate the system reliability, wind speed is approximated by the discrete Markov process (Markov chains) with a finite number of states [4], [6]. An exemplar of wind speed model with n states is shown in Fig. 1. This model reflects the probability, the frequency and the duration attributes of wind speed. It is assumed that the wind speed is statistically stationary. The transitions between wind speed states and wind turbine states are independent and the transitions between all states are considered. To estimate the wind model parameters, the exponential distribution or the sample adjustment can be used [4]. In this project, a realization or a sample path of the wind speed is used to estimate the probability, the frequency and transition rate of each wind state. Since the total number of samples is very large (long realization), the probability can be estimated as follows [4]:

$$p_{c,i} = \frac{\sum_{j=1}^{N} n_{ij}}{\sum_{k=1}^{N}\sum_{j=1}^{N} n_{kj}} \tag{1}$$

where $p_{c,i}$ is the probability of wind being in state i, n_{ij} is the number of transitions from state i to state j, and N is the number of states.

The transition rate between any two states is calculated based on frequency balance between them as follows [4]:

$$\rho_{i,j} = \frac{N_{ij}}{D_i} \tag{2}$$

where N_{ij} is the number of transitions from state i to state j and D_i is the duration of state i.

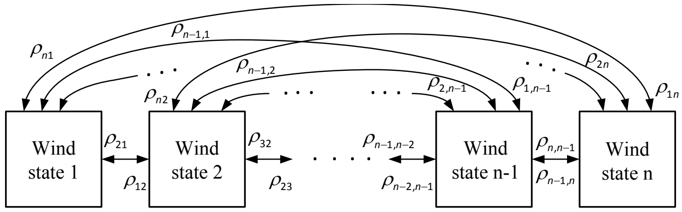

Fig. 1. Wind speed model with n states.

2) Modeling of wind turbine output: The output power of a wind turbine depends on two factors: wind speed and turbine availability. The non-linear relationship between wind power output and wind speed is shown in Fig. 2 and equation (3) [29].

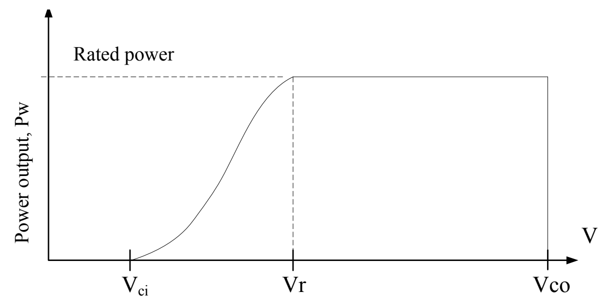

Fig. 2. Wind power output and wind speed relationship.

$$P_w = \begin{cases} 0 & 0 \le V \le V_{ci} \\ (A + B \times V + C \times V^2)P_r & V_{ci} < V \le V_r \\ P_r & V_r < V \le V_{co} \\ 0 & V_{co} < V \end{cases} \tag{3}$$

where V_{ci}, V_{co}, V_r, P_r are the cut-in, cut-out, rated speed, and rated power of the wind turbine, respectively. The constants A, B, and C are as follows [8]:

$$A = \frac{1}{(V_{ci} - V_r)^2}[V_{ci}(V_{ci} + V_r) - 4(V_{ci}V_r)\frac{(V_{ci} + V_r)^3}{2V_r}]$$
$$B = \frac{1}{(V_{ci} - V_r)^2}[4(V_{ci} + V_r)\frac{(V_{ci} + V_r)^3}{2V_r} - (3V_{ci} + V_r)]$$
$$C = \frac{1}{(V_{ci} - V_r)^2}[2 - 4\frac{(V_{ci} + V_r)^3}{2V_r}]$$

3) Modeling of wind farm capacity outage: The model of wind farm output is the combination of wind speed model and wind turbine model. In the wind turbine model, the wind turbine availability is represented by a binary state component (the turbine is in service or out of service) which is similar to the conventional generators. While considering the wind farm output model, some assumptions have been made:

- All the turbines in a wind farm are approximately subject to the same wind speed. Because of the consistent behavior of wind turbines with the wind speed variation on the entire wind farm, similar wind turbines have similar outputs with some deviation [30] and their average outputs are approximately equal.
- All the turbines have the same failure rate λ_t and repair rate μ_t.
- All the states with the same output power are combined into one state.

As discrete convolution will be used later to calculate reliability of the integrated system, the model of wind farm output only considers the individual probability for each outage power state of the wind farm and its frequency to the lower outage capacity states. Also, all the transitions among wind states are considered, which is more appropriate than the birth and death Markov chain. This method is more convenient than previous methods as this method reduces the computational burden of calculating the transition frequencies of states to higher outage capacity states, since the required frequencies can be obtained just by considering transitions to lower outage capacity states. The model of wind farm outage is shown in matrix form in Fig. 3. In this figure, the capacity outage corresponding to each state is shown; these will be duly used in performing the discrete convolution. It should be noted that only the transitions from one state to other states with lower capacity outages are shown. The reason is that only these transitions are necessary when calculating the individual probability and frequency of wind farm states to other states with lower capacity outages.

