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Stochastic Approach for Active and Reactive Power Management in Distribution Networks

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Abstract- In this paper, a stochastic method is proposed to assess the amount of active and reactive power that can be injected/absorbed to/from grid within a distribution market environment. Also, the impact of wind power penetration on the reactive and active distribution-locational marginal prices is investigated. Market-based active and reactive optimal power flow is used to maximize the social welfare considering uncertainties related to wind speed and load demand. The uncertainties are modeled by Scenario-based approach. The proposed model is examined with 16-bus UK generic distribution system.

Index terms—Active and reactive optimal power flow, social welfare maximization, uncertainty modelling, distribution locational marginal prices.

I. INTRODUCTION

A. Motivation and Approach

The intermittent and unpredictable nature of wind energy introduces a significant operational variability and uncertainty that must be managed with the renewable energy sources (RES) integration into distribution networks [1]. Distribution network operators (DNOs) have to develop a reasonable operating strategy taking into consideration the quantity of active and reactive power that can be injected/absorbed to/from the grid, interrupting loads while keeping network security. This paper provides a stochastic method in order to assess the active and reactive power that can be injected/absorbed into/from the grid by WTs. Also, the impact of wind power penetration on social welfare (SW), as well as active and reactive distribution distribution-locational marginal prices (D-LMPs) are investigated considering uncertainties associated with wind speed and load demand within a distribution market environment.

B. Literature Review

Several studies have involved the use of renewable distributed generators (DGs) as providers of ancillary services such as reactive power support. The authors in [2] introduced a proper Coordination technique among the DGs and on an on-load tap changing substation switched capacitors, transformers, and feeder-switched capacitors without requiring communication. In [3], the possibility of providing ancillary services such as reactive power and primary frequency support from modern wind farm’s output to the grid, including detailed analysis of wind farms capability curves and different cost components related to reactive power generation are examined.

Few studies have been carried out on simultaneous considering of active and reactive power optimal power flow. A general optimal power flow (OPF) problem was introduced for the first time by Carpentier in early 1960's [4]. In [5], OPF was divided into two suboptimal problems, optimal reactive power problem and optimal active power problem, where these two suboptimal problems were solved separately. In [6] the authors have determined optimal penetration of DGs by using OPF to minimize the system energy losses. In [7], reactive power procurement is modeled by using a security constraint optimal power flow (SCOPF) taking into consideration the voltage stability criterion to minimize energy losses and the cost of reactive power procurement. Also, in [8] the transition losses and the total generation costs of reactive power have been minimized at different voltage stability margins by proposing reactive power market. In [9], the social benefits (which normally comprise of the cost function of real power generation and benefit function of consumers) are maximize by using a theory of real-time pricing of real and reactive powers. In [10] a three-step approach has been presented which considers the calculation of marginal benefits and the maximization of social welfare. In [11], a modified nodal pricing approach has been used to calculate the price of reactive power which can be derived from OPF in normal and emergency conditions. In [12], the authors have used a modified OPF to minimize the production cost of active and reactive power. Dai et al [13] have included the opportunity cost of dispatching reactive power from generators into OPF problem in order to obtain reactive power marginal price. In [14] a new design of reactive power capacity market based on annual auctions have been proposed to procure of the reactive power service. The authors in [15] have solved the reactive power pricing by considering the active and reactive power production costs of generators and capital cost of capacitors in the OPF problem to find reactive D-LMPs. Also, AC-OPF has been used to calculate the D-LMPs for active and reactive power[16]. Hao and Papalexopoulos [17] have discussed the characteristics of structure reactive power that must be take into consideration in order to improve a framework for reactive power pricing and management. The results show that the marginal price of reactive power is less than 1% of active power and strongly depends on the network constraints. In [18] a probabilistic approach of providing optimal reactive power in electricity market has been proposed taking into consideration load forecasting uncertainties. A pay-as-pay mechanism has been considered by the authors in [19] to design a new reactive power market. In this mechanism, the local nature of reactive power has considered implicitly. In [20] a new design of reactive power market based on procurement of reactive power resources on a seasonal basis and a real-time reactive power dispatch has been proposed. Regarding to uncertainty, usually probability density function (PDF) and membership function are using to describe uncertainty parameters. PDF uses when the historical data of uncertainties are available such as wind speed or load demand. Otherwise, if no statistical data about uncertainty parameter are available, membership function will be used [21]. A powerful tool to assess the impact of DGs takes into account the uncertainties related with operation/investments of DGs on distribution network has been introduced in [22].

