

Energy Storage to Improve Reliability of Wind Integrated Systems under Frequency Security Constraint

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Abstract—The integration of wind power into the grid causes numerous stability and reliability issues due to its low inertia and intermittent nature. To ensure system stability, wind power production has to be restricted, which implies that the system cannot absorb the entire output available from wind generation, especially if the output is high. Consequently, the reliability of the integrated system is adversely affected. In order to improve the system reliability, energy storage can be used, which is emerging as a prominent solution for enhancing supply continuity. Complete utilization of an energy storage device can be achieved if it is properly coordinated with wind and conventional generation. This paper proposes a new method to coordinate energy storage with the existing system to improve the system reliability while maintaining the system frequency security. The effectiveness of the model is demonstrated on the IEEE RTS-79 system.

Index Terms—Energy storage, frequency security, inertia, integration limit, reliability indexes, wind power.

I. INTRODUCTION

With the advantages of being abundant and environment-friendly, wind power is gradually replacing conventional generation at an ever-increasing pace. Moreover, with the development of advanced wind turbine technologies, the leveled cost of wind power is becoming more competitive with conventional generation. In [1], the Department of Energy lays out a detailed, long-term goal to produce 35% of the U.S. electric energy from wind power by 2050 using both land-based and offshore wind resources. According to a report by the European Wind Energy Association [2], the combined wind energy production of the EU is projected to meet 31% of their total electricity demand by 2030. In order to meet these targets, various technical problems associated with wind integration must be addressed. Among these are the negative effects of wind integration on frequency stability [3]–[6] and reliability [7], [8]. Wind generation amplifies the problem of frequency fluctuation due to its intermittence since frequency fluctuation is aggravated by the imbalance between generation and load. In addition to its variable nature, wind turbines with low inertia cause a larger variation in frequency if they replace the conventional generators. These factors impact the stable operation of the power system. Often, wind production must be limited.

Numerous solutions have been proposed to improve system stability and reliability in the presence of wind power. Integration of energy storage [9]–[11], advanced control strategies [12]–[14], and accurate forecasting [15], [16] have been investigated. Energy Storage System (ESS) has emerged to be a very effective technology that can assist wind integration, and

improve system reliability and security due to its fast response and high storage capacity [17].

As reported in the Electrical Energy Storage white paper [18], ESSs have been implemented by electric utilities and consumers all over the world. Application of ESSs is predicted to go up with the increasing integration of renewable energy into the grid [18]. According to a report by Sandia National Laboratories [19], the capacity of grid-integrated storage world-wide equaled 2.2% of the generating capacity in 2011. The U.S. has about 24.6 GW of grid storage, which is 2.3% of the total generation capacity [20]. The database reported 202 storage system deployments with different types of technologies in the U.S. [20]. Moreover, New York, Hawaii, Texas, California, and Washington have all proposed important policies that make it mandatory to maintain certain penetration levels of storage [20]. ESSs provide multiple benefits to the operation of power systems, such as assisting in meeting peak demands and energy management, improving the integration of renewable generation, and improving power system stability and reliability.

Even though ESSs tend to be efficient, their operation must be optimized so as to maximize the benefits provided to the grid. According to [21], the system obtains the maximum benefits from an ESS if it is coordinated with conventional generation and wind generation. The control strategy of an ESS can be designed to cater to various needs, such as mitigation of the fluctuation of renewable power output [22]–[25], maximization of the economic benefits by minimizing energy cost [26], load management for deferral of system upgrades, and minimizing the system losses [27]. In other works, an ESS (utility scale) has also been used as a control measure in a corrective form of the security-constrained unit commitment problem [28], for improvement of corrective security [29], or just for planning of emergency backup resources [30]. ESS is also considered as an important component for improving the grid reliability [31], [32]. In [33], the size of the ESS was determined by a specific percentage of demand while evaluating reliability of generating systems containing wind power and ESS. In [34]–[36], ESS has been used to assist in the penetration of renewable energy resources to improve the reliability of the system. The control strategy used here is based on the principle that the amount of energy used in charging, or generated during discharging of the ESS is equal to the imbalance between the supply and demand. ESS has also been used to compensate for shortage of system ramp rates in case of contingencies [37]. In [38], the capability of

an ESS to provide energy during generation shortage based on its capacity has been estimated. Improvement of the frequency and voltage responses by means of an ESS has been shown in [39]. A method for operating an ESS to maximize the value of the wind power in a competitive market system has been presented in [40]. In [41], an optimal operating strategy and a sizing method for an ESS for peak shaving has been presented.

However, the prior work reported above does not address the issue of frequency stability while considering the operation of large-scale ESS being used to support the integration of wind power into the grid. To overcome this drawback, this paper proposes an improved methodology for incorporating an ESS with wind and conventional generation to improve system reliability while securing the frequency stability of the system.

The remainder of this paper is organized as follows. Section II explains the development of the frequency security constraint in a wind-integrated system. Section III proposes an improved method to cooperate the operation of conventional generators, wind power generators, and ESS to ensure the system frequency stability. The reliability evaluation of wind generation is presented in section IV. Simulation results, discussions, and a conclusion about the effectiveness of the new method are covered in Section V and VI, respectively.

