Maximum Penetration Level of Wind Generation Considering Power System Security Limits

Abstract – In this paper, a method is proposed for determining the maximum penetration level of wind farms (WF) into the power system; it takes power system transient stability as well as frequency security criteria into consideration. Considering the probabilistic nature of wind speed, the probabilistic transient stability analysis (P-TSA) is introduced and applied to determine the maximum penetration level of WFs. The effect of overall system reduced inertia due to increasing capacity of WFs is investigated. A fast approach for deriving system frequency drop after a sudden disturbance is employed which is suitable for on-line frequency stability constrained unit commitment incorporating WFs. The feasibility and effectiveness of the proposed method is evaluated using the IEEE 9-bus test system.

Keywords: Wind power, Probabilistic transient stability, Frequency stability, Maximum penetration level

NOMENCLATURE

c	Scale factor for Weibull distribution
D	Damping
E'_d , E'_q	Voltages behind reactance
E_{fd}	Field voltage
H	Inertia
I_d , I_q	Stator currents
k	Shape factor for Weibull distribution
n	Number of generators

P_d	Size of individual units in a power plant
$P_{n\text{-}s}$	Synchronous generator capacity
$P_{n\text{-}w}$	Wind farm capacity
R_f	Stabilizing voltage feedback
S_i	Unit *i* capacity
T'_{do} ,T'_{qo}	Open circuit time constants
T_e ,T_m	Electrical and mechanical torques
v	wind speed
v_{in}	Cut-in wind speed
v_{out}	Cut-out wind speed
v_r	Nominal wind speed
V_R	Regulator voltage
V_{ref}	Reference voltage
V_t	Terminal voltage
x'_d , x'_q	Subtransient reactance
x_d , x_q	Transient reactance
δ	Rotor angular displacement
ω	Rotor speed
ω_s	Synchronous speed

I. INTRODUCTION

Rapid expansion of wind power generation in power systems is an inevitable fact today. Global awareness of harmful effects of carbon dioxide emissions, which are the byproduct of fossil fuels, as well as limited available fuel resources encourage the use of clean energies as much as possible.

Among the well-known renewable resources, wind power has gained the spotlight thanks to the quick development in wind energy conversion technology. However, the penetration level of wind farms (WF) cannot be increased arbitrarily to dominate the whole power generation. This is due to the fact that WFs cannot always provide certain amount of power similar to the conventional synchronous generators. This can be explained by the probabilistic and intermittent nature of wind speed. Therefore, there is always a need for other energy resources which can be relied on for the time that the power provided by the WFs is not sufficient to meet the demand, i.e. large amount of generation reserve.

In addition to the generation reserve concern, there are other issues corresponding to the increasing penetration of WF into the power system. Among these issues, power system stability is from crucial importance, which will be discussed later in this section. Medium-size wind generation units, usually categorized in the distributed generation (DG) units [**1**], are installed in the distribution levels. Increasing the capacity of installed DGs would make problems in voltage profile, harmonic level, thermal limits of conductors, protection schemes and short-circuit levels in distribution network. The issues relating to voltage increase due to the DG installation are studied and the maximum penetration level is determined accordingly in [**2**]. Harmonic injection into the network by DGs would limit the maximum possible installation capacity according to the IEEE 519-1992 [**3**]. This is studied in [**4**] and the maximum penetration level is thus determined. Thermal constraints, equipment ratings, short-circuit levels, and voltage rise effects are taken into account for optimal allocation of DGs in [**5**]. An evolutionary algorithm is employed in [**6**] for optimal sizing and siting of DGs considering economic aspects and some network criteria.

Although excellent research has been conducted on determination of the maximum penetration level of DGs into the distributed network, there is, to the best knowledge of the authors, no major research on the maximum possible level of WF penetration into the transmission/subtransmission network taking the power system stability into account as a criterion. A transfer function approach is employed in [**7**] to show that the continuous fluctuations in WF generated power would make problems for system frequency and speed governor systems. Considering the thermal and voltage limits, the maximum penetration level of WFs in Crete Island is calculated in [**8**]. The impacts of WFs on the power system frequency stability in Iowa are studied in [**9**]. Also, it is shown that the increasing capacity of WFs based on doubly fed induction generator (DFIG) technology would deteriorate the system frequency recovery after a large disturbance. *N*-1 and *N*-2 line outage contingency criteria on the Irish power system are studied incorporating WFs in the network [**10**]; thus, intentional decrease in WF generation is proposed as a method for preventing the outage of conventional units which, in turn, would decrease overall system inertia. However, the power system stability considerations are left behind.

