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Probabilistic Method of Wind Generation Placement for Congestion Management

S. Z. Moussavi, A. Badri, and F. Rastegar Kashkooli

***Abstract*—**Wind farms (WFs) with high level of penetration are being established in power systems worldwide more rapidly than other renewable resources. The Independent System Operator (ISO), as a policy maker, should propose appropriate places for WF installation in order to maximize the benefits for the investors. There is also a possibility of congestion relief using the new installation of WFs which should be taken into account by the ISO when proposing the locations for WF installation. In this context, efficient wind farm (WF) placement method is proposed in order to reduce burdens on congested lines. Since the wind speed is a random variable and load forecasts also contain uncertainties, probabilistic approaches are used for this type of study. AC probabilistic optimal power flow (P-OPF) is formulated and solved using Monte Carlo Simulations (MCS). In order to reduce computation time, point estimate methods (PEM) are introduced as efficient alternative for time-demanding MCS. Subsequently, WF optimal placement is determined using generation shift distribution factors (GSDF) considering a new parameter entitled, wind availability factor (WAF). In order to obtain more realistic results, N-1 contingency analysis is employed to find the optimal size of WF, by means of line outage distribution factors (LODF). The IEEE 30-bus test system is used to show and compare the accuracy of proposed methodology.

***Keywords*—**Probabilistic optimal power flow, Wind power, Point estimate methods, Congestion management

I. Introduction

RENEWABLE energies are becoming a permanent part of the existing power systems. The Independent System Operator (ISO) acts as a policy maker to reduce the power generated by fossil-fueled units and persuade investors for constructing generation units based on renewables. Wind power has surpassed other renewable energy resources in size and number. Besides, environmental issues pertaining to the fossil-fueled power stations have made the wind power one of the most attractive alternatives for replacing the conventional power plants. The first technical steps from the ISO point of view in this procedure are to find a proper location for wind farm (WF) installation, the size of WF and required modifications in power system elements [1].

Wind availability depends on the geographical aspects of a region and there is a wind speed map for almost all over the world. Assume that several buses inside a power system have strong potential for WF installation. The ISO should then take into account other factors in determining the location. One factor is to relieve the congested transmission lines by the new power injections.

Contingency analysis is carried out in [1] for ensuring system security when WFs are to be installed and proper places are determined for maximizing the economic benefits and security promotion of the grid. In [2] a method is proposed based on Monte Carlo Simulations (MCS) in which the forced outage rate of equipments is used in the stochastic programming and scenario reduction techniques are also employed. Congestion management (CM) using proper power injection reduces the losses in transmission network and also removes the part of locational marginal prices (LMP) related to congestion costs. System reliability analysis is performed in [3] and WF location based on maximizing reduction in transmission losses and enhancing system reliability is determined.

A probabilistic model for wind generation is proposed in [4] which uses a long-term period data for generating a Markov chain based on Weibull distribution for wind speed. That study only considers the statistical characteristics of wind speed and wind turbine failures during a long period and the status of other system components is assumed to be deterministic. Due to the probabilistic nature of wind speed availability and uncertainties existing in the forecasted data [5], deterministic approaches are not suitable for analyzing the systems including WFs. Besides, load forecasts and system configuration are also affected by uncertainties. Several probability distribution functions (PDF) for wind speed have been developed in the literature [6]. The most widely accepted PDF is the two-parameter Weibull distribution [7]. This model has been used frequently in power flow analysis and other power system studies [8], [9]. However, this model is valid only for long-term studies and does not give a measure for the wind speed at specific time. Time-series data are also available from annual reports and based on these data, prediction for near future can be made with relatively small estimation error. Day ahead forecasting calculated using data from multiple years is used here and constant speed is assumed for each hour. Moreover, daily load curve is assumed to be given and constant loads are considered during each hour based on this curve. Therefore, during each hour, load and wind speed data may contain uncertainties due to these approximations. In order to include these uncertainties in power flow analysis, normal distributions for forecasted data with some variances should be presumed.

To solve these types of problems, we need to employ the probabilistic optimal power flow (P-OPF) techniques. The

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outputs of this method are also PDFs of the voltage magnitudes and angles, active power generation dispatch, line flows and LMP at specific hour. Based on these results, the ISO will be able to make decisions for the operation of the power system.

Continuously increasing demand for energy causes serious problems for both generation and transmission companies. Frequent congestions in transmission lines are the most critical problems because of jeopardizing the power system stable operation. Difficulties associated with the construction of new transmission lines or power plants have forced the operators to economic utilization of existing equipment. As a remedy, some methods have been recently proposed for transmission line CM using optimal placement of distributed generation (DG) resources. In [10], highest LMP method and total congestion rent difference method were used to locate DGs for the sake of congestion relief. The bus with highest LMP value is the first candidate for placing a DG. The influences of DGs on CM and spot prices are studied in [11]. However, in [10]-[11], the probabilistic nature of wind speed as well as line outage analysis are not taken into account.

Aiming at congestion relief considering the uncertainties, adequate methodologies are required for solving the P-OPF problem in order to find the congested lines. In the previous literatures, several methods have been proposed such as truncated Taylor series expansion method [12], the first-order second-moment method (FOSMM) [13], the cumulant method [14], the point estimate method [15], [16] and MCS as a measure for determining the accuracy of all these methods. Some deficiencies of mentioned approaches are reported in [17], [18].