II. MODELING OF FREQUENCY SECURITY CONSTRAINT IN A WIND-INTEGRATED SYSTEM

As one of the important indicators of stability in power systems, frequency is strictly maintained at a scheduled value by the operation of load frequency control (LFC). Whenever there is an imbalance between the load and the generation, LFC immediately restricts the frequency fluctuation by inertia, governor action, load and other damping mechanisms. These actions determine the maximum frequency deviation and to some extent the frequency recovery duration. Automatic Generation Control (AGC) changes the generator set point to compensate for the remaining frequency deviation.

In the presence of wind generation, the combination of the already variable nature of load and the intermittence of wind causes more disturbances in the system. Accordingly, the system frequency suffers more deviation due to the disturbances. Under normal operation, the system frequency must be maintained within safe limits. To satisfy this condition, a minimum amount of system inertia is vital to maintain the regulation capability. However, the low or zero inertia characteristic of wind turbines introduces additional negative effects to the frequency regulation when wind generation gradually replaces conventional generation [42], [43]. With wind integration, the system frequency deteriorates and its restoration duration of frequency is prolonged due to the reduction of regulation capability. The impact of different levels of inertia on frequency deviation is illustrated in Fig. 1. The lower the inertia (when more wind power replaces conventional generation), the larger the frequency deviation. When the system inertia drops below a certain level, the frequency violates the predetermined limits. Hence, the penetration of wind generation is limited. The approach to estimate the limit of wind power integration is shown as follows.

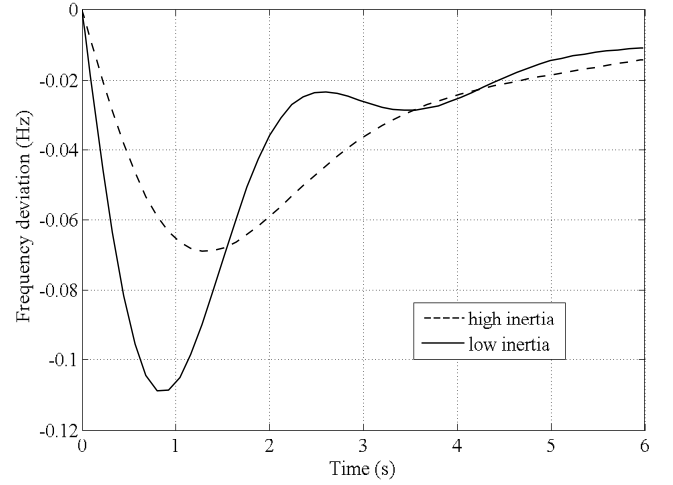


Fig. 1. Frequency deviation with different values of inertia

Fig. 2 represents the LFC model for a multi-machine system [44] with m machines. This model was developed based on the sensitivity analysis of the frequency deviation to the governor parameters for the low-order LFC model [45]. The sensitivity of the maximum frequency deviation to governor parameters using linear curve-fitting [44] is shown in Table I.

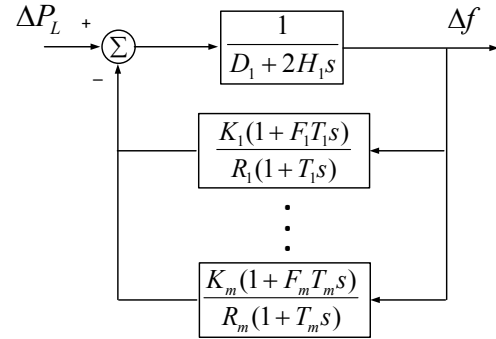


Fig. 2. LFC model for a multi-machine system [44].

TABLE I
SENSITIVITY OF THE MAXIMUM FREQUENCY DEVIATION TO GOVERNOR PARAMETERS

Parameters	K	H	D	R	T_R	F_H
Min	0.8	3	0	0.03	4	0.1
Max	1.2	9	2	0.08	11	0.35
Sensitivity	0.49	0.03	0.05	-9.14	-0.01	1.35

The notations used in Table I are defined below.

- $K(s)$ = LFC controller
- H = equivalent inertia
- D = load damping
- R = equivalent regulation constant
- T_R = governor time constant
- F_H = power fraction from HP turbine

Due to the low sensitivity of the maximum frequency deviation to the governor time constants, the governor time

constants for generators in the system are assumed to be identical without significant loss of accuracy [44].

