Link to publisher's version: *http://dx.doi.org/10.1016/j.renene.2017.06.074*

Citation: Mokryani G, Hu Y-F, Papadopoulos P et al (2017) A deterministic approach for active distribution networks planning with high penetration of wind and solar power. Renewable Energy. 113: 942-951.

A Deterministic Approach for Active Distribution Networks Planning with High Penetration of Wind and Solar Power

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***Abstract* – In this paper, a novel deterministic approach for the planning of active distribution networks within a distribution market environment considering multi-configuration of wind turbines (WTs) and photovoltaic (PV) cells is proposed. Multi-configuration multi-period market-based optimal power flow is utilized for maximizing social welfare taking into account uncertainties associated with wind speed, solar irradiance and load demand as well as different operational status of WTs and PVs. Multi-period scenarios method is exploited to model the aforementioned uncertainties. The proposed approach assesses the effect of multiple-configuration of PVs and WTs on the amount of wind and solar power that can be produced, the distribution locational marginal prices all over the network and on the social welfare. The application of the proposed approach is examined on a 30-bus radial distribution network.**

***Index Terms* — Wind power, active network management, social welfare, market-based optimal power flow, distribution network operators, distribution locational marginal prices.**

Nomenclature

A. Sets and Indices

i,j	Index of system buses running from 1 to NB
w	Index of wind turbine
G	Index of substation
D	Index of loads
t	Index of energy block offered by wind turbines running from 1 to NT
q	Index of energy bids submitted by loads running from 1 to NQ

s	Index of scenarios running from 1 to *NS*
c	Index of configurations running from 1 to *NC*
y	Index of years running from 1 to *NY*

B. Variables

$(P/Q)^{w}_{i,t,s,c,y}$	Active/reactive power generated by wind turbines at bus *i*, block *t*, scenario *s*, configuration *c* and year *y* in MW/MVAr
$(P/Q)^{G}_{i,t,c,y}$	Active/reactive power at substation, block *t*, configuration *c* and year *y* in MW/MVAr
$V_{i,s,c,y}/\delta_{i,s,c,y}$	Voltage/voltage angle at bus *i*, scenario *s*, configuration *c* and year *y* in Volt/Radian
$\phi^{w}_{i,s,c,y}$	Power factor angle of WTs at bus *i*, scenario *s*, configuration *c* and year *y* in radian
T_{ij}	Tap magnitude of OLTC

C. Parameters

α	Load growth rate
β	Operational status of each WT
$\beta_{i,c}$	Operational status of WTs at bus *i* and configuration *c*
c	Scale coefficient
v	Wind speed in m/s
v_m	Mean value of wind speed in m/s
v_{ci}/v_{co}	Cut-in/cut-off wind speed in m/s
v_r	Rated wind speed in m/s
π_s	Probability of state *s*
$(P/Q)^{D}_{i,q,s,y}$	Active/reactive consumption of loads at bus *i*, block *q*, scenario *s*, configuration *c* and year *y* in MW/MVAr
$V_i^{\min}/V_i^{\max}$	Min/max voltage at each bus in Volt
$\delta_i^{\min}/\delta_i^{\max}$	Min/max voltage angle at each bus
$Q_i^{w,\min}/Q_i^{w,\max}$	Min/max reactive of WTs at bus in MVAr
$P^{w}_{i,rated}$	WTs rated active power in MW
$\gamma^{w}_{i,s,c}$	Percentage of active power generated by WTs at scenario *s* and configuration *c*
$P_i^{G,\min}/P_i^{G,\max}$	Min/max active power at substation in MW
$Q_i^{G,\min}/Q_i^{G,\max}$	Min/max reactive power at substation in MVAr

$C_{i,q}^{D}$ — Price for the energy bid *q* at bus *i* submitted by load *D* in £/MWh

$C_{i,t}^{w}$ — Price for the energy selling *t* at bus *i* by WT *w* in £/MWh

$C_{i,t}^{G}$ — Price for the energy selling *t* at substation in £/MWh

G_{ij} / B_{ij} — Real/imaginary part of the element in the admittance matrix corresponding to the i^{th} row and j^{th} column in mho

$I_{ij}^{\max}$ — Maximum current flow of wires in A

***Index Terms* — Wind and solar power, electricity market, social welfare, multi-configuration, distribution network operators.**

NOMENCLATURE

D. Sets and Indices

i,j — Index of system buses running from 1 to *NB*

w — Index of WTs running from 1 to *NW*

pv — Index of PVs running from 1 to *NPV*

G — Index of substation running from 1 to *NG*

D — Index of loads

t — Index of energy block offered by WTs and PVs running from 1 to *NT*

q — Index of energy bids submitted by dispatchable loads running from 1 to *NT*

m — Index of periods running from 1 to *NM*

c — Index of configurations running from 1 to *NC*

h — Number of hours

E. Variables

$P_{i,t,m,c}^{(w/pv)}$ — Active power generated by WTs/PVs at bus *i*, block *t*, period *m*, and configuration *c*

$Q_{i,t,m,c}^{(w/pv)}$ — Reactive power generated by WTs/PVs at bus *i*, block *t*, period *m*, and configuration *c*

$(P/Q)_{i,t,c}^{G}$ — Active/reactive power at substation, block *t*, and configuration *c*

$V_{i,m,c} / \delta_{i,m,c}$ — Voltage/voltage angle at bus *i*, period *m*, and configuration *c*

$\phi_{i,m,c}^{(w/pv)}$ — Power factor angle of WTs/PVs at bus *i*, period *m*, and configuration *c*

