2011 American Control Conference
on O'Farrell Street, San Francisco, CA, USA
June 29 - July 01, 2011

Impact Analysis of Wind Generation on Voltage Stability and System Load Margin

Rui Ma, *Member, IEEE*, and Garng M. Huang, Senior *Member, IEEE*

Abstract—**Due to the environmental concerns and induced political incentives, wind power penetration has been increasing in many countries around the world. However, wind power generation is very different from conventional power generation due to stochastic and intermittent nature of the wind. The wind power may not be available or generating the demanded amount as needed. Thus, these mandates to promote wind power need to be balanced by studies on their impacts on power system operations and control. However, new approach is needed to properly quantify the voltage stability of power system.**

Accordingly, this paper addresses the modeling of the stochastic and intermittent wind generation and its use to predict the associated stability margin in terms of system load margin. To model the variation nature of stochastic and intermittent wind power injection as the load increases, we propose to use the Weibull distribution of wind speed to model the intermittent factor. The slip of asynchronous wind generators is introduced as a new state variable, and thus new power balance equations including the slip as a state variable are formulated. The balance between the average electromechanical power conversion and mechanical power of wind turbines is utilized to incorporate wind stochastic and intermittent uncertainty. As a first step, we investigate the impacts of the wind generation on static power flows. In terms nonlinear control terminology, we are investigating the stochastic nature of the equilibrium points associated with the uncertainty of the wind generation. Accordingly, we derive a novel sensitivity index of voltage stability considering the stochastic and intermittent nature of wind speed through the slip effect, using the Jacobian matrix for the newly formulated power flow equations. In addition, the probabilistic stability margins in terms of load for various wind speed distribution and penetration are investigated by use of the proposed CPF and Monte Carlo method. The proposed methods are illustrated on the IEEE 39-bus system and the results show that the stochastic and intermittent wind power injection will significantly affect the stability margin and its slip.

***Index Terms*-- Wind power generation, Weibull distribution, stochastic and intermittent of wind speed, power flow analysis, continuation power flow (CPF), stability margin, voltage stability.**

I. INTRODUCTION

Due to environmental concerns, many incentives have been created through political movements for wind power, which has zero emission. For example, Texas has mandated the wind penetration should exceed 6GW by 2015 from 2 GW of 2009. DOE roadmap also recommends 20% delivery of wind power by 2030. Many similar mandates are popping up all over the world. However, wind power generation is very different from conventional power generation due to stochastic and intermittent nature of the wind. The wind power may not be available or generating the demand amount when needed. Accordingly, these mandates to promote wind power need to be balanced by studies on their impacts on power system operations and control. An alarming case, which almost collapsed the system in ERCOT on Feb. 26 2008, indicates the urgency of such studies. Note that, in 2008, the wind power penetration for the warning case was rather low compared to the mandated amount in the near future.

The traditional approaches use saddle-node bifurcations (SNBs) that indicate the load limits and critical voltage have been focuses in voltage stability analysis [1]-[5]. The Continuation Power Flow, one of the most widely used computing methods of SNBS, is a prediction-correction scheme to find a solution path for a set of power equations that including load parameter [6]-[8]. Various types of bifurcations that consider the impact of load models has been studied [9]. In [10], a CPF method with multiple nonlinear power injection variation that solved by piecewise-linear model is proposed. These techniques can make the power flow equations remain well conditioned so that divergence due to a singular Jacobian matrix will not be encountered.

In addition, there are some general probabilistic approaches: [11]-[15]. However, so far researchers (either deterministically or stochastically) did not analyze one asynchronous nature of the wind generations, which use induction generators, and thus is characterized by a slip state. In this paper, we model the wind generation including a new slip state. Furthermore, wind speed, which is random, determines power generation by the generator power curves based on cut-in speed, maximum power output, and cut-out speed. As a consequence, the operation status of wind generation is uncertain due to cut-in or cut out wind speed. Therefore, we will incorporate this characteristic into power flow equations that include slip as a state variable for our study to investigate stability margin in terms of system load margin.

We organize our paper as follows: Section II gives the details on our power flow equations and thus the associated CPF method that consider slips as new state variables for system loadability studies. The stochastic and intermittent wind speed and how it influences our power flow equations will be discussed. Section III gives the computational algorithm for the probabilistic system loadability approach

Rui Ma is with the Department of Electrical Engineering, Changsha Univeristy of Science and Technology, Changsha, 410076,China (e-mail: ruimacsust@yahoo.com).

