

Frequency Response in the Presence of Renewable Generation: Challenges and Opportunities

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ABSTRACT Due to their many advantages, renewable energy resources (RERs) are proliferating rapidly to satisfy a significant portion of the global energy demand. It is predicted that the importance of RER generation will continue to increase in the future of the energy industry. In spite of all their known benefits, the integration of RERs poses several challenges to system stability and reliability. Low inertia characteristics and the intermittent output of RERs introduces additional variation into an already variable grid frequency. System regulation capability and reliability are reduced as RERs gradually replace conventional generators. This paper reviews the challenges associated with RER integration on system frequency response and how these challenges affect system reliability. Advanced methods for mitigating challenges associated with increasing RER integration, while ensuring system security, are discussed, and the necessary mathematical background is provided in concise form. A model is developed for determining the maximum level of RER penetration based on stability constraints. Emerging methods to advance the integration of RERs are discussed.

INDEX TERMS Frequency deviation, frequency response characteristic, frequency stability, renewable energy resources, reliability, security constraints.

NOMENCLATURE

ΔP_C	Supplementary control action.	T_R	Speed governor time constant.
$K(s)$	LFC Controller.	F_H	Fraction of turbine power generated by high pressure unit.
ΔP_{RERs}	Disturbance caused by RERs.	ω_n	System natural frequency.
ΔP_{load}	Non-frequency sensitive load change.	ζ	System damping ratio.
ΔP_L	Load disturbance.	t_{max}	Time at frequency nadir.
$T_{i,j}$	Synchronizing torque coefficient.	Δf_{max}	Frequency nadir.
B_i	Frequency bias factor.	Δf_s	Frequency nadir safe limit.
β_i	Frequency response characteristic.	$p_{c,i}$	Wind speed state probability for state i .
R_i	Equivalent regulation constant.	$n_{i,j}$	Number of transition from state i to j .
ACE	Area Control Error.	N	Total number of wind speed states.
$TG_{k,i}$	Turbine-governor transfer function.	$\rho_{i,j}$	Wind speed transition rate.
$\Delta P_{tie,i}$	Tie-line power exchange.	P_w	Wind turbine output.
H_i	Equivalent inertia constant.	V_{ci}	Cut-in speed of wind turbine.
Δf	Frequency deviation.	V_{co}	Cut-out speed of wind turbine.
D_i	Load damping constant.	V_r	Rated speed of wind turbine.
r_r	Fraction of inertia contributed by RERs.	P_r	Rated power of wind turbine.
r_c	Fraction of conventional generator inertia reduced in presence of RERs.	$C_{i,j}$	Capacity outage in MW.

$D_{u,i}$	Duration of state i .
$P_{tb,i}$	Available probability of wind turbine at state i .
$p_{i,j}$	Probability of capacity outage state.
p_u	Probability of up state of wind turbine.
p_d	Probability of down state of wind turbine.
m	Number of turbines in the system.
C_m^{m-i+1}	The selection $m - i + 1$ turbines at a time.
μ_{cv}	The repair rate of a conventional generator.
$f_{i,j}$	Frequency of transition between capacity outage states.
P_r, β^+	Equivalent probability and frequency of a capacity outage level.
$P(X)$	Cumulative probability of a capacity outage level X .
$F(X)$	Cumulative frequency of a capacity outage level X .
$P_{w,i}$	Available wind power at state i .
L_i	Load at state i .
$P_{cv,i}$	Conventional generator power at state i .
P_{lim}	Penetration limit of ESS.
E_{mim}	Minimum capacity of ESS.
E_{max}	Maximum capacity of ESS.
E_{lim}	Maximum charging/discharging rate of ESS.
T_i	State duration of component i .
λ_i	Failure rate.
U_i	Uniform distributed random number.
$LOLP$	Loss of Load Probability.
$LOLF$	Loss of Load Frequency.
$EDNS$	Energy Demand Not Supplied.
$LOLE$	Loss of Load Expectation.

I. INTRODUCTION

THE International Energy Agency (IEA) has reported that global energy demand is steadily increasing with economic and technological growth [1]. Presently, the main supply for worldwide energy demand is conventional energy generators. However, non-renewable fossil fuels are gradually-diminishing finite resources, and have been proven to have negative impacts on the environment [2]. To overcome these issues and maintain adequate power supply, the energy industry is shifting towards the integration of renewable energy resources (RERs). Compared to conventional energy resources, RERs have unlimited supply, low operational cost, and are less harmful to environment. Additionally, RER-based generators can be installed throughout diverse geographical areas, including remote areas with limited access to transmission lines. The advanced technologies associated with the integration of RERs, their low levelized cost of energy, supportive regulatory policy, environmental challenges, and demand for modern energy have led to an accelerated development of RERs in the power grid. With heightened public awareness came greater support, as RERs accounted for 26.2% of global energy consumption

in 2018 and are expected to reach 45% by 2040 [3]. IEA predicts that RERs will become the largest sector of energy generation, providing a total of one-third of total energy demand worldwide by 2025 [4]. With the levelized cost of energy dramatically decreasing in the past decade, renewable energy continues to present itself as a promising form of modern energy. The deployment of RERs gives rise to several economic benefits as well as pollution mitigation when compared to conventional methods, but has not been without complication as they are integrated into the electrical power grid. RER penetration poses challenges to system stability and reliability if appropriate measures are not employed to mitigate associated problems such as output intermittency and total system inertia reduction. The undesirable effects accompanied by total system inertia reduction become evident under frequency disturbance conditions. Under normal operating conditions, systems must provide a minimum inertia to maintain frequency regulation capabilities. As RER-based generators replace conventional generators, system frequency stability deteriorates in the form of extended and accelerated frequency deviation, which may lead to load shedding or even system collapse if sufficient regulation capability is not reserved. RER integration is responsible for a reduction in system regulation capacity, as reported in HydroQuébec TransÉnergie, Western Interconnect, Electric Reliability Council of Texas, and The North American Electric Reliability Corporation (NERC) [5]–[10]. With intermittent generation output and low inertia, the presence of RER not only adds more variation to already fluctuated frequency and reduces frequency regulation capability [11], [12], it also can cause congestion on transmission lines [13] and violation in voltage stability [14], [15]. Moreover, unlike conventional generation with controllable power output, the output of RER strongly depends on nature conditions. Therefore, RER integration also poses challenges to system reliability when it gradually replaces conventional generation. Besides, the limit of RER integration must be considered in a rich-RER environment system to ensure system resilience. Due to characteristics of RERs, it is necessary to investigate their effects on system stability and reliability. As a result, impacts of RERs on system stability are important to understand in the context of determining maximum acceptable levels of RER integration. This limit on RER integration means that only the amount of RERs that satisfy stability constraints may be dispatched at a given time. Accordingly, there is a need for re-evaluating the reliability of integrated systems. To mitigate the negative impacts of RERs and advance RER integration, energy storage systems (ESS) have presented a favorable solution, although ESS operating strategies must be carefully considered. Therefore, it is recommended that more advanced operating approaches be developed in support of RER integration.