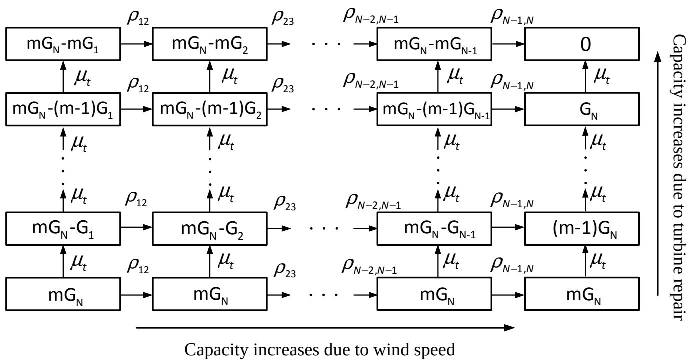

Fig. 3. State transition diagram for wind farm (the transitions between non-adjacent states are not shown for the sake of clarity).

In Fig. 3, m is number of wind turbines, G_j is the output of a single turbine at wind state j, and the transitions between non-adjacent states are not shown for the sake of clarity.

The capacity outage of each state can be represented as:

$$C_{i,j} = mG_N - (m - i + 1)G_j \tag{4}$$

The individual probability of each outage state in Fig. 3 is calculated as follows:

$$p_{i,j} = p_{tb,i}p_{c,j} \tag{5}$$

where $p_{tb,i}$ is the probability of all wind turbines at state (i, j) and is calculated as follows:

$$p_{tb,i} = C_m^{m-i+1} p_u^{m-i+1} p_d^{i-1} \tag{6}$$

where p_u and p_d are the probabilities of a wind turbine being up and down, respectively. C_m^{m-i+1} is the combination of m turbines taken $m - i + 1$ at a time.

The individual jumping frequency to the lower capacity outage states of each outage state in Fig. 3 is calculated as follows:

$$f_{i,j} = p_{i,j} \sum \rho_{i,j}^+ \tag{7}$$

where $\rho_{i,j}^+$ is the transition rate of state (i, j) to other states with lower capacity outages.

After grouping all states with the same capacity outages into one state, the probability of a capacity outage X and its frequency to the lower outage capacity is calculated as follows:

$$P_r(X) = \sum_{i,j} p_{i,j}(X) \tag{8}$$

$$\beta^+(X) = \frac{\sum_{i,j} f_{i,j}(X)}{P_r(X)} \tag{9}$$

If the impact of wind intermittence and low inertia is not considered, the results of wind farm probability and frequency can be used to combine with conventional generators to estimate the reliability of the system. However, this method is only appropriate when the level of wind penetration is low. When wind integration is high, the frequency stability of the system is negatively affected. Hence, it is necessary to consider the impact of wind intermittence and low inertia to ensure the system stability while system reliability is calculated.

B. Modeling the Impact of Wind Intermittence and Low Inertia

Due to its well-known uncertainty characteristics, wind power causes problems in maintaining the system frequency. In the presence of wind, the frequency disturbance gets worse in both density and magnitude. As required by power system standards, the frequency deviation must remain within the safe limits. To ensure the frequency security, several methods have been proposed. As described in [26], [27], the reserve requirement is mandatory for the wind turbine to support frequency regulation. The wind generators have to operate below their available output power to ensure that they have the ability to provide reserve for frequency regulation. The reserve requirement is implemented in wind generators by Delta control. The idea behind this control is to maintain a certain amount of power reserve so that the wind generators have the ability to respond and alter their outputs quickly both with positive and negative power ramps. As a result, the total available wind power might not be absorbed completely into the system. Because of the reserve requirement, the contribution of wind power to the reliability of the system reduces due to the decrease in injected wind power.

Besides the uncertainty, one of the drawbacks of wind is that wind turbines have very low inertia compared to that of conventional generators. This property of wind also introduces negative effects on the frequency regulation when wind generators replace conventional generators—larger frequency deviation and longer restoration time [28]. These negative effects become more adverse if the penetration of wind power increases [24], [25]. Due to the negative effect of wind on system frequency, the amount of wind that can be injected into the system is limited to ensure system stability. The method to estimate the penetration limit of wind power has been presented in previous works based on the stability power quality criteria: system minimum reserve requirement, the network congestions, voltage stability, system capacity, frequency stability, thermal violations [31], [32], transient stability limit, frequency security constraint [33], and wind-thermal coordination scheduling [34]. In this paper, the fast approximation of penetration limit based on the sensitivity analysis of maximum frequency deviation is developed.

To estimate the penetration limit of wind power based on frequency security, it is necessary to understand the mathematical model of the system frequency. Fig. 4 is the model of LFC for the multi-machine system proposed in [35] based on

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the sensitivity of the frequency deviation to the governor parameters for the low-order LFC model [36] using linear curve-fitting. The sensitivity of the maximum frequency deviation to governor parameters in [35] is shown in Table I.