In present paper, a generic approach considering uncertainties associated with wind speed, load forecasts and transmission system structure (*N*-1 contingency analysis) is proposed with the purpose of CM. This will give a clue to the ISO for recommending appropriate locations for new WF installations to the non-governmental organizations. Here, generation shift distribution factors (GSDF) as well as a new parameter entitled, wind availability factor (WAF) are employed as useful tools for determining that power injection at which buses would help the congested lines. To complete the model, N-1 contingency analysis is employed to obtain WF optimal size considering transmission system structure. Credible transmission contingencies are listed and the severest case is determined using line outage distribution factors (LODF) for the line(s) of interest [19] taking into account the probabilistic nature of wind. P-OPF is used to solve the problem with MCS as the solver to recognize the vulnerable lines to congestion. In addition, PEMs are proposed as an alternative for time consuming MCS. Various orders of PEMs are compared and the 3PEM is shown to be the most appropriate solving method.

The paper is organized as follows: In Section II, some concepts used in this paper including wind turbine power conversion formula, PEMs, OPF formulation and sensitivity factors are described. The proposed method is described in Section III and simulation results are provided in Section IV. The paper is concluded by listing the main findings of the study.

II. Definition of Used Concepts

A. Wind Turbine Power Conversion Equation

Wind speed is converted to electrical power by different types of wind turbine generators. The most common type is variable speed structure. The simplified power conversion equation used for this type is [8], [9]:

$$P_w = \begin{cases} 0 & v < v_{in} \quad or \quad v > v_{out} \\ P_{w,rated} & v_r < v < v_{out} \\ P_{w,rated}\dfrac{(v - v_{in})}{(v_r - v_{in})} & v_{in} < v < v_r \end{cases} \qquad (1)$$

where:
P_w: wind turbine output power (p.u.)
v: wind speed (m/s)
v_{in}: cut-in wind speed (m/s) in which wind turbine starts the power generation
v_{out}: cut-out wind speed (m/s) in which wind turbine is disconnected from network
v_r: rated wind speed
$P_{w,rated}$: rated power of wind turbine

A more accurate equation is a cubic relation between the output power and wind speed for $v_{in}<v<v_r$ [20], [21]:

$$P_w = 0.5\rho\, v^3 A \quad W(\qquad (2)$$

in which A is the cross-section swept by the wind turbine blades in m^2 and ρ is the air density.

B. Probability Density Functions for Wind Speed

Uncertainties associated with the forecasted data of wind speed can be taken in to account by using a normal distribution for the data with a standard deviation. A normal PDF is formulated as follows:

$$f(v) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(v-\mu)^2}{2\sigma^2}} \qquad (3)$$

in which v is the wind speed, μ is the mean value and σ is the variance of wind speed.

In the case that a general comprehension of wind speed distribution for a relatively long period of time is needed, the two-parameter Weibull PDF is the best representative [22].Typical PDFs assuming the Normal and Weibull PDFs are shown in Fig. 1. Mean value and variance for Normal PDF are assumed as 8 m/s and 0.1 m/s.

Time-series data are also available for each region from annual reports. These forecasted data for a day ahead planning have acceptable estimation errors and thus can be relied on.

C. Point Estimate Method [15]

Suppose that X is a vector of m random variables (*RV*s) and $Y = G(X) = G([x_1, x_2, \ldots, x_m])$ is a nonlinear function of X. We are going to find the statistical characteristics of Y (e.g. mean value and variance), with the assumption that PDF of X is given. Using 2PEM, we need to numerically calculate $G(X)$ $2m$ times. Let $M_i(x_k)$, μ_k and σ_k represent the i^{th} order central moment, mean, and standard deviation of $k^{th}RV$ (x_k), respectively. Define $\lambda_{k,i}$ for $k^{th}RV$:

$$\lambda_{k,i} = \frac{M_i(x_k)}{\sigma_k^i} \tag{4}$$

Using Taylor series expansion of $G(X)$ about mean values of input variables (X) and neglecting the i^{th} derivatives of $G(X)$ with respect to X for i higher than 3, the following procedure provides the required quantities for 2PEM:

$$\xi_{k,i} = \frac{\lambda_{k,3}}{2} + (-1)^{3-i}\sqrt{m + \left(\frac{\lambda_{k,3}}{2}\right)^2} \tag{5}$$

(a)