The load disturbance ΔP_L is assumed to be a step function to clearly show the maximum frequency deviation. The representation for frequency deviation can be developed using Fig. 2 as follows:

$$\Delta f = \frac{\frac{\Delta P_L}{s}}{D + 2Hs + \sum_{i=1}^m \frac{K_i(1+F_i T_R s)}{R_i(1+T_R s)}} \quad (1)$$

Equation (1) can be written as [44]:

$$\Delta f = \frac{\Delta P_L}{2HT_R s} \frac{1 + T_R s}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (2)$$

Equation (2) can be represented as a combination of two terms to serve as an intermediate step for inverse Laplace transformation:

$$\Delta f = \frac{\Delta P_L}{2HT_R s} \frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2} + \frac{\Delta P_L}{2H(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad (3)$$

Applying inverse Laplace transformation to equation (3), the frequency deviation can be shown in the time-domain as:

$$\Delta f = \frac{\Delta P_L}{2HT_R\omega_n^2} \left(1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \cos(\omega_n \sqrt{1-\zeta^2} t - \phi)\right) + \frac{\Delta P_L}{2H\omega_n \sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin(\omega_n \sqrt{1-\zeta^2} t) \quad (4)$$

where

$$\phi = \tan^{-1}\left(\frac{\zeta}{\sqrt{1-\zeta^2}}\right) \quad (5)$$

$$\omega_n = \sqrt{\frac{1}{2HT_R}(D + R_T)} \quad (6)$$

$$\zeta = \frac{1}{2} \frac{2H + T_R(D + F_T)}{\sqrt{2HT_R(D + R_T)}} \quad (7)$$

$$F_T = \sum_{i=1}^m \frac{K_i F_i}{R_i} \quad (8)$$

$$R_T = \sum_{i=1}^m \frac{K_i}{R_i} \quad (9)$$

When the frequency deviation is maximum, the derivative of frequency deviation with respect to time equals zero.

$$\frac{d\Delta f}{dt} \Big|_{\Delta f = \Delta f_{max}} = 0 \quad (10)$$

Combining equation (4) and equation (10), the time at which the frequency deviation gets maximum, and the maximum value of frequency deviation can be obtained as:

$$t_{max} = \frac{1}{\omega_n \sqrt{1-\zeta^2}} \tan^{-1}\left(\frac{\omega_n \sqrt{1-\zeta^2}}{\zeta\omega_n - 1/T_R}\right) \quad (11)$$

$$\Delta f_{max} = \frac{\Delta P}{R_T + D} \left(1 + e^{-\zeta\omega_n t_{max}} \sqrt{\frac{T_R(R_T - F_T)}{2H}}\right) \quad (12)$$

When wind generators with low inertia replace the conventional generators, the total inertia of the system decreases. If the reduction in the system inertia due to the replacement

of conventional generation by wind power is α_{cv} and the inertia from wind turbines is α_w , the new values of the system inertia and the equivalent regulation constant can be shown as follows:

$$H_{new} = H_{old}(1 - \alpha_{cv} + \alpha_w) = \alpha H_{old} \quad (13)$$

$$R_{new} = R_{old}/(1 - \alpha_{cv} + \alpha_w) = R_{old}/\alpha \quad (14)$$

With the modified values of H and R in presence of wind, the value of the maximum frequency deviation is modified as follows:

$$\Delta f_{max} = \frac{\Delta P}{\alpha R_T + D} \left(1 + e^{-\zeta_{new}\omega_{n,new}t_{max}^{new}} \sqrt{\frac{T_R(R_T - F_T)}{2H}}\right) \quad (15)$$

where

$$F_{Tnew} = \sum_{i=1}^m \alpha \frac{K_i F_i}{R_i} = \alpha F_T \quad (16)$$

$$R_{Tnew} = \sum_{i=1}^m \alpha \frac{K_i}{R_i} = \alpha R_T \quad (17)$$

$$\omega_{n,new} = \sqrt{\frac{1}{2\alpha HT_R}(D + \alpha R_T)} \quad (18)$$

$$\zeta_{new} = \frac{1}{2} \frac{2\alpha H + T_R(D + \alpha F_T)}{\sqrt{2\alpha HT_R(D + \alpha R_T)}} \quad (19)$$

Due to the frequency security constraint, the maximum frequency deviation must stay within safe limits:

$$\Delta f_{max} \leq \Delta f_s \quad (20)$$

The sensitivity analysis results in Table I show that:

- As the values of the equivalent regulation constant and power fraction from HP turbine of the system are often much bigger than the damping, $\omega_{n,new}$ and ζ_{new} do not change considerably with the variation of damping value.
- The sensitivity of the maximum frequency fluctuation to the equivalent regulation constant (−9.14) and to power fraction from HP turbine (1.35) is much higher than that to the system damping (0.05).
- The variation in load damping causes an insignificant change on the exponential component.

From the above observation, the values of ζ_{new} and $\omega_{n,new}$ and the inertia reduction limit α_{max} can be approximated without losing the accuracy as follows:

$$\omega_{n,new} = \sqrt{\frac{1}{2\alpha HT_R}(\alpha R_T)} = \sqrt{\frac{R_T}{2HT_R}} \quad (21)$$

$$\zeta_{new} = \frac{1}{2} \frac{2\alpha H + \alpha T_R F_T}{\sqrt{2\alpha HT_R \alpha R_T}} = \frac{1}{2} \frac{2H + T_R F_T}{\sqrt{2HT_R R_T}} \quad (22)$$

$$\alpha_{max} = \frac{\Delta P_L}{\Delta f_s R_T} \left(1 + e^{-\zeta_{new}\omega_{n,new}t_{max}} \sqrt{\frac{T_R(R_T - F_T)}{2H}}\right) \quad (23)$$

Using the limits of inertia reduction, the maximum amount of wind generation which can be integrated into the grid is determined.