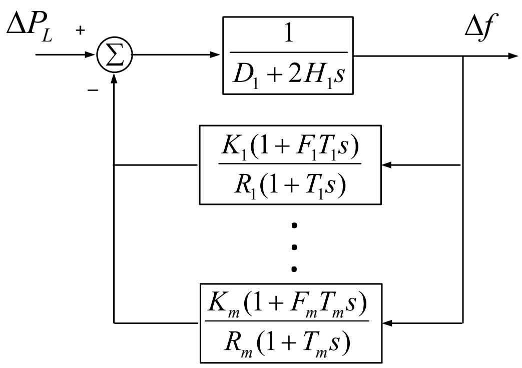

Fig. 4. Multi-machine LFC model [35].

TABLE I
SENSITIVITY OF FREQUENCY NADIR TO GOVERNOR PARAMETERS

Parameters	T_R	H	F_H	D	R
Min	4	3	0.1	0	0.03
Max	11	9	0.35	2	0.08
Sensitivity	−0.01	0.03	1.35	0.05	−9.14

As shown in the sensitivity results, the sensitivity of the maximum frequency deviation to the governor time constant is very small. Therefore, it is assumed in [35] that the governor time constants for the system governors are identical without significantly compromising the accuracy.

Assuming that load disturbance is a step function, the frequency deviation can be shown by the following equation [35]:

$$\Delta f = \frac{\frac{\Delta P_L}{s}}{D + 2Hs + \sum_{i=1}^{m} \frac{K_i(1+F_iT_Rs)}{R_i(1+T_Rs)}} \tag{10}$$

Taking the inverse Laplace transform, the time-domain of frequency deviation can be given as:

$$\Delta f = \frac{\Delta P_L}{2HT_R\omega_n^2}(1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\cos(\omega_n\sqrt{1-\zeta^2}t - \phi)) + \frac{\Delta P_L}{2H\omega_n\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\sin(\omega_n\sqrt{1-\zeta^2}t) \tag{11}$$

where

$$\phi = \tan^{-1}(\frac{\zeta}{\sqrt{1-\zeta^2}}) \tag{12}$$

$$\omega_n = \sqrt{\frac{1}{2HT}(D + R_T)} \tag{13}$$

$$\zeta = \frac{1}{2}[\frac{2H + T_R(D + F_T)}{\sqrt{2HT_R(D + R_T)}}] \tag{14}$$

$$F_T = \sum_{i=1}^{m} \frac{K_iF_i}{R_i} \tag{15}$$

$$R_T = \sum_{i=1}^{m} \frac{K_i}{R_i} \tag{16}$$

At the maximum frequency deviation, the derivative of frequency deviation equals zero. Hence, the time of the maximum frequency deviation and the maximum frequency deviation can be derived as [35]:

$$t_{max} = \frac{1}{\omega_n\sqrt{1-\zeta^2}}\tan^{-1}(\frac{\omega_n\sqrt{1-\zeta^2}}{\zeta\omega_n - 1/T}) \tag{17}$$

$$\Delta f_{max} = \frac{\Delta P}{R_T + D}(1 + e^{-\zeta\omega_n t_{max}}\sqrt{\frac{T_R(R_T - F_T)}{2H}}) \tag{18}$$

Assuming that the fraction of reduction in the system inertia when wind power replaces the conventional generators is α_{conv}, and the inertia that wind contributes to the system is α_w, the new values of system inertia and the equivalent regulation constant can be expressed by:

$$H^{new} = H^{old}(1 - \alpha_{conv} + \alpha_w) = \alpha H^{old} \tag{19}$$

$$R^{new} = R^{old}/(1 - \alpha_{conv} + \alpha_w) = R^{old}/\alpha \tag{20}$$

Applying the new values of H and R to equation (18), the new value of the maximum frequency deviation in the presence of wind power is given as:

$$\Delta f_{max} = \frac{\Delta P}{\alpha R_T + D}(1 + e^{-\zeta^{new}\omega_n^{new}t_{max}^{new}}\sqrt{\frac{T(R_T - F_T)}{2H}}) \tag{21}$$

where

$$F_T^{new} = \sum_{i=1}^{m} \alpha\frac{K_iF_i}{R_i} = \alpha F_T \tag{22}$$

$$R_T^{new} = \sum_{i=1}^{m} \alpha\frac{K_i}{R_i} = \alpha R_T \tag{23}$$

$$\omega_n^{new} = \sqrt{\frac{1}{2\alpha HT_R}(D + \alpha R_T)} \tag{24}$$

$$\zeta^{new} = \frac{1}{2}\frac{2\alpha H + T_R(D + \alpha F_T)}{\sqrt{2\alpha HT_R(D + \alpha R_T)}} \tag{25}$$

To ensure system security, the maximum frequency deviation should not exceed the safe limit:

$$\Delta f_{max} \leq \Delta f_s \tag{26}$$

As the value of D is often much smaller than R_T and F_T, the values of ω_n^{new} and ζ^{new} do not have a notable change when changing D. Also, the sensitivity of maximum frequency deviation to D (0.05) is much less than that to R (−9.14) and F_H (1.35). Moreover, the change in load damping does not have a large impact on the exponential term. Therefore, it is reasonable to approximate the values of ω_n^{new} and ζ^{new} and the limit α_{max} as follows:

$$\omega_n^{new} = \sqrt{\frac{1}{2\alpha HT_R}(\alpha R_T)} = \sqrt{\frac{R_T}{2HT_R}} \tag{27}$$

$$\zeta^{new} = \frac{1}{2}\frac{2\alpha H + \alpha T_RF_T}{\sqrt{2\alpha HT_R\alpha R_T)}} = \frac{1}{2}\frac{2H + T_RF_T}{\sqrt{2HT_RR_T}} \tag{28}$$

$$\alpha_{max} = \frac{\Delta P_L}{\Delta f_s R_T}(1 + e^{-\zeta \omega_n t_{max}} \sqrt{\frac{T_R(R_T - F_T)}{2H}}) \quad (29)$$

Based on the limit of inertia reduction, the maximum amount of wind integrated into the system is defined.