This paper presents some major challenges and opportunities associated with a global increase in RER penetration, and is organized with the following seven sections: Section II presents the effects of RER integration on system frequency

regulation capability. Section III discusses a method for evaluation of RER penetration limits based on frequency security requirement. Section IV describes the impacts of RER integration on system reliability. Section V proposes an advanced approach to employ ESS for the improvement of system reliability under stability constraints. Section VI discusses emerging approaches to further advancing RER integration. Finally, section VII provides concluding remarks and possible future research opportunities.

II. EFFECTS OF RER INTEGRATION ON SYSTEM FREQUENCY

High levels of RER integration negatively impacts stable system operations by causing higher frequency deviations and longer recovery durations when subjected to frequency disturbances. When system frequency deviates too far from its nominal value, and the rate of change of frequency violates acceptable limits, protection systems are activated and leads to direct load shedding. If conditions are severe, the system may collapse. Therefore, it is important to understand system frequency control in the context of RER integration. When the system is subjected to a disturbance (a mismatch between supply and consumption), system frequency deviates from its nominal value. System frequency is restored to nominal value by the implementation of load frequency control (LFC) via three stages: primary (inertial) response, secondary response, and tertiary response [16]. In the first stage, frequency deviation is hindered by inertia and load damping. The second stage follows with regulation of generator outputs by adjusting prime mover inputs. The first two stages stabilize system frequency and are triggered by maximum frequency deviation and duration of frequency recovery. To recover frequency back to its nominal value, Automatic Generation Control (AGC) adjusts generator set point. During the final stage, generators are rescheduled for future regulation. As RER-based generators replace conventional generators, governor action becomes less effective due to a reduction in total system inertia. The result is a restricted ability to regulate generation outputs throughout the system. Additionally, maximum frequency deviation increases and recovery is prolonged. The mechanism for LFC in the presence of RERs is as follows.

Traditionally, mechanical power is converted to electrical power via rotation of a generator turbine. Rotor speed will deviate in response to any imbalance between input and output. The governor's objective is to sense any disturbance causing unbalance, and send an input control signal to the turbine for frequency recovery. The combined actions of governor, turbine, rotating mass, and load damping are shown in the LFC model in Fig. 1 [17]. In the LFC model, disturbances caused by RERs and loads are represented by $\Delta P_L(s)$, as RER-based generation is considered to be a negative load.

$$\Delta P_{tie,i} = \sum_{j=1, j \neq i}^N \Delta P_{tie,ij} = \frac{2\pi}{s} \left(\sum_{j=1, j \neq i}^N T_{ij} \Delta f_i - \sum_{j=1, j \neq i}^N T_{ji} \Delta f_j \right) \quad (1)$$

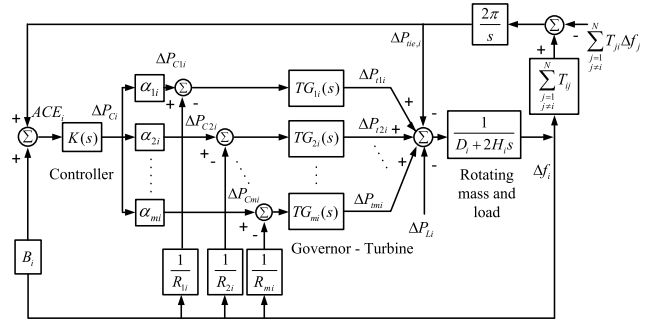


FIGURE 1. LFC of an interconnected system in the presence of RERs.

B_i = frequency bias factor which is calculated as below [18]:

$$B_i = \beta_i = \frac{1}{R_i} + D_i \quad (2)$$

Although RER outputs are uncertain, it is required that RERs contribute to frequency regulation in some power grids [19], [20]. With improved control strategies, wind turbines may contribute some inertia and partially support LFC [21]–[29]. As shown in [30]–[32], wind turbines may also have a droop characteristic. The use of synchronverters [28] allows wind turbines to mimic synchronous generators. Yet, wind turbine inertia contribution is determined by turbine type and available generator output. Solar farms may also contribute to frequency regulation by operating below capacity and adjust outputs in response to power system disturbances [33].

Assuming the fraction of inertia that RERs can contribute is r_r , the fraction of total conventional generator inertia reduced by the integration of RERs is r_c . The updated system inertia constant is then calculated as follows:

$$H_{new,i} = H_{old,i}(1 + r_r - r_c) \quad (3)$$

The term r_r considers both the actual inertia provided by RER power generation and other artificial inertia that may be synthetically emulated.

