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Incorporating Wind Intermittency into Probabilistic Optimal Power Flow

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Abstract—**Wind energy is an intermittent, volatile energy source which is difficult to forecast. This issue causes many problems in power system scheduling and planning esp. in power balance issue and also in optimal reserve allocation. This paper proposes an Optimal Power Flow (OPF) model incorporating wind power generation. Moreover, this model takes into consideration the cost of managing intermittency while Lattice Monte Carlo Simulation (LMCS) is used to generate scenarios. The cost of managing intermittency is applied to the objective function as two terms; Cost of spilled wind power and cost of using reserve to compensate the deficit in wind power generation. Finally, the simulation is done on IEEE 39-bus test system to verify the effectiveness and efficiency of the presented model.**

Keywords—**Wind Power Intermittency, Optimal Power Flow, Lattice Monte Carlo Simulation and Skewness**

I. INTRODUCTION

Nowadays, increasing price of fossil fuels and energy production cost, in addition to increasing global concerns on environmental issues cause energy section to seek an alternative. In this regard, Renewable Energy Sources (RESs) would be a good choice to replace fossil fuels. Among RESs, wind energy is the most famous energy source. So far, many countries have integrated wind power generation into their power systems. In spite of all good features with wind power, such as zero-emission and relatively low cost energy, using wind power may lead to several problems due to its intermittent, volatile nature i.e. power system's planners have to use complicated methods to operate power systems [1]. It is obvious that wind power generation varies with wind speed variations. In other words, wind power is a function of wind speed [2]. There are many solutions considered to compensate wind intermittency, such as Energy Storage Systems (ESSs) and also transacting power with adjacent power systems. Moreover, fast response generating units is one of the most effective ways to deal with wind power uncertainty.

In recent decades, researchers have tried to investigate the possibility of integrating wind power generation into power systems. Ref [3] proposes a model to incorporate wind power into the Optimal Power Flow (OPF) in which a model is suggested to cover costs caused by wind farms. The presented model is based on Weibull distribution of wind speed and wind turbine model. Coordinated wind-thermal power generation is presented in [4] to reduce the risk due to wind power uncertainty in which the problem is formulated as Mixed-Integer Programming (MIP). This model maximizes the expected profit while risk of energy trading is controlled. Ref [5] uses a hybrid method based on branch and bond technique and Dynamic Programming (DP) to coordinate wind-thermal scheduling problem to ensure secure energy provision in an isolated hybrid power system. A simple dispatching method on the basis of Direct Search Method (DSM) is proposed in [5] to reduce the computational burden of the problem.

Furthermore, Ref [6] has developed an efficient tool to aid policy makers in determining the first-order risks taking into consideration wind power intermittency in California. This research work shows that increase in wind power penetration may lead to remarkable increase in risks associated with loss in California. Ref [7] has extended a stochastic OPF model considering wind power integration in which the Probability Density Function (PDF) of wind speed is derived using quadratic approximation of power curve of wind turbine. An algorithm is proposed in ref.[8] for scenario generation and reduction based on Particle Swarm Optimization (PSO) to model power system uncertainties in the presence of wind power production. The suggested method would be useful for power system operators in day-ahead scheduling problems associated with uncertainty.

A novel simulation method is suggested in [9] to determine the effects of large-scale wind power generation on cost, reliability and environment. This research uses efficient tools like Unit Commitment (UC) and Economic Load Dispatch (ELD) to redispatch conventional generating units considering wind power output for present and also for the next 36 hours of the system. Ref [10] proposes a multi-period stochastic OPF model including offshore wind farms considered with Doubly-Fed Induction Generator (DFIG) turbine wherein scenario-based simulation technique is used to model the wind power uncertainty. This model would be applicable to obtain a proper

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active/reactive power scheduling of wind-thermal power system.

This paper proposes the problem of coordinating wind-thermal power system using OPF model. The uncertainty caused by wind power generation has twofold effect as wind power spillage and deficit that both of them are stated in terms of cost. These costs are considered as extra costs to manage wind intermittency. The objective function of the problem includes energy provision using thermal units plus the cost due to energy provision by wind units. Moreover, the variable rotor resistance induction generator is considered for wind units.