Garng M. Huang is with the Department of Electrical Engineering, Texas A&M University,College Station, TX, 77843 USA (e-mail: ghuang@neo.tamu.edu).

based on CPF incorporating the stochastic and intermittent wind generation as the load increases. Section IV proposes a novel Sensitivity index of voltage stability considering the uncertainty of wind speed. Section V gives some numerical results of the IEEE 39-Bus System and provides interpretations of the results, and Section VI draws our conclusion.

II. FORMULATION OF CPF WITH STOCHASTIC AND INTERNITTENT OF WIND SPEED

A. Probability model of Wind speed

The average wind speed in most area can be described by Weibull distribution [14], its parameters can be fitted by historical wind speed data. A large number of measurement data from wind speed show that wind speed changes usually in the range of 0m/s to 25m/s.

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp[-(\frac{v}{c})^{k}] \qquad (1)$$

where v is the average wind speed (m/s); c is the scale coefficient (m/s) and k is the shape coefficient whose value is usually between 1.8 and 2.3. Scale coefficient and shape coefficient are different in different areas. Since the distribution is determined by k and c, we will describe the distribution by Weibull(k,c).

The probability distribution of wind speed is given through integral of (1):

$$F(v) = \int_{0}^{+\infty} f(v)dv = 1 - \exp[-(\frac{v}{c})^{k}] \qquad (2)$$

B. Model of the mechanical output of a wind turbine

The mechanical power output $P_m^{'}$ of wind turbine is given by [15]:

$$P_m^{'} = 0.5\rho\pi R^2 v^3 C_p \qquad (3)$$

Where ρ is the air density, R is the blade radius, and C_p is power coefficient. It is a nonlinear function of the tip speed and the pitch angle. In this paper, the mechanical power output of wind generator can be represented as the subsection function of the wind speed as follows,

$$P_m = \begin{cases} 0 & v \le v_{ci}, v > v_{co} \\ P_m^{'} \dfrac{v - v_{ci}}{v_r - v_{ci}} & v_{ci} < v \le v_r \\ P_m^{'} & v_r < v \le v_r \end{cases} \qquad (4)$$

Where v_r is the rated wind speed, v_{ci} is the cut-in wind speed, and v_{co} is the cut-out wind speed.

C. Asychronous wind generator model with stochastic and intermittent wind speed

In this paper, the standard squirrel cage induction generator and the wound rotor induction generator is applicable to induction generators. The relation between the real and reactive power can be determined by the use of the simplified induction generator circuit in Fig.1.

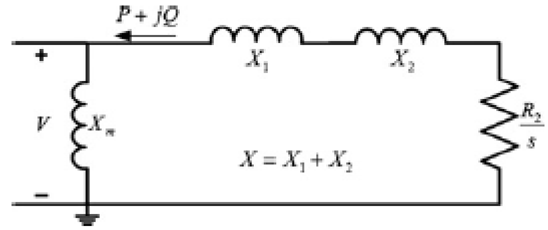

Fig. 1. Equivalent circuit of an induction generator

X_1 is the leakage reactance of the stator, X_2 is the leakage reactance of rotor , R_2 is the resistance of the rotor, X_m is magnetising reactance, s is the per unit slip of the asynchronous generator, respectively.

The magnetizing losses and the stator losses are ignored. It is also assumed that X_m together with any shunt capacitor banks are included in the calculation of the network bus admittance matrix.

The active power and reactive power can be represented as the function of the slip and voltage as follows:

$$P_w = P = \frac{-sR_2}{R_2^2 + s^2X^2} V^2 \ge 0 \qquad (5)$$

$$Q_w = Q = \frac{-s^2X}{R_2^2 + s^2X^2} V^2 \le 0 \qquad (6)$$

The equations (5) and (6) indicate that the active power output and reactive power output of asynchronous wind generator are the function of the slip and voltage.

The output of reactive power of asynchronous wind generator can be rewrite as follows,

$$Q_w = \frac{sX}{R_2} P_w \qquad (7)$$

Ignoring the real power loss of wind generator active we can relate power and mechanical power by eq. (8) at each steady state,

$$P_w - P_m = 0 \qquad (8)$$

The equation also can be rewritten as follows,

$$P_w = \frac{-sR_2}{R_2^2 + s^2X^2} V^2 = \begin{cases} 0 & v \le v_{ci}, v > v_{co} \\ P_m^{'} \dfrac{v - v_{ci}}{v_r - v_{ci}} & v_{ci} < v \le v_r \\ P_m^{'} & v_r < v \le v_r \end{cases} \qquad (9)$$

The equation (7) show that the slip of asynchronous wind generator is the function of the wind speed and voltage; and thus, the impact of stochastic wind speed on the output of real power and reactive power of asynchronous wind generator can be modeled by the slip of asynchronous wind generator.