Probabilistic transient stability analysis (P-TSA) considering the uncertainties associated with the type, location, duration, and impedance of the short-circuit fault as well as system operating point and circuit breakers' operation time was previously done in the literature [**11**], [**12**], [**13**]. P-TSA for a WF connected to an infinite bus was carried out by the authors of [**14**]; besides the factors mentioned before, they also have included the uncertainties associated with the wind speed in their study. The same authors have studied the P-TSA of a power system incorporating WFs [**15**]; besides the aforementioned factors, the effects of WF sizes and locations on the overall system stability as well as the uncertainties associated with the wind turbine model were studied. Also, the impact of WF penetration level on the power system transient stability was studied assuming the squirrel cage induction generator technology. However, the effect of system reduced inertia due to the application of DFIGs was left behind.

In this paper, a method for determining the maximum penetration level of WFs into the network considering system transient stability as well as frequency security criteria is proposed. This method is based on the probabilistic nature of wind speed and DFIG technology. The IEEE 9-bus test system is used to demonstrate the effectiveness of the proposed method.

The paper is organized as follows: in Section II, a background on system modeling and wind characteristics is given. Section III describes the proposed method and Section IV gives the obtained results by applying the proposed method to the test system. The paper is concluded in Section V.

II. BACKGROUND

In this section, a review on the basic concepts used in the study is given. These include power system dynamic model and wind speed probability density function (PDF). Each subject is discussed in a separate subsection in the following.

A. Power System Dynamic Model

Dynamic behavior of power system is described by a set of differential-algebraic equations (DAE) [**16**]. Considering the two-axis model for the synchronous generators, the following equations describe the machine dynamic behavior:

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}}\left(-E'_d - (x_q - x'_q)I_q\right) \tag{1}$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}\left(E_{fd} - E'_q - (x_d - x'_d)I_d\right) \tag{2}$$

$$T_e = E'_d I_d + E'_q I_q - (x'_d - x'_q) I_q I_d \tag{3}$$

$$\frac{d\omega}{dt} = \frac{\omega_s}{2H}\left(T_m + T_e - D(\omega - \omega_s)\right) \tag{4}$$

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{5}$$

IEEE Type I excitation system is defined by the 3rd order model shown in Fig. 1, including the saturation effect ($S_E(E_{fd})$) as:

$$S_E\left(E_{fd}\right) = A\,e^{(B.E_{fd})} \tag{6}$$

in which A and B are constants described in [**16**].

A typical re-heat steam turbine together with the speed governor is modeled as shown in Fig. 2 [**17**]. This model is further simplified to represent a system frequency response (SFR) model for online applications in [**17**], [**18**]. The simplified model is represented in Fig. 3, in which $\Delta P_0(s)$ is a disturbance in total load or generation for which the system frequency response ($\omega\Delta$) is to be calculated. In this model, H_T and D_T are the system equivalent inertia and damping, respectively which are calculated as:

$$H_T = \frac{\sum_{i=1}^{n} S_i H_i}{\sum_{i=1}^{n} S_i} \tag{7}$$

$$D_T = \frac{\sum_{i=1}^{n} S_i D_i}{\sum_{i=1}^{n} S_i} \tag{8}$$

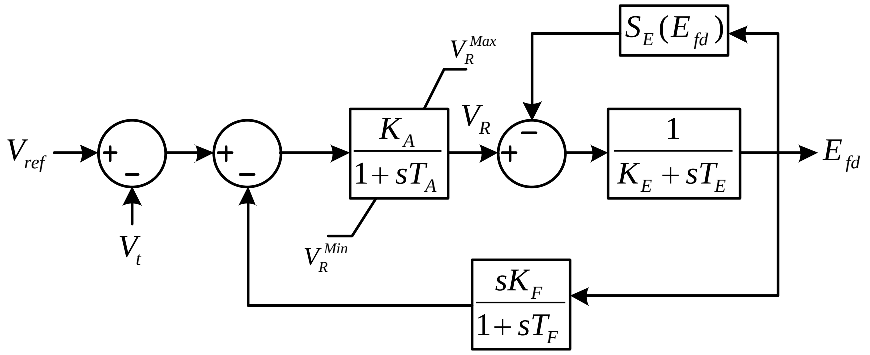

Fig. 1. IEEE Type I excitation system [16**].**

A WF based on DFIG technology is simulated using the simplified negative load model.