T_{ij}	Tap magnitude of OLTC

F. Parameters

β	Operational status of each WT/PV
$\beta_{i,c}$	Operational status of WTs/PVs at bus *i* and configuration *c*
η_m, χ_m, ω_m	Levels of wind, PV and demand profiles, respectively for m^{th} multi-period scenario
$(P/Q)^D_{i,q,m}$	Active/reactive consumption of loads at bus *i*, block *q*, period *m*, and configuration *c*
$V_i^{\min} / V_i^{\max}$	Min/max voltage at each bus
$\delta_i^{\min} / \delta_i^{\max}$	Min/max voltage angle at each bus
$P_i^{w,\min} / P_i^{w,\max}$	Min/max active power of WTs
$Q_i^{pv,\min} / Q_i^{pv,\max}$	Min/max reactive power of PVs
$P_i^{w,\min} / P_i^{w,\max}$	Min/max active power of WTs
$Q_i^{pv,\min} / Q_i^{pv,\max}$	Min/max reactive power of PVs
$P_i^{G,\min} / P_i^{G,\max}$	Min/max active power at substation
$Q_i^{G,\min} / Q_i^{G,\max}$	Min/max reactive power at substation
$C_{i,t}^{w}$	Price for the energy selling *t* at bus *i* by WTs
$C_{i,t}^{pv}$	Price for the energy selling *t* at bus *i* by PVs
$C_{i,t}^{G}$	Price for the energy selling *t* at substation
G_{ij} / B_{ij}	Real/imaginary part of the element in the admittance matrix corresponding to the i^{th} row and j^{th} column
$I_{ij}^{\max}$	Maximum current flow

I. Introduction

Recently, a huge number of photovoltaic (PV) cells are deployed in the UK. The Government's target is to achieve 15% of electricity generation from renewable energy sources (RES) by 2020. Nevertheless, both PV and wind turbines (WTs) have high concentration in different regions of the UK [1-3]. However, in 2014, the European Union (EU) was the world leader in residential PV installation with more than 40W installed per individual averagely, which is 10 times more than the rest of the world. One of the most important EU 2020 strategies is the share of renewables in gross final energy consumption.

The target for the EU to be achieved by 2020 is the share of 20% from RES in gross final consumption of energy. However, RES will play an important role in assisting the EU meet its energy needs beyond 2020. Thus, Member States have already agreed on a new target for RES installation of at least 27% by 2030.

Among the 28 EU Member States, a third have already achieved the level needed to meet their national 2020 targets including Bulgaria, the Czech Republic, Estonia, Croatia, Italy, Lithuania, Romania, Finland, Sweden, Denmark and Austria [4].

The installation of large amounts of RES in distribution networks introduces several economic and technical challenges to distribution network operators (DNOs). Thus, DNOs should develop a rational operating approach considering dispatching distributed generators (DGs), interrupting loads, and purchasing power from the wholesale market subject to network constraints [5]. However, active network management (ANM) integration schemes, including coordinated voltage control (CVC) of on load tap changers (OLTCs) and adaptive power factor control (PFC) of DGs, are advantageous for DNOs in comparison with the management of passive networks [6-8].

Several works have been carried out on the advantages of ANM. ANM implementations has been proposed in [9-10]. Online ANM application and joint ANM and demand side management are proposed in [11-14]. Besides, many studies have been reported about the planning and operation of distribution networks with integration of DGs [15-20]. In [15], a probabilistic expansion planning technique, which minimizes the investment, budget to construct new lines. In [16], the authors proposed a probabilistic approach to determine the capacity limits of wind power taking into account power transfer and voltage limits. In [17], the authors proposed a stochastic optimization approach for minimizing the active power losses of the lines using WTs' power factor control. In [18], the application of ANM schemes based on optimal power flow algorithm has been investigated. In [19], the authors proposed a probabilistic approach to find the PVs' optimal size in order to minimize the total power losses in distribution networks. In [20], the authors proposed an innovative approach for distribution network planning considering customer interruption and investment costs.

In [21], the authors have proposed a state reduction algorithm in DG planning problems and reliability analysis to determine the minimum number of states required to represent the behaviour of wind speed and solar irradiance.

Reference [22], proposes a multistage electricity generation expansion planning incorporating energy storage systems, which minimizes the planning cost and environmental pollution simultaneously.

In [23], the authors have presented a multi-objective optimization problem for distribution network expansion planning. The model minimizes costs and emissions simultaneously and determines the optimal sizing, placement and network reinforcements over the planning horizon.

In [24], the authors have proposed a multiyear model for the planning of distribution network. The model determines the optimal expansion scheme of medium voltage distribution network including the reinforcement pattern of primary feeders as well as location and size of DGs over the planning horizon. An evolutionary algorithm called Binary Chaotic Shark Smell Optimization has been proposed to solve the optimization problem.

In [25], a bi-level model for distribution network and renewable energy sources expansion planning under a demand response framework is proposed. The target of the distribution network and generation planner, modeled through the upper-level problem, is to minimize generation and network investment cost while meeting the demand. The lower level problem is considered for the minimization of overall payment faced by the consumers.

In [26], a stochastic two-stage multi-year mixed-integer linear programming (MILP) model for distribution system expansion planning in order to obtain the optimal allocation and timing of renewable DGs has been proposed. The authors in [27-29], proposed a multi-stage stochastic linear programming for joint expansion planning of renewable DGs and distribution networks.

Table I shows a taxonomy of proposed methodologies for RES integration into distribution networks. The gap that this paper fills is how the combination of multi-configuration of renewable DGs and ANM schemes can effect on the WTs' and PVs' generated active power and D-LMPs within a distribution market environment.

This paper proposes an innovative method, which can be used as a tool for DNOs, to assess the generated power by WTs and PVs considering: 1) uncertainties related to the stochastic nature of wind power, solar irradiance and load demand, 2) multi-configuration of WTs and PVs and 3) ANM schemes including CVC and PFC. The proposed approach also determines the effect of the aforementioned factors on the distribution-locational marginal prices (D-LMPs). Multi-configuration multi-period market-based optimal power flow (MMMOPF) is used for maximizing the social welfare (SW) taking into account aforementioned uncertainties. A distribution market model within the control area of DNO is proposed under a distribution market structure on the basis of pool and bilateral contracts. In this paper, the DNO is assumed to be the market operator of the proposed distribution acquisition market [30-31].