C. Contributions

To the best of our knowledge, no stochastic method to assess the active and reactive D-LMP in distribution networks from the DNOs perspective within a distribution market environment considering uncertainties has been reported in the literature. The main contributions of this paper are listed below:

- To provide a stochastic approach for evaluating the SW and the impact of WTs' penetration on the reactive and active D-LMPs in distribution networks within a distribution market environment considering uncertainties.
- To model the uncertainties associated with load demand and wind speed in the distribution system by using scenario-based approach.

D. Paper organization

The rest of paper are organized as follows. Section II explain distribution market formulation. Section III explain the uncertainty modeling. Section IV presents case study and simulation results. Conclusion is presented in Section V.

II. Distribution Market Formulation

Usually, the power market structure framework considers different DG technologies inside a DNOs control area. DNO is defined as the market operator which determines the optimization process and the price estimation for acquisition of reactive and active power [23-25]. In other words, DNOs purchase active and reactive power according to the offers of DGs, bids of loads and delivered it to the final customers while keeping system security. The major aim of DNO is to maximize social welfare that includes the maximum consumers' benefit function and minimum cost of energy [26].

In this paper, the active and reactive power offers from generators (substation and WTs) and active and reactive bids of loads are sent in form of block to the distribution market [27]. The difference between them known social welfare which can be maximized as follow:

$$\text{Maximize SW} = \left(\sum_{i=1}^{NB}\sum_{s=1}^{NS} \pi_s C_i^{l,P} P_{i,s}^{l} + \sum_{i=1}^{NB}\sum_{s=1}^{NS} \pi_s C_i^{l,Q} Q_{i,s}^{l} \right) - \sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{ss,P} P_{i,s}^{ss} - \sum_{i=1}^{NB}\sum_{s=1}^{NS} C_i^{ss,Q} Q_{i,s}^{ss} - \sum_{i=1}^{NB}\sum_{s=1}^{NS} \pi_s C_i^{w,P} P_{i,s}^{w} - \sum_{i=1}^{NB}\sum_{s=1}^{NS} \pi_s C_i^{w,Q} Q_{i,s}^{w} \quad (1)$$

where, $P_{i,s}^{l}$, $P_{i,s}^{ss}$ and $P_{i,s}^{w}$ are the active power for load, substation (slack bus) and WTs at each bus *i* at scenario *s* respectively. $Q_{i,s}^{l}$, $Q_{i,s}^{ss}$ and $Q_{i,s}^{w}$ are the reactive power for load, substation and WTs at each bus *i* at scenario *s*, respectively. $C_i^{ss,P} / C_i^{w,P}$, are the offer prices for active power of substation / WTs at each bus *i* at scenario *s*. $C_i^{ss,Q} / C_i^{w,Q}$ are the offer prices for reactive power of substation / WTs at each bus. $C_i^{l,P}$ and $C_i^{l,Q}$ are the bid prices for active and reactive power load at each bus *i*,
respectively. π_s is the corresponding probability at scenario *s*.

