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Probabilistic Approach for Wind Generation Placement Aiming at Congestion Management

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Abstract – *Due to the increment in energy demands, congestion in transmission lines becomes frequent. As a solution, forcing counter flows through these lines will eliminate the need for new transmission line installation. In this context, efficient wind farm (WF) placement method is proposed in order to reduce burdens on congested lines. 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. Since the wind speed is a random variable and load forecasts also contains uncertainties, probabilistic approaches instead of deterministic methods should be used for this type of study. Aiming at this purpose, normal distribution is assumed for loads and wind speed at peak demand according to forecasted data and vulnerable lines to congestion with corresponding probability densities are determined. AC probabilistic optimal power flow (P-OPF) is formulated and solved using Monte Carlo Simulations (MCS). Besides, point estimate methods (PEM) are used as efficient alternative for time-demanding MCS. Sensitivity factors are employed to show that injection at which buses would reduce the flow at concerned lines. N-1 contingency analysis is also carried out using the sensitivity factors for ensuring system reliable operation. The proposed methodology is tested on a 30-bus test system.*

***Keywords**: Probabilistic Optimal Power Flow, Wind Power, Point Estimate Methods, Congestion Management*

Nomenclature

A	Swept area by turbine blades
a_i, b_i, c_i	Coefficients of quadratic generation cost for G_i
$A_{l\text{-}k,i}$	GSDF of Bus i on Line l to k
AS_i	Available space in Area i
c	Scale factor
$E(Y)$	Expected value of Y
F_i^{lim}	Limit on Line i power flow
F_i^{max}	Maximum power flow in Line i
F^k	Pre-contingency power flow in Line k
F^{post}	Vector of line flows in post-contingency
F^{pre}	Vector of line flows in pre-contingency
k	Shape factor
$LODF^k$	Vector of LODFs for Line k outage
$M_i(x_k)$	i^{th} order central moment of x_k
P_{Gi}	Active power of G_i
P_{ij}	Power flowing through Line i to j
P_w	Wind turbine output power
$P_{w,rated}$	Wind turbine rated power
Q_{Gi}	Reactive power of G_i
S	WF size
V	Bus voltage magnitude
v	Wind speed
v_{in}	Cut-in wind speed
v_{out}	Cut-out wind speed
v_r	Rated wind speed
WS_i	Average wind speed in Area i
δ	Bus voltage angle
$\Delta F_{l\text{-}k}$	Change in active power flow in Line l to k
ΔG_i	Change in generation at Bus i
ΔG_r	Change in generation at reference bus
ρ	Air density
σ_k	Standard deviation of x_k
μ_k	Mean value of x_k

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I. Introduction

Renewable energies are becoming a permanent part of the existing power systems. 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. This means that even without any need for new generation resources, 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. In this study, we only consider the wind generation units. 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 [2]. Considering the case that several buses inside a power system have strong potential for WF installation, the ISO should take into account other factors in determining the location. One factor is to relieve the congested transmission lines by the new power injections. This was previously studied in [3] using Monte Carlo Simulations (MCS). The forced outage rate of equipment is used in the stochastic programming and scenario reduction techniques were also employed. Congestion management (CM) using proper power injection will reduce the losses in transmission network and also remove the part of locational marginal prices (LMP) related to congestion costs [4].

Recently, some researchers have studied this subject within the areas of power system security and reliability. Contingency analysis is carried out in [1] for ensuring system security when WFs are to be installed and proper places are thus determined for maximizing the economic benefits and security promotion of the grid. System reliability analysis was performed in [5] and WF location based on maximizing the reduction in transmission losses and enhancing system reliability was determined. Locating and sizing of TCSC was also done in [6] aiming at congestion management.

A probabilistic model for wind generation is proposed in [7] 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 [8], 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 [9], [10]. The most widely accepted PDF is the two-parameter Weibull distribution [11]. This model has been used frequently in power flow analysis and other power system studies [12], [13]. 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 the 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 outputs of this method are also PDFs of the voltage magnitudes and angles, active power generation dispatch, line flows and locational marginal prices (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 [14], 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 [15], [16]. 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.