II. MATHEMATICAL MODELING

As mentioned above, the proposed problem is formulated as a single-objective optimization problem while operation cost of the system is considered to be minimized. In addition, it is assumed that wind units are owned by Generation Companies (GENCOs) and imposing two separated costs to system operation as: a) A penalty for not using all available wind power; b) The cost due to using reserve to compensate wind power deficit. The objective function of the proposed problem can be mathematically stated as follows:

$$Min \quad \sum_{i=1}^{N_{th}} C(i)(P_{th}(i)) + \sum_{j=1}^{N_{wind}} \left[\begin{array}{l} C(j)P_{wind}(j) + \\ \sum_{s=1}^{M} \left[C_{def}(j)\left(\pi(j,s)u(j,s)\right) + C_{res}(j)\left(\pi(j,s)h(j,s)\right) \right] \end{array} \right] \qquad (1)$$

Where, $P_{th}(i)$ is the scheduled power of thermal unit j, $P_{wind}(j)$ is the scheduled power of wind unit j, $C(i)(P_{th}(i))$ is the fuel cost of thermal unit i which is defined as $a(i)P_{th}^2(i) + b(i)P_{th}(i) + c(i)$. Furthermore, $C_{def}(j)$ is the cost coefficient due to not using all available wind power generation and $C_{res}(j)$ is the cost coefficient of using reserve to compensate wind power shortfall.

These costs coefficients are represented in Table 1. It is noted that $u(j,s)$ and $h(j,s)$ denote the values obtained from $w(j,s) - P_{wind}(j)$ and $P_{wind}(j) - w(j,s)$, respectively; as shown in Eq.(2) and (3). Also s is the number of scenarios. $\pi(j,s)$ indicates the probability of each scenario for available wind power while $w_c(j,s)$ represents the wind power installed capacity. N_{th} indicates the number of thermal generating units and N_{wind} is the number of wind power units.

Table 1. Cost coefficient for wind units

	$C(j)$ $(\$/MWh)$	$C_{def}(j)$ $(\$/MWh)$	$C_{res}(j)$ $(\$/MWh)$
Wind unit 1	25	24.5	25.5
Wind unit 2	25	24.5	25.5

The stochastic model of wind power generation includes wind speed forecast errors characterized by Weibull PDF. Note that, $Wind\_Sur(j)$ and $Wind\_Def(j)$ are costs imposed to system due to managing intermittency and calculated using wind power scenarios. Note that, $Wind\_Sur(j)$ and $Wind\_Def(j)$ denote expected spilled power of wind unit j and expected deficit of power pertaining to wind unit j, respectively. Based on power-speed curve of the wind turbine used in this paper [11], significant errors in forecast value and the scheduled value wind power occur in the region of high steep on the curve (Fig. 1).

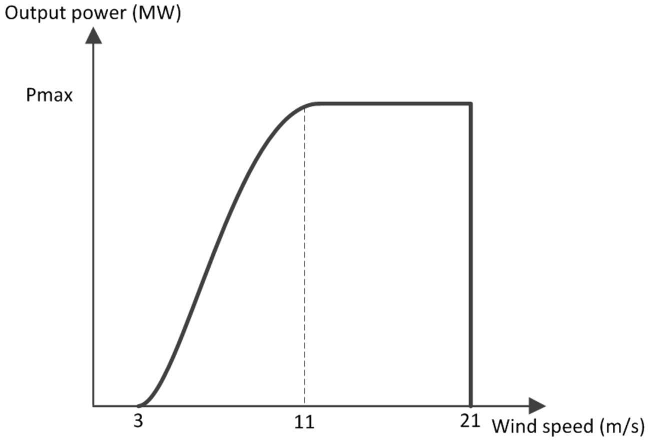

Fig. 1. Power-speed curve of the considered wind turbine

However, in order to characterize the cost due wind power intermittency two factors are considered [3]: a) The probability of occurring wind power surplus; b) The difference between the scheduled wind power and the available one.