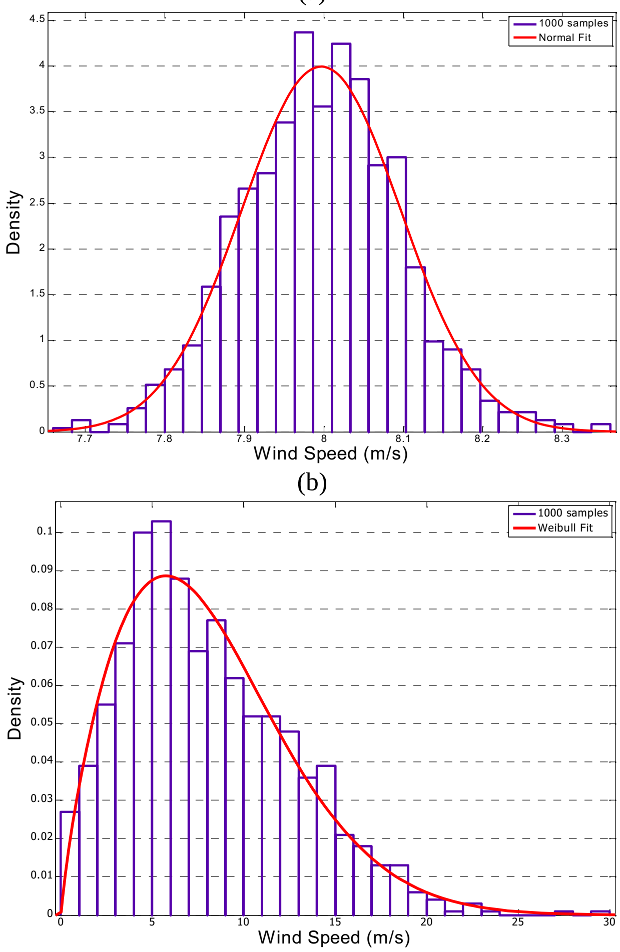

Fig. 1 Typical probability density functions for wind speed: (a) Normal PDF; (b) Weibull PDF

$$p_{k,i} = \frac{1}{m}\frac{(-1)^i\,\xi_{k,3-i}}{\zeta_k}, \quad i = 1, 2 \tag{6}$$

$$\zeta_k = 2\sqrt{m + \left(\frac{\lambda_{k,3}}{2}\right)^2} \tag{7}$$

$$x_{k,i} = \mu_k + \xi_{k,i}\sigma_k, \quad k = 1, 2, \ldots, m \tag{8}$$

This means that for each RV (x_k), two values are obtained ($x_{k,1}$ and $x_{k,2}$). Finally, we have:

$$E(Y^j) = \sum_{i=1}^{m}\sum_{k=1}^{2} p_{k,i}\, G([\mu_1, \mu_2, \ldots, x_{k,i}, \ldots, \mu_{m-1}, \mu_m])^j \tag{9}$$

Therefore, we should evaluate $G(X)$ two times for each RV. For deriving μ and σ^2 of Y, the following formulas are used:

$$\mu = E(Y), \sigma^2 = E(Y^2) - \mu^2 \tag{10}$$

For $2m+1$ PEM (with the last concentration located at mean values), the procedure is similar to the 2PEM.For example, 3PEM is formulated as:

$$\xi_{k,j} = \frac{\lambda_{k,3}}{2} + (-1)^{3-j}\sqrt{\lambda_{k,4} - \frac{3}{4}\lambda_{k,3}^2} \qquad for\ j = 1, 2, \ \xi_{k,3} = 0 \tag{11}$$

$$p_{k,j} = \frac{(-1)^{3-k}}{\xi_{k,j}(\xi_{k,1} - \xi_{k,2})}, \quad k = 1, 2 \tag{12}$$

$$p_{k,3} = \frac{1}{m} - \frac{1}{\lambda_{k,4} - \lambda_{k,3}^2} \tag{13}$$

For more information on PEMs refer to [15], [16].

D. OPF Formulation

The formulation for security constrained OPF aiming at minimizing system costs used in this study is as follows:

$$\begin{aligned} &Min.\ f(P_G) = \sum (a_i P_{Gi}^2 + b_i P_{Gi} + c_i) \\ &s.t.\ \ G(\delta, V, Q_G, P_G) = 0 \\ &P_{G_{min}} \le P_G \le P_{G_{max}} \\ &Q_{G_{min}} \le Q_G \le Q_{G_{max}} \\ &V_{min} \le V \le V_{max} \\ &|S_{ij}(\delta, V)| \le S_{ij_{max}} \end{aligned} \tag{14}$$

where a_i, b_i and c_i are constants corresponding to the conventional quadratic genercation cost of generator i; P_{Gi} *and* Q_{Gi} stand for the generator i active and reactive powers; V and δ represent the bus voltage magnitudes and angles; $G(\delta, V, Q_G, P_G)=0$ represents the load flow equations; S_{ij} represents the power flowing through the line between buses i and j.

Lagrange function for solving this problem is formulated as follows:

$$\begin{aligned} L &= f(P_G) + \lambda^T(G(\delta,V,Q_G,P_G)) \\ &+\gamma_U^T(P_G - P_G^{\max}) + \gamma_L^T(P_G^{\min} - P_G) \\ &+\beta_U^T(Q_G - Q_G^{\max}) + \beta_L^T(Q_G^{\min} - Q_G) \\ &+\eta_U^T(S - S_{ij}^{\max}) + \eta_L^T(S_{ij}^{\min} - S_{ij}) \\ &+\mu_U^T(V - V^{\max}) + \mu_L^T(V^{\min} - V) \end{aligned} \tag{15}$$

in which $\lambda, \gamma_U, \gamma_{L,} \beta_U, \beta_L, \eta_U, \eta_L, \mu_U,$ and μ_L are Lagrange multipliers corresponding to equations in (14). Karush-Kuhn-Tucker [23] is applied to solve the problem.