B. Wind Speed

Wind speed is a random variable which can be predicted to some extent. However, there is always an uncertainty associated with the predicted values. The direction and mean value of wind speed is a function of the geographical aspects of specific area. Generally, in high altitude and off-shore regions, the wind speed is rather high which makes these places suitable for WF installation.

For long-term studies, a general probability density function (PDF) describing the wind speed variation is the Weibull distribution. This is used widely in power system studies before and is accepted by the experts in this area [**15**], [**19**]. The Weibull PDF is described as:

$$f_v(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \tag{9}$$

The power generated by the wind turbine is calculated as [**19**]:

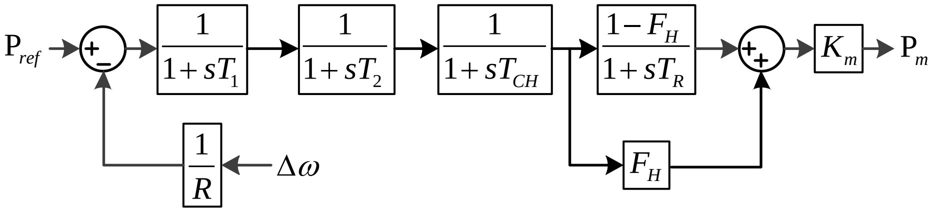

Fig. 2. Simplified model of re-heat steam turbine and associated speed governor [17].

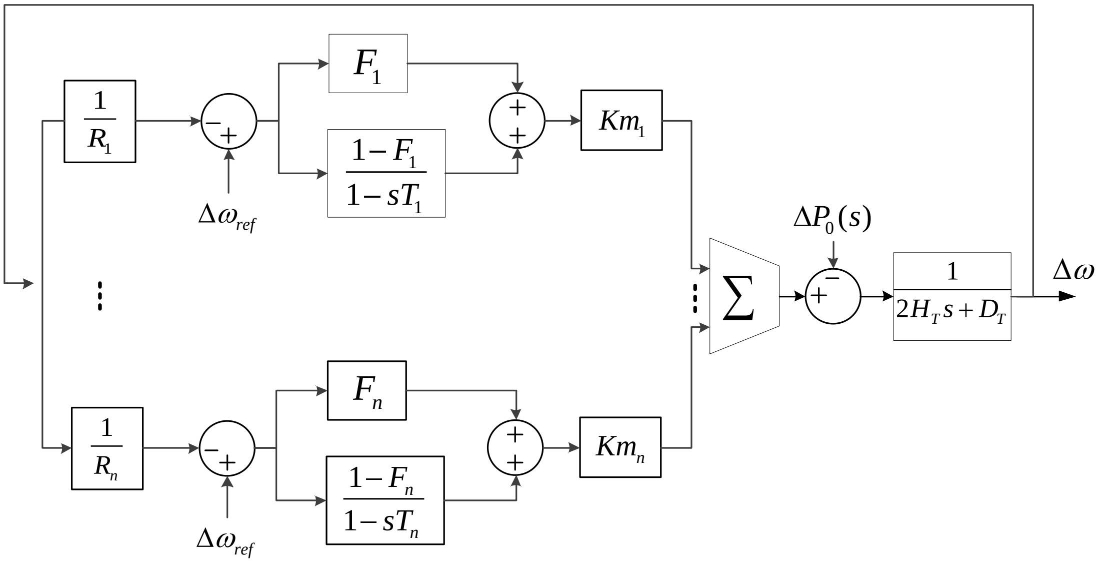

Fig. 3. Simplified system frequency response to a power imbalance disturbance [18].

$$P_w = \begin{cases} 0 & v < v_{in} \text{ or } v > v_{out} \\ P_{n-w} & v_r < v < v_{out} \\ P_{n-w}(v - v_{in})/(v_r - v_{in}) & v_{in} < v < v_r \end{cases} \tag{10}$$

For typical parameters given in Table I, the PDF of wind speed and generated power are numerically derived for 1000 samples and depicted in Fig. 4.