The presence of RERs not only causes a reduction in the total system inertia constant, but also modifies the equivalent regulation constant:

$$R_{new,i} = \frac{R_{old,i}}{1 + r_r - r_c} \quad (4)$$

When the equivalent regulation constant changes, new area frequency response characteristics may be evaluated as follows:

$$\beta_{new,i} = B_{new,i} = \frac{1}{R_{old,i}}(1 + r_r - r_c) + D_i \quad (5)$$

Because of the change in R and β , the area control error is also affected:

$$ACE_{new,i} = \Delta P_{tie,i} + \beta_{new,i} \Delta f_i \quad (6)$$

From LFC in Fig. 1, the frequency deviation is determined as:

$$\Delta f_i(s) = \frac{\sum_{k=1}^m TG_{ki}(s)\Delta P_{Cki}(s) - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s)}{2H_{new,i}s + D_i + \frac{\sum_{k=1}^m TG_{ki}(s)}{R_{new,i}}} \quad (7)$$

Applying the final value theorem to 7, the steady state value of frequency deviation Δf_{iss} is shown as:

$$\begin{aligned} \Delta f_{iss} &= \lim_{s \rightarrow 0} s \Delta f_i(s) \\ &= \lim_{s \rightarrow 0} s \left(\frac{\sum_{k=1}^m TG_{ki}(s)\Delta P_{Cki}(s) - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s)}{2H_{new,i}s + D_i + \frac{\sum_{k=1}^m TG_{ki}(s)}{R_{new,i}}} \right) \end{aligned} \quad (8)$$

Assuming that the tie-line power exchange $\Delta P_{tie,i}(s)$ will reach zero at steady state [17] and the system has enough reserve $\Delta P_{Ci} = \Delta P_{Li}$, equation (8) will approach zero at steady state:

$$\Delta f_{iss} = 0 \quad (9)$$

Although system frequency is recovered, it fluctuates further from nominal value and recovery time is increased. From equation (1), it can be seen that a change in system frequency causes an increase in tie-line power flow; an undesirable effect for each balancing authority.

For a stand-alone system, there is no tie-line connecting other balancing authorities. Hence, $\Delta P_{tie,i}(s) = 0$ in equation (7).

Using the developed model, the nadir of frequency deviation and moment it occurs can be determined. Therefore, the limit of RER penetration may be evaluated and is presented in the following section.

III. DETERMINATION OF INTEGRATION LIMIT OF RERs BASED ON FREQUENCY DEVIATION

Based on the analysis in Section II, it can be seen that the displacement of conventional generators with a considerable amount of RER-based generation decreases equivalent system inertia, while increasing the system regulation constant. The decrease in system inertia, coupled with increased output fluctuations, degrades the system's ability to maintain frequency deviation within safe limits. Therefore, the integration of RERs must be limited.

Power system stability has been a major focus in the determination of RER penetration limits. For example, several research works have considered network congestion [34], [35], voltage stability [36], [37], system capacity [38], [39], frequency stability [40], [41], and thermal violations [42], [43] as integration limit constraints. Similarly, [44]–[49] have incorporated the transient stability limit and frequency security constraints, [50]–[52] consider harmonic limit, and [53], [54] take into account the wind-thermal coordination factor in estimating RER penetration limits. The limit of RER penetration to island networks has also been evaluated in [55], [56]. However, the aforementioned

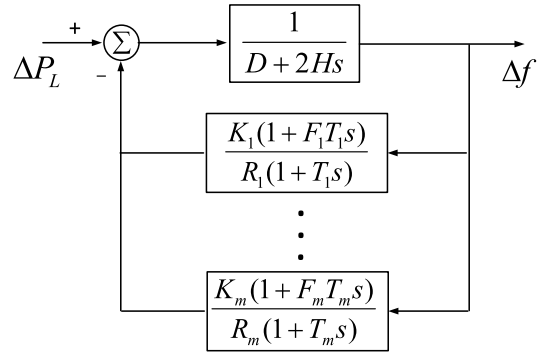


FIGURE 2. Multi-machine LFC model.

works do not provide a generalized mathematical model to determine the maximum RER penetration limit within a multi-machine system.

In this section, a general mathematical formula is derived to estimate the RER penetration limit, based on maximum frequency deviation limit. In the mathematical formula, sensitivity analysis is utilized to evaluate the influence of varying RER penetration levels on maximum system frequency deviation. The final result will provide a general estimate for RER penetration limits that satisfies system frequency security constraints.

A. LOAD FREQUENCY CONTROL OF MULTI-MACHINE SYSTEM

In this section, a mathematical model of a system LFC is analyzed to estimate maximum system frequency deviation under a load disturbance. For this purpose, a LFC for the multi-machine system proposed in [57], [58] is used. The LFC model is derived based on a sensitivity analysis followed by linear curve-fitting on the low-order LFC model proposed in [59]. The sensitivity analysis examines the impact of governor parameters on the system frequency deviation, results of which are presented in [57].

The sensitivity analysis in [57] shows that among all of the variables, the regulation constant R and the portion of total power generated by the high pressure (HP) turbine F_H has the greatest influence on the maximum frequency deviation. In contrast, the nadir of frequency deviation has low sensitivity to the governor time constant T_R , inertia H , and load damping D . Thus, [57] has employed a constant governor time constant for all governors in the system.

Assuming a step load disturbance, it can be inferred from Fig. 2 that the frequency deviation can be determined by [57]:

$$\Delta f = \frac{\frac{\Delta P_L}{s}}{D + 2Hs + \sum_{i=1}^m \frac{K_i(1 + F_i T_{RS})}{R_i(1 + T_{RS})}} \quad (10)$$

If all values of T_R are identical for all generators, equation (10) can be written as [57]:

$$\Delta f = \frac{\Delta P_L}{2HT_{RS}} \frac{1 + T_{RS}}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (11)$$

where

$$\omega_n = \sqrt{\frac{1}{2HT}(D + R_T)} \quad (12)$$

$$\zeta = \frac{1}{2} \frac{2H + T_R(D + F_T)}{\sqrt{2HT_R(D + R_T)}} \quad (13)$$

$$F_T = \sum_{i=1}^m \frac{K_i F_i}{R_i} \quad (14)$$

$$R_T = \sum_{i=1}^m \frac{K_i}{R_i} \quad (15)$$

Equation (11) can be rewritten as follows:

$$\Delta f = \frac{\Delta P_L}{2HT_R s^2 + 2\zeta\omega_n s + \omega_n^2} + \frac{\Delta P_L}{2H(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad (16)$$