E. Generation Shift Distribution Factors

Generation shift distribution factor(GSDF) or $A_{l-k,i}$ factor is defined as the increase in power flowing through line between buses l and k due to unit increase in generated power at bus i, with the assumption that all loads are constant and the extra generated power is absorbed by the slack bus [23]:

$$\begin{aligned} \Delta F_{l-k} &= A_{l-k,i}\Delta G_i \\ \Delta G_r &= -\Delta G_i \end{aligned} \tag{16}$$

where

ΔF_{l-k} is the change in active power flow between buses l and k

$A_{l-k,I}$ is the A factor of a line joining buses l and k

ΔG_i is the change in generation at bus i, with the reference bus excluded

ΔG_r is the change in generation at reference bus (generator) r

$A_{l-k,i}$ is calculated using the definition of a reactance matrix and the DC load flow approximation. The A factor measures the incremental use of transmission network by generators and loads. Also note that GSDFs are dependent on the selection of reference bus and independent of operational conditions of the system.

F. Line Outage Distribution Factors

In contingency analysis, the impacts of lines or generators outages are investigated to ensure stable and safe post-contingency operation of power system. If one line is disconnected, its flow is distributed between the existing lines. For calculating the amount of flow changes in the other lines, LODFs are used [23]. For the outage of Line k, other line flows are calculated as:

$$F^{post} = F^{pre} + LODF^k \times F^k \tag{17}$$

in which F^{post} and F^{pre} are the vectors of all line flows in post and pre-contingency periods respectively, $LODF^k$ is the vector of LODF associated with the outage of line k, and F^k is the pre-contingency flow of Line k. A formula in matrix form is also proposed in [19] for multi-contingency which reduces the computational burden of contingency analysis.

III. Proposed Approach

The proposed method includes two main steps dealing with determining WF optimal placement and size, respectively .The following subsections describe these steps.

A. Optimal Placement

GSDFs could be a good measure for selecting a bus for injecting extra power so that congestion in some lines would decrease. It is reasonable to choose the bus with maximum GSDF associated with the line(s) of interest. However, wind availability is a decisive factor which should be taken into account. This will increase the benefits for the investors beside the alleviation of the congestions. There is a wind availability map for each area which ranks the buses according to their wind availability. Moreover, there should be enough space far from the metropolitan areas for WF installation. In light of these circumstances, we define the wind availability factor (WAF) for each area as:

$$\begin{aligned} &WAF_i = f_i(AS_i, WS_i) \\ &0 \le AS_i \le 1,\ 0 \le WS_i \le 1 \end{aligned} \tag{18}$$

in which AS_i is the available space in Area i, WS_i is the average wind speed in this area, and f_i is a function which gives appropriate weights to each of AS and WS. AS and WS are per-united by the corresponding maximum available value. Here, we consider a linear relation and equal weights for AS and WS. Therefore the function becomes as:

$$f_i(AS_i, WS_i) = AS_i + WS_i \tag{19}$$

The value returned by this function is between 0 and 2.

Overall procedure for determining the optimal placement of WF for congestion relief is shown in Fig. 2. Observe that both the GSDF and WAF are important when selecting the optimal location.

B. Optimal Size

For computing the size of WF, we have to neglect the line flow limit on congested line and run the P-OPF to find the amount of line flow in case of N-1 contingency. The following formula gives the size of WF at Bus i:

$$S = \frac{\alpha_k F_k^{\lim} + (F_k^{\max} - F_k^{\lim})}{A_{k,i}} \tag{20}$$

in which S is the size of WF in MVA, F_k^{lim} is the limit on Line k and F_k^{max} is the maximum flow in Line k in case of most sever contingency occurrence, $A_{k,i}$ is the GSDF between Bus i and Line k, and α_k is the factor that shows the security margin considered for Line k flow.

Proposed algorithm is demonstrated in the flowchart represented by Fig. 3. In this flowchart, congestion probability is determined as:

$$\text{Congestion Probability} = \Pr\{\eta > 0\} \quad (21)$$

in which η is the Lagrange multiplier associated with the congested line. This probability should be greater than a predefined value, ε.

IV. Simulation Results

A. Locating WF for Probabilistic CM

In this section, we are going to find the optimal location for installing WF in order to reduce the flow in congested lines. A 30-bus test system is used for the simulations [24]. Corresponding parameters are given in Tables A. 1 to A. 3 in Appendix.

Table A. 2 shows the load data in each bus. This data is obtained using the mean values during the season that congestion occurs more frequently. Using the demand data, OPF is run and found that the limit on line from Bus 27 to Bus 25 is violated.