III. PROPOSED METHOD

A. Transient Stability Considerations

A method for P-TSA of power system for determining the maximum penetration level of WF is given here. First, the worst case fault scenario is determined for the system. It is assumed that the appropriate place for WF installation has been decided and the wind speed parameters are derived for that place. Power plant *s* is selected for step-wise outage when the WF capacity grows. This power plant is comprised of *m* smaller units which can be switched off-line individually based on short-term unit commitment. The capacity of each unit is P_d. This procedure is formulated as follows:

TABLE I

PARAMETERS FOR WEIBULL PDF AND WIND TURBINE ENERGY CONVERSION FORMULA

c	k	v_r (m/s)	v_{out} (m/s)	v_{in} (m/s)	P_{nw} (MW)
9	1.7	12	30	4	30

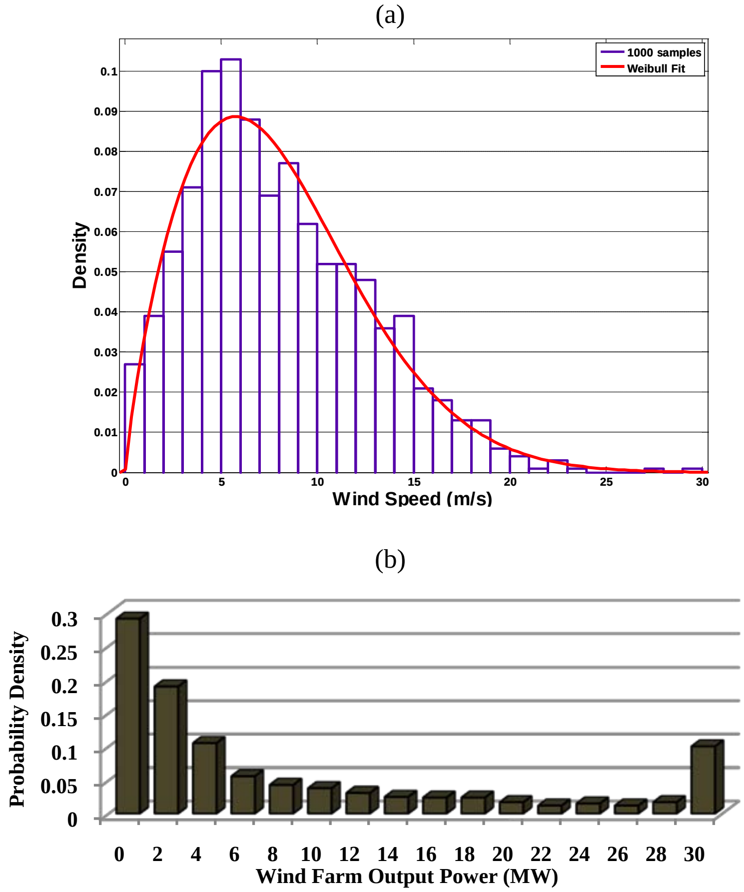

Fig. 4. PDF of: (a) Wind speed; (b) Wind turbine generated power

$$P^{i}_{n-w} = P_d\, i \tag{11}$$

$$P^{i}_{n-s} = P^{0}_{n-s} - P^{i}_{n-w} \tag{12}$$

$$H^{i}_{s} = H^{0}_{s}\left(1 - \frac{P^{i}_{n-w}}{P^{0}_{n-s}}\right) \tag{13}$$

in which i is the step of WF capacity increase and zero superscript means the initial value. The next steps of the proposed method are explained in Fig. 5. The transient stability criterion is based on the maximum relative rotor angle deviation (MRRAD) of synchronous machines. If any MRRAD exceeds a predefined value, e.g. α radians, the case would be classified as an unstable case [**20**]. From the view point of P-TSA and using Monte Carlo Simulations, the PDF of MRRADs are derived and then converted to the cumulative distribution function (CDF) using the following formula:

$$F(r) = \Pr\{y < r\} = \int_{-\infty}^{r} f(y)dy \tag{14}$$

in which y is an arbitrary random variable and r is the target probability. Using this formula, the probability of stability can easily be calculated as:

$$\Pr(\text{Stability}) = \min\left\{\Pr(\text{MRRAD}_i < \delta_{\max})\ , \forall i\right\} \tag{15}$$

Equation (15) states that all the machines should satisfy the minimum required probability of stability, which is represented by β. If the probability of stability in a certain level of WF penetration is lower than a predefined value, e.g. β = 80%, the algorithm is terminated and maximum penetration level is given. β is assumed to be specified by the power system operator.