D. Continuation Power flow model with stochastic and intermittent wind speed

To model the nature of stochastic and intermittent wind generation as the load increases, the power balance between mechanical power and electro-mechanical power in each steady state and the intermittent factor of asynchronous wind generator should be incorporated into the conventional CPF.

The slip of an asynchronous wind generator is taken as a new state variable. The power balance equation is added as a new balance equation.

For let λ represent the load parameter such that

$$0 \le \lambda \le \lambda_{critical}$$

$$\begin{cases} P_{Wi} + P_{Gi0}(1+\lambda k_{Gi}) - (P_{Li0} + \lambda(k_{Li} S_{\Delta base}\cos\varphi_i)) - \\ \qquad V_i \sum_{j\in i} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \\ Q_{Wi} + Q_{Gi} - (Q_{Li0} + \lambda(k_{Li} S_{\Delta base}\sin\varphi_i)) - \\ \qquad V_i \sum_{j\in i} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0 \\ P_m - P_{Wi} = 0 \end{cases} \quad (10)$$

For each bus *i,* the subscripts *W*,*L* and *G* denote wind generation , load and conventional generation, respectively. The voltages at buses *i* and *j* are $V_i\angle\theta_i$ and $V_j\angle\theta_j$, respectively. G_{ij} and B_{ij} are the conductance and susceptance of $(i,j)^{th}$ element of node admittance matrix Y_{BUS} . P_{Gi0} is the active power at bus *i* in the base case and k_{Gi} is the rate of changer as λ varies. P_{Li0} , Q_{Li0} are active and reactive power of load at bus *i* in the base case, φ_i is power factor angle of load, and k_{Li} is the multipliers to designate the rate of load change at bus *i.* We distribute that the unbalanced power caused by wind generators through an assumed economic dispatch ratio over the committed generation units.

In this model, as the load increases, if $v \le v_{ci}$ or $v > v_{co}$, then $s = 0$,and thus, $P_{wi} = 0$ and $Q_{wi} = 0$. In this case, the wind generator is zero; the proposed CPF is reduced into a conventional problem. Otherwise, P_{mi} , sP_{wi} , and Q_{wi} are all random variables depending on the stochastic wind speed.

III. Simulation Algorthim

A step-by-step description of the proposed probability stability Margin Approach for power systems incorporating the stochastic and intermittent wind generation is summarized in e the following.

Step 1) Identify the stochastic and intermittent wind generation distribution parameters through historical data.

a) According to historical wind speed data of different wind farms, the Weibull distribution parameters *v*, *c* and *k* can be identified. The simulated wind sequence is obtained by the wind forecasting produced by Weibull random producer.

b) The mechanical power sequence is generated by (3) and (4).

Step 2) Solve the proposed PF equations (10) that incorporates the stochastic and intermittent wind generation for a sample path of a Monte Carlo (MC) simulation.

a) The general formulation of proposed CPF

If f is used to denote the whole set of equations, the problem can be expressed as

If $P_m \ne 0$, $s \ne 0$,then

$$f(\mathbf{V}\boldsymbol{\theta}\mathbf{s}, \ ,\lambda) = 0 \quad 0 \le \lambda \le \lambda_{critical} \quad (11)$$

If $P_m = 0$, $s = 0$, then

$$f(\mathbf{V}\boldsymbol{\theta} \ ,\lambda) = 0 \qquad 0 \le \lambda \le \lambda_{critical} \quad (12)$$

Where $\mathbf{V}$ represents the vector of bus voltage magnitudes, $\boldsymbol{\theta}$ represents the vector of bus voltage angles and $\mathbf{s}$ represents the vector of asynchronous wind generation slips.

b) Build up the current load demand pattern P_{Li0} and real generation pattern P_{Gi0}

c) Obtain the future wind power injection and load variations according to look-ahead wind speed and load variation or short-term wind speed and load forecasting.

d) Solve the continuation power flow with the stochastic and intermittent wind generation.

e) Generate another sample path as needed.