Aiming at the mentioned goal, 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 [17], the first-order second-moment method (FOSMM) [18], the cumulant method [19], the point estimate method [21], [22] and MCS as a measure for determining the accuracy of all these methods. Some deficiencies of mentioned approaches are reported in [22], [23].

In this paper, generation shift distribution factors (GSDF) are employed as a useful tool for determining that power injection at which buses would help the congested lines. To complete the model, credible transmission contingencies are listed and the severest case is determined using line outage distribution factors (LODF) for the line(s) of interest [24]. MCS is used to solve the P-OPF problem and to recognize the vulnerable lines to congestion. In addition, PEMs are used as an alternative for time consuming MCS. Various orders of PEMs are compared and the 3PEM is shown to be more accurate than other methods.

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 its application is demonstrated in a 30-bus system in Section IV. Also, PEMs are employed and compared to MCS in this section. The paper is concluded by listing the main findings of the study.

II. Definition of Used Concepts

II.1. 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 [12], [13]:

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

A more accurate equation is a cubic relation between the output power and wind speed for $v_{in}<v<v_r$ [25], [26]:

$$P_w = 0.5\rho\, v^3 A \quad (\mathrm{W}) \tag{2}$$

II.2. PDFs 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 some standard deviation. 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 [27]:

$$f_v(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \tag{3}$$

in which $f_v(v)$ is the PDF of wind speed. Parameter estimation methods for determining the values of c and k from the measured data of wind speed have been reported in the literature. These parameters depend on the geographical characteristics of a region, thus their values varies from area to area.

Time-series data are also available for each region from annual reports [2]. These forecasted data for a day ahead planning have acceptable estimation errors and thus can be relied on. A sample time-series measurement of diurnal wind speed at Amagro (Spain) is shown in Fig. 1 obtained from [25].We use this data in the forthcoming sections.

II.3. Point Estimate Method

Suppose that X is a vector of m RVs and $Y = G(X) = G([x_1,x_2,...,x_m])$ 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. Define $\lambda_{k,i}$ for k^{th} RV as:

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

Using Taylor series expansion of $G(X)$ about μ_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:

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

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

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

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

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

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

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

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

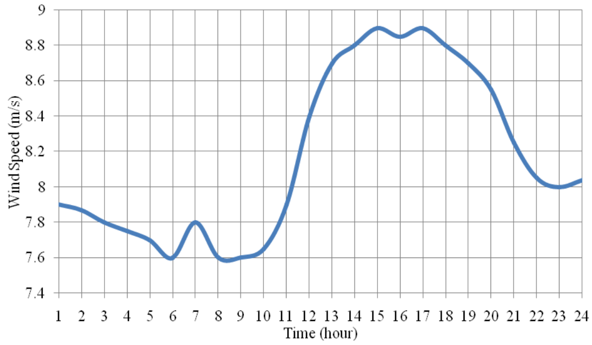


Fig. 1. Diuneral pattern of wind speed at Amagro weather station, Spain, 1999 [25]

For $2m+1$ PEM (with the last concentration located at mean values), the procedure is similar to the 2PEM. Due to lack of space, interested readers are encouraged to study [20], [28] to find more about the mathematical background of PEMs.

II.4. OPF Formulation

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

$$\begin{aligned} & Min. \ \left(\sum\left(a_i P_{Gi}^{\ 2} + b_i P_{Gi} + c_i\right)\right) \\ & s.t. \ \ G\left(\delta, V, Q_G, P_G\right) = 0 \\ & \quad P_{G_{min}} \le P_G \le P_{G_{max}} \\ & \quad Q_{G_{min}} \le Q_G \le Q_{G_{max}} \\ & \quad V_{min} \le V \le V_{max} \\ & \quad \left|P_{ij}\left(\delta, V\right)\right| \le P_{ij_{max}} \\ & \quad \left|P_{ji}\left(\delta, V\right)\right| \le P_{ji_{max}} \end{aligned} \tag{11}$$

where $G(\delta,V,Q_G,P_G)=0$ represents the load flow equations.