From the above analysis, it is clear that the entire available wind generation in the system cannot always replace

the conventional generation due to the frequency security constraint. Therefore, there is an amount of wind power in the system which is not integrated. This surplus wind power will be utilized to charge the ESS. The coordination of wind generation, conventional generation and ESS based on the frequency security is presented in the following section.

III. OPERATING STRATEGY OF ENERGY STORAGE AND SYSTEM GENERATION

An ESS is useful in mitigating the variation of the wind power output. However, it also has to operate in a manner that ensures system stability. This paper presents a strategy to coordinate the ESS, wind, and conventional generation to avoid the violation of system frequency limit. Frequency security is ensured by imposing limits on the reduction of system inertia as shown in section II.

The main idea of this coordination is that the amount of wind generation which cannot be integrated into the system due to the frequency security constraint will be used to charge the ESS. The advanced control strategy of the ESS is stated as follows.

If the available wind generation is less than the wind penetration limit, the ESS will be utilized to provide the demand. However, the ESS will be deployed if the available wind generation is more than the wind penetration limit, but the surplus of the demand compared to the wind penetration limit is more than the power from conventional generation. Hence, the ESS, the wind, and conventional generation are coordinated to satisfy the system demand. From the proposed idea, the ESS state time series is calculated as follows:

$$E_{i+1} = \begin{cases} E_i + (P_{cv,i} - L_i + P_{lim}) \times t & \text{if } \begin{cases} P_{w,i} \geq P_{lim} \\ P_{cv,i} < L_i - P_{lim} \end{cases} \\ E_i + (P_{w,i} - P_{lim}) \times t & \text{if } P_{w,i} < P_{lim} \\ E_i + (P_{w,i} - P_{lim}) \times t & \text{if } \begin{cases} P_{w,i} \geq P_{lim} \\ P_{cv,i} \geq L_i - P_{lim} \end{cases} \\ E_i & \text{otherwise} \end{cases} \quad (24)$$

$$= \begin{cases} E_i + (P_{cv,i} - L_i + P_{lim}) \times t & \text{if } \begin{cases} P_{w,i} \geq P_{lim} \\ P_{cv,i} < L_i - P_{lim} \end{cases} \\ E_i + (P_{w,i} - P_{lim}) \times t & \text{if } P_{w,i} < P_{lim} \\ E_i + (P_{w,i} - P_{lim}) \times t & \text{if } \begin{cases} P_{w,i} \geq P_{lim} \\ P_{cv,i} \geq L_i - P_{lim} \end{cases} \\ E_i & \text{otherwise} \end{cases} \quad (25)$$

where P_{lim} is the penetration limit of wind generation and t is the time duration. P_{lim} is estimated based on equation (23).

While operating within the system, the charging and discharging rates, and the maximum and minimum storage capacities of the ESS must be considered carefully. If these factors are taken into account, the detailed control strategy of the ESS becomes more complicated and is developed as follows.

If the maximum and minimum capacities of the ESS are E_{max} and E_{min} , and the charging and discharging rates are considered linear within a 5-hour period, then the maximum energy that can be charged or discharged in an interval t is given by $E_{lim} = (E_{max} - E_{min})/5 \times t$ [33]. The minimum storage capacity is 20% of the maximum capacity. Assuming that $P_{w,i}$, $P_{cv,i}$ and L_i represent the total power from wind, conventional generators and load respectively, at step i , the ESS state time series E is calculated as follows:

Case 1: Discharge. Let the available wind power be greater than the wind penetration limit, and the output from conventional generation be less than the surplus of the demand compared to the wind penetration limit. The ESS capacity is considered to be not lower than its minimum capacity. ($P_{w,i} \geq P_{lim}$, $\Delta P_i = L_i - P_{cv,i} - P_{lim} > 0$, and $E_i \geq E_{min}$).

- When $E_i - E_{min} \geq \Delta P_i$:

$$E_{i+1} = \begin{cases} E_i - \Delta P_i \times t & \text{if } \Delta P_i \leq E_{lim} \\ E_i - E_{lim} \times t & \text{if } \Delta P_i > E_{lim} \end{cases} \quad (26)$$

- When $E_i - E_{min} < \Delta P_i$:

$$E_{i+1} = \begin{cases} E_i - (E_i - E_{min}) \times t & \text{if } E_i - E_{min} \leq E_{lim} \\ E_i - E_{lim} \times t & \text{if } E_i - E_{min} > E_{lim} \end{cases} \quad (27)$$

Case 2: Discharge. Let the available wind power be less than the wind penetration limit and the ESS capacity be not lower than its minimum capacity ($\Delta P_{w,i} = P_{lim} - P_{w,i} > 0$ and $E_i \geq E_{min}$).

$$E_{i+1} = \begin{cases} E_i - \Delta P_{w,i} \times t & \text{if } \begin{cases} \Delta P_{w,i} \leq E_{lim} \\ E_i - E_{min} \geq \Delta P_{w,i} \end{cases} \\ E_i - (E_i - E_{min}) \times t & \text{if } \begin{cases} E_i - E_{min} < \Delta P_{w,i} \\ E_i - E_{min} \leq E_{lim} \end{cases} \\ E_i - E_{lim} \times t & \text{otherwise} \end{cases} \quad (28)$$

Case 3: Charge. It is assumed that the wind power limit and the conventional generation meet the demand and the ESS is not fully charged ($E_i < E_{max}$ and $P_{w,i} - P_{lim} \geq 0$, and $P_{cv,i} + P_{lim} - L_i \geq 0$).