Besides, two other important factors can be considered to model the cost of wind power shortfall: a) The probability of occurring wind power shortfall; b) The difference between scheduled power and the real value. Accordingly, the spilled wind power and the deficit in wind power can be stated as Eqs. (2) and (3), respectively.

$$Wind\_Sur(j) = \sum_{s=1}^{M} Max\left\{\left[w(j,s) - P_{wind}(j)\right], 0\right\} \pi(j,s) \qquad (2)$$

$$Wind\_Def(j) = \sum_{k=1}^{M} Max\left\{\left[P_{wind}(j) - w(j,s)\right], 0\right\} \pi(j,s) \qquad (3)$$

Where, $w(j,s)$ is the available wind power. The method used in the paper to generate scenarios is LMCS method and also discretized PDF. It is worth-mentioning that LMCS has several advantages over conventional Monte Carlo Simulation (MCS). Further information on LMCS would be available from [12] and [13]. In order to well model the wind power uncertainty, 10,000 scenarios of wind speed are generated at first. As it is obvious, larger number of scenarios leads to more precise modeling the uncertainty but with the price of high computational burden which may cause interactivity of the solution. Hence, this paper uses a novel scenario reduction based on backward method [14, 15] to reduce the number of scenarios to 100 scenarios. It is worth-mentioning that wind speed forecast is available.

III. INDUCTION GENERATOR TURBINE

Nowadays, most wind units utilize induction machines as their generators that are available in different types. The induction generator used in this paper is a squirrel cage induction generator/wound rotor induction generator with variable rotor resistance. Since, the wind generator model would lead to more realistic solutions, the limitations of active and reactive power and their relation to the voltage must be determined [16]. Eq. (4) represents this limitation while the equivalent circuit of an induction generator can be illustrated as Fig. 2.

$$P^2 + Q^2 + \frac{V^2 Q}{X} = 0 \tag{4}$$

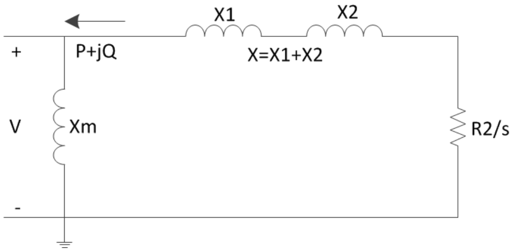

Fig. 2. Equivalent circuit of an induction generator

Considering the values of P and V, the P-Q curve of a squirrel cage/wound rotor induction generator can be shown as Fig. 3.

Note that, the reactive power of wind unit is also limited as below:

$$\frac{-V^2}{2X} \le Q \le 0 \tag{5}$$

Also, the active power of wind unit must be equal or greater than zero.

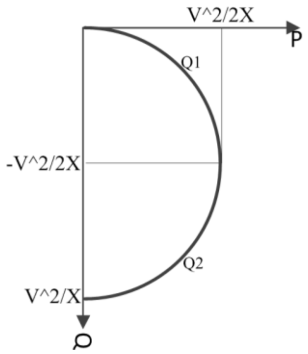

Fig. 3. P-Q curve for a squirrel cage/wound rotor induction generator

IV. OPTIMAL POWER FLOW

OPF is an optimization problem considering the constraints of power systems, through which, by adjusting control variables like generation of units, other variables are optimally adjusted. In this regard, this section represents the constraints of power system including equality and inequality ones. The first but the most important constraints refer to active and reactive power balance at each bus that is written in mathematical form respectively as:

$$\sum P_g(i) - P_d(i) = 0 \tag{6}$$

$$\sum Q_g(i) - Q_d(i) = 0 \tag{7}$$

While the power output of generators and voltages are limited through (8), (9) and (10)

$$P^{\min}(j) \le P(j) \le P^{\max}(j) \tag{8}$$

$$Q^{\min}(j) \le Q(j) \le Q^{\max}(j) \tag{9}$$

$$V^{\min}(i) \le V(i) \le V^{\max}(i) \tag{10}$$

In addition, the power injection of each bus can be stated as:

$$P(i) = |V(i)| \sum_{n=1}^{N} |Y(i,n)||V(n)| \cos(\delta(i) - \delta(n) - \theta(i,n)) \tag{11}$$

$$Q(i) = |V(i)| \sum_{n=1}^{N} |Y(i,n)||V(n)| \sin(\delta(i) - \delta(n) - \theta(i,n)) \tag{12}$$