II.5. Generation Shift Distribution Factors

Generation shift distribution factor(GSDF) or $A_{l\text{-}k,i}$ 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 [29]:

$$\begin{aligned} \Delta F_{l-k} &= A_{l-k,i} \Delta G_i \\ \Delta G_r &= -\Delta G_i \end{aligned} \tag{12}$$

$A_{l\text{-}k,I}$ 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 notice that GSDFs are dependent on the selection of reference bus and independent of operational conditions of the system.

II.6. 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 that how much will be the change in other lines' flow, LODFs are used. For the outage of Line k, other line flows are calculated as [24]:

$$F^{post} = F^{pre} + LODF^k \times F^k \tag{13}$$

A formula in matrix form is also proposed in [24] for multi-contingency which reduces the computational burden of contingency analysis.

III. Proposed Approach

The proposed method includes two main steps. The first step determines the location of WF installation and the second determines its size. 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 [5]. This will increase the benefits for the investors beside the alleviation of the congestions. There is a wind availability map for each area [2] 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:

$$\begin{aligned} & WAF_i = f_i\left(AS_i, WS_i\right) \\ & 0 \le AS_i \le 1, \ 0 \le WS_i \le 1 \end{aligned} \tag{14}$$

in which f_i is a function which gives appropriate weights to each one of AS and WS, both of which are per-united by the corresponding maximum available value. We consider a linear relation and equal weights and therefore the function becomes:

$$f_i\left(AS_i, WS_i\right) = AS_i + WS_i \tag{15}$$

The value returned by this function is between 0 and 2. For computing the size of WF, we have to neglect the line flow limit on congested line and run the OPF to see that how much the line is overloaded. The following formula gives the size of WF:

$$S = \frac{\alpha_i F_i^{lim} + \left(F_i^{max} - F_i^{lim}\right)}{A_{k,i}} \tag{16}$$

in which S is the size of WF in MVA, F_i^{lim} is the limit on Line i and F_i^{max} is the maximum flow in Line i when the flow limit constraint is neglected in MVA and $A_{k,i}$ is the GSDF between Bus k and Line i.

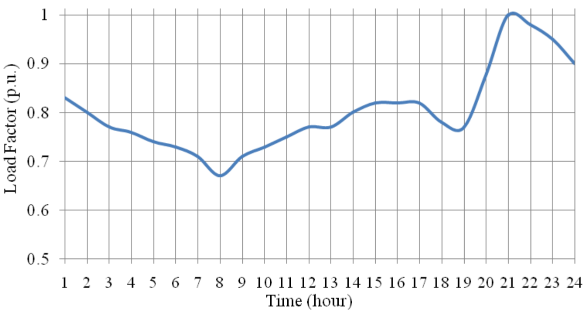


Fig. 2. Daily load curve at a summer day, 2005, Tehran, Iran [32]

The overall procedure is summarized in the following arrangement:

Main Step1:
Step1: Load forecasts are collected and the worst case (in which the line is severely congested) is determined using OPF
Step2: Acceptable variances for loads and wind speed considering normal PDF is assumed
Step3: GSDFs for congested Line i are calculated and buses are ranked according to their GSDFs
Step4: Considering the GSDFs and WAF of buses, appropriate locations for WF installation are decided

Main Step2:
Step1: LODFs for congested Line i are calculated and line outages are ranked according to their impact on Line i flow
Step2: Disconnecting the most influential line and neglecting the flow limit on Line i, the P-OPF problem is solved (using either MCS or PEMs) and the maximum flow in Line i (F_i^{max}) is computed
Step3: The size of WF is calculated using the given formula and choosing an acceptable value for α
Step4: The P-OPF incorporating WF in the system is run for ensuring the congestion relief
Step5: The procedure is repeated with higher values of α if the probability of congestion occurrence is not as low as desired
In the next section, the proposed method is evaluated in a 30-bus test system.

IV. Simulation Results

IV.1. Locating WFs 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 [30]. Corresponding parameters are given in Tables A.1 to A.3 in Appendix.