TABLE I. COMPARISON OF PROPOSED METHOD WITH EXISTING ONES

Reference	Multi-configuration	Multi-period	Distribution market	ANM schemes
6	No	No	No	Yes
7	No	No	No	Yes
8	No	Yes	No	Yes
10	No	No	No	Yes
11	No	No	No	Yes
12	No	No	No	Yes
13	No	No	No	Yes
26-27	No	Yes	No	No
28-29	No	Yes	No	No
30	No	No	Yes	No
31	No	No	Yes	No
Proposed method	**Yes**	**Yes**	**Yes**	**Yes**

To the best of authors' knowledge, no deterministic approach for the planning of distribution networks within a distribution market environment taking into account multi-configuration of WTs and PVs and ANM schemes has been reported in the literature. The power system operation's dynamic nature has not been considered in the current studies with DG integration. In [6-8], for instance, the authors have not addressed the effect on the integration of DG level when one or more DGs are not present. Furthermore, the existence of a distribution market environment has not been addressed in the aforementioned studies. Hence, the major contributions of this paper are listed below:

1) Proposing a novel MMMOPF-based method, which considers the operational status of renewable DGs (i.e. WTs and PVs) and evaluates the dispatched active power of WTs and PVs taking into account various multi-configurations within the distribution market environment, which has not been addressed so far.
2) Providing comprehensive analysis and results on how multi-configuration of WTs and PVs and ANM schemes can affect the amount of generated power by WTs and PVs as well as the D-LMPs throughout the network.
3) Maximizing the SW by using a MMMOPF taking into account different combinations of load demand, wind and PV generation.

The remainder of this paper is organized as follows. In Section II, the proposed approach's structure is described. Sections III and IV respectively explain the multi-configuration of WTs and PVs and uncertainty modeling. Problem formulation is discussed in Section V. Case study and simulation results are presented in Section VI. Finally, in Section VII, conclusions are discussed.

II. THE STRUCTURE OF THE PROPOSED METHOD

The stochastic variations of wind speed, solar irradiance and load demand are modelled by multi-period scenarios approach as described in Section IV. For each combination of wind speed, solar irradiance and load demand, different MMMOPFs are carried out to maximize SW considering multiple-configuration of WTs and PVs taking into account ANM schemes and network constraints. The generated power by WTs, SW, and D-LMPs are the products of the proposed approach. In the following the steps performed by the proposed approach are explained as shown in Fig.1:

1) Set the candidate buses according to wind speed and solar irradiance historical data.
2) Define the size and speed- and solar irradiance-power curves of WTs and PVs, respectively.
3) Calculate the offer price of WTs and PVs as discussed in Section VI.
4) For every configuration and period, the SW is maximized by using the MMMOPF considering network constraints. The formulation of the distribution market and the optimization problem are explained in Section V.
5) The results of the proposed approach provide the generated power by WTs and PVs, social welfare, and D-LMPs.

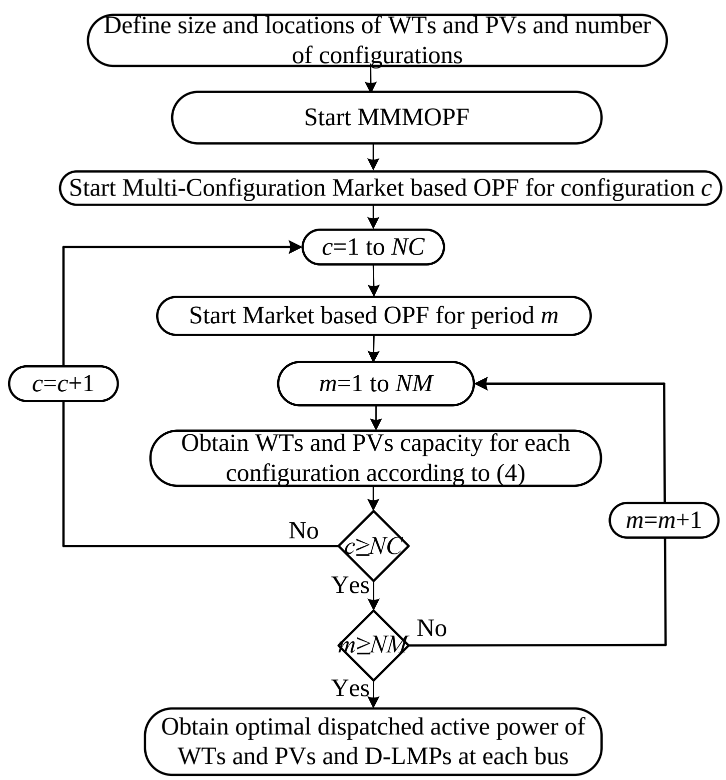


Fig.1.The structure of the proposed method

III. Multi-configuration of WTs and PVs

In this paper, the objective of MMMOPF approach is to incorporate multi-configuration of WTs and PVs are described as the operational status of WTs and PVs, and are selected on the basis of the decisions of DNO. The total number of all possible multi- configurations for WTs/PVs number is represented in the following:

$$1 \le NC \le (2^{NDG} - 1) \quad (1)$$

where *NDG* is the WTs' and PVs' total number. The total configurations are mentioned as the number of multi-configuration of WTs and PVs. For instance, if a system has two WTs and two PVs, then there are up to 15 possible multi-configurations of WTs and PVs for the DNOs to select. To characterize WTs and PVs operational status at bus *i* and configuration *c*, a binary parameter is described. The operational status of each WT/PV and all WTs/PVs are defined according to (2) and (3), respectively.

$$\beta_{i,c} = \begin{cases} 1, & \text{if a WT/PV at } i^{th} \text{ bus is operating} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

$$\beta = \begin{bmatrix} \beta_{1,(w_1/pv_1)} & \beta_{1,(w_2/pv_2)} & \cdots & \beta_{1,(w_N/pv_N)} \\ \beta_{2,(w_1/pv_1)} & \beta_{2,(w_2/pv_2)} & \cdots & \beta_{2,(w_N/pv_N)} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{c,(w_1/pv_1)} & \beta_{c,(w_2/pv_2)} & \cdots & \beta_{c,(w_N/pv_N)} \end{bmatrix}_{(NC \times NDG)} \quad (3)$$

The capacity constraint for WTs and PVs in relation to their operational status for each configuration is defined as follows:

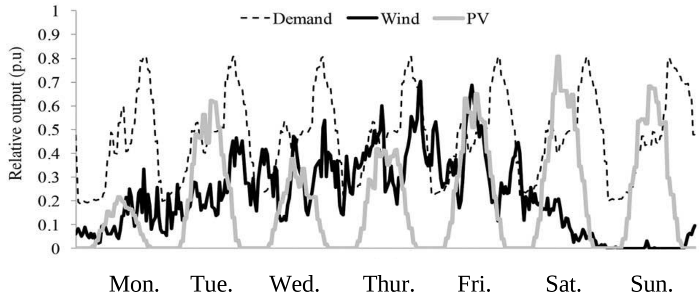
$$P_{i,c}^{(w/pv)} = \begin{cases} 0 \le P_{i,c}^{(w/pv)} \le P_{i,c}^{(w/pv),\max}, & \forall \ \beta_{i,c} = 1 \\ 0, & \forall \ \beta_{i,c} = 0 \end{cases} \quad (4)$$

IV. Uncertainty Modelling

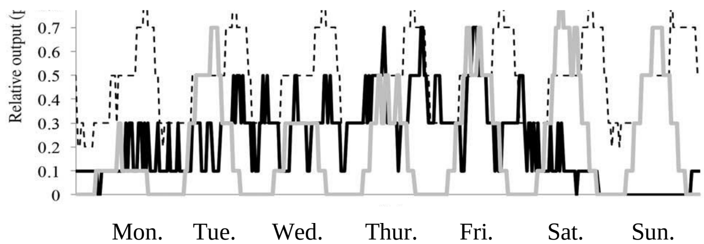
Load demands versus wind and PV generations profiles are studied using a UK network's historic data, recorded within a year time on the basis of half hourly figures (17520 periods) [32]. Fig. 2(a) shows a one-week snapshot sample of the original profile data. The load factors of demand, wind, and PV profiles are respectively 53.1%, 27.4%, and 9.6%. The original profile data with 17520 periods will have huge computational burden. For this reason, data discretization and aggregation processes are utilized. In this paper, firstly the discretization of the original profile data with 17520 periods is performed then reduced to 131 periods, as explained in the following.

1) Data Discretization Process: In the process of discretization, some ranges are taken into account to allocate the profile data of demand, wind and PV generation within different intervals as presented in Table II. The relative output of a profile data in a given range is the average value of the range limits, for example 0.3 p.u. for (20%, 40%]). Other assumptions are considered which are substantial to provide for worst-case scenarios of renewable generation and load demand. For instance, since minimum demand is about 20%, values near or less than 20% is assumed to be 20%, and for values more than 95% is 100% for maximum demand. Likewise, for wind and PV data, values below 3% is assumed to be 0, and above 97% is 100%. The profile data after the discretization process is shown in Fig. 2(b).

2) Data Aggregation Process: The data discretization process produces 17520 periods which is similar to the original data. On the other hand, there are lots of inter-periods that can be aggregated. Therefore, each set of inter-periods is characterized by one period with the whole period's total coincident hour. As presented in Table III, the total number of 17520 periods for demand, wind, and PV profiles is reduced to 131 multi-period scenarios after data discretization and aggregation process.



(a)



(b)

Fig.2. Hourly demand, wind and solar power production in the second week of July 2005 for central Scotland (a) original profile data (b) profile data after discretization process.

TABLE II. DATA DISCRETIZATION PROCESS

Demand profile			Wind and PV profiles		
No.	Bins (%)	Ranges (%)	No.	Bins (%)	Ranges (%)
1	20	[0, 20]	1	0	[0, 3]
2	30	(20, 40]	2	10	(3, 20]
3	50	(40, 60]	3	30	(20, 40]
4	70	(60, 80]	4	50	(40, 60]
5	90	(80, 95]	5	70	(60, 80]
6	100	(95, 100]	6	90	(80, 97]
			7	100	(97, 100]

V. PROBLEM FORMULATION

A. Formulation of Distribution Acquisition Market

A distribution market model, called the distribution acquisition market, is proposed here under a distribution market structure based on pool and bilateral contracts. The DNO is assumed to be the market operator of the acquisition market that determines the optimization process for the acquisition of active power and price estimation. Dispatchable loads, WTs and PVs submit active power offers and bids, in form of blocks, to the market every hour [33-34]. The objective of the DNO is maximizing SW.

TABLE III. MULTI-PERIOD SCENARIOS OF DEMAND AND RENEWABLE GENERATIONS

m	*D* (%)	*W* (%)	*PV* (%)	*h*	*m*	*D* (%)	*W* (%)	*PV* (%)	*h*
1	20	0	0	16	67	50	70	70	14.5
2	20	10	0	29.5	68	50	90	70	3.5
3	20	30	0	22	69	50	0	90	1.5
4	20	50	0	15.5	70	50	10	90	2
5	20	70	0	7	71	50	30	90	1
6	20	90	0	2.5	72	50	50	90	3
7	20	0	10	1.5	73	50	70	90	2.5
8	20	10	10	1.5	74	50	30	100	1
9	20	30	10	0.5	75	70	0	0	219.5
10	20	10	30	1	76	70	10	0	288
11	30	0	0	519	77	70	30	0	205
12	30	10	0	684.5	78	70	50	0	157.5
13	30	30	0	379.5	79	70	70	0	92.5
14	30	50	0	287	80	70	90	0	49
15	30	70	0	213.5	81	70	100	0	1
16	30	90	0	106.5	82	70	0	10	156
17	30	100	0	1	83	70	10	10	191
18	30	0	10	54	84	70	30	10	92.5
19	30	10	10	100.5	85	70	50	10	95.5
20	30	30	10	63	86	70	70	10	71
21	30	50	10	38.5	87	70	90	10	43
22	30	70	10	21.5	88	70	0	30	19.5
23	30	90	10	16	89	70	10	30	30
24	30	0	30	12	90	70	30	30	21.5
25	30	10	30	15.5	91	70	50	30	23.5
26	30	30	30	13.5	92	70	70	30	11
27	30	50	30	7.5	93	70	90	30	9
28	30	70	30	4	94	70	0	50	5.5
29	30	90	30	3.5	95	70	10	50	4.5
30	30	0	50	2	96	70	30	50	1.5
31	30	10	50	4	97	70	50	50	3.5
32	30	50	50	1	98	70	90	50	1
33	30	70	50	0.5	99	70	90	70	1
34	30	0	70	0.5	100	70	0	90	1
35	30	10	70	1.5	101	90	0	0	201.5
36	30	30	70	2	102	90	10	0	162
37	30	70	70	0.5	103	90	30	0	115.5
38	50	0	0	191	104	90	50	0	121
39	50	10	0	197.5	105	90	70	0	81
40	50	30	0	122	106	90	90	0	37
41	50	50	0	99	107	90	100	0	1
42	50	70	0	63	108	90	0	10	37
43	50	90	0	43	109	90	10	10	70
44	50	100	0	2	110	90	30	10	49
45	50	0	10	270.5	111	90	50	10	38
46	50	10	10	333	112	90	70	10	27
47	50	30	10	193.5	113	90	90	10	10.5
48	50	50	10	153.5	114	90	0	30	2.5
49	50	70	10	90	115	90	10	30	1.5
50	50	90	10	38.5	116	90	30	30	0.5
51	50	0	30	191	117	90	50	30	0.5
52	50	10	30	283	118	90	70	30	1
53	50	30	30	175.5	119	90	90	30	0.5
54	50	50	30	133.5	120	100	0	0	46
55	50	70	30	101.5	121	100	10	0	20.5
56	50	90	30	69.5	122	100	30	0	17
57	50	0	50	56.5	123	100	50	0	22.5
58	50	10	50	96	124	100	70	0	22
59	50	30	50	75	125	100	90	0	7.5
60	50	50	50	50.5	126	100	100	0	0.5
61	50	70	50	39.5	127	100	0	10	2
62	50	90	50	32.5	128	100	30	10	1
63	50	0	70	18.5	129	100	50	10	1.5
64	50	10	70	40	130	100	70	10	1.5
65	50	30	70	15	131	100	90	10	1
66	50	50	70	13.5					