- When $P_{w,i} - P_{lim} \geq E_{max} - E_i$:

$$E_{i+1} = \begin{cases} E_i + (E_{max} - E_i) \times t & \text{if } E_{max} - E_i \leq E_{lim} \\ E_i + E_{lim} \times t & \text{if } E_{max} - E_i > E_{lim} \end{cases} \quad (29)$$

- When $P_{w,i} - P_{lim} < E_{max} - E_i$:

$$E_{i+1} = \begin{cases} E_i + (P_{w,i} - P_{lim}) \times t & \text{if } P_{w,i} - P_{lim} \leq E_{lim} \\ E_i + E_{lim} \times t & \text{if } P_{w,i} - P_{lim} > E_{lim} \end{cases} \quad (30)$$

Case 4: No change. The status of the ESS remains the same in all other scenarios.

In summary, the four cases can be represented as follows:

$$E_{i+1} = \begin{cases} E_i - \min(\Delta P_i, E_{lim}, E_i - E_{min}) \times t & \text{case 1} \\ E_i - \min(\Delta P_{w,i}, E_{lim}, E_i - E_{min}) \times t & \text{case 2} \\ E_i + \min(E_{max} - E_i, E_{lim}, P_{w,i} - P_{lim}) \times t & \text{case 3} \\ E_i & \text{case 4} \end{cases} \quad (31)$$

$$= \begin{cases} E_i - \min(\Delta P_i, E_{lim}, E_i - E_{min}) \times t & \text{case 1} \\ E_i - \min(\Delta P_{w,i}, E_{lim}, E_i - E_{min}) \times t & \text{case 2} \\ E_i + \min(E_{max} - E_i, E_{lim}, P_{w,i} - P_{lim}) \times t & \text{case 3} \\ E_i & \text{case 4} \end{cases} \quad (32)$$

The operating strategy of an ESS proposed in this paper is more advanced than the strategy proposed in [33] as this research work includes the frequency stability constraint, which is represented by the restriction of wind power integration

based on the limits of the maximum frequency deviation. In [33], the wind energy integration is limited to a fixed percentage of the system load with the assumption that wind power has the priority to serve the system load. The operation of wind power and ESS in [33] therefore neglects the frequency security requirement of the system. In this paper, only the amount of wind power, which can be sustained by the system while preserving frequency stability, can be injected. This will impact the operating strategy of the ESS, and is the main contribution of this paper.

IV. RELIABILITY EVALUATION OF A WIND FARM USING MONTE CARLO SIMULATION

Conventional generators are generally modeled as two-state units. However, it is more accurate to model a wind farm as a multi-state unit considering the variability of the wind speed and the reliability of wind turbines [46]. In this work, the reliability of wind farms is evaluated by the application of Monte Carlo simulation. The reliability model of a wind farm is shown as follows.

A. Wind speed modeling

Due to its continuous and random characteristics, wind speed can be modeled using a Markov chain with a finite number of states. The transitions between all the states are considered. The transitions between wind turbine states and wind speed states are independent. In this study, a large sample of wind speed is utilized to determine the transition rate of wind states. Based on the frequency balance, transition rate between any two states is estimated as follows [47]:

$$\rho_{i,j} = \frac{N_{ij}}{D_{ij}} \quad (33)$$

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

B. Wind turbine output modeling

The power output of a wind turbine is a function of wind speed and turbine availability. The relationship between wind speed and wind power output is represented by the following equation (34) [48].

$$P_w = \begin{cases} 0 & \text{if } 0 \leq SW_t \leq V_{ci} \\ (A + B \times SW_t + C \times SW_t^2)P_r & \text{if } V_{ci} < SW_t \leq V_r \\ P_r & \text{if } V_r < SW_t \leq V_{co} \\ 0 & \text{if } V_{co} < SW_t \end{cases} \quad (34)$$

where V_r , V_{ci} , V_{co} , P_r , are the wind turbine's rated, cut-in, cut-out speeds, and rated power, respectively. The constants A , B , C are expressed as follows [49]:

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

C. Wind farm output modeling

The wind farm output model considers both the wind speed and the wind turbine. For simplification, it is assumed that all the turbines in a wind farm are subject to the same wind speed and they have the same failure rate λ_t and repair rate μ_t . The wind farm output model is shown in Fig. 3 where each value in each state shows its capacity output.

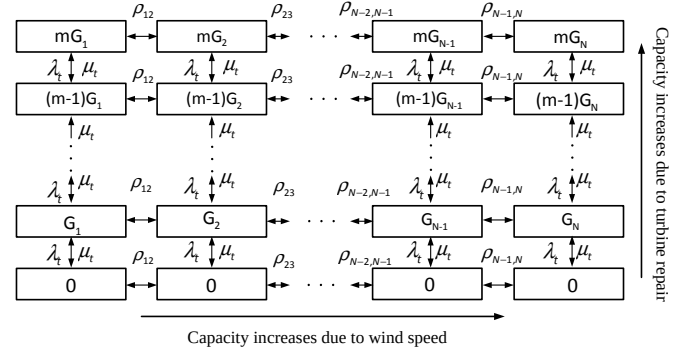


Fig. 3. State transition diagram for a wind farm (transitions between non-adjacent states are not shown in order to reduce clutter).