Taking the inverse Laplace transform to convert frequency deviation to time-domain:

$$\Delta f = \frac{\Delta P_L}{2HT_R\omega_n^2} \left(1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \cos(\omega_n\sqrt{1-\zeta^2}t - \phi)\right) + \frac{\Delta P_L}{2H\omega_n\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin(\omega_n\sqrt{1-\zeta^2}t) \quad (17)$$

where

$$\phi = \tan^{-1}\left(\frac{\zeta}{\sqrt{1-\zeta^2}}\right) \quad (18)$$

At the nadir of frequency deviation, the derivative of frequency deviation equals zero. Therefore, the moment when frequency deviation reaches its maximum value can be derived as [57]:

$$t_{max} = \frac{1}{\omega_n\sqrt{1-\zeta^2}} \tan^{-1}\left(\frac{\omega_n\sqrt{1-\zeta^2}}{\zeta\omega_n - 1/T}\right) \quad (19)$$

$$\Delta f_{max} = \frac{\Delta P}{R_T + D} \left(1 + e^{-\zeta\omega_n t_{max}} \sqrt{\frac{T_R(R_T - F_T)}{2H}}\right) \quad (20)$$

Based on the above analysis, determination of maximum RER penetration can be developed as follows.

B. THE LIMIT OF RER PENETRATION BASED ON FREQUENCY SECURITY

The limit of RER penetration will be determined based on the constraint on maximum frequency deviation. The nadir of frequency deviation is dependent on total system inertia and equivalent regulation constant, as seen in equation (20). As RERs replace conventional generators, system inertia decreases and the regulation constant increases. To model this characteristic, α is introduced such that $\alpha = 1 + r_r - r_c$ in equation (3). Considering the impact of RER integration, the new values of inertia and regulation constant are $H^{new} = \alpha H^{old}$ and $R^{new} = R^{old}/\alpha$. Applying H^{new} and R^{new} to equation (20):

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

where

$$F_T^{new} = \sum_{i=1}^m \alpha \frac{K_i F_i}{R_i} = \alpha F_T \quad (22)$$

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

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

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

To uphold adequate system security, system frequency deviation should not exceed the maximum allowable limits:

$$\Delta f_{max} \leq \Delta f_s \quad (26)$$

While the nadir of frequency deviation Δf_{max} depends on α and ΔP_L , the maximum allowable reduction in inertia is difficult to obtain directly based on security condition in equation (26). Hence, an approximation technique based on sensitivity analysis is developed to examine the variation of the maximum frequency deviation due to changes in RER penetration. Two cases are considered:

Case 1: If the load damping is equal to zero $D = 0$: equations (24) and (25) become:

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

$$\zeta^{new} = \frac{1}{2} \frac{2\alpha H + \alpha T_R F_T}{\sqrt{2\alpha HT_R \alpha R_T}} = \frac{1}{2} \frac{2H + T_R F_T}{\sqrt{2HT_R R_T}} \quad (28)$$

Equations (27) and (28) show that ω_n^{new} and ζ^{new} are no longer a function of n and they stay the same, as the case without RERs. As a result, α does not have any impacts on the moment that maximum frequency deviation occurs t_{max} . Therefore, the nadir of frequency deviation only changes following the change of n and ΔP_L in the fraction $\frac{\Delta P_L}{\alpha R_T + D}$. From this analysis, the limit n can be deduced from the frequency deviation limit Δf_s . Replace the left-hand side of equation (26) by equation (21) and let D equal to zero, the maximum reduction of inertia can be obtained as:

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

If the inertia reduction is larger than α_{max} , system frequency deviation is bigger than the safe limit and violate the stability constraint. Therefore, equation (29) show the maximum level that system inertia can reduce while maintaining system stability. From the maximum reduction level of inertia, the maximum penetration of RERs based on frequency security can be inferred.

Case 2: If the load damping deviates from zero: While D is assumed to be non-zero, it is still much smaller than the R_T and F_T in equations (24) and (25). Therefore, ω_n^{new} and ζ^{new} are less sensitive to the changes in D . Also, from [57], maximum frequency deviation sensitivity

to changes in D (0.05) is much less significant than to changes in R (−9.14) and F_H (1.35). Hence, the impact of load damping can be ignored without a significant loss in accuracy. The approximation can also be verified by analyzing the effect of exponential term in equation (21). Since the maximum value of the exponential term (e^{-x}) is unity and it approaches zero for larger values of x , load damping does not greatly influence the exponential term. Accordingly, it is reasonable to approximate ω_n^{new} , ζ^{new} , and the limit α_{max} as in the case when D equals zero per the equations (27), (28), and (29). Therefore, equation (29) still can be applied to find the limit of inertia reduction and give a high accurate results. This inertia limit can be used to determine the maximum penetration of RER similar to Case 1. The above approximation was verified with time-domain simulation, as reported in [60].

IV. RELIABILITY OF RER-INTEGRATED SYSTEMS CONSIDERING THE EFFECTS OF UNCERTAINTY AND LOW INERTIA

Following the increasing integration of RERs in power systems, development of RER-integrated system reliability models has become a focus of recent research [61]–[72]. Analytical and state sampling methods have been the most prominent among wind power reliability models. Past works in [73], [74] have developed wind power models and investigated their influence on the reliability of RERs integrated systems. As an upgrade to the aforementioned works, the influence of different wind regimes, spatial wind speed correlations, wake effects [65], [75]–[80], turbine output correlations [68], [81], wind farm aggregation [69], transmission constraints [82], and increasing number of wind turbines [83] are all considered in reliability models. The reliability model of power system in the presence of RER generation and energy storage was also investigated in [62], [69], [70].

While prior works have considered multiple factors in their reliability models, they do not simultaneously capture the impacts of intermittency and low inertia contribution. This section will present a reliability model that takes into account these impacts [84]. The improved reliability model in [84] has been developed using the following two criteria:

- RER-based generators must operate below nominal output power so that they are capable of ramping in response to frequency regulation [19], [20].
- Intermittency and low inertia characteristics of RERs negatively impact system regulation [85], [86], and thus the level of RER integration must be limited for the sake of maintaining system stability.

Based on the above two criteria, it is clear that the system cannot absorb all available RER output power due to security reasons. Therefore, grid reliability must be re-evaluated in the presence of RERs. A reliability model using discrete convolution for a wind farm is presented, and the same process can be applied to other types of RERs.