a. Constraints market-based active and reactive OPF

1) Equality constraints for active and reactive power are, as follow

a. Active power flow at each bus

$$\sum_{i=1}^{NB} P_{i,s}^{ss} + \sum_{i=1}^{NB} P_{i,s}^{w} - \sum_{i=1}^{NB} P_{i,s}^{l} = \sum_{j=1}^{NB} V_{i,s} V_{j,s} [G_{i,j} \cos(\delta_{i,s} - \delta_{j,s}) + B_{i,j} \sin(\delta_{i,s} - \delta_{j,s})] \quad (2)$$

b. Reactive power flow at each bus

$$\sum_{i=1}^{NB} Q_{i,s}^{ss} + \sum_{i=1}^{NB} Q_{i,s}^{w} - \sum_{i=1}^{NB} Q_{i,s}^{l} = \sum_{j=1}^{NB} V_{i,s} V_{j,s} [G_{i,j} \sin(\delta_{i,s} - \delta_{j,s}) - B_{i,j} \cos(\delta_{i,s} - \delta_{j,s})] \quad (3)$$

where $G_{i,j}$ and $B_{i,j}$ are the real and imaginary parts of the elements in the bus admittance matrix (Y-bus matrix) corresponding to the i^{th} row and j^{th} column, respectively.

2) Inequality constraints

a. Active power capacity constraints at the substation

$$P_{i,s}^{ss,\min} \le P_{i,s}^{ss} \le P_{i,s}^{ss,\max} \quad (4)$$

b. Reactive power capacity constraints at the substation

$$Q_{i,s}^{ss,\min} \le Q_{i,s}^{ss} \le Q_{i,s}^{ss,\max} \quad (5)$$

c. Active power constraints for WTs generation

$$P_{i,s}^{w,\min} \le P_{i,s}^{w} \le P_{i,s}^{w,\max} \quad (6)$$

d. Reactive power constraints for WTs generation

$$Q_{i,s}^{w,\min} \le Q_{i,s}^{w} \le Q_{i,s}^{w,\max} \quad (7)$$

where, $P_{i,s}^{ss}$, $P_{i,s}^{w}$ are the active power capacity of substation and WTs at each bus at scenario *s*, respectively. $Q_{i,s}^{ss}$ and $Q_{i,s}^{w}$ are respectively the reactive power of substation and WTs at each bus and scenario *s*. $P_{i,s}^{ss,\min} / P_{i,s}^{ss,\max}$, $Q_{i,s}^{ss,\min} / Q_{i,s}^{ss,\max}$, $P_{i,s}^{w,\min}$ / $P_{i,s}^{w,\max}$ and $Q_{i,s}^{w,\max} / Q_{i,s}^{w,\max}$ represent the min/max values of active and reactive power they can assume.

e. Voltage constraint at each bus

$$V_{i,s}^{\min} \le V_{i,s} \le V_{i,s}^{\max} \quad (8)$$

where, $V_{i,s}$ is the voltage quantity at bus i and scenario s. $V_{i,s}^{\min}$ / $V_{i,s}^{\max}$ are the min/max values of voltage they can assume.

III. UNCERTAINTY MODELLING

The uncertainties related to wind speed and load demand are modeled by scenario-based approach which can be defined as a probable realization of an uncertain parameter [21]. In this paper, 24 scenarios are generated using probability density function (PDF) of each wind speed and load demand.

a) Wind Speed Modelling

The behavior of wind power generation, usually is modeled by Weibull probability density function (PDF)[28]. Weibull PDF is based on a comparison of actual wind speed at different sits and wind speed estimated using the Weibull PDF. The PDF for this distribution is given by [29]:

$$f_w(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} \exp\left[-(\frac{v}{c})^k \right] \quad (9)$$

where, v, c and k are respectively the wind speed, the scale index and the shape index.

In order to combine the output power which, introduce by WTs, the continuous PDF has been divided into states with tacking into account the specific limits of wind speed. The probability of every state is calculated using the following equation:

$$\pi_w = \int_{v_{w1}}^{v_{w2}} f_w(v)dv \quad (13)$$

$$v_s = \frac{v_{w1} + v_{w2}}{2} \quad (14)$$

where v_1 and v_2 are the starting and ending points of the wind speed's interval in state w, respectively.