IV. Sensitivity Index of Voltage Stability with Stochastic and Internittent Wind Speed

To assess the voltage stability for each bus of the power system interconnected with the stochastic and intermittent wind generations, sensitivity indices of reactive power versus voltage is derived in this section. A power system is characterized by a set of nonlinear dynamic equations, but it can be simplified into algebraic power flow equations at steady state. The Jacobian matrix or reduced matrix of power flow is usually used to assess the voltage stability. As the load increases, at the saddle node bifurcation which leads to voltage collapse, the Jacobian matrix of that becomes singular. At the same time, the voltage stability can be detected by the sensitivity information of Jacobian matrix or reduced Jacobian matrix. The QV sensitivity index is one of the most widely used method to evaluate the voltage stability of power system.

However, there are differences between the traditional QV sensitivity index and that of the proposed in this section. Note that the slip of asynchronous wind generator is added as a new state variable and intermittent factor and the mechanical and electromechanical power considering the stochastic and intermittent wind speed are incorporated in the proposed CPF.

At the each load level, If $P_m \ne 0$, $s \ne 0$, then the power flow equations can be expressed as follows:

$$\begin{bmatrix} \Delta\mathbf{P} \\ \Delta\mathbf{Q} \\ \Delta\mathbf{P_m} \end{bmatrix} = \begin{bmatrix} \mathbf{J_{P\theta}} & \mathbf{J_{PwV}} + \mathbf{J_{PV}} & \mathbf{J_{Pws}} \\ \mathbf{J_{Q\theta}} & \mathbf{J_{QwV}} + \mathbf{J_{QV}} & \mathbf{J_{Qws}} \\ \mathbf{0} & \mathbf{J_{PmV}} & \mathbf{J_{Pms}} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{\theta} \\ \Delta\mathbf{V} \\ \Delta\mathbf{s} \end{bmatrix} \quad (13)$$

Since asynchronous wind generator always produce active power while absorb reactive power, and that voltage is closely related to the reactive power, we assume that the power system is in static angle stability at each load level as the load increases. Thus, the incremental active power can be regard as zero.

The static voltage stability sensitivity that considered the stochastic and intermittent of wind speed and the slip factor can be represented as follows:

$$\Delta s = -J_{Pms}^{-1} J_{Pmv} \Delta V \qquad (14)$$

$$\Delta \theta = -J_{P\theta}^{-1}[(J_{pv} + J_{pmv}) - J_{pms} J_{pms}^{-1} J_{pmv}]\Delta V \qquad (15)$$

$$\frac{\Delta Q}{\Delta V} = (J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}) + (J_{Qwv} - J_{Q\theta} J_{P\theta}^{-1} J_{Pmv}) - (J_{Qws} J_{Pms}^{-1} J_{PmV}) \qquad (16)$$

Where the equation (14) is the sensitivity information of the slip versus voltage, the equation (15) gives the sensitivity information of the angle versus voltage and the equation (16) gives the sensitivity information of the reactive power versus voltage, respectively. In equation (16), the first item of the right side is related to the traditional power flow, the second item of that is in terms of the injection power of asynchronous wind generator versus voltage and the third item denotes the sensitivity information of slip versus voltage. More importantly, the proposed sensitivity index including the slip of asynchronous wind generator that related to the information of stochastic and intermittent wind generation, it can be used to assess the voltage stability for each bus as the load increases.

If $v \le v_{ci}$ or $v > v_{co}$, then $s = 0$,and thus, $P_{wi} = 0$ and $Q_{wi} = 0$ in the load increasing , the Sensitivity information is simplified as a conventional power flow:

$$\Delta \theta = -J_{P\theta}^{-1} J_{pv} \Delta V \qquad (17)$$

$$\frac{\Delta Q}{\Delta V} = (J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}) \qquad (18)$$

All the above sensitivity components can be easily incorporated into the linearized continuation power flow equations (11) and (12).

V. CASE STUDIES

This paper addresses the impact of the intermittent and stochastic asynchronous wind generation as the load increases on probabilistic load margins related to voltage collapse. It aims to incorporate the intermittent and stochastic wind generation during the load increasing into the Continuation Power Flow so as to capture the intermittent and stochastic nature of load margins and to obtain the probabilistic load margins and the information of voltage stability for the power system interconnected with wind farms.