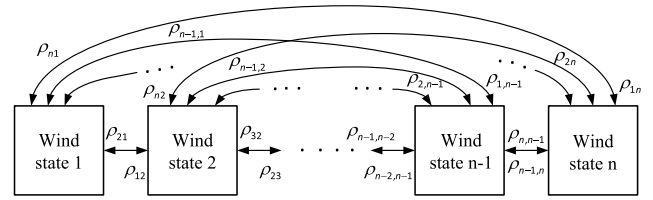


FIGURE 3. Wind speed model with n states.

A. RELIABILITY OF THE INTEGRATED SYSTEM CONSIDERING THE IMPACTS OF UNCERTAINTY AND LOW INERTIA

1) RELIABILITY MODEL OF WIND FARM

a: WIND SPEED MODEL

For modeling wind speed within the wind farm reliability model, the discrete Markov process has been utilized. With the Markov process, wind speeds assume a discrete number of states with each state having an associated state probability, frequency, and duration. Since wind turbines also assume several states, transitions with respect to wind speed are independent. This model holds an advantage over the Birth and Death Markov Chain, as the transitions between wind states are comprehensive. Considering a sample path for wind speed, the state probability can be estimated as follows:

$$P_{c,i} = \frac{\sum_{j=1}^N n_{ij}}{\sum_{k=1}^N \sum_{j=1}^N n_{kj}} \quad (30)$$

Using frequency balance, the transition rate between two states is given by [75]:

$$\rho_{i,j} = \frac{N_{ij}}{D_{u,i}} \quad (31)$$

b: WIND TURBINE OUTPUT MODEL

In the reliability model of a wind turbine, output power is dependent on the input wind speed at any instant and the availability of the turbine. An approximate non-linear expression for wind turbine power output, in terms of input wind speed, is shown in equation (32) [87].

$$P_w = \begin{cases} 0 & 0 \leq V \leq V_{ci} \\ (A + B \times V + C \times V^2)P_r & V_{ci} < V \leq V_r \\ P_r & V_r < V \leq V_{co} \\ 0 & V_{co} < V \end{cases} \quad (32)$$

The constants A , B , and C are shown in [81].

c: MODELING OF WIND FARM CAPACITY OUTAGE

The wind farm output model incorporates both the wind speed model and the wind turbine model discussed above. Wind turbine availability, similar to conventional generators, can be represented by a binary state component. The wind farm output model has been developed considering that the whole wind farm is subjected to same wind speed and has similar outputs with some deviation [88]. Additionally, it is assumed

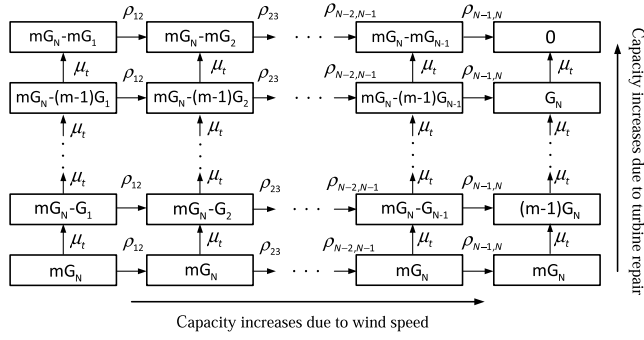


FIGURE 4. Wind farm state transition diagram (transitions between non-adjacent states not shown for simplicity).

here that all wind turbines possess equivalent failure rates λ_i and repair rates μ_i , and that all states with the same output power may be grouped into one state.

Since the proposed wind farm reliability model is based on discrete convolution, the concept of capacity outage is used in the wind farm reliability model. Each outage state has a state probability and frequency of transitioning to lower outage states. Only frequency to lower states are needed, so the method is computationally inexpensive.

A wind farm outage model in matrix form is illustrated in Fig. 4. From the figure, each state's capacity outage can be seen along with its transition to lower outage states. Since only the transitions to lower capacity outages are required in the discrete convolution, they are shown in Fig. 4. The capacity outage states and their transition to lower states are used in calculating the state probabilities and frequency to lower capacity outage states.

The wind farm capacity outage in matrix form is shown in Fig. 4. In the figure, m denotes the total number of wind turbines and G_j is the power output of a single turbine at wind speed state j ,

The capacity outage of each state in Fig. 4 is given as:

$$C_{i,j} = mG_N - (m - i + 1)G_j \quad (33)$$

The state probability associated with each capacity outage state is expressed as follows:

$$p_{i,j} = p_{tb,i} p_{c,j} \quad (34)$$

The value of $p_{tb,i}$ can be calculated as follows:

$$p_{tb,i} = C_m^{m-i+1} P_u^{m-i+1} P_d^{i-1} \quad (35)$$

For each outage state in Fig. 4, since only transition to lower capacity outages are considered, the associated frequency of transition is calculated as follows:

$$f_{i,j} = p_{i,j} \sum \rho_{i,j}^+ \quad (36)$$

Since the states with equal capacity outage can be combined into a single state, they have an equivalent state probability and frequency to lower outage levels. For an

equivalent outage X , the probability and frequency are as follows:

$$P_r(X) = \sum_{i,j} p_{i,j}(X) \quad (37)$$

$$\beta^+(X) = \frac{\sum_{i,j} f_{i,j}(X)}{P_r(X)} \quad (38)$$

Neglecting the impact of wind power output intermittency and inertia reduction characteristics, the capacity outage probability and frequency can be directly combined with the conventional generators to obtain system reliability. However, this method only applies to systems with low wind power penetration. Within high wind power-integrated systems, the impacts of output intermittency and inertia reduction must be included in the reliability model. The following section presents a method to ensure that the wind-integrated system reliability model satisfies stability constraints.

2) MODELING THE EFFECTS OF WIND UNCERTAINTY AND LOW INERTIA

High wind power penetration introduces difficulties in frequency regulation due to the associated power output intermittency and low inertia characteristics. To support frequency regulation, reserve requirements are mandatory for wind power generation [19], [20], [89] i.e. some of the available power from wind generators must be curtailed to ensure adequate reserves for frequency regulation capability. Reserve requirements are typically implemented by Delta Control, in which the wind generators retain sufficient power reserve for positive and negative power ramps. As a result, to satisfy reserve requirements, all available wind power cannot be integrated into the system, resulting in a reduced wind power contribution to reliability.