Hence, the active power which is generated by WTs can be determined by using its power curve as follows:

$$P_w(v) = \begin{cases} 0, & 0 \le v \le v_{ci} \\ P_{rated} \times \dfrac{v - v_{ci}}{v_r - v_{ci}}, & v_{ci} \le v \le v_r \\ P_{rated}, & v_r \le v \le v_{co} \\ 0, & v_{co} \le v \end{cases} \quad (15)$$

where, v_{ci}, v_r and v_{co} are the cut-in speed, rated speed and cut-off speed of the WTs, respectively. Therefore, the active and reactive wind power at bus i, scenario s and configuration c are calculated as follows:

$$0 \le P_{i,s}^w \le \gamma_{i,s}^w \times P_{i,rated}^w \quad (16)$$

$$0 \le Q_{i,s}^w \le \gamma_{i,s}^w \times Q_{i,rated}^w \quad (17)$$

where, $\gamma_{i,s}^w$ is the percentage of active and reactive power which are generated by WTs at scenario s.

b) Load Modelling

The load demands at each bus are also modelled using a Normal PDF [30, 31].

c) *Combined Generation-Load Model*

In this paper, the wind speed and the load states are assumed to be independent in order to construct the whole set of scenarios by combining scenarios as follows:

$$\pi_s = \pi_D \times \pi_w \quad (18)$$

where, π_D and π_w are the probabilities of demand load and wind states. Table I gives combined wind and load states and corresponding probabilities.

IV. CASE STUDY AND SIMULATION RESULTS

The following analyses are based on 33kV, 16-bus UK generic distribution system (UKGDS) and its data are available in [32]. Here, it is assumed that three WTs are installed at bus 3, 10 and 13. The voltage limits are assumed to be between V_{min}=0.94 p.u and V_{max}= 1.06 p.u. The power factor of WTs assumed to be 0.95 lagging. The total peak demand for active and reactive power are 38.2 MW and 7.7 MVAr, respectively. Fig. 1 shows the single-line diagram of 16-bus UKGDS. In this paper, it is assumed that 660 kW WTs are installed at candidate buses. Normal and Weibull PDF are used to model four states for demand loads and six states for WTs, respectively. The corresponding probabilities of combined load demand and wind states are presented in Table I.

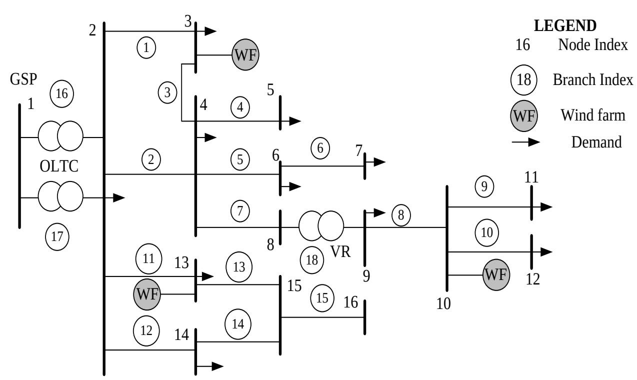

Fig. 1. single- line diagram of 16-bus UKGDS

The active and reactive bid prices of loads are respectively presented in Tables II and III. It is assumed that there are three blocks for each maximum demand load. The active and reactive offer prices of substation are assumed to be 160 £/MWh and 120 £/ MVArh, while for WTs are 70£/MWh and 50 £/MVArh respectively. [26, 33-36].