1

The cleared quantities and prices are calculated by SW maximization taking into account network constraints within the distribution market. The MMMOPF is formulated as follows:

$$\text{Maximize SW} = \sum_{q=1}^{NQ}\sum_{i=1}^{NB}\sum_{m=1}^{NM}\omega_m C_{i,q}^{D} P_{i,q,m}^{D} - \sum_{t=1}^{NT}\sum_{i=1}^{NB}\sum_{m=1}^{NM}\sum_{c=1}^{NC}\eta_m C_{i,t}^{w} P_{i,t,m,c}^{w} - \sum_{t=1}^{NT}\sum_{i=1}^{NB}\sum_{m=1}^{NM}\sum_{c=1}^{NC}\chi_m C_{i,t}^{pv} P_{i,t,m,c}^{pv} - \sum_{t=1}^{NT}\sum_{i=1}^{NB}\sum_{c=1}^{NC} C_{i,t}^{G} P_{i,t,c}^{G} \quad (5)$$

subject to

$$\left(\sum_{t=1}^{NT}\sum_{i=1}^{NG} P_{i,t,c}^{G} + \sum_{t=1}^{NT}\sum_{i=1}^{NB}\eta_m P_{i,t,m,c}^{w} + \sum_{t=1}^{NT}\sum_{i=1}^{NB}\chi_m P_{i,t,m,c}^{pv} - \sum_{q=1}^{NQ}\sum_{i=1}^{NB}\omega_m P_{i,q,m}^{D}\right) = \sum_{j=1}^{NB} V_{i,m,c} V_{j,m,c} T_{ij}\left\{G_{ij}\cos(\delta_{i,m,c}-\delta_{j,m,c}) + B_{ij}\sin(\delta_{i,m,c}-\delta_{i,m,c})\right\} \quad (6)$$

$$\left(\sum_{t=1}^{NT}\sum_{i=1}^{NG} Q_{i,t,c}^{G} + \sum_{t=1}^{NT}\sum_{i=1}^{NB}\eta_m Q_{i,t,m,c}^{w} + \sum_{t=1}^{NT}\sum_{i=1}^{NB}\chi_m Q_{i,t,m,c}^{pv} - \sum_{q=1}^{NQ}\sum_{i=1}^{NB}\omega_m Q_{i,q,m}^{D}\right) = \sum_{j=1}^{NB} V_{i,m,c} V_{j,m,c} T_{ij}\left\{G_{ij}\sin(\delta_{i,m,c}-\delta_{j,m,c}) - B_{ij}\cos(\delta_{i,m,c}-\delta_{i,m,c})\right\} \quad (7)$$

$$\sqrt{(G_{ij}^2 + B_{ij}^2)(V_{i,m,c}^2 + \frac{V_{j,m,c}^2}{T_{ij}^2} - 2\frac{V_{i,m,c}V_{j,m,c}\cos(\delta_{i,m,c}-\delta_{j,m,c})}{T_{ij}})} \le I_{ij}^{\max} \quad (8)$$

$$V_i^{\min} \le V_{i,m,c} \le V_i^{\max} \quad (9)$$

$$\delta_i^{\min} \le \delta_{i,m,c} \le \delta_i^{\max} \quad (10)$$

$$P_i^{w,\min} \le P_{i,t,m,c}^{w} \le P_i^{w,\max} \quad (11)$$

$$Q_i^{w,\min} \le Q_{i,t,m,c}^{w} \le Q_i^{w,\max} \quad (12)$$

$$P_i^{pv,\min} \le P_{i,t,m,c}^{pv} \le P_i^{pv,\max} \quad (13)$$

$$Q_i^{pv,\min} \le Q_{i,t,m,c}^{pv} \le Q_i^{pv,\max} \quad (14)$$

$$P_i^{G,\min} \le P_{i,t,c}^{G} \le P_i^{G,\max} \quad (15)$$

$$Q_i^{G,\min} \le Q_{i,t,c}^{G} \le Q_i^{G,\max} \quad (16)$$

Active and reactive power balance at each bus is represented in (6) and (7). Equation (8) represents branch flow constraints. Voltage constraints at each bus are represented in (9) and (10). The constraints of active and reactive power generated by WTs and PV are represented in (11)-(14). The capacity constraints of substation are characterized in (15) and (16).