Previous work evaluating the reliability of a power system in the presence of wind considers all of the available wind output in the reliability model. However, in view of the two problems mentioned before that affect the amount of integrated wind power, the traditional reliability model of the system with wind power should be re-evaluated. The real amount of wind power injected into the system is lower than the available wind output, which means that the reliability of the system is negatively affected.

C. Capacity Outage Probability and Frequency Table

While combining the wind turbine model with the wind speed model, wind generation is treated as a generator with multiple derated states. The Unit Addition Algorithm with discrete convolution is utilized to build a Capacity Outage Probability and Frequency Table (COPAFT) [37]. The COPAFT of the integrated system which includes conventional generators and wind generators is built as follows:

1) Build COPAFT for all conventional generators: Each conventional generator is modeled as a two-state unit. The cumulative probability of a capacity outage stage of X MW after adding a unit of capacity C MW is as follows [37]:

$$P(X) = \sum_{i=1}^{2} P'(X - C_i) p_{cv,i} \quad (30)$$

where $P(X)$ is the "new" cumulative probability of the capacity outage state X MW and $P'(X - C_i)$ is the "old" cumulative probability of the capacity outage state $X - C_i$ MW. If $X \leq C_i$ then $P'(X - C_i) = 1$. $p_{cv,i}$ is the individual probability of the conventional generator with the capacity outage C_i.

The cumulative frequency $F(X)$ for a forced outage of X MW is given as follows [37]:

$$F(X) = \sum_{i=1}^{2} F'(X - C_i) p_{cv,i} + (P'(X - C_2) - P'(X)) p_{cv,2} \mu_{cv} \quad (31)$$

where μ_{cv} is the repair rate of conventional generator. If $X \leq C_i$ then $F'(X - C_i) = 0$

2) Including wind farms: As mentioned in the previous section, wind farms are modeled as multi-state generators. Each capacity outage level is associated with a probability and frequencies of transitions to higher or lower outage levels; however in this analysis we consider only the transitions to lower outage levels for frequency calculation, since the system is considered to be frequency balanced.

The cumulative probability and frequency of the capacity outage state X MW is calculated as follows:

$$P(X) = \sum_{i=1}^{N} P'(X - C_{w,i}) P_{r,i} \quad (32)$$

$$\begin{aligned} F(X) = & \sum_{i=1}^{N} F'(X - C_{w,i}) P_{r,i} \\ & + \sum_{i=1}^{N-1} (P'(X - C_{w,i+1}) - P'(X - C_{w,i})) P_{r,i+1} \beta_{i+1}^{+} \\ & + (P'(X - C_{w,N}) - P'(X - C_{w,1})) P_{r,N} \beta_N^{+} \end{aligned} \quad (33)$$

As can be seen from equations (32) and (33), the equations (30) and (31) are special cases of equations (32) and (33) with $N = 2$. This means that the conventional generator can be regarded as a special case of a multi-state unit where the number of states equals 2.

The probability calculations are easy to understand. The frequency calculations may be understood as follows. Consider adding a two-state unit of capacity C to an existing COPAFT with states $x_1, x_2, \cdots$. Fig. 5 shows the states created as a result of adding the two-state unit.

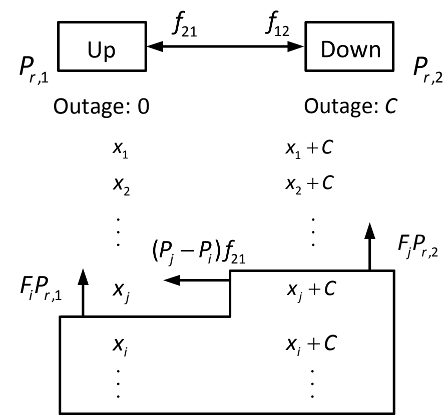

Fig. 5. Unit addition diagram for a two-state unit.

The first column shows the outage states prior to the addition of the new unit, and the second column shows the new outage states created. The set of states inside the polygon is described by $\{C_O \geq x_i\}$. In the steady state, the frequency of encountering the set is equal to the frequency of exiting the set [37]. This frequency can therefore be computed as:

$$F(C_O \geq x_i) = F_i P_{r,1} + F_j P_{r,2} + (P_j - P_i) f_{12} \quad (34)$$

where the first two terms result from the changes in states of units other than the unit being added, while the last term results from a change in the state of the unit being added.

When this concept is extended to the addition of wind farms as multi-state units, the state frequency diagram assumes the form shown in Fig. 6, and the general form shown in (33) is used to calculate cumulative frequencies.