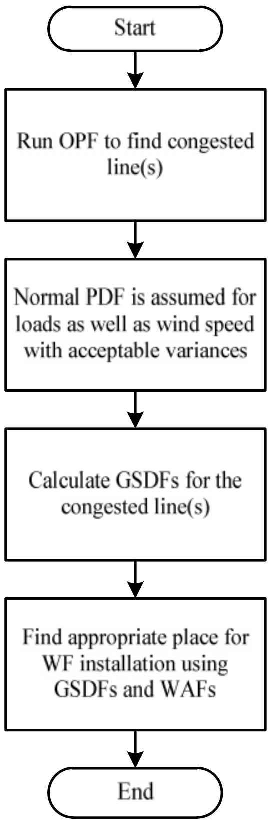

Fig. 2 Proposed algorithm for determining optimal location of WF

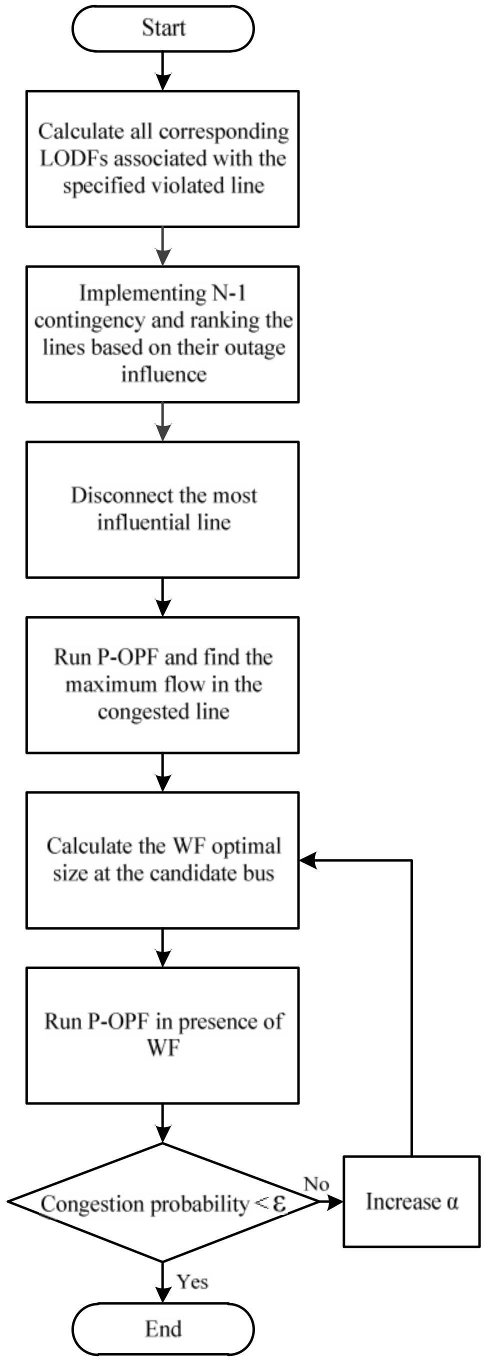

Fig. 3 Proposed algorithm for determining the optimal size of WF

For statistical purposes, assuming a normal distribution for the load at each bus (with a variance (σ) of 10%), 1000 MCS have been run for solving P-OPF problem and the results for line 25-27 flow are shown in Fig. 4(a). In this figure, the vertical axis shows the PDF found numerically (out of 1000 samples) for the corresponding Lagrange multipliers (on the horizontal axis). Consequently, LMPs have got high values. This is depicted in Fig. 5(a) for Bus 25.

GSDFs for line 25-27 are calculated and reported in Table I. Regarding the GSDFs, it can be inferred that injections at buses 26, 25 and 24 have the most significant and desirable

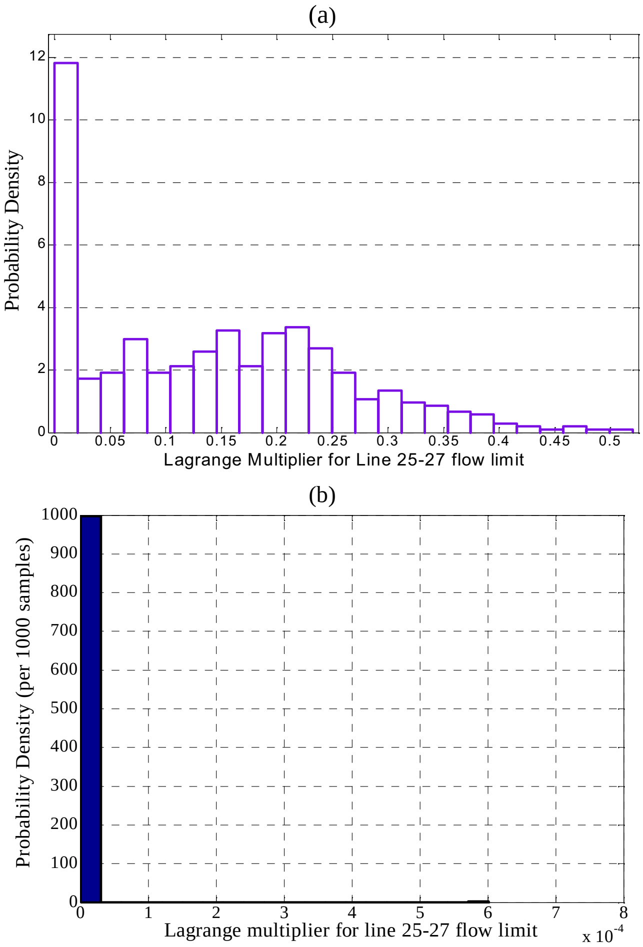

Fig. 4 Probability density of Lagrange multipliers corresponding to line 25-27 flow limit for 1000 MCS: (a) base case; (b) a WF is connected to Bus 26