In Fig. 3, the notations used are as follows:

- m = number of wind turbines.
- N = number of wind classes.
- G_j = output power of a turbine at the wind class j .

Sequential Monte Carlo simulation is used to estimate the wind integrated system reliability as follows.

D. Sequential Monte Carlo simulation for a wind farm

Monte Carlo method is used for stochastic simulation with random numbers. In power system reliability, Monte Carlo can be used to replace analytical methods when time-dependent issues are considered or a large set of states is involved [50], [51]. In Monte Carlo simulation, a system can be divided into many components. The behavior of these components can be deterministic or probability distributions. All components are then combined to estimate system reliability. Monte Carlo simulation performs multiple sampling and generates results while meeting the sampling time limit or the convergence condition.

In this paper, the reliability of the wind-integrated system is estimated using sequential Monte Carlo simulation. All components are assumed to be up in the initial state. Then, the duration of each component in its present state is calculated. The value of the state duration of component i is calculated using an exponential distribution as follows:

$$T_i = -\frac{1}{\lambda_i} \ln(U_i) \quad (35)$$

where U_i is a uniformly distributed random number; λ is the failure rate at the up state and the repair rate at the down state of the i_{th} equipment.

However, equation (35) must be modified when it is applied to a multi-state wind farm. A derated state model can be utilized for a wind farm and each state of the wind farm can

be considered as a derated state. Assuming that the present state of a wind farm is state j , k is the states that state j can transit to, l is the number of states that state j can transit to, duration of the component in state j is given by:

$$T_j = \min(T_{up,k}) \quad k = 1, \dots, l \quad (36)$$

where

$$T_{up,k} = -\frac{1}{\lambda_{jk}} \ln(U_k) \quad (37)$$

For each duration of a state, the imbalance between load and generating capacity is determined. This process is repeated for a given time span and then the reliability indexes are calculated. The Loss of Load Expectation (LOLE) and Loss of Load Probability (LOLP) can be obtained from the duration for which the load is higher than the generating capacity. The Energy Demand Not Supplied (EDNS) is determined from the amount of load that is greater than the generating capacity and also for the duration for which this is true. The Loss of Load Frequency (LOLF) is determined from the number of times that the imbalance moves from a positive value to a negative value. The reliability indices in S sampling years can be estimated as follows [50]:

Loss Of Load Expectation (hour/year):

$$LOLE = \frac{\sum_{i=1}^S (\text{Loss of Load Duration } i)}{S} \quad (38)$$

Loss Of Load Probability:

$$LOLP = LOLE \times 8760 \quad (39)$$

Loss Of Energy Expectation (MWh/year):

$$LOEE = \frac{\sum_{i=1}^S (\text{Energy Not Supply } i)}{S} \quad (40)$$

Loss Of Load Frequency (failures/year):

$$LOLF = \frac{\sum_{i=1}^S (\text{Loss of Load Occurance } i)}{S} \quad (41)$$

The algorithm for sequential Monte Carlo simulation is presented in Fig. 4.

V. SIMULATION AND RESULTS

The improved approach is simulated on the modified IEEE-RTS system. The original IEEE-RTS system includes 32 conventional generators with a total capacity of 3405 MW. In the augmented IEEE-RTS system, 43 identical wind farms replace 860 MW of 6 conventional generators. Each wind farm has 80 MW rated power with 10 identical wind turbines. The data for IEEE-RTS system reliability evaluation can be found in [52]. The inertia data for conventional generators of IEEE-RTS system is shown in Table II [52]. Due to the low sensitivity of maximum frequency deviation to governor parameters, the governor parameters of conventional generations were chosen as uniformly distributed random values within appropriate ranges as shown in Table I. This does not compromise the accuracy of analysis [44]. Since the capacity value of wind power is relatively low, the capacity of the wind farms is chosen to be much higher (about 4 times) than that of the conventional generators they replace. This ensures that the