B. Incorporation of ANM Schemes

1) Coordinated Voltage Control [35]

The secondary voltage of the OLTC will be considered as a variable maintaining its value within a certified range as follows:

$$T_{ij}^{\min} \le T_{ij} \le T_{ij}^{\max} \tag{17}$$

2) Adaptive Power Factor Control

DNOs could determine power factor for RES inverters to provide reactive power support to the grid [36]. For example, in the UK, DNOs keep the power factor of WTs and PVs in the range of 0.95 leading and 0.95 lagging. Thus, the following constraint applies:

$$\phi_i^{w/pv,\min} \le \phi_{i,m,c}^{w/pv} \le \phi_i^{w/pv,\max} \tag{18}$$

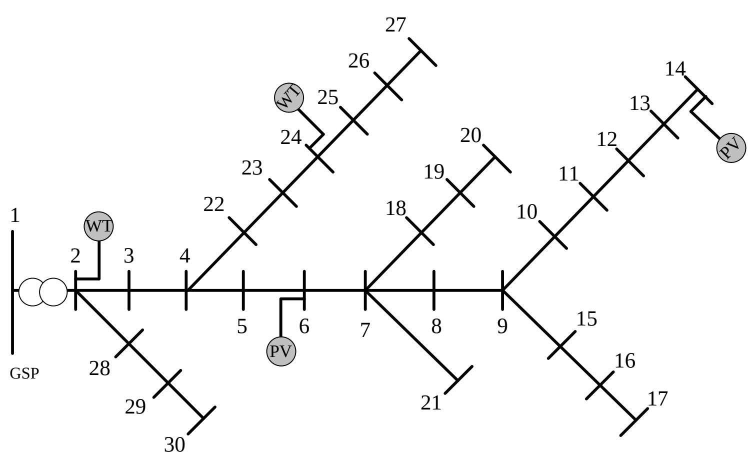


Fig.3. 30-bus radial distribution system

VI. CASE STUDY AND SIMULATION RESULTS

30-bus radial distribution system is explained in this section, which is used to examine the proposed approach. The following analyses are based on 33 kV 30-bus whose data are available in [37]. Fig.3 shows the single-line diagram of the distribution system. A 30-MVA 132/33 kV transformer is used to supply the feeders. An OLTC, allocated between buses 1 and 2, has a target voltage of 1.05 p.u. at the secondary. Voltage limits are assumed to be: V_{min}= 0.94 and V_{max}= 1.06 p.u. and the power factor of both PVs and WTs vary between 0.95 leading to 0.95 lagging. In this paper, it is assumed that buses 2, 6, 14 and 24 are four possible locations for installing PVs and WTs. Section IV presents the multi-period scenarios of demand versus WTs and PVs used in this paper. Two 3 MW WTs at buses 2, 24 and two 2 MW PVs at buses 6 and 14 are installed. It is supposed that maximum four WTs and PVs can be installed at each candidate bus. For every period and configuration, this is represented by four equal blocks in the WT's and PV's offer with the same price. The offer price at substation is assumed to be 120 £/MWh. With regards of DLs' bids, it is supposed that there are three blocks for each DL, as given in Table IV. Table V presents all the possible multi-configuration of WTs and PVs for the four WTs and PVs locations using (1).

TABLE IV. QUANTITY AND PRICE OF DISPATCHABLE LOADS

	Quantity (MW)			Price (£/MWh)		
Bus No.	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3
2	0.34	0.24	0.15	140	140	100
4	0.40	0.25	0.15	140	130	100
6	0.18	0.18	0.12	150	120	100
14	0.20	0.28	0.15	150	120	100
24	0.20	0.18	0.13	140	120	100
21	0.25	0.20	0.12	140	120	90
29	0.43	0.20	0.15	140	110	100
30	0.25	0.20	0.10	140	125	100

TABLE V. DESCRIPTION OF MULTI-CONFIGURATION OF WTS

AND PVS

Multi-configuration	WT and PV status/location			
	Bus 2	Bus 24	Bus 6	Bus 14
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1
5	1	1	0	0
6	1	0	1	0
7	1	0	0	1
8	0	1	1	0
9	0	1	0	1
10	0	0	1	1
11	0	1	1	1
12	1	0	1	1
13	1	1	0	1
14	1	1	1	0
15	1	1	1	1

A. WTs' and PVs' Offer Price Calculation from the DNOs Perspective

To determine the price of WTs' and PVs' offers, financial data, i.e. life time of PVs and WTs, interest rate, depreciation time, and installation cost are considered as summarized in Table VI. The annual cost for WTs and PVs is calculated as follows [38]:

$$Ann\_Cost = \frac{r(1+r)^n}{(1+r)^n - 1} \times Inst\_Cost \qquad (19)$$

where r is the interest rate, n is the depreciation period in years, *Inst_Cost* is the installation cost, and *Ann_Cost* is the annual cost for depreciation. The offer price of WTs and PVs is calculated by dividing the annual costs by the number of equivalent hours as presented in Table VI.

TABLE VI. FINANCIAL DATA FOR CALCULATING THE OFFERS PRICE OF 3 MW WT AND 2 MW PV

Size	WT	PV
	3 MW	2 MW
Installation cost (£/kW)	950	1400
Depreciation time (years)	10	10
Interest rate (%)	3	3
Number of equivalent hours (h)	4000	4000
Capacity factor (%)	46	46
Annual cost (£/kW-year)	334.10	168.81
Offer Price (£/MWh)	**27.84**	**40.00**

The offer prices of WTs and PVs for different values of capacity factor ranging from 28% to 46%, interest rate of 3% and the same installation costs, as presented in Table VI, is shown in Fig.4.

In addition, the offer prices is calculated for various values of interest rates ranging from 3% to 10%, the capacity factor of 46% and the same installation costs, as presented in Table VI, is shown in Fig.5.

It is obvious from Figs. 4 and 5 that the offer prices of WTs and PVs decreases by increasing the capacity factor and increases by increasing the interest rate. As a result, offer price has inverse relation with CF and direct relation with interest rate.