The proposed approach is applied to the IEEE 39-bus system as shown in Fig.1 for demonstration. In order to assess the wind penetration on probabilistic load margins, two cases have been studied. The wind farms installed an aggregated 60 MW asynchronous wind generator that connected into transmission network by a transformer, we assume the impedance of the transformer and connected line can be ignored. To study the reactive characteristic of asynchronous wind generator, we assume no reactive compensation of wind farms. Two wind penetration level will be studied, In one case, the asynchronous wind generator is installed at bus 15, in this situation, the wind penetration level is 1%. In the other case, asynchronous wind generators are installed at both bus-15 and bus-16., thus the wind generation level is 2%. The parameters of asynchronous wind turbine generators are given in Table I.

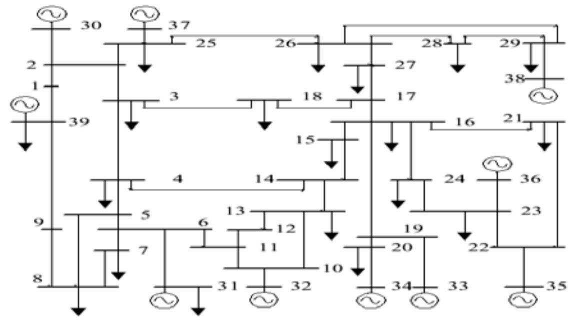

Fig. 1. IEEE 39-bus system

TABLE I

PARAMETERS OF ASYNCHRONOUS WIND TURBINE GENERATORS

Parameters	values	Parameters	values
ρ /(kg/m^3)	1.2245	U_N(KV)	0.69
A/m^2	1840	X_1/ Ω	0.05070
R/m	23	R_2/ Ω	0.00486
v_{ci} /(m/s)	3	X_2/ Ω	0.14910
v_{co} /(m/s)	20	X_m/ Ω	2.20590
v_r (m/s)	13.5		

A. *Impact of stochastic and intermittent wind speed on load margins*

In the first case, asynchronous wind generators are connected at bus-15. Table II related to Weibull (2,7) and Table III related to Weibull(1.8,12) illustrate the loading parameter, voltage at bus-15, the slips and the output of the asynchronous wind generator.

TABLE II

LOAD PARAMETER, VOLTAGE, SLIP AND OUTPUT OF THE ASYNCHRONOUS WIND TURBINE GENERATOR AT BUS-15 WINTH WEIBULL (2, 7)

Loading Parameter λ (p.u.)	Voltage V(p.u.)	Slip S(p.u.)	Active power Pw(p.u.)	Reactive power Qw(p.u.)
0	1.1459	-0.00982	2.281368	-4.60968
0.25241	1.1301	0	0	0
0.75464	1.0904	-0.01222	2.386743	-5.99976
1.2504	1.0369	0	0	0
1.4802	1.0051	0	0	0
1.5876	0.98819	-0.01287	2.022002	-5.34765
1.6392	0.97946	-0.00185	0.363469	-0.13851
1.739	0.96132	0	0	0
1.833	0.94238	0	0	0
2.1542	0.85468	-0.01157	1.41793	-3.37473
2.2102	0.83212	-0.02188	1.72312	-7.75759
2.2952	0.78492	-0.01023	1.102094	-2.32029
2.312	0.69107	-0.01242	0.96183	-2.47431
2.1156	0.66749	-0.02001	1.094053	-4.50453
1.8016	0.69687	-0.01327	1.021859	-2.79014
1.731	0.70784	-0.02087	1.239283	-5.32178
1.496	0.74947	-0.02034	1.383474	-5.79009
1.4002	0.76635	0	0	0
1.2154	0.79607	-0.02309	1.583756	-7.52447
1.0324	0.82159	-0.00215	0.296301	-0.13108

In Table II, the slip is zero at some load levels because the wind speed is smaller than the cut-in wind speed or is larger than the cut-out wind speed during the load increasing. Table II and Table III not only show that the intermittent factor and output of wind generator are changed as the load increases but also show that the stochastic wind power injections may be different at different loading levels and different wind distributions . In addition, we can see this phenomenon where the reactive power is a minus value. Conventional synchronous generator can supply real power and reactive power at the same time, however, Asynchronous wind generator is that it will absorb reactive power from the power grid while injecting active power to the grid. This can increase the reactive demand and deteriorate voltage stability of the power system.