From above analysis, the COPAFT of the integrated system is constructed to estimate system reliability.

III. Results and Discussion

The proposed approach is tested on the modified IEEE-RTS system with 43 identical wind farms. The original system includes 32 conventional generators with a total capacity of 3405 MW. The modified IEEE-RTS system has 26 conventional

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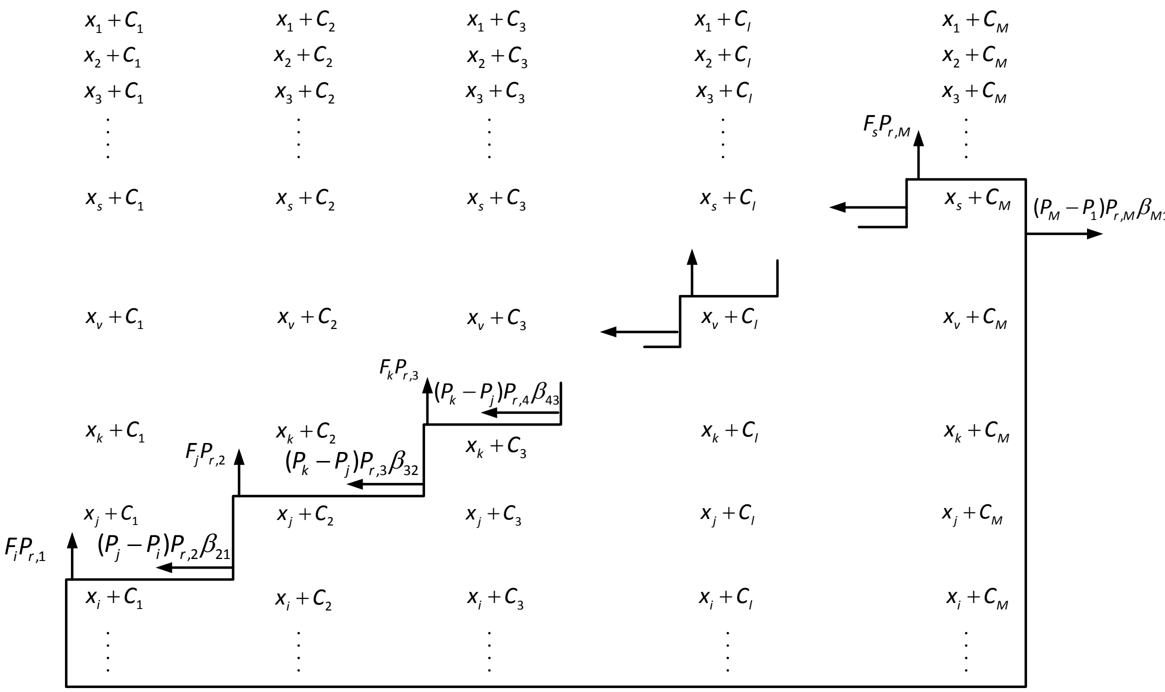

Fig. 6. State frequency diagram for unit addition.

generators and 43 identical wind farms. Each wind farm has 10 wind turbines, each with 8 MW rated power. The data for IEEE-RTS system can be found in [38]. The inertia data of IEEE-RTS system is shown in Table II [38]. The reliability of the system is evaluated for two cases: i) considering and ii) neglecting the impacts of wind intermittence and low inertia. The total rated power of the wind turbines is 3440 MW. This wind generation replaces six conventional generators with a total capacity of 860 MW. The replaced conventional generators include four 76 MW coal generators at bus 1 and 2, one 155 MW coal generator at bus 15, and one 400 MW nuclear generator at bus 21. As wind generation does not always operate at its rated power, the total rated wind generation is chosen so that the amount of replaced conventional generation equals 25% of the total rated wind capacity. The wind data is extracted from [39] which is provided by National Renewable Energy Laboratory (NREL). Available data are collected over ten minutes periods. However, the data is clustered into one hour periods. The wind turbines are considered with the mean time to failure and the mean time to repair of 3600 hours and 150 hours, respectively. The cut-in, rated and cut-out speeds are 4, 12, and 25 m/s, respectively.

Considering one-hour intervals, the annual wind speed is represented by eight states with a step size equal to 1 m/s. This is because some of the states were combined together since they produce identical power (states 1– 6 produce 0 MW and states 12 – 25 produce 8 MW). Therefore, each wind turbine is treated as an eight-state unit. The transition rates among the eight states are shown in Table III.

Four scenarios will be investigated to show the effect of the intermittence and low inertia of wind generation on system reliability:

Scenario 1: The effects of intermittence and low inertia of wind generation are not considered.