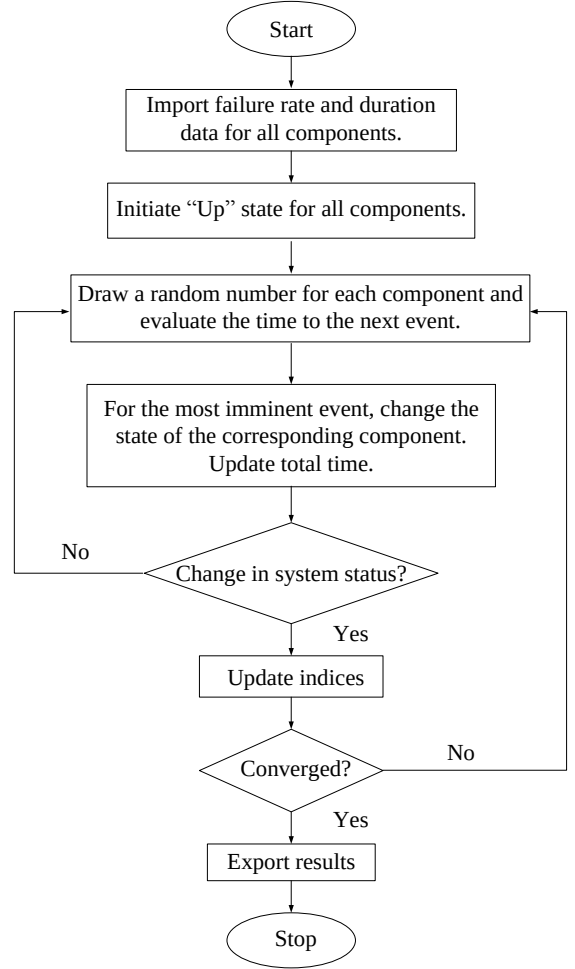


Fig. 4. Algorithm of Monte Carlo simulation method.

reliability of the modified system is comparable to that of the original system. The wind data used in the simulation is extracted from [53]. The data is clustered into one hour intervals based on ten-minute intervals of wind data provided.

TABLE II
INERTIA DATA OF IEEE-RTS

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

The mean time to repair and the mean time to failure of wind turbines are 150 and 3600 hours, respectively. The cut-in, rated and cut-out speeds of wind turbines are 6, 12, and 25 m/s, respectively. After clustering wind data, the annual wind speed is represented by eight states from 0 to 8 m/s since some of the states, which produce identical power, are combined into one state (power output of states 1 to 6 is 0 MW and states 12 to 25 is 8 MW). Hence, one wind generator is considered as a generator with 8 derated states. An ESS with maximum capacity of 30 MWh is installed at each wind farm to improve the system reliability. This capacity is chosen based on the EPRI-DOE report, which discusses the application of ESS

for long duration power quality support [54]. The transition rates of each output state of a wind farm are shown in Table III. Four scenarios are examined to show the impact of the proposed operating strategy on the reliability of the wind-integrated system. Wind power integration with and without considering frequency security constraint is shown in Fig. 5.

Scenario 1: In the first scenario, reliability evaluation of the wind-integrated IEEE-RTS system is implemented without frequency security constraint or ESS. The impact of wind power on the system frequency is neglected. All the available wind power output will be included in evaluating system reliability. Using the data in Table III, the reliability indexes of the modified system are determined. The results are shown in Table IV to compare with other scenarios.

Scenario 2: In the second scenario, reliability of the wind-integrated system is evaluated in the presence of ESS but without the frequency security constraint. In this scenario, the operation of the ESS follows the method proposed in [33]: if the available wind power is less than a specific percentage ($X\%$) of the load, the stored energy can discharge to supply the load. The total wind power and storage power used cannot exceed that limit. The stored energy also serves the load if the available wind power is greater than the limit, and the power from conventional generators is less than $(1 - X)\%$ of load. In this paper, the limit is chosen to be 30% of the maximum load while calculating the system reliability.

Scenario 3: In this scenario, reliability evaluation of the modified IEEE-RTS system with wind integration is implemented with frequency security constraint but without the ESS. Based on the developed model of the frequency security constraint in section II, the limit of inertia reduction is defined. The inertia of conventional generators is shown in Table II. The inertia of each wind farm can be chosen as 0.25 pu. Load disturbance is modeled by a 0.1 pu step function and load damping is assumed to be 2 pu. The safe limit of frequency deviation is ± 0.1 Hz [55]. Applying the system dynamic data to (20), the maximum reduction of system inertia is 18.2%. This means that $(1 - \alpha_{cv} + \alpha_w)$ must be always greater than 81.8%. This limit is combined with the condition that if a conventional generation is replaced, its inertia will not be included in total system inertia and if a wind generation is integrated into the system, its inertia will be included, will yield the maximum α_{cv} to be 26.12% and α_w to be 7.92% ($26.12\% - 18.2\% = 7.92\%$). Then, P_{lim} is determined based on the value of α_w and inertia of the wind turbines. Therefore, the maximum penetration of wind power is 2789 MW and only 705 MW of conventional generation can be replaced to secure the system frequency. The system reliability is then evaluated and shown in Table IV.

Scenario 4: The operation of ESS follows the method proposed in section III. When the wind penetration limit is higher than the available wind generation, the ESS will discharge to assist the demand. If the available wind generation is more than wind penetration limit, but the surplus of the demand compared to the wind penetration limit is more than conventional generation output, the ESS will also discharge.

If wind power is more than the penetration limit and the total generation of the system meets the expectation of the demand, the ESS will be charged. The results for this scenario are shown in Table IV.