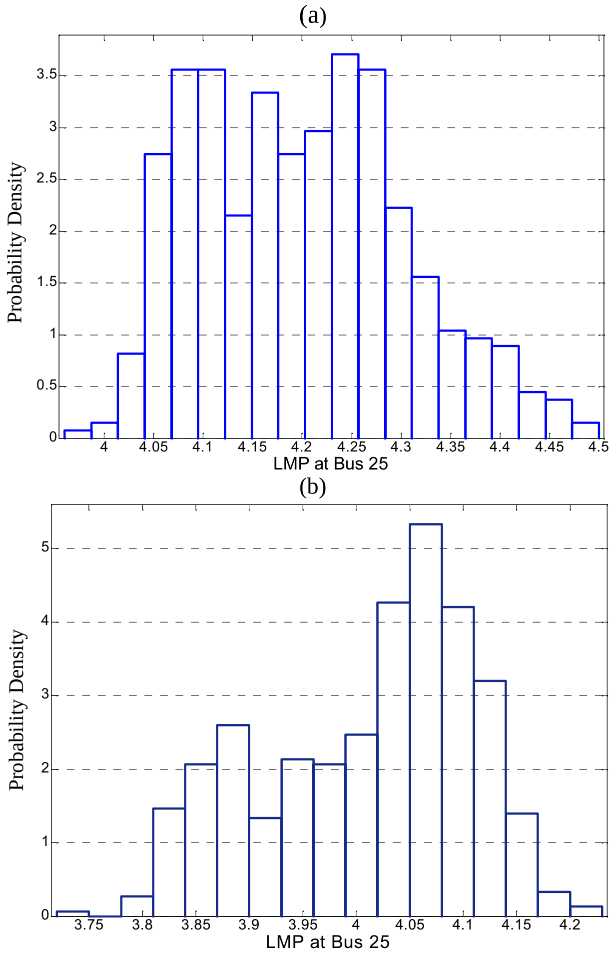

Fig. 5 LMPs at Bus 25: (a) base case; (b) a WF is connected at Bus 26

TABLE I
GSDFs FOR LINE BETWEEN BUSES 25 AND 27 AND WAF FOR EACH BUS IN 30-BUS SYSTEM (WAF: WIND AVAILABILITY FACTOR)

Bus	GSDF	WAF	Bus	GSDF
1	0	0.32	7	0.0051
2	0.0009	0.43	8	0.0124
3	-0.0029	0.12	9	-0.0607
4	-0.0035	0.32	10	-0.0956
5	0.0035	0.5	11	-0.0607
6	0.0061	0.25	12	-0.0771
13	-0.0771	0.12	19	-0.0984
14	-0.091	0.61	20	-0.0977
15	-0.1018	0.6	21	-0.1188
16	-0.085	0.15	22	-0.1254
17	-0.0925	0.14	23	-0.1524
18	-0.0996	0.39	24	-0.2207
25	-0.479	0.98	28	0.0437
26	-0.479	1.26	29	0.3567
27	0.3567	0.84	30	0.3567

impacts on the flows through this line. It is apparent that appropriate places for our purpose are generally among the load-side buses. Therefore, we are not apprehensive about causing congestion in other lines by injecting power at the mentioned buses. Besides, OPF is run for the case and thus no congestion will allowed. Table I shows the hypothetical values of WAF for each bus. Regarding calculated GSDFs and corresponding WAF, bus 26 is selected for WF installation. We consider a normal distribution for wind speed forecasted data and the WF output power is calculated from (1). This forecasted data are based on the mean values of measurements from previous years.

B. Determining the WF size for Probabilistic CM

At this point, *N*-1 contingency analysis for the congested line is carried out using the LODFs reported in Table A. 4. LODF values are in per unit of the line flows and are converted to MW in the next column. We consider the severest case in which the line with the highest LODF is disconnected. Table A. 4 shows that the outage of line 27-28 leads to the largest impact on the flow of line 25-27.

The limit on Line 25-27 is 16 MVA and the maximum power flowing through this line is 20.8 MVA. This can be easily found using MCS results. Suppose that it is decided to compensate the flow in this line by α_i% besides the extra 4.8 MVA flow to ensure the secure margin from the flow limit. This limit is the minimum of thermal limit, voltage stability limit and angular stability limit.Initial value of α is considered to be 20%. In this example, WF capacity is calculated using

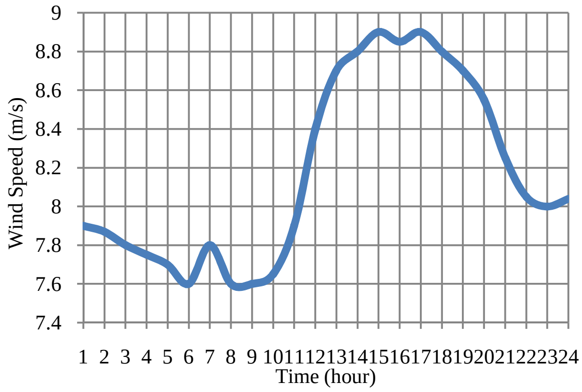

Fig. 6 Diurnal pattern of wind speed at Amagro weather station, Spain, 1999 [20]

(20) as [0.2×16 + (20.8-16)]/0.4790 ≈16.70 MW. Thus, an 18 MW WF consisted of 12×1.5MW wind turbines may be sufficient for installation at Bus 26. Average wind speed at the same season that the load data are collected is shown in Fig. 6. Locating WF in appropriate place, it is observed that the congestion has been successfully removed from Line 25-27, as depicted in Fig. 4(b). Subsequently, LMP at Bus 25 is also reduced, as illustrated in Fig. 5(b).

Although the proposed method has shown desirable results, the procedure of finding the lines which are prone to congestion and evaluating the result of WF placement using MCS are rather time consuming. Besides, the procedure has to be repeated for other lines which may be congested to ensure the congestion relief while loads and wind speed are varied. In the next subsection, we show the application of PEMs for reducing the computational burden.