This procedure can also be repeated for other places of WF installation and other candidate power plants for the step-wise outage its units.

B. *Frequency Security Considerations*

For frequency security studies, the probabilistic nature of wind speed is not important any more. This is due to the fact that the active power dispatches have no major effect on system primary frequency response after a large disturbance. Therefore, only the units' capacity and inertia are taken into account. Suppose that Power Plant n is chosen for stepwise outage which is comprised of m smaller units that can be switched off-line individually based on short-term unit commitment. The capacity of each unit is P_d. Assuming a negative load model for the WF due to inability of DFIG wind turbines to provide inertial response, the overall system inertia and damping at k^{th} step are calculated as:

$$H_T^k = \frac{(S_n - kP_d)(1-\frac{kP_d}{S_n})H_n + \sum_{i=1}^{n-1} S_i H_i}{\sum_{i=1}^{n} S_i} \tag{16}$$

$$D_T^k = \frac{(S_n - kP_d)(1-\frac{kP_d}{S_n})D_n + \sum_{i=1}^{n-1} S_i D_i}{\sum_{i=1}^{n} S_i}, \ k = 1,\dots,m \tag{17}$$

Then, using the SFR model described before, the system frequency drop is calculated for any load increase/generation loss disturbance. According to the grid codes or system operators' requirements for the minimum frequency nadir after a large-unit outage, the maximum penetration level of WF is then determined.

IV. Simulation Results

A. Transient Stability Criteria

The proposed method is evaluated using the IEEE 9-bus test system shown in Fig. 6. A WF is connected at Bus 5 and Gen1 is selected as the reference bus. System data are given in [**16**] and modified values are given in Appendix. A 3-phase fault is applied at Bus 7 which is cleared after 270 ms by opening Line 5-7. Two hundred samples are generated for wind speed using Weibull PDF for the simulations. Two scenarios for increasing the WF capacity are assumed:

1- Gen3 is selected for step-wise outage

2- Gen2 is selected for step-wise outage

Each scenario is described in the following.

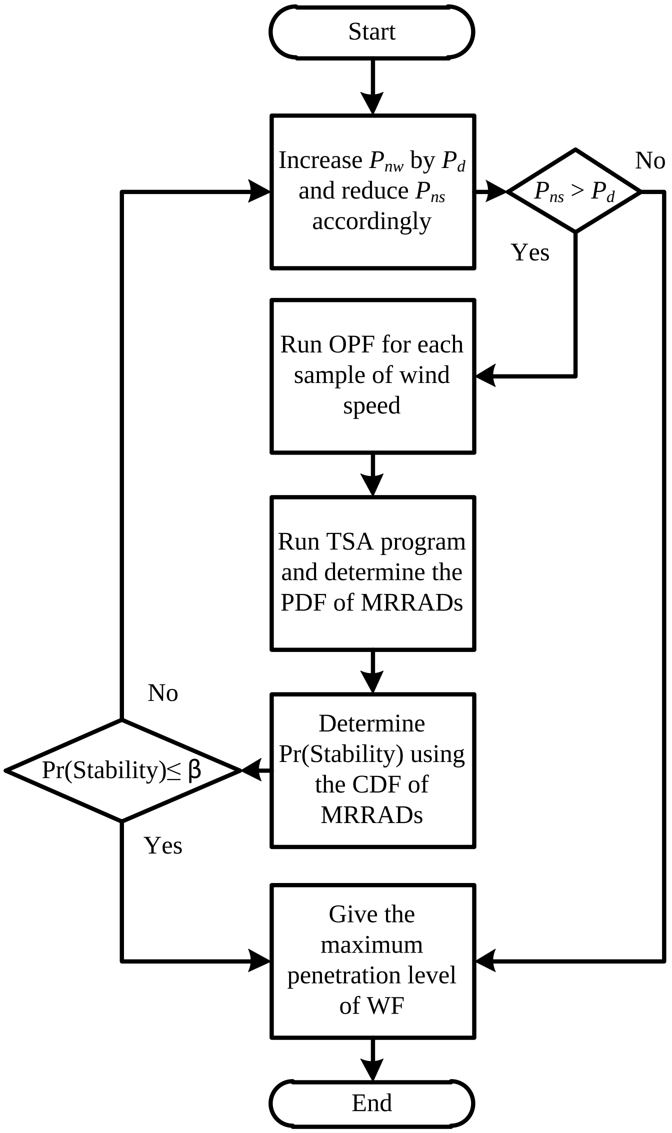

Fig. 5. Flowchart representation of proposed approach.