TABLE II
SYSTEM INERTIA DATA

Unit group	U_{12}	U_{20}	U_{50}	U_{76}	U_{100}	U_{155}	U_{197}	U_{350}	U_{400}
Unit size (MW)	12	20	50	76	100	155	197	350	400
Inertia (MJ/MW)	0.34	0.56	1.75	2.28	2.80	4.65	5.52	10.5	20

TABLE III
TRANSITION RATES BETWEEN WIND SPEED STATES

State	1	2	3	4	5	6	7	8
1	0.799	0.119	0.048	0.019	0.008	0.004	0.001	0.002
2	0.319	0.3	0.228	0.104	0.034	0.004	0.007	0.003
3	0.121	0.212	0.346	0.198	0.083	0.025	0.01	0.005
4	0.037	0.085	0.212	0.314	0.251	0.069	0.019	0.013
5	0.017	0.023	0.09	0.193	0.359	0.223	0.074	0.022
6	0.005	0.006	0.026	0.091	0.226	0.361	0.213	0.073
7	0.004	0.004	0.008	0.021	0.084	0.221	0.371	0.287
8	0.001	0.001	0.001	0.004	0.011	0.036	0.101	0.846

When the variability and inertia impacts are neglected, all the available wind output is integrated into the grid. The capacity outage of a wind turbine for each wind state and its probability are shown in Table IV. For simplicity, the output of wind turbine is approximated to the closest integer. Based on the data provided in Table III, IV and applying the proposed method, the COPAFT for a wind farm with 10 wind turbines is constructed and shown in Table V. The reliability indexes of the integrated system are calculated and shown in Table VI for comparison with other scenarios.

Scenario 2: In this case, the spinning reserve requirement is considered.

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Considering the spinning reserve requirement, the wind generators have to operate at the lower level of its available power output. Assuming that the spinning reserve requirement of wind generation is 15% of wind available output, the wind power that integrates into the system reduces. As a result, the reliability of the system becomes worse. The comparison of available wind power and real wind power that integrates into the system for 100 hours can be seen in Fig. 7. The capacity outage of a wind turbine for each wind state and its probability are shown in Table IV. The COPAFT for a wind farm with reserve requirement is constructed and shown in Table V. The reliability indexes of the integrated system are calculated and shown in Table VI.

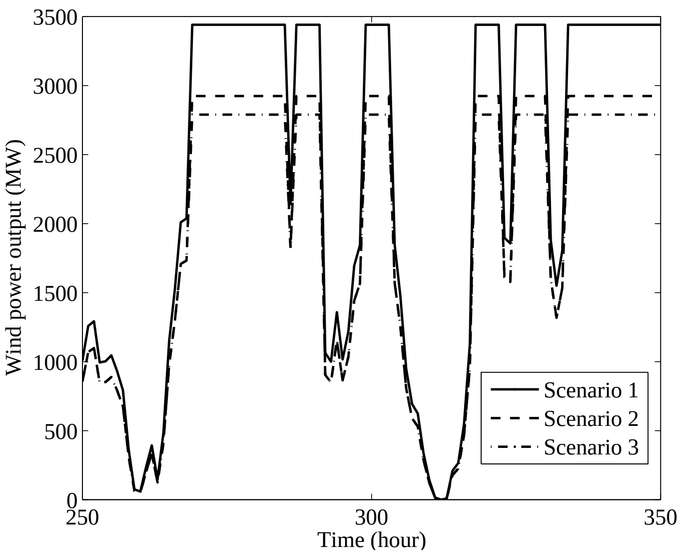

Fig. 7. Available wind output and integrated wind output for the scenarios.

Scenario 3: In this case, both the spinning reserve requirement and the limit of wind penetration due to frequency security are considered.

Considering the impact of stochasticity and low inertia of wind on the frequency, the integrated wind power must be limited. This limit is implemented by the constraint of reduction of inertia as presented in the previous section. The dynamic parameters of the conventional generators are chosen within appropriate ranges which are shown in Table I [35]. The inertia of each wind farm is smaller than that of a conventional generator and can be chosen as 0.25 pu. The load damping value of the system is assumed a value of 2. Load disturbance is simulated by a 0.1 pu step function. The maximum frequency deviation is compared with the safe limit of frequency deviation ± 0.1 Hz [40] to define how much wind generation should be integrated into the main grid. Applying the data of the system dynamics to equation (21), the maximum reduction of inertia of the system is found to be 18.2%. As the inertia of the system is directly proportional to the output of the conventional generators and the inertia of wind power is considered, the maximum penetration limit of wind generation is 2789 MW to ensure the system frequency security. Therefore, only 697 MW of conventional generation can be replaced. This condition is combined with the spinning requirement of wind to give the real allowable integrated wind power. The comparison of available wind power with real wind power that integrates into system, considering both spinning reserve requirement and frequency security condition for 100 hours, can be seen in Fig. 7.

Scenario 4: In this case, large-scale energy storage is considered, to improve the reliability of the wind-integrated system. With large wind penetration, the operation of the wind generation and energy storage should be coordinated [41], [42]. The principle of this coordination is that the surplus hourly wind power, which has not been integrated into the main grid due to system stability requirement, will be stored. The work in this paper will add to the method presented in [42] by considering frequency stability as the system stability requirement. The improved coordination is stated as follows.