C. Application of PEMs in the Solution of P-OPF

In this subsection, the concentration is on the solution methods of P-OPF problem for a power system including WFs in order to find the lines that are prone to congestion. The 30-bus test system is employed again for comparative purposes. Although MCS gives relatively accurate results, it is computationally expensive. For finding the vulnerable lines to congestion, PEMs are employed as powerful tools. Table II compares the mean values (μ) and variances (σ) of line flows obtained by PEMs to MCS results. Lagrange multipliers for flow limit on Line 25-27 are compared in Table III.3PEM gives more accurate results for both μ and σ compared to 2PEM. For the sake of completeness, 5PEM has also been evaluated and the obtained results for line flows were the same as 3PEM, hence are not reported here. However, for Lagrange multipliers 3PEM and 5PEM give relatively different values, as reported in Table III. Non-zero Lagrange multipliers show the lines prone to congestion. There are 20 loads in the 30-bus test system. Therefore, we have 20 RVs here. According to the PEM, the problem should be solved h times, which h equals the number of RVs (m) times the order of PEM in use (n).For our purpose, using 2PEM, the OPF should be solved 40 times while using 3PEM and 5PEM this becomes 60 and 100 times, respectively. However, due to the accuracy of the results, 3PEM is a viable alternative for MCS. Table IV compares the CPU time and number of iterations required for each of the mentioned methods. Time consumed by MCS has reduced by 96%, 93.6% and 89.6% when 2PEM, 3PEM and 5PEM are used instead, respectively.

TABLE II
MEAN VALUES AND VARIANCES OBTAINED BY PEMS AND MCS FOR LINE FLOWS. RELATIVE ERROR (E) FOR EACH QUANTITY (Y) IS CALCULATED AS: $E = |Y_{PEM} - Y_{MCS}|/|Y_{MCS}|$

Line		Mean Values (μ)			Variances (σ)		
From	To	2PEM	3PEM	MCS	2PEM	3PEM	MCS
1	2	26.30	25.64	25.64	5.43	0.44	0.43
1	3	25.31	24.69	24.69	4.27	0.30	0.29
2	4	23.52	22.85	22.86	3.58	0.36	0.37
3	4	20.61	20.01	20.01	3.18	0.33	0.32
2	5	17.78	17.32	17.33	3.23	0.37	0.36
2	6	28.20	27.22	27.22	4.59	0.47	0.46
4	6	26.17	24.66	24.66	5.32	0.84	0.81
5	7	17.62	17.18	17.18	3.18	0.36	0.35
6	7	7.36	7.77	7.77	2.44	0.97	0.98
6	8	25.94	25.39	25.39	5.25	1.32	1.32
6	9	16.81	16.63	16.63	3.41	0.57	0.56
6	10	7.03	6.92	6.92	1.36	0.27	0.27
9	11	13.19	13.19	13.19	3.05	0.68	0.68
9	10	3.61	3.43	3.43	0.36	0.59	0.60
4	12	8.02	8.27	8.27	0.79	0.56	0.55
12	13	-24.50	-22.81	-22.82	9.09	0.59	0.57
12	14	7.48	7.26	7.26	1.70	0.23	0.23
12	15	12.98	12.19	12.19	2.92	0.31	0.32
12	16	12.06	11.63	11.64	3.68	0.32	0.32
14	15	-0.79	-1.00	-1.00	0.15	0.21	0.20
16	17	6.40	5.99	5.99	2.40	0.30	0.31
15	18	12.38	12.26	12.26	3.47	0.36	0.37
18	19	7.02	6.91	6.91	2.24	0.34	0.33
19	20	-4.45	-4.60	-4.60	0.35	0.39	0.39
10	20	8.75	8.89	8.89	1.28	0.41	0.41
10	17	4.68	5.04	5.04	0.14	0.48	0.48
10	21	-4.97	-5.47	-5.47	0.57	0.57	0.55
10	22	-5.62	-5.91	-5.91	0.93	0.24	0.23
21	22	-24.47	-24.96	-24.96	4.90	0.58	0.59
15	23	-10.46	-11.33	-11.33	2.98	0.38	0.37
22	24	-3.53	-5.25	-5.24	1.65	0.44	0.46
23	24	6.96	6.09	6.09	3.07	0.44	0.43
24	25	-7.40	-9.98	-9.96	1.24	0.26	0.26
25	26	5.60	5.59	5.59	1.22	0.27	0.27
25	27	-13.16	-15.75	-15.74	2.56	0.00	0.07
28	27	-9.68	-12.14	-12.13	4.63	0.58	0.59
27	29	8.51	8.48	8.48	2.04	0.33	0.33
27	30	8.97	8.93	8.93	2.16	0.42	0.42
29	30	3.95	3.94	3.94	0.94	0.28	0.28
8	28	-6.29	-6.75	-6.75	1.88	0.29	0.29
6	28	-3.34	-5.32	-5.32	2.74	0.39	0.39
ΣE		2.84	0.011	-	254.9	1.65	-

TABLE III
LAGRANGE MULTIPLIERS OBTAINED BY PEMS AND MCS FOR FLOW LIMIT ON LINE 25-27

Mean Values (μ)				Variances (σ)			
2PEM	3PEM	5PEM	MCS	2PEM	3PEM	5PEM	MCS
0	0.1249	0.1348	0.1446	0	0.1623	0.1722	0.1280

TABLE IV
CPU TIME AND NUMBER OF ITERATIONS REQUIRED FOR PEMS AND MCS IN A PC (DUAL-CORE CPU 2×2800 GHZ AND 2GB OF RAM)