The simulation shows that Weibull distribution parameters of the wind speed have significant impacts on the operation states, output of asynchronous wind generators, and the stability margins. For example, Table II shows that the maximal loading parameter is 2.312 with Weibull (2,7), while the maximal loading parameter is 2.3369 with Weibull(1.8,12). It is obvious that the operation status and output of wind generators are different with different Weibull distribution parameters.

B. Impact of stochastic and intermittent wind speed on probabilistic load margins

The analysis of numerical results based on one sample simulation. The MC simulation, the reason for this the stochastic and intermittent wind generation during the load increase, the numerical results is naturally probabilistic. In this simulation, we investigate the impact of stochastic and intermittent wind generation on load margins without considering other uncertain factors in this simulation.

In Fig.2, the MC method aims at obtaining a probability distribution function of load margins at the point of voltage collapse considering the stochastic and intermittent wind generation. In this case, the probability distribution of the maximal loading parameter is obtained by 1000 samples with Weibull (2,7) and 1% wind penetration level.

The MC simulation results are shown in Fig.2, from which we know that the loadability takes values mostly between 2.34 and 2.33.

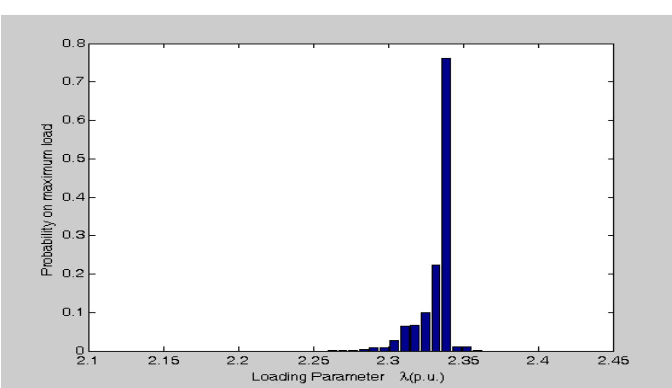

Fig. 2. Probability distribution of the loadability in the IEEE 39-bus system with stochastic and intermittent wind speed of Weibull(2,7) and 1% wind penetration level

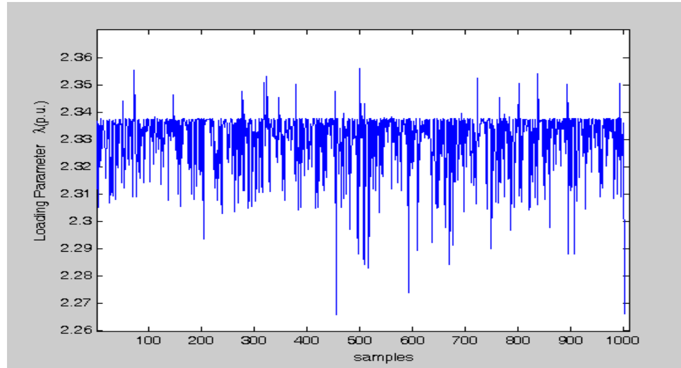

Fig. 3. MC simulation for maximal loading parameter in the IEEE 39-bus system with bus-15 connected wind generators with stochastic and intermittent wind speed of Weibull (2,7) and 1% wind penetration level. Fig 4 gives the slips of the same case. 1000 samples are computed.

Note that the slip of the asynchronous wind generator is also uncertain during the load increase. In addition to the loads, due to the stochastic and intermittent wind speed, different probability distributions of wind speed lead to different slips and its probability density function, from the equation (7), (8) and (9), we know that output of real and reactive power is a function of the slip and the wind speed .

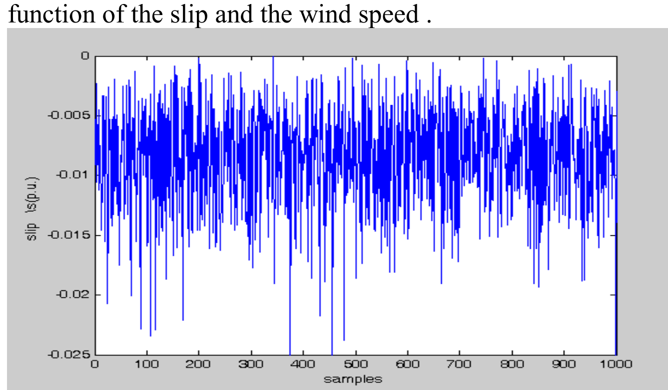

Fig.5 shows the probability distribution of the asynchronous wind generator slip in the IEEE 39-bus system with bus-15 connected wind generators with stochastic and intermittent wind speed of Weibull (2,7) with 1% wind penetration level.