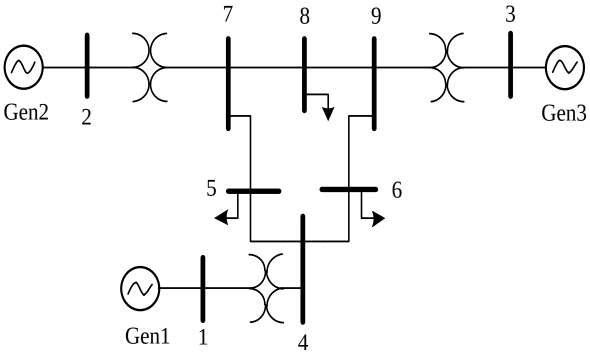

Fig. 6. The IEEE 9-bus test system [16**].**

1. *First Scenario*

Gen3 is a 154 MVA power plant comprises of 7 MVA units. The WF capacity is increased in 20 steps and for each step, the Weibull parameters given in Table I are used for calculating the PDF of WF output power. Figure 7 depicts the PDF histograms of MRRADs of Gen2 and Gen3 as a function of WF penetration level. It is obvious that for WF capacity above 126 MW, the probability of stability is lower than 1. This can be understood by deriving the CDF of MRRAD for Gen2, as shown in Fig. 8.

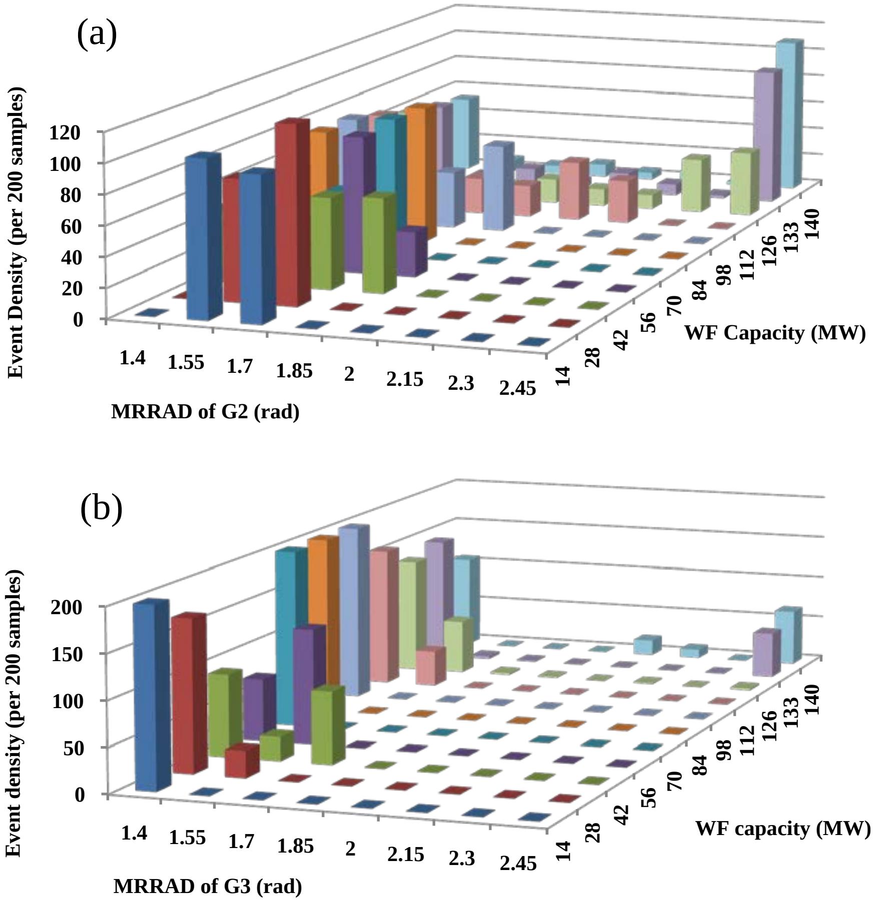

Fig. 7. Event density in first scenario as a function of WF capacity for MRRADs of: (a) Gen2; (b) Gen3.