Where, $|Y|$ represents the magnitude of admittance matrix of power system, δ is the voltage angle at each bus and θ is the angle of admittance matrix [17].

V. SIMULATION RESULTS

The proposed model is implemented on IEEE 39-bus New England test system comprising 10 generators, which is a well-known system. Moreover, the computer system employed to solve the problem is Intel Core i5 PC with 2.53 GHz clock speed and 4 GB RAM. The data of the test system would be available from [18]. The total active and reactive loads of this system are 6150.5 MW and 1409.5 MVaR, respectively. It is worth-mentioning that the scheduling is performed for one hour. In addition, two wind generation units are considered at buses 28 and 29 and bus 31 is considered as the slack bus. The capacity of these two wind units connected at buses 28 and 29 are 15 MW and 20 MW, respectively. It is assumed that wind units operate at 50% of their capacity.

This paper has studied different skewness of wind speed forecast to well show the effect of wind power generation on power system. In this regard, five shape parameters of Weibull PDF are applied to scenario generation procedure as below:

$$k = 1, 1.5, 2, 2.5, 3$$

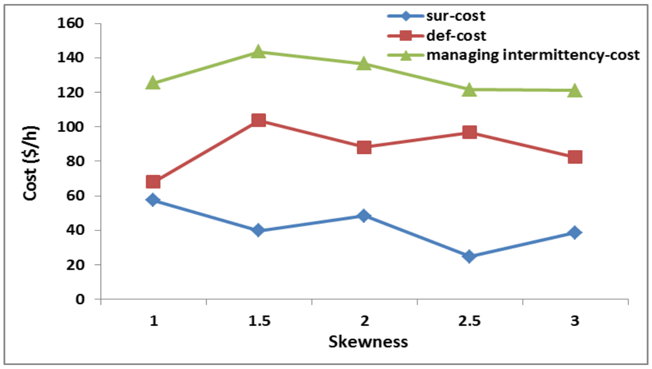

Fig. 4. Cost of managing wind intermittency

It is noted that the left skewness is negative and the right skewness is positive. Fig. 4 depicts the cost due to managing intermittency in the case of compensating wind power deficit and using reserve. It is obvious that, when the skewness is toward right, the wind power is overestimated. The power outputs of generating units for different skewness are represented in Table 2.

Table 2. Dispatched power output of generating units

Bus No	Pmin	k=1	k=1.5	k=2	k=2.5	k=3	Pmax
28	0	2.3	4.9	5.8	6	6.3	7.5
29	0	2.3	5.8	7.1	7.5	8	10
30	0	400	400	400	400	400	400
31	0	822.2	822.7	822.6	822.6	822.6	1200
32	0	539.9	539.7	539.9	539.9	539.9	800
33	0	701.4	695	692.7	692.1	691.3	750
34	0	600	600	600	600	600	600
35	0	0	0	0	0	0	750
36	0	650	650	650	650	650	650
37	0	600	600	600	600	600	600
38	0	777.3	777.2	777.2	777.2	777.2	950
39	0	1100	1100	1100	1100	1100	1100

VI. CONCLUSION

The wind power uncertainty not only causes economic load dispatch to be more complicated, but also causes concerns on secure operation of power systems. Thus, this paper presents a stochastic OPF model including wind power generation implemented on IEEE 39-bus test system. Furthermore, LMCS is employed to generate scenarios and the number of scenarios is reduced using a novel scenario reduction method. It can be concluded from simulation results that, integrating intermittent wind power generation into modern power system may impose additional cost to system due to managing the wind intermittency.

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