Along with output intermittency, wind turbines have the drawback of negligible inertia contribution to the system compared to conventional generators. This characteristic implies a negative impact on frequency regulation, with larger frequency deviations and longer restoration times as wind generators replace conventional generators [85]. This impact intensifies with higher penetration of wind power [9], [10]. Thus, the level of wind power penetration must be limited to ensure system frequency stability.

The method to assess wind power integration limits, based on inertia reduction limit, has been presented in section III. In order to ensure frequency security, the maximum amount of wind penetration is defined by the inertia reduction limit.

Previous works evaluating the reliability of a wind-integrated power systems have considered all available wind output in the reliability model. However, the aforementioned issues dictate that wind power integration must be limited to ensure system stability. Thus, traditional reliability models of

wind-integrated systems should be re-evaluated to account for system stability concerns.

B. CAPACITY OUTAGE PROBABILITY AND FREQUENCY TABLE

The reliability model considers a wind farm as a cohort of generators with multiple de-rated states. The de-rated states are obtained by the variation in input wind power and unavailability of individual wind turbines. The Unit Addition Algorithm, which uses discrete convolution is utilized to build a Capacity Outage Probability and Frequency Table (COPAFT) [90]. The COPAT of a wind-integrated system involves combining the COPAFT of conventional generators and wind farms. The two stage process is outlined as follows:

1) COPAFT FOR CONVENTIONAL GENERATORS

Each conventional generator can either be available or unavailable i.e. they do not have de-rated states. Thus, with the addition of a new conventional generator with capacity C MW, the cumulative probability of a capacity outage state X MW can be expressed as follows [91]:

$$P(X) = \sum_{i=1}^2 P'(X - C_i) p_{cv,i} \quad (39)$$

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 capacity outage, C_i .

The cumulative frequency $F(X)$ for a capacity outage of X MW is given as follows [91]:

$$F(X) = \sum_{i=1}^2 F'(X - C_i) p_{cv,i} + (P'(X - C_2) - P'(X)) p_{cv,2} \mu_{cv} \quad (40)$$

If $X \leq C_i$ then $F'(X - C_i) = 0$

2) COPAFT IN THE PRESENCE OF WIND FARMS

The wind farm reliability model treats wind farms as multi-component, multi-state generators with de-rated states due to input wind intermittency and turbine availability. As a result, multiple outage states are encountered in the presence of wind turbines. Each capacity outage level has an associated state probability and transition frequency to lower outage levels. For frequency calculations, only the transition to lower outage states are considered since the system is frequency balanced. The cumulative probability and frequency of the capacity outage state X MW is calculated as follows:

$$P(X) = \sum_{i=1}^N P'(X - C_{w,i}) P_{r,i} \quad (41)$$

$$F(X) = \sum_{i=1}^N F'(X - C_{w,i}) P_{r,i} + \sum_{i=1}^{N-1} (P'(X - C_{w,i+1}) - P'(X - C_{w,i})) P_{r,i+1} \beta_{i+1}^+ + (P'(X - C_{w,N}) - P'(X - C_{w,1})) P_{r,N} \beta_N^+ \quad (42)$$

As can be seen from equations (41) and (42), the equations (39) and (40) are closely related to equations (41) and (42) with $N = 2$. Multi-state generators such as the wind farms can be treated as a special case of a two-state generator, such as the conventional generators.

The capacity outage state frequency in diagrammatic form is shown in Fig. 5, where the transitions to lower capacity outage levels are illustrated. In the reliability model, the general form shown in (42) is used to calculate cumulative frequencies.

The combination of COPAFT for conventional generators and multi-state wind farms yields the COPAFT for the integrated system. The COPAFT is then analyzed using a discrete convolution to estimate the following reliability indices: LOLP, LOLF, and EDNS.

V. APPLICATION OF ENERGY STORAGE TO IMPROVE RELIABILITY OF RER INTEGRATED SYSTEMS UNDER FREQUENCY STABILITY CONSTRAINT

From the analysis in Sections II and IV, it is clear that high levels of RER integration in power systems can be detrimental to system reliability and frequency stability. The main concerns are caused by intermittent outputs and low inertia characteristics associated RER-based generation. Mitigation measures for the aforementioned problems encountered due to high RER penetration have been addressed amply in literature. Some of the prominent measures are the application of energy storage [92]–[94], improved control strategies [95]–[99], and advanced forecasting measures [100], [101]. Among the discussed measures, energy storage systems (EESs) have proven to be very effective in improving system reliability and frequency stability due to their speedy response and substantial storage capacity [102], [103].

While ESSs have been successful in improving power system reliability and stability, their operation strategies should be optimized to obtain more optimal technical and economical benefits. Research in [104]–[106] shows that the maximum benefits of ESS can be obtained using appropriate coordinated control between conventional sources, RERs, and ESSs. The operational strategies of ESSs are deployed based on desired benefiting factors, such as renewable power output smoothing [107]–[110], energy cost minimization [70], load management, and system losses minimization [111], [112]. Deployment of ESS is used as a control measure in the corrective form of the unit-commitment problem [113], corrective security improvement [114], and emergency backup resources [115]. ESSs, with appropriate operational strategies, can also be deployed to obtain power system reliability benefits, especially in RER integrated