Table I. Combined wind and load states and corresponding probabilities

State #	Load (%)	Wind (%)	π_s
s_1	100.00	100.00	0.0008
s_2	100.00	85.30	0.0030
s_3	100.00	58.50	0.0080
s_4	100.00	40.60	0.0025
s_5	100.00	35.10	0.0010
s_6	100.00	00.00	0.0006
s_7	75.00	100.00	0.0088
s_8	75.00	85.30	0.0330
s_9	75.00	58.50	0.0880
s_{10}	75.00	40.60	0.0275
s_{11}	75.00	35.10	0.0110
s_{12}	75.00	00.00	0.0066
s_{13}	55.00	100.00	0.0120
s_{14}	55.00	85.30	0.0450
s_{15}	55.00	58.50	0.1200
s_{16}	55.00	40.60	0.0375
s_{17}	55.00	35.10	0.0150
s_{18}	55.00	00.00	0.0090
s_{19}	35.00	100.00	0.0024
s_{20}	35.00	85.30	0.0090
s_{21}	35.00	58.50	0.0240
s_{22}	35.00	40.60	0.0075
s_{23}	35.00	35.10	0.0030
s_{24}	35.00	00.00	0.0018

Table II. Active bid prices for the loads

Bus No.	Active power bid price Blocks (MW@£/MWh)		
	b_1	b_2	b_3
2	2.50@280	1.90@260	1.01@250
3	1.10@260	0.70@250	0.13@230
4	0.03@260	0.02@250	0.01@240
5	9.20@250	6.10@240	3.10@230
6	1.10@240	0.60@230	0.26@230
7	0.90@250	0.60@220	0.40@220
9	0.22@220	0.19@220	0.15@220
10	1.40@220	0.90@210	0.40@200
11	1.60@210	0.80@200	0.45@200
12	0.40@220	0.26@200	0.15@190
13	0.70@200	0.20@190	0.11@170
14	0.30@190	0.20@180	0.08@170

Table III. Reactive bid prices for the loads

Bus No.	Reactive power bid price Blocks MVAr@£/MVArh		
	b_1	b_2	b_3
2	0.600@240	0.300@220	0.190@210
3	0.210@220	0.120@210	0.060@190
4	0.005@220	0.003@210	0.002@200
5	2.100@210	1.200@110	0.440@190
6	0.200@200	0.150@190	0.050@190
7	0.210@210	0.100@180	0.080@180
9	0.060@180	0.030@180	0.020@180
10	0.220@180	0.190@170	0.150@160
11	0.300@170	0.200@160	0.080@160
12	0.090@180	0.060@160	0.030@150
13	0.100@160	0.070@150	0.030@130
14	0.060@150	0.040@140	0.020@130

The proposed method has been implemented in GAMS and solved using IPOPT [37] on a PC with Core i7 CPU and 16 GB of RAM. Market-based active and reactive optimal power flow is used to maximize the social welfare subject to network constraints. Figs. 2 and 3 show the total dispatched active and reactive power generated by WTs in all scenarios at buses 3,10 and 13.

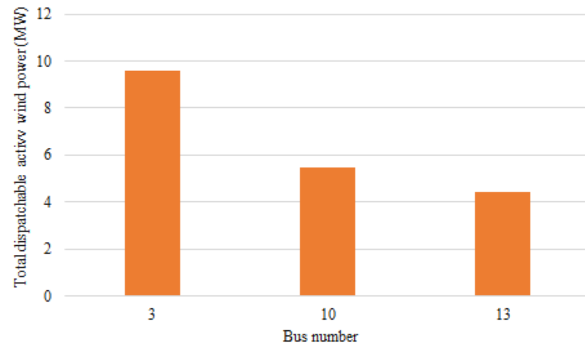

Fig. 2. Total dispatched active power at candidate buses in all scenarios

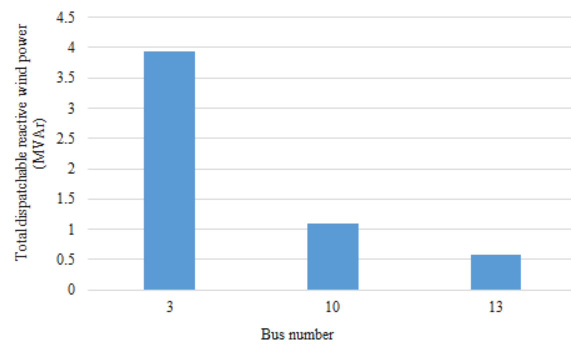

Fig. 3. Total dispatched reactive power at candidate buses for all scenarios

Bus 3 and bus 13 have respectively the highest and lowest dispatched active and reactive power compared to bus 10. The dispatched active and reactive power by WTs at each bus is limited by WTs' active and reactive offer prices, bid prices of active and reactive loads, and voltage constraints at each bus and thermal limits of the lines.