Table A.2 shows the load data per bus for the peak demand day of the year at 21 o'clock. Figure 2 depicts the load factor for that day in which the values are in per unit of total demand. Such data should be obtained from the average of a number of years and considering the load annual increment. Using the peak demand data, OPF is run and it was found that the line from Bus 27 to Bus 25 has reached its limit. 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. 3(a). In this figure, the vertical axis shows the number of events (out of 1000 samples) for the corresponding Lagrange multipliers on the horizontal axis (divided into equally distributed intervals). This type of representation is referred to as histogram. Consequently, LMPs have got high values. This is depicted in Fig. 4(b) for Bus 25.

GSDFs for line 25-27 are calculated using MATPOWER [31] 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 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 the above discussions and given data, Bus 26 is selected for WF installation. We consider a normal distribution for wind speed forecasted data at the specific hour and the WF output power is calculated from Eq. (2).

IV.2. Determining the Size of WFs for Probabilistic CM

At this point, N-1 contingency analysis for the congested line is carried out using the LODFs reported in Table II. 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 (in MW and with minus sign) is disconnected at the peak demand time and we have to solve the congestion problem for this system state. Table II 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 in the severest case is 20.8 MVA. This can easily be found using MCS results. Suppose that it is decided to compensate the flow in this line by α_i% beside the extra 4.8 MVA flow to ensure the secure margin from the flow limit, which 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 as $(0.2\times16 + 20.5-16)/0.4790 \approx 16.07$ MW. Thus, a18 MW WF consisted of 12×1.5MW wind turbines is found to be sufficient for installation 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**	**WAF**	**Bus**	**GSDF**	**WAF**	**Bus**	**GSDF**	**WAF**	**Bus**	**GSDF**	**WAF**
1	0.0000	0.32	7	0.0051	0.5	13	-0.0771	0.12	19	-0.0984	0.58	25	-0.4790	0.98
2	0.0009	0.43	8	0.0124	0.16	14	-0.0910	0.61	20	-0.0977	0.58	26	-0.4790	1.26
3	-0.0029	0.12	9	-0.0607	0.61	15	-0.1018	0.6	21	-0.1188	0.65	27	0.3567	0.84
4	-0.0035	0.32	10	-0.0956	0.41	16	-0.0850	0.15	22	-0.1254	0.65	28	0.0437	0.81
5	0.0035	0.5	11	-0.0607	0.41	17	-0.0925	0.14	23	-0.1524	0.37	29	0.3567	0.9
6	0.0061	0.25	12	-0.0771	0.22	18	-0.0996	0.39	24	-0.2207	0.7	30	0.3567	1.10

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

Line			**Line Flows**		**LODF×Line Flows**	
From	To	LODF	Active Power	Reactive Power	Active Power	Reactive Power
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

Wind speed at the peak demand hour is obtained from Fig. 1. Simulating again, it was observed that the congestion has successfully disappeared from Line 25-27, as depicted in Fig. 3(b). LMP at Bus 25 is also reduced, as illustrated in Fig. 4(b). At lighter load levels, the wind speed is generally higher and therefore there is no need for investigating these cases.

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 vary. In the next subsection, we show the application of PEMs for reducing the computational burden.

IV.3. 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 III compares the mean values (μ) and variances (σ) of line flows obtained by PEMs to MCS results. Lagrange multipliers are compared in Table IV, where the multipliers for other line limits not reported are zero.

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 for avoiding redundancy. However, for Lagrange multipliers 3PEM and 5PEM give relatively different values, as reported in Table IV. Non-zero Lagrange multipliers show the lines prone to congestion. There are 20 loads in the 30-bus test system. Therefore, we have 20 random variables 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).