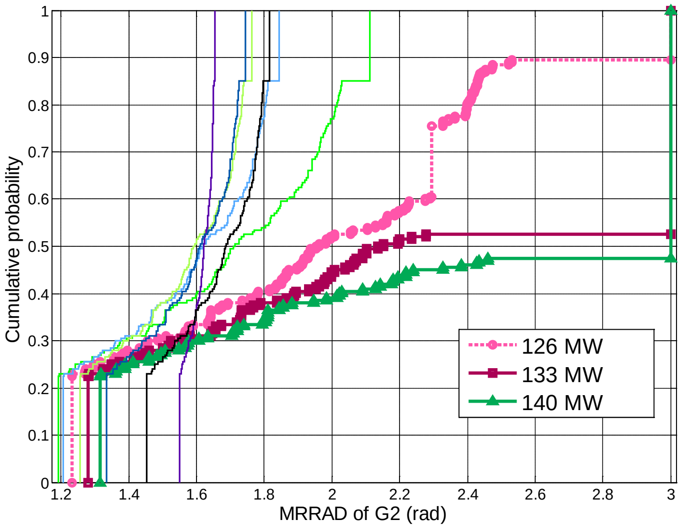

Fig. 8. CDF of MRRAD of Gen2 in the first scenario.

In this figure, the probability of stability for 126, 133 and 140 MW WF is 0.89, 0.52 and 0.48, respectively. Assuming $\beta = 0.8$, the penetration levels above 130 MW are not secure from the view point of system transient stability.

Here, only one power plant is considered for the outage of its units. However, the WF penetration level could be further increased by distributing the stepwise unit outages to more than one power plant. Moreover, the WF could also be distributed all over the system instead of being aggregated at only one bus. This would help the unit commitment and OPF programs to distribute the amount of power added by the WFs to reduce the generation of more than one unit without jeopardizing the system security limits.

2. *Second Scenario*

Gen2 is a 150 MVA power plant comprised of 10 MVA units. The WF size is increase in 12 steps and the TSA program is run for determining the MRRADs at each step. Figure 9 illustrates the PDF histogram of MRRADs. As can be seen, in levels of 30 and 40 MW, the probability of stability is lower than 1 and in higher levels it is brought back to unity. This has happened due to the OPF dispatch results which highly influence the transient stability of power system. Therefore, it is not always the case that increasing the WF capacity would decrease the probability of stability and other factors including generators' dispatch are also influential.

Based on the above observations, it is possible to increase the maximum penetration level of WF by revising other units' dispatch to ensure high probability of system transient stability. This could be done by using the transient stability constrained optimal power flow (TSC-OPF) which guarantees power system stability by changing the dispatch pattern [**20**].

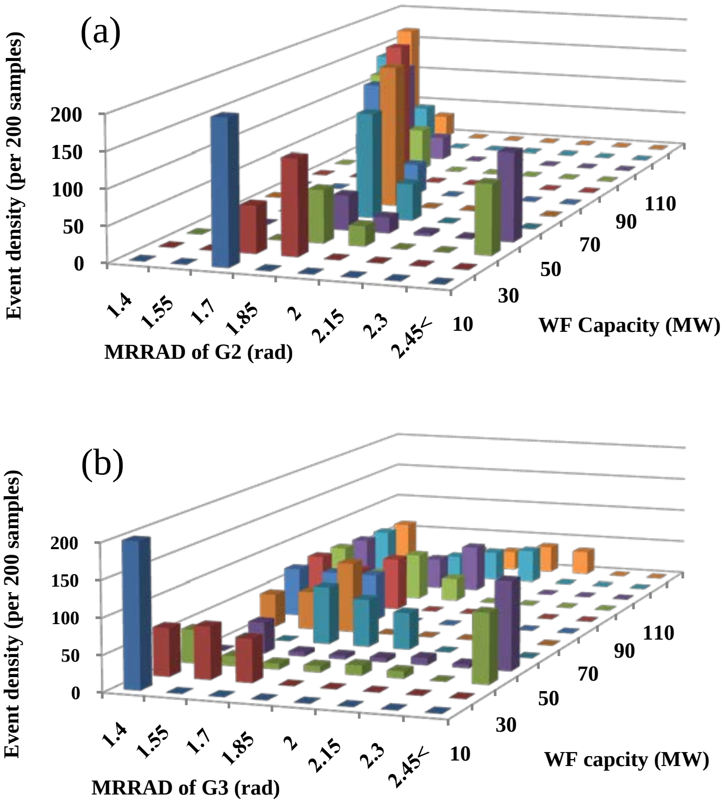

Fig. 9. Event density in second scenario as a function of WF capacity for MRRADs of: (a) Gen2; (b) Gen3.