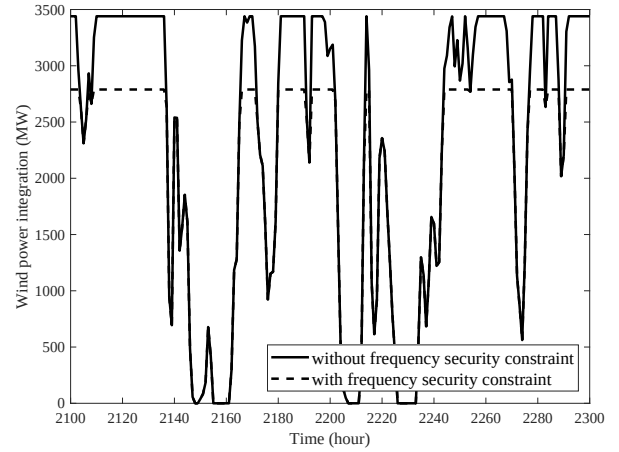


Fig. 5. Wind power integration.

TABLE III
TRANSITION RATES AMONG WIND SPEED STATES

State	8	7	6	5	4	3	2	1
8	0.8459	0.1013	0.036	0.011	0.0038	0.001	0.0005	0.0005
7	0.2872	0.3713	0.2212	0.0841	0.0207	0.0078	0.0039	0.0039
6	0.0729	0.2127	0.3608	0.2258	0.0908	0.0263	0.006	0.0048
5	0.022	0.0738	0.2225	0.359	0.1927	0.0903	0.0231	0.0165
4	0.0126	0.0189	0.0694	0.2513	0.3144	0.2121	0.0846	0.0366
3	0.005	0.0099	0.0248	0.083	0.1983	0.3457	0.2119	0.1214
2	0.0029	0.0072	0.0043	0.0343	0.1044	0.2275	0.3004	0.319
1	0.0016	0.0011	0.0043	0.0081	0.0188	0.0478	0.1188	0.7996

TABLE IV
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)
Scenario 1	53.9153	17.2032	0.0062	0.5255	4603.2
Scenario 2	30.8117	10.8648	0.0035	0.2776	2431.6
Scenario 3	65.3270	25.3656	0.0075	0.7801	6834.1
Scenario 4	35.2342	13.5783	0.0042	0.3479	3047.6

In order to show the improvement of frequency response when considering frequency security constraint over the existing system, frequency deviation over time domain under the influence of different values of system parameters is shown in Fig. 6. In Fig. 6, three values of inertia are used to demonstrate the impact of the proposed method. The first value ($H = 111.82$ MJ/MW) is 100% of system inertia, which satisfies the frequency constraint. The second value ($H = 91.47$ MJ/MW) is 81.8% of total inertia, which equals the limit of frequency security constraint. The third value ($H = 78.26$ MJ/MW) is

70% of total inertia. The third value violates the constraint and therefore the frequency deviation is below the safe limit. It should be noted that although Fig. 6 only shows the change in inertia, other parameters are also adjusted accordingly during the simulation.

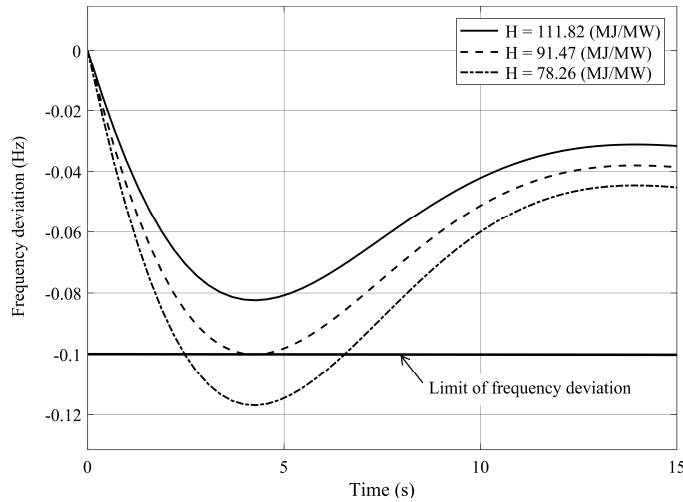


Fig. 6. Frequency deviation for different values of inertia.

From the simulation results, some observations can be made:

- 1) The ESS has a positive effect on system reliability in both scenarios: with or without the frequency security constraint. All the indexes LOLP, LOLE, LOLF, LOLE, and EDNS reduce with the assistance of ESS in scenarios 2 and 4 and this implies that the system reliability is improved.
- 2) Considering the frequency security constraint, the wind power that can be integrated into the system is limited. Hence, the reliability of the system decreases in both scenarios 3 and 4 compared to scenarios 1 and 2.
- 3) By comparing scenarios 2 and 4, it is clear that the system reliability deteriorates if frequency security is considered even in the presence of ESS.

The analysis and simulation results show that it is important to consider the frequency security while estimating the reliability of the system with the application of ESS. Otherwise, it is possible that the operators overestimate the ability to improve system reliability by application of an ESS.

VI. CONCLUSION

This paper presents a new operating method for ESSs in a wind-integrated grid. This new method coordinates the operation of wind, conventional generators and ESS to improve reliability while ensuring system frequency security. A mathematical model for the ESS operation is developed and is then validated using Monte Carlo simulation. This method would benefit the system operators in both operation and planning of power systems with a high penetration of renewable energy. Besides the integration of an ESS and increasing the inertia of wind turbines, using demand response can be another way of improving the reliability of power system in the presence of renewable generation.

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