TABLE III
MEAN VALUES AND VARIANCES OBTAINED BY PEMS AND MCS FOR LINE FLOWS

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
$\Sigma\varepsilon^*$		2.84	0.011	-	254.9	1.65	-

* Relative error (ε) for each quantity (Y) is calculated as:

$\varepsilon = |Y_{PEM} - Y_{MCS}|/|Y_{MCS}|$

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 V 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 IV
LAGRANGE MULTIPLIERS OBTAINED BY PEMS AND MCS FOR FLOW LIMIT ON LINE 25-27

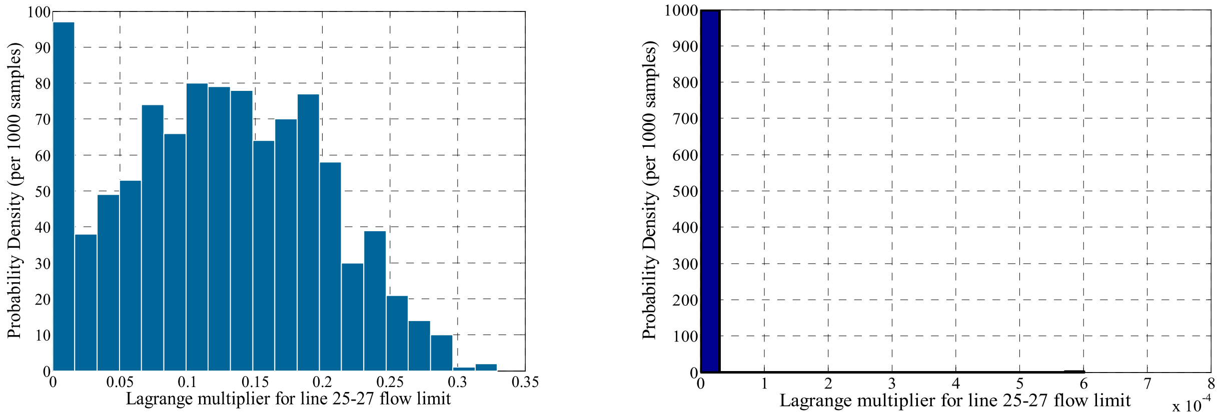
Mean Values (μ)				**Variances (σ)**			
2PEM	3PEM	5PEM	MCS	2PEM	3PEM	5PEM	MCS
0	0.1249	0.1348	0.1446	0	0.1623	0.1722	0.1280

TABLE V
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

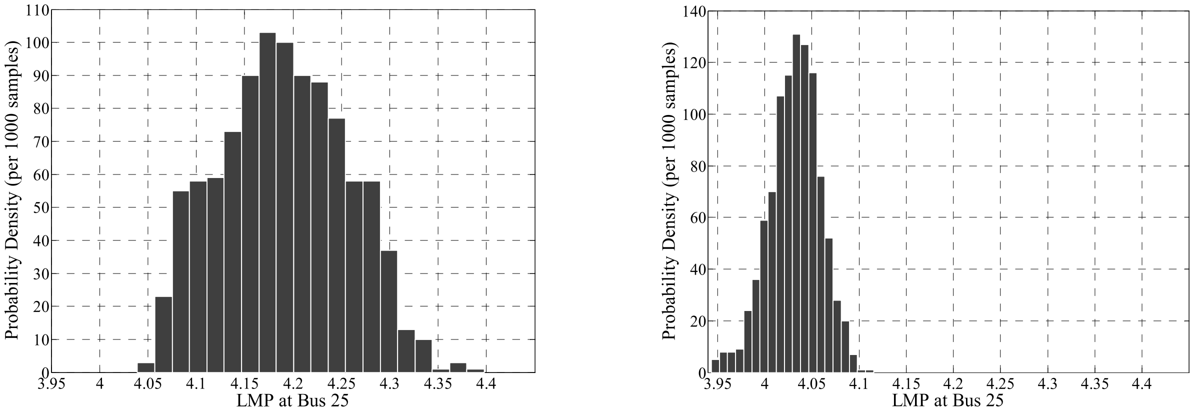
V. Conclusion

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.



(a) (b)

Figs. 3. 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



(a) (b)

Figs. 4. LMPs at Bus 25: (a) base case; (b) a WF is connected at Bus 26

Appendix

TABLE A.1

TRANSMISSION LINE PARAMETERS FOR 30-BUS TEST SYSTEM

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

TABLE A.2

LOAD DATA FOR 30-BUS TEST SYSTEM (MW/MVAR)

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

TABLE A.3

GENERATORS DATA FOR 30-BUS TEST SYSTEM (MW/MVAR)

Bus	P_{max}	P_{min}	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

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