If the available wind power is less than the wind integration limit, then the stored energy can be used to supply the load. However, the stored energy can be discharged if the available wind power is greater than the wind integration limit, and the power from conventional generation is less than the difference between the load and the wind integrated limit. In other words, the wind generation, the conventional generation, and the energy storage are all coordinated to meet the system demand. Assuming that the integration limit of wind is P_{li}, the time series representing the energy storage state is calculated as follows:

$$E_{t+1} = \begin{cases} E_t + P_{w,t} - P_{li} & P_{w,t} \geq P_{li} \text{ and } P_{c,t} \geq P_L - P_{li} \\ E_t + P_{c,t} - P_L + P_{li} & P_{w,t} \geq P_{li} \text{ and } P_{c,t} < P_L - P_{li} \\ E_t + P_{w,t} - P_{li} & P_{w,t} < P_{li} \\ E_t & \text{otherwise} \end{cases}$$

where $P_{w,t}$ and $P_{c,t}$ are total power generation of the wind farms and the conventional generators at time t. The charging and discharging rate is considered linear using a 5-hour discharging period. The maximum energy by which the storage can charge and discharge in a time interval Δt is $(E_{max} - E_{min})/5 \times \Delta t$ where E_{max} and E_{min} are the maximum and minimum capacity of the storage [42]. The minimum storage capacity is assumed to be 20% of the maximum capacity.

In this scenario, an energy storage system with maximum capacity of 30 MW each is installed at each wind farm to improve the system reliability. Both the spinning reserve requirement and the limit of wind penetration due to frequency security are included.

A. Results

The capacity outage of a wind turbine for each wind state and its probability are shown in Table IV. The COPAFT for a wind farm, considering the reserve requirement and the frequency security, is constructed and shown in Table V. The reliability indexes of the original IEEE-RTS system and the augmented IEEE-RTS system considering the spinning reserve requirement, the limit of wind penetration due to frequency security, and the energy storage are calculated and shown in

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Table VI. It should be noticed that the capacity outages of three scenarios are different as shown in Table V. The reason for this difference is that due to the frequency stability, some states with the high level of wind integration is removed (the system cannot absorb these high levels of wind generation and maintain stability). Because spinning reserve requirement and the limit of wind penetration due to frequency security are considered in both scenario 3 and 4, the results for scenario 3 in Table V will be utilized for scenario 4.

TABLE IV
THE CAPACITY OUTAGES AND PROBABILITIES OF A WIND TURBINE FOR THE FIRST THREE SCENARIOS

Scenario 1		Scenario 2		Scenario 3	
C_{O1}	$P_{r,i}$	C_{O2}	$P_{r,i}$	C_{O3}	$P_{r,i}$
8	0.212	8	0.212	8	0.212
6.8945	0.08	7.1156	0.08	7.1156	0.08
6.0977	0.092	6.47816	0.092	6.47816	0.092
5.082	0.09	5.6656	0.09	5.6656	0.09
3.899	0.104	4.7192	0.104	4.7192	0.104
2.4794	0.096	3.58352	0.096	3.58352	0.096
0.8758	0.0882	2.30064	0.0882	2.45	0.326
0	0.2378	1.6	0.2378		

TABLE V
THE PROBABILITY AND FREQUENCY OF A WIND FARM WITH 10 WIND TURBINES

State	Scenario 1			Scenario 2			Scenario 3		
	C_{O1}	$P_{r,i1}$	β_1^+	C_{O2}	$P_{r,i2}$	β_2^+	C_{O3}	$P_{r,i3}$	β_3^+
1	0	0.1581	0	12	0.1581	0	16	0.1581	0
2	8	0.0659	0.0067	19	0.1245	0.1388	22	0.0659	0.0067
3	9	0.0586	0.2872	25	0.0244	0.2939	23	0.0586	0.2872
4	16	0.0368	0.1974	26	0.0124	0.0067	29	0.0368	0.1974
5	23	0.0046	0.2939	32	0.006	0.2277	34	0.0046	0.2939
6	24	0.0014	0.0067	33	0.0635	0.2856	35	0.0014	0.0067
7	25	0.0635	0.2856	38	0.027	0.2923	36	0.0635	0.2856
8	30	0.027	0.2923	39	0.0001	0.0067	40	0.027	0.2923
9	32	0.0001	0.0067	42	0.005	0.2923	42	0.0001	0.0067
10	36	0.005	0.2923	45	0.0689	0.3183	45	0.005	0.2923
11	39	0.0689	0.3183	47	0.0006	0.2923	47	0.0689	0.3183
12	41	0.0006	0.2923	49	0.0287	0.325	49	0.0006	0.2923
13	43	0.0287	0.325	52	0.0054	0.3247	50	0.0287	0.325
14	47	0.0054	0.3247	55	0.0601	0.3522	54	0.0054	0.3247
15	51	0.0607	0.3519	56	0.0006	0.325	57	0.0607	0.3519
16	54	0.025	0.3589	58	0.025	0.3589	59	0.025	0.3589
17	57	0.0047	0.3589	60	0.0047	0.3589	61	0.0047	0.3589
18	60	0.0005	0.3589	63	0.0005	0.3587	64	0.0005	0.3587
19	61	0.0612	0.321	64	0.0612	0.321	65	0.0612	0.321
20	63	0.0255	0.3277	65	0.0256	0.3277	66	0.0256	0.3277
21	65	0.0048	0.3277	67	0.0048	0.3277	68	0.0048	0.3277
22	67	0.0005	0.3277	69	0.0005	0.3277	69	0.0005	0.3277
23	69	0.0531	0.3806	71	0.0531	0.3806	71	0.0531	0.3806
24	70	0.0221	0.3873	72	0.0263	0.3862	72	0.0221	0.3873
25	71	0.0041	0.3873	73	0.0005	0.3873	73	0.0041	0.3873
26	72	0.0005	0.3873	80	0.2124	0.2005	74	0.0005	0.3873
27	80	0.2124	0.2005				80	0.2124	0.2005