Moreover, we would like to know the impact of wind penetration level on loadability in term of the voltage collapse.

Fig. 6 gives the probability distribution of load margins in the IEEE 39-bus system with bus-15 and bus-16 connected to wind generators with stochastic and intermittent wind speed of Weibull (2,7). We can know that the loadability value decreases when bus-15 and bus-16 are both connected to asynchronous wind generators with the same Weibull distribution of wind speed, in other words, the wind penetration level increase from 1% to 2%. These results tell us that the voltage collapse margin will suffer as the wind penetration increases. This can be explained that the reactive power demand will be increased with the increase of asynchronous wind penetration.

In Fig.7, we see that the maximal loading parameters with bus-15 and bus 16 connected to asynchronous wind generators mostly lie between 2.175 and 2.17, which is decreased from 2.34, and almost 10 percent decrease. Note wind penetration is only a 1% increase here.

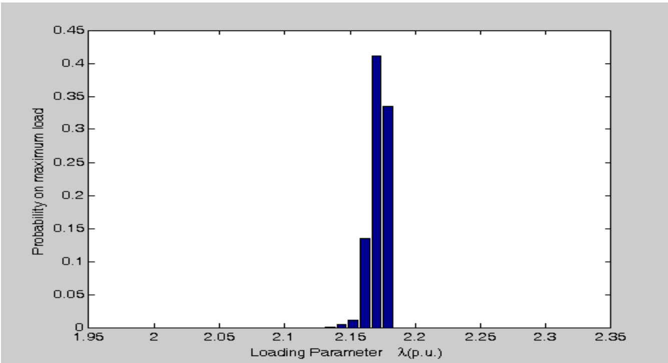

Fig. 6. Probability distribution of load margins in the IEEE 39-bus system with bus-15 and bus-16 connected to wind generators with stochastic and intermittent wind speed of Weibull (2,7) with the penetration increase from 1% to 2%.

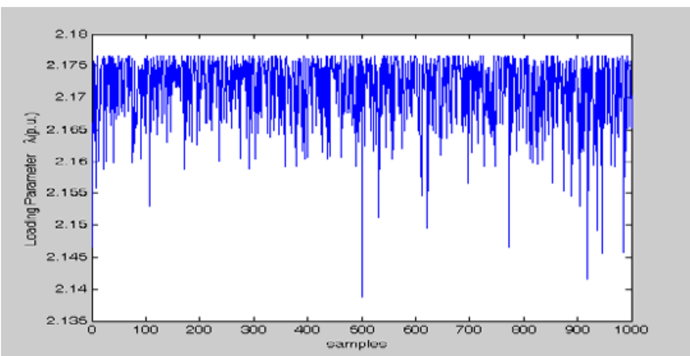

Fig. 7 MC simulation for load margins in the IEEE 39-bus system with bus-15 and bus-16 connected to wind generators with stochastic and intermittent wind speed of Weibull(2,7) and the penetration increase from 1 % to 2 %.

VI. CONCLUSIONS

This paper describes an approach to calculate the load margin based on the proposed continuation power flow incorporating the stochastic and intermittent wind generation and on the MC method. The variation nature of stochastic and intermittent wind power injection during the load increasing is modeled by the wind speed Weibull distribution and the theory of power transfer of asynchronous wind generators. The slip of the asynchronous wind generator and the balance of the average wind turbine electromechanical power and mechanical power are incorporated into the continuation power flow by the new state variable and the new equation. Therefore, the proposed novel continuation power flow can be capable of handling the stochastic and intermittent wind power injection as the load increases. In addition, the novel reactive-voltage stability sensitivity index considering the stochastic and intermittent wind speed is also presented. The simulation results show that the characteristic of wind speed Weibull distribution and penetration level of asynchronous wind generation can significantly affect the load margin that related to the voltage collapse.

VII. REFERENCES

[1] Dobson and H.D. Chiang, "Towards a theory of voltage collapde electric power system," *System & Control Letters,* vol. 13, pp. 253-262, 1989.

[2] C. A. Canizares, "On bifurcations, voltage collapse and load modeling," *IEEE Trans. Power System*, vol. 10, pp. 512-522, Feb. 1995.

[3] H. G. Kwatny, A. K. Pasrija, L. Y. Bahar, "Static Bifurcations in Electric Power Networks: Loss of Steady State Stability and Voltage Collapse". *IEEE Trans. On Circuits and Systems*, vol.33, pp.981 ~991, 1986.