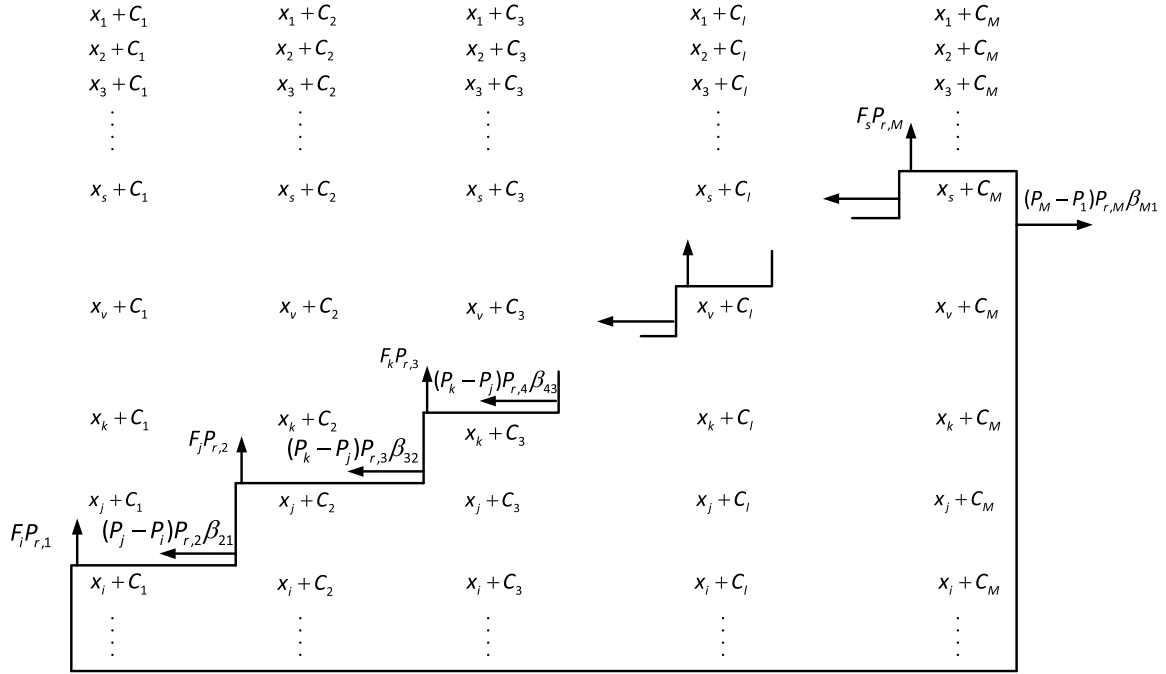


FIGURE 5. State frequency diagram for a multi-state unit.

systems [116]. As an example, [117]–[120] have incorporated ESSs to facilitate the reliable operation of systems with heavy RER penetration. The control strategies employed in the aforementioned works consider generation-load imbalance as the sole factor in charging and discharging ESSs. However, as RER integration is limited due to frequency stability concerns, operational strategies for ESSs should be revised to account for RERs that cannot be dispatched. This section addresses an advanced method to increase system reliability by coordination of RERs, ESSs, and conventional generators, while satisfying frequency stability conditions [84].

A. OPERATING STRATEGY OF ESSs AND SYSTEM GENERATION

ESSs have proven to be useful in moderating the uncertainty of RERs' output. Moreover, ESSs can be deployed for enhancement of system stability. In this section, an improved strategy for ESSs is formulated in conjunction with RER and conventional generation for system frequency stability. The main idea of the proposed coordinated strategy is that surplus outputs of RERs, not allowed to be dispatched to the system under frequency stability constraints, is utilized to charge ESSs. This control strategy not only assists in system frequency regulation, but also takes advantage of surplus power. The ESS control strategy is discussed as follows.

If available RER power outputs do not exceed the RER integration limit, ESSs will dispatch power to supply the demand. ESSs can also dispatch power if RERs power outputs do exceed the RER integration limit, and if conventional generator outputs do not exceed the demand compared to

RERs limits. ESSs are charged if the available output of RERs are greater than the integration limit, and total power output caters to load. A time-series representation of the proposed operation strategy is as follows:

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

The above operational strategy should consider additional factors regarding ESS operational constraints for a more comprehensive ESS reliability model. Factors such as ESS charging rates, ESS discharging rates, maximum battery capacity, and minimum battery capacity should all be considered in formulation of the operational strategy. These considerations add an additional level of complexity to the operational strategy, and is discussed in detail as follows:

Using the linear charging and discharging rates during a 5-hour discharging duration, the maximum energy that ESSs can charge and discharge within a time interval t is $E_{lim} = (E_{max} - E_{min})/5 \times t$, as shown in [117]. Minimum storage capacity is considered 20% of the maximum capacity.

At step i , the ESS state time series E is calculated as follows:

Scenario 1: Discharge: The available output of RERs is higher than the RER integration limit, and conventional generation output is lower than the surplus of the demand

compared to the RER integration limit. ESS capacity is considered higher than its minimum capacity. ($P_{w,i} \geq P_{lim}$, $\Delta P_i = L_i - P_{cv,i} - P_{lim} > 0$, and $E_i \geq E_{min}$).

Scenario 2: Discharge: Available RER output is lower than the RER integration limit, and ESS capacity is higher than its minimum capacity ($\Delta P_{w,i} = P_{lim} - P_{w,i} > 0$ and $E_i \geq E_{min}$).

Scenario 3: Charge: RER and conventional generation power output meets the demand, and the energy storage is not fully charged ($E_i < E_{max}$ and $P_{w,i} - P_{lim} \geq 0$, and $P_{cv,i} + P_{lim} - L_i \geq 0$).

Scenario 4: No change: The state of ESSs remains the same otherwise.

The four scenarios can be summarized as follows:

$$E_{i+1} =$$

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

B. RELIABILITY EVALUATION OF A RER-INTEGRATED SYSTEM USING MONTE-CARLO SIMULATION

The Monte Carlo method has been heavily used for stochastic simulation with random numbers. In power system reliability, some components such as ESSs are time-dependent, and Monte Carlo methods are preferred to analytical methods. In Monte Carlo simulations, a system can be divided into many components with each component behaving as deterministic, or with a certain probability distribution. The individual components are then combined to estimate system reliability. In the Monte Carlo simulation for reliability evaluations, multiple sampling is performed and results are generated until the sampling time limit is reached or the convergence condition is encountered.