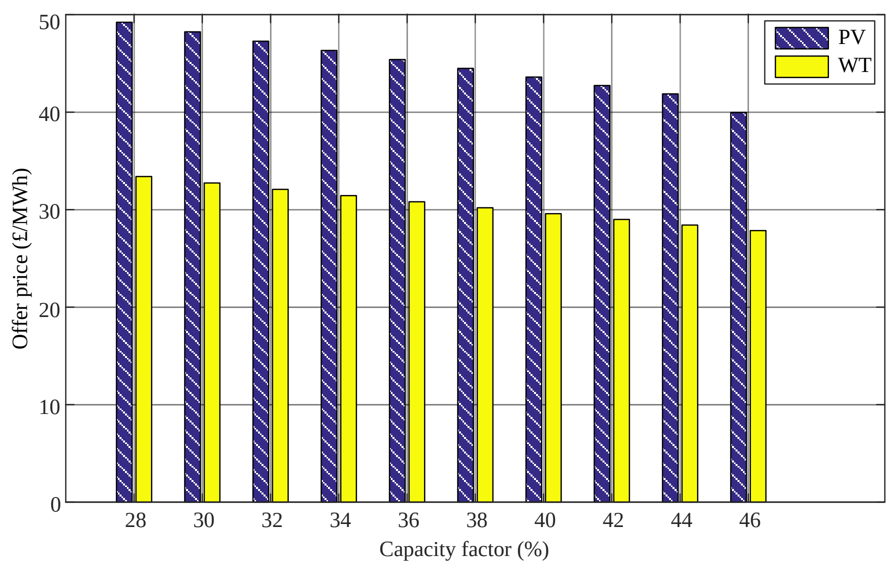


Fig. 4. Offer prices of WTs and PVs for different CFs and 3% insterest rate

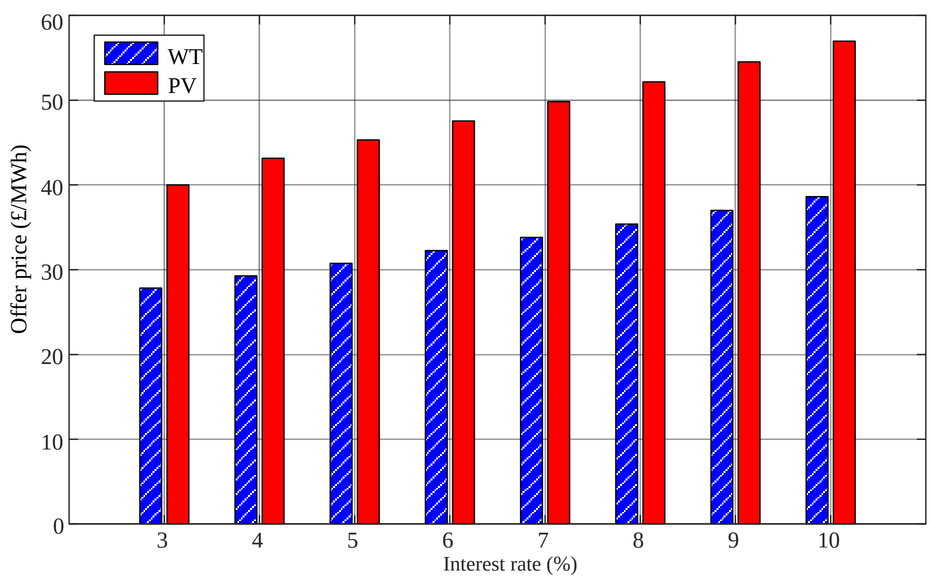


Fig. 5. Offer prices of WTs and PVs for different interest rates and capacity factor of 46%

The proposed method has been coded in GAMS and solved using CONOPT solver [39] on a PC with Core i7 CPU and 16 GB of RAM. In order to investigate the impact of multi-configuration of WTs and PVs and ANM schemes on the SW, dispatched active power of WTs and PVs and D-LMP, two scenarios are considered as given in Table VII.

TABLE VII. SCENARIOS

Scenarios	CVC	PFC	PF= 0.95 lagging
A	-	-	✓
B	✓	✓	-

The total dispatched active power of WTs and PVs for each configuration and all periods is shown in Fig.6. Configuration 3 (i.e. one PV at bus 6) has the lowest dispatched active power in comparison with that in configurations 2, 3 and 4. This is mainly due to higher bid price of PVs (compared with WTs) and lower bid quantity at bus 6 compared with those at buses 2, 14 and 24 (see Table III) and voltage constraints as well as the lines thermal limits.

Configuration 10 has the lowest dispatched active power in comparison with that in configurations 5, 6, 7, 8 and 9 (i.e. the combination of one PV and one WT or both). This is also due to the lower bid quantity, higher bid price at buses 6 and 14 compared with those in other buses and higher offer price of PVs compared with WTs as well as the voltage and thermal constraints at these buses and lines connecting these buses, respectively. It is also evident that configuration 15 (i.e. two WTs at buses 2 and 24 and two PVs at buses 6 and 14) has almost the same dispatched active power of that in configurations 11, 12, 13 and 14. As a result, configurations 3, 4, 10 and 15 are not economical.

The total dispatched active power in both scenarios for all configurations at all candidate buses is shown in Fig.7. It is evident that in scenario *B* by considering ANM schemes higher active power can be dispatched by PVs and WTs in comparison with those in scenario *A*.

The total SW for each configuration is shown in Fig.8. It is obvious that configurations 3, 4 and 10 have the lowest and 11, 12, 13, 14 and 15 the highest value of SW in comparison with others. This is due to the lowest and highest dispatched active power at these configurations respectively as renewable DGs installation increases the SW.