[4] Garng Huang,Tong Zhu; "A new method to find the voltage collapse point," PES Summer Meeting, 1999. IEEE, Volume:2, 18-22 July 1999, Pages:1324-1329.

[5] Garng Huang,Kun Men," Fast small disturbance voltage stability margin estimation by integration with intelligent load adjustments," Power Engineering Society Summer Meeting, 2005 IEEE, June 12-16, 2005 Page(s): 1985-1992.

[6] V. Ajjarapu and C. Christy, "The continuation power flow: A tool for steady state voltage stability analysis," IEEE Trans. Power Syst., vol.7, no. 1, pp. 416–123, Feb. 1992.

[7] C. A. Canizares and F. L. Alvarado, "Point of collapse and continuation methods for large AC/DC systems," *IEEE Trans. Power Syst.*, vol. 8,no. 1, pp. 1–8, Feb. 1993.

[8] H. D. Chiang, A. J. Flueck, K. S. Shah, and N. Bale, "CPFLOW: A practical tool for tracing power system steady state stationary behavior due to load and generation variations," *IEEE Trans. Power Syst.*, vol. 10, no. 2, pp. 623–634, May 1995.

[9] W. Xu and Y. Mansour, "Voltage stability analysis using generic dynamic load models," *IEEE Trans. Power Syst.*, vol. 9, no. 1, pp. 479–493, Feb. 1994.

[10] Shao-Hua Li and Hsiao-Dong Chiang, "Continuation Power Flow With Nonlinear Power Injection Variations: A Piecewise Linear Approximation," *IEEE Trans. Power Syst.*, vol. 23, no. 4, pp. 1637–1643, Nov. 2008.

[11] Z. Xiuhong, W. Kewen, L. Ming, Y. Wanhui, and C. T. Tse, "Two extendend approaches for voltage stability studies of quadratic and probabilistic continuation load flow," in *Proc. PowerCon*, Hong Kong, Nov.26–27, 2002.

[12] Y. Kataoka, "A probabilistic nodal loading model and worst case solutions for electric power system voltage stability assessment," *IEEE Trans. Power Syst.*, vol. 18, no. 4, pp. 1507–1514, Nov. 2003.

[13] Edwin Haesen, Cindy Bastiaensen, Johan Driesen, Member, and Ronnie Belmans, "A Probabilistic Formulation of Load Margins in Power Systems With Stochastic Generation" *IEEE Trans. Power Syst.,* vol. 24, no.2, pp. 951–958, May. 2009.

[14] Eknath Vittal, Mark O'Malley, and Andrew Keane, "A Steady-State Voltage Stability Analysis of Power Systems With High Penetrations of Wind," IEEE Trans. Power Syst., vol. 25, no.1, pp. 433–442, Feb. 2010.

[15] P.Vijayan , S.Sarkar, and V. Ajjarapu, "A Novel Voltage Stability Assessment Tool to Incorporate Wind Variability," In proc. 2009 *IEEE Power & Energy Society General Meeting*, pp. 1-8.

[16] G.J. Bowden, P.R. Barker, V.O. Shestopal and T.W. Twidell, "The Weibull Distribution Function and Wind Power Statistics," *Wind Engineering*, vol. 7, pp. 85-98, 1983.

[17] N.D. Hatziagryriou, T.S. Karakatsanis and M. Papadopoulos, "Probabilistic load flow in distribution systems containing dispersed wind power generation," *IEEE Trans on Power Systems*, vol. 8, pp. 159-165, 1993.

[18] K. C. Divya and P. S. N. Rao, "Effect of grid voltage and frequency variations on the output of wind generators," *Elect. Power Compon. Syst.*, vol. 36, no. 6, pp. 602–614, Jun. 2008.

[19] Feijoo A E , Cidras J . Modeling of wind farms in the load flow analysis. *IEEE Trans on Power Systems* , 2000 , 15 (1) :110-115

[20] Fuerte Esquivel C R , Tovarherandez J H , Gu Tierr Alcaraz, et al . Discussion of"modeling of wind farms in t he load flow analysis". *IEEE Trans on Power Systems* , 2001 , 16 (4) : 951.

[21] V. Ajjarapu, "Identification of steady state voltage stability in power systems," *Int. J. Elect. Power Energy Syst.*, vol. 11, pp. 43–46, 1991.