Due to the presence of ESS, the reliability of RERs-ESS-integrated systems is evaluated using a Monte Carlo-State duration sampling method. Initially, all of the components are supposed to be in the up state. Then, the state duration of component i is determined using an exponential distribution:

$$T_i = -\frac{1}{\lambda_i} \ln(U_i) \quad (43)$$

This equation can only be applied to 2-state unit. RERs with multiple output values, a de-rated state model must be used. Each state of RER generation is designed as one de-rated state. Assuming that RER generation transitions from state j to state k , the duration that generation stays in state j is:

$$T_j = \min(T_{up,k}) \quad k = 1, \dots, l \quad (44)$$

where

$$T_{up,k} = -\frac{1}{\lambda_{jk}} \ln(U_k) \quad (45)$$

For each sampling duration, load and generation are compared and the ESS state is updated as per the operation

strategy described in sub-section V.A. This process is repeated until the convergence criteria is met, then the reliability indexes LOLE, LOLP, LOLF, EDNS are evaluated.

VI. EMERGING OPPORTUNITIES TO FURTHER ADVANCING RENEWABLE ENERGY INTEGRATION

Thus far we have examined the impact of renewable resources on grid reliability and frequency stability, and shown how energy storage can play a role in advancing RER integration by both smoothing temporal variation and compensating for displaced inertia. Use of storage resources continues to be an opportunity that is being researched and expanded. There are some other opportunities that show potential to support increased integration of RER, particularly the use of grid-forming inverters and the concept of virtual energy storage. In this section we shall provide a review of these concepts, in decreasing order of maturity.

A. APPLICATIONS OF ENERGY STORAGE SYSTEMS

To address the reduction in grid frequency regulation due to generation intermittency and decreasing system inertia caused by high levels of RER integration, several solutions have been discussed. Among the solutions, the most prominent are the integration of ESS in its different forms [93], [94], [102], [112], [119], as well as the advanced interfacing and control strategies of power electronic components in the context of RERs and ESSs [97], [99], [121], [122]. Along with the advancements in hardware, other strategies such as improved communication systems among control areas [123], accurate forecasting of RERs [100], [101], optimal siting and sizing of RERs [124], and variability mitigation [125], [126] are prevalent.

While the solutions described above facilitate effective RER integration, ESSs have emerged as the most viable solution. High storage capacity, coupled with appropriate control strategies for quick response, renders ESSs the preferred medium for RER integration and stability enhancement [102]. Despite technical advantages and decreasing costs, grid-scale implementation of ESS is still economically expensive.

B. USE OF GRID-FORMING INVERTERS

Advancements in control of power electronic interfaces have opened up several possibilities in utilizing grid-forming inverters in maintaining frequency regulation. Due to their fast dynamics, they are able to maintain a stable frequency in the presence of short-term imbalances in power. However, the technology is still being utilized in microgrids, largely because of present-day limitations on their power capabilities. Yet they can provide significant benefits at the microgrid scale. As the ambit of microgrids grows, and more microgrids become capable of maintaining their frequency, they will, in a sense, present a reduced inertial burden to the grid.

To improve system stability, control strategies of grid-forming inverter in a hybrid stand-alone and isolated

microgrids are discussed in [127]–[129]. The use of virtual inertia from energy storage and the grid-connected inverter has been addressed in [130] to support regulation of system frequency. In another application, inverter-based DGs serve as agents to support both voltage and frequency stability [131].

C. GRID-SCALE VIRTUAL ENERGY STORAGE

This concept potentially allows the exploitation of energy storage without the high costs of physical ESS installations. The notion of, “virtual energy storage,” introduced in [123], that uses the concept of period power exchange among balancing authorities. Period power, which is the difference between scheduled interarea exchange of power and constant scheduling within the control areas, is “virtual energy” and each balancing authority is called “virtual energy storage”. Virtual energy is based on the regulation constant, and total system reduction, by eradicating period power from area control errors.

The concept of “virtual energy” is extended to an advanced concept “grid scale virtual energy storage”. The proposed method differs from [123] in that “grid scale virtual energy storage” utilizes frequency deviation, as opposed to the period power in [99]. In terms of the area control error (ACE), the method in [123] involves the first term whereas the proposed method involves the second term. The operating principle of “grid scale virtual energy storage” is in the use of frequency deviation in ACE to reduce regulation for all control areas under disturbance. The proposed method retains the advantages of negligible capital investment, while providing considerable stability benefits.

Maintenance of frequency with safe limits is one of the most important concerns with respect to stability and power quality. The nominal frequency of 60 Hz with minimum deviation in the US has been of paramount concern since the 1930s. While the NERC has preset frequency deviation bounds and ACE standards, which have been maintained by balancing conventional generation and load, increasing RERs penetration disrupts the ability to maintain these standards. While the focus in easing RERs penetration lies in the implementation of ESSs, an alternative approach is to address the intermittency associated with RERs. Additionally, the concept of Frequency Drift proposed by the NERC [132] illustrates that shift of the system operating frequency slightly away from nominal value could yield reliability and economical benefits. Implementation of this concept would require utilization of the proposed “grid scale virtual energy storage”. With a slight shift from the 60 Hz system operating frequency, diversity in ACEs can contribute to the effective deployment of each control area as “virtual energy storage” with respect to other areas.

The proposed method can offer reduction in area regulation constants, transmission losses, capital costs, and ACE in virtual energy storage, thus offering several technoeconomic benefits. “Grid-scale virtual energy storage” can be combined with “physical” EES to improve the system

stability and reliability, which in turn advance the integration of RERs.

VII. CONCLUSION

This paper presents the main challenges and opportunities of high RER integration in electrical power grids. The challenges include: impacts of the intermittent and non-dispatchable features of RERs on frequency stability and the effects of RERs on total system inertia, frequency regulation constants, tie-line flows, and area control errors. Investigation of these impacts provides more accurate information regarding system operations. This paper also presents a model for determining the maximum level of RER integration, based on the frequency stability criterion and sensitivity analysis. An improved method to evaluate system reliability with high RER penetration is presented. This model supports system operators to avoid overestimation of system reliability. An ESS operating method in support of RER integration is also presented. In this method, coordination of RERs, ESSs, and conventional generators are implemented to advance system reliability while maintaining system frequency stability. These methods are critical in the assistance of power system operators for planning and operating systems with a high RER penetration levels.

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