Fig. 4 shows the social welfare (SW) at each scenario. In scenario 15, SW has the highest amount which is equal to about 52 £/h which is due to the highest probability of this scenario compared to other ones (i.e. 0.12) as presented in Table I.

Figs. 5 and 6 show the active and reactive D-LMPs at candidate buses. Bus 3 has the lowest active and reactive D-LMPs whereas bus 13 has the highest active and reactive D-LMPs. This is mainly due to the highest and lowest dispatched active and reactive power at these buses respectively.

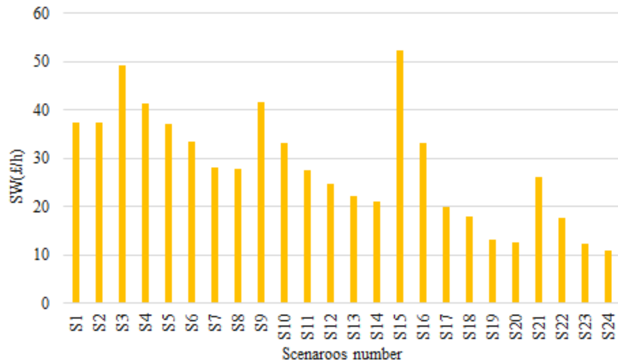

Fig.4. Social welfare for each scenario

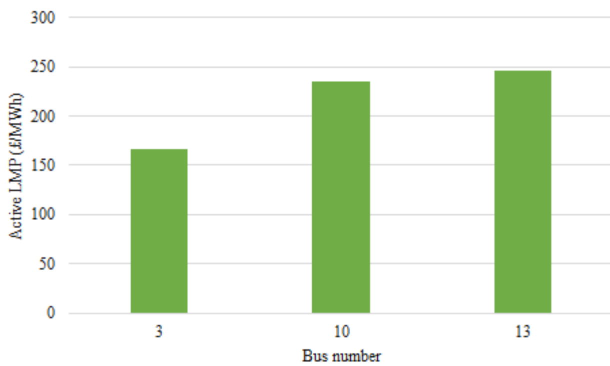

Fig. 5. Active D-LMP at candidate buses for all scenarios

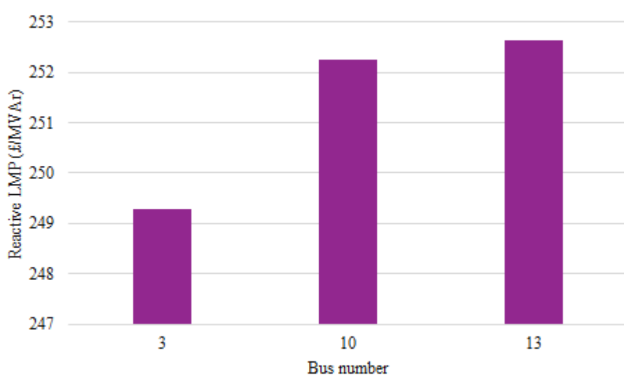

Fig. 6. Reactive D-LMP at candidate buses for all scenarios

V. Conclusion

In this paper, a stochastic approach is proposed to evaluate the amount of active and reactive power that can be injected/absorbed to/from the grid from WTs. Also, it used to investigate the impact of wind power penetration on the SW and on active and reactive D-LMPs from the point of view of DNOs. Scenario-based approach is used to model the uncertainty related to the wind speed and load demand. The proposed method proves that the impact of amount of active and reactive power WTs penetration through the network on active and reactive D-LMPs reduction and maximizing SW.

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