B. Frequency Stability Criteria

The test system parameters used for this part are given in Appendix. WF size is increased by five steps of 40 MW. Gen3 is selected for the stepwise outage of its units. Overall system inertia and damping are then calculated using (16) and (17). Figure 10 (a) shows the system frequency after a sudden 20% load increment. For better judgment, the frequency nadirs are plotted as a function of WF capacity in Fig. 10 (b). Using the obtained result, the maximum penetration level of WF can be determined considering the grid code or system operator requirements. For instance, if up to 1.8 Hz initial frequency drop is acceptable, then, according to Fig. 10 (b), the maximum penetration level of WF would be 120 MW.

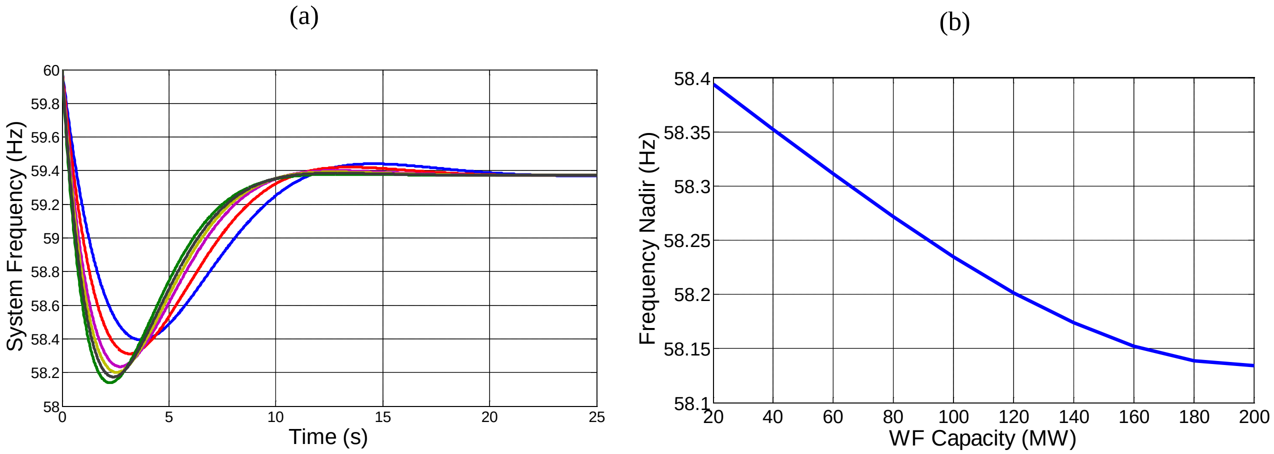

Fig. 10. (a) System frequency after a load increase of 20% using the simplified SFR model; (b) System frequency nadir as a function of WF capacity.

V. CONCLUSIONS

A probabilistic method for transient stability analysis of a system incorporating wind generation was proposed. Using this method, a maximum penetration level for wind generation is determined. The proposed method is applicable for unit commitment and OPF considering transient stability limits. In addition, a frequency security limit was also derived taking into account the effect of reduced inertia due to replacing conventional synchronous units by wind generation. Maximum penetration level of wind generation based on converter-driven technologies which do not participate in system inertial response, e.g. DFIGs or permanent magnet synchronous generators, is then determined. Frequency security constrained unit commitment is believed to be a solution for increasing the wind capacity limit. This would keep more synchronous machines on-line to ensure frequency security. The issue of transient stability may also be resolved using transient stability constrained OPF instead of conventional OPF.

Appendix

TABLE II

PARAMETERS FOR GOVERNOR MODEL AND SYNCHRONOUS MACHINES IN THE IEEE 9-BUS SYSTEM

R	K_m	F	T (s)	D	H (s)	S (MVA)	Gen. No.
0.04	0.27	0.3	10	0.2	8	200	1
0.04	0.11	0.15	16	0.3	4	150	2
0.02	0.19	0.2	12	0.1	6	154	3

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