From the simulation results, it is clear that the operating conditions (spinning reserve requirement, frequency security) have a negative effect on the reliability of the integrated system. In the presence of these conditions, all the reliability indexes deteriorate. When wind power replaces the conventional generators, the Loss of Load Probability (LOLP) increases from 0.0012 to 0.002. The LOLP gets worse when considering spinning reserve requirement (0.0055) and frequency security (0.0084). As LOLP increases, the Loss of Load Expectation (LOLE = LOLP $\times$ 8760) also increases (from 9.369 to 17.52, 48.18, and 73.584 hours/year (h/y)). Due to the integration of wind, the Loss of Load Frequency (LOLF) increases from 2.016 failures/year (f/y) in the base case to 9.636 f/y. In scenarios 2 and 3, LOLF is even worse with 26.28 and 37.668 f/y, respectively. A similar situation occurs when investigating Expected Demand not Severed (EDNS) and Loss of Energy Expectation (LOEE). EDNS increases from 0.1641 MW/year (MW/y) to 0.2190, 0.5840, 0.9125 MW/y in scenarios 1, 2, and 3, respectively. Due to the degradation of EDNS, LOEE increases accordingly. In scenario 4, the system reliability is improved due to the assistance from the energy storage as shown in Table VI. The reason for the deterioration is as follows.

TABLE VI
THE RELIABILITY INDEXES OF THE AUGMENTED IEEE-RTS SYSTEM FOR FOUR SCENARIOS

Index	LOLE h/y	LOLF f/y	LOLP	EDNS MW/y	LOEE MWh/y
Base case	9.369	2.016	0.0012	0.1641	1433.75
Scenario 1	17.52	9.636	0.002	0.2190	1918.44
Scenario 2	48.18	26.28	0.0055	0.5840	5115.84
Scenario 3	73.584	37.668	0.0084	0.9125	7993.50
Scenario 4	64.531	34.660	0.0074	0.7956	6969.50

- In the first scenario, the integration of wind power with a lower reliability level compared to the conventional generators causes the decrease of the integrated system reliability. The more wind power with a low reliability level, the worse the reliability.
- In the second scenario, the spinning reserve requirement makes the available wind power, which will dispatch to the main grid, to decrease (15%). This reduction in turn causes decrease in the system reliability. Since the idea behind this requirement is to maintain a certain amount of power reserve so that the wind generators have the ability to respond and alter their outputs quickly with power ramps, an increase in the reserve requirement causes the injected wind power and the system reliability to decrease further and vice versa.
- When both spinning reserve requirement and frequency security are considered in the third scenario, the amount of wind power accepted by the system is limited due to the violation of frequency deviation. This limit creates a further decline of reliability indexes compared to the second scenario, which shows that the limit of wind penetration is more sensitive to the reliability indexes than to the spinning reserve requirement.
- In the presence of energy storage, the reliability of the system is improved. By storing the surplus wind power,

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the energy storage assists the system when demand is not satisfied by wind farms and conventional generators.

The system reliability can be enhanced by incorporating improved forecast of wind speed, increasing inertia of wind via advanced control strategies. In addition to the above mentioned methods, demand response is also another way of mitigating some of the reliability issues brought about by high penetration of renewable generation.

B. Discussion

The work in this paper presents an improved method to evaluate the adequacy of wind integrated systems. Future work will consider the inclusion of the transmission lines in system reliability investigation. When the transmission lines are considered, the reliability of supply at any load bus in the system depends on both generation and transmission adequacy. In this case, the power flows must be modeled appropriately. The method presented herein can accommodate any power flow model in power systems. The reliability model can generally be stated as follows.

$$\text{Min } C_T = \sum_{i=1}^{NB} C_i \tag{35}$$

Subject to:

- Power balance conditions. These conditions can be represented by means of a capacity flow model [43], a DC power flow model [44], or an AC power flow model [45], depending on the required accuracy and on the availability of system data.
- Equipment availability and capacity constraints.

Here, C_T is the power not served, C_i is the power curtailed at bus i_{th}, and N_B is the number of buses. For any encountered scenario, power will be routed through the network in such a manner as to minimize the power outage.

IV. Conclusion

This paper has presented the effects of stochasticity and low inertia characteristics of wind power on the reliability of the system. This work has shown that the reliability of the integrated system decreases when system security has to be ensured. This is one of the important aspects that has not been investigated in depth in prior research. The validity of the proposed method has been investigated and supported by a mathematical analysis and simulation. The effect of the energy storage on improving the integrated system reliability was also examined. The technique presented here will assist the system operator in better dispatch to maintain system stability and reliability as increasing amounts of renewable resources are integrated into the power grid. The technique is also helpful for power system planning to ensure system stability.

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