Method	CPU time (s)	Number of Iterations
MCS	111.7751	1000
2PEM	4.6905	40
3PEM	7.1626	60
5PEM	11.5891	100

V. CONCLUSION

A probabilistic approach for WF placement with the objective of congestion relief was proposed in this paper. This method can also be applied to any DG placement procedure. Loads and WF output power variations are modeled using their forecasted data. Normal PDFs for loads and wind speed are assumed to include the uncertainties that are the byproduct of data forecasting. Then, the OPF problem was solved through 1000 MCS. The problem of computationally expensive MCS is solved by employing the PEMs. It was shown that 3PEM gives accurate results for mean values and variances of line flows. GSDFs are used as a good measure for detecting the buses which have desirable impact on the congested line(s). LODFs are employed for contingency analysis and a generic approach is formulated for calculating the size and location for new WF installation aiming at CM. Application of the proposed methodology was demonstrated in a 30-bus test system. This method is useful for the ISO to propose some appropriate locations for WF installations to the investors. This way, the benefit of the investors as well as transmission congestion costs and security will be optimized. Uncertainties associated with the forecasted data are also covered and WAF was introduced to include the geographical aspect of the area.

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TABLE A. I
TRANSMISSION LINE PARAMETERS FOR 30-BUS TEST SYSTEM

From	To	R (p.u.)	X (p.u.)	B (p.u.)	Limit (MVA)
1	2	0.02	0.06	0.03	130
1	3	0.05	0.19	0.02	130
2	4	0.06	0.17	0.02	65
3	4	0.01	0.04	0	130
2	5	0.05	0.2	0.02	130
2	6	0.06	0.18	0.02	65
4	6	0.01	0.04	0	90
5	7	0.05	0.12	0.01	70
6	7	0.03	0.08	0.01	130
6	8	0.01	0.04	0	32
6	9	0	0.21	0	65
6	10	0	0.56	0	32
9	11	0	0.21	0	65
9	10	0	0.11	0	65
4	12	0	0.26	0	65
12	13	0	0.14	0	65
12	14	0.12	0.26	0	32
12	15	0.07	0.13	0	32
12	16	0.09	0.2	0	32
14	15	0.22	0.2	0	16
16	17	0.08	0.19	0	16
15	18	0.11	0.22	0	16
18	19	0.06	0.13	0	16
19	20	0.03	0.07	0	32
10	20	0.09	0.21	0	32
10	17	0.03	0.08	0	32
10	21	0.03	0.07	0	32
10	22	0.07	0.15	0	32
21	22	0.01	0.02	0	32
15	23	0.1	0.2	0	16
22	24	0.12	0.18	0	16
23	24	0.13	0.27	0	16
24	25	0.19	0.33	0	16
25	26	0.25	0.38	0	16
25	27	0.11	0.21	0	16
28	27	0	0.4	0	65
27	29	0.22	0.42	0	16
27	30	0.32	0.6	0	16
29	30	0.24	0.45	0	16
8	28	0.06	0.2	0.02	32
6	28	0.02	0.06	0.01	32

TABLE A. II
LOAD DATA FOR 30-BUS TEST SYSTEM

Bus	P (MW)	Q (MVAr)	Bus	P (MW)	Q (MVAr)
1	0	0	7	24.8	10.9
2	23.7	12.7	8	32	30
3	4.4	1.2	9	0	0
4	9.6	1.6	10	7.8	2
5	0	0	11	0	0
6	0	0	12	13.2	7.5
13	0	0	19	11.5	3.4
14	8.2	1.6	20	4.2	0.7
15	10.2	2.5	21	19.5	11.2
16	5.5	1.8	22	0	0
17	11	5.8	23	5.2	1.6
18	5.2	0.9	24	10.7	6.7
25	0	0	28	0	0
26	5.5	2.3	29	4.4	0.9
27	0	0	30	12.6	1.9

TABLE A. III
GENERATORS DATA FOR 30-BUS TEST SYSTEM

Bus	P_{max}(MW)	P_{min}(MW)	Q_{max}	Q_{min}	a	b	c
1	80	0	150	-20	0.02	2	0
2	80	0	60	-20	0.0175	1.75	0
22	50	0	62.5	-15	0.0625	1	0
27	55	0	48.7	-15	0.00834	3.25	0
23	30	0	40	-10	0.025	3	0
13	40	0	44.7	-15	0.025	3	0

TABLE A. IV
LODFS ASSOCIATED WITH LINE 25-27 (ONLY VALUES GREATER THAN 0.5MVA ARE REPORTED)

LINE			LINE FLOWS		LODF×LINE FLOWS	
FROM	TO	LODF	P	Q	P	Q
4	6	0.0506	19.68	11.86	0.996	0.600
6	8	0.0465	24.40	23.61	1.135	1.098
4	12	-0.1906	11.20	-7.38	-2.134	1.407
21	22	-0.0700	-20.76	-18.34	1.453	1.284
22	24	-0.3689	-2.11	4.63	0.770	-1.708
23	24	-0.2184	3.47	3.56	-0.759	-0.777
24	25	-1.0000	-7.40	1.43	7.398	-1.429
28	27	1.0000	-8.21	-9.17	-8.212	-9.171
6	28	0.1633	-2.46	-5.33	-0.402	-0.871