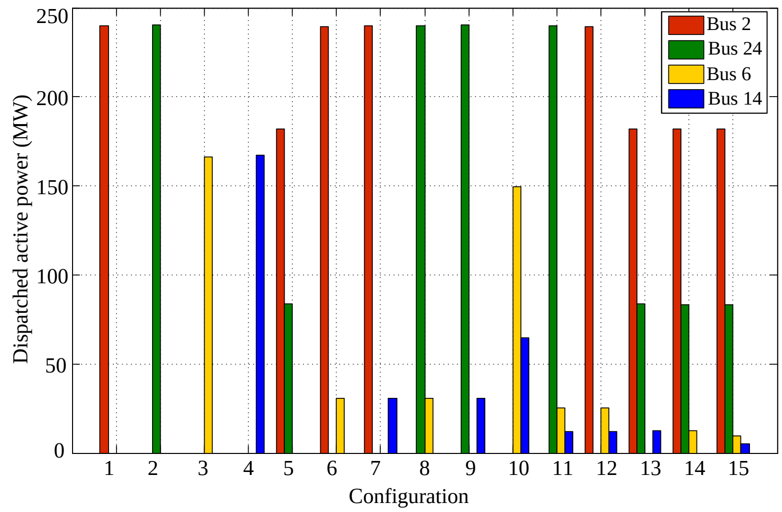


Fig.6. Total dispatched active power of WTs and PVs for each configuration

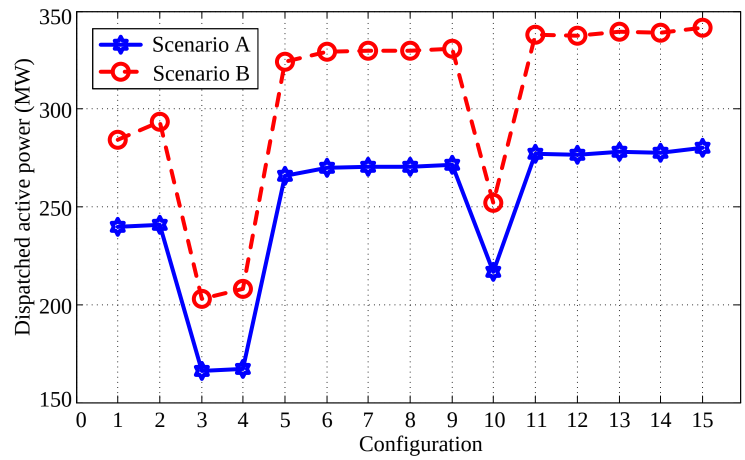


Fig.7. Total dispatched active power of WTs and PVs in each configuration and different scenarios

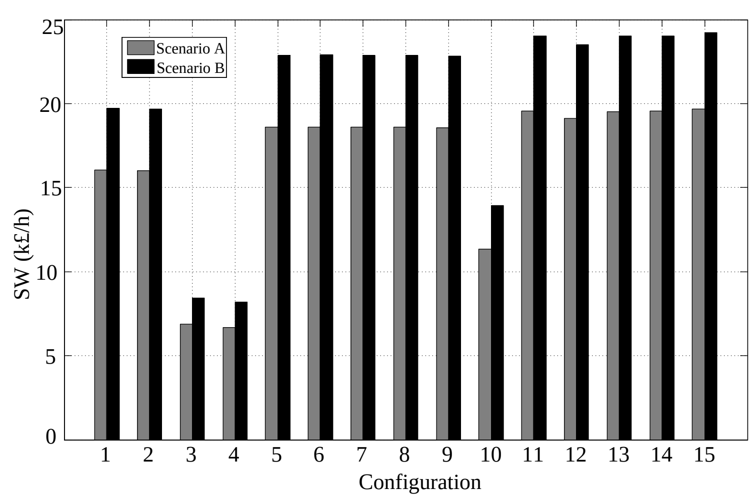


Fig.8. Total SW in all configurations and both scenarios

The total D-LMPs for each configuration and both scenarios are shown in Fig. 9. It is seen that configurations 3, 4 and 10 have the highest and configurations 11, 12, 13, 14 and 15 the lowest D-LMPs. This is also due to the lowest and highest dispatched active power at these configurations, respectively. It can be concluded that configurations 3, 4, 10 and 15 are not economical. For example, in configuration 10, the dispatched active power and the SW, are much lower and the D-LMP is higher than those in other configurations (i.e. a combination of two WTs or PVs). It is also observed that the D-LMP decreases by about 15% in scenario *B* by incorporating ANM schemes in comparison with those in scenario *A*. Therefore, by incorporating ANM schemes, more wind and PV power could be integrated into the grid in comparison with those in passive networks, therefore, D-LMPs reduce significantly.

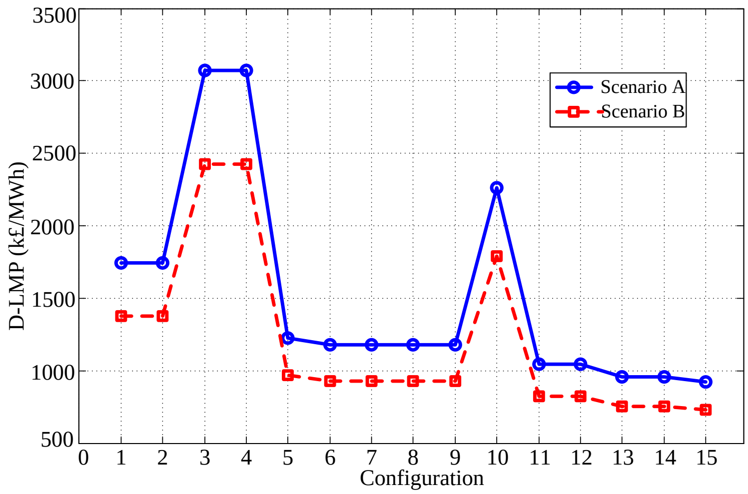


Fig.9. Total D-LMPs in all configurations and both scenarios

VII. CONCLUSIONS

In this paper, a deterministic approach for the planning of active distribution networks within a distribution market environment is proposed. ANM is considered as an important means of increasing the capability of distribution networks to install renewable DGs. In the future, ANM will characterize an efficient solution for DNOs to integrate and operate RES in distribution networks, therefore, contributes to reducing the tensions between DG developers, who aim at maximizing their profits by increasing energy production, and DNOs, who aim at minimizing network operating and investment costs.

The method considers ANM schemes and multi-configuration of WTs and PVs. MMMOPF is utilized to maximize SW taking into account uncertainties associated with wind speed, solar irradiance and load demand. It is revealed that the multi-DG configurations under ANM schemes could increase the potential of wind and solar power penetration at certain locations and consequently decreases D-LMPs. It is worth noting that in order to choose the most proper ANM scheme, each scheme or a combination of them should be assessed taking into account the economic benefits under different scenarios.

The proposed approach can be used as a tool for DNOs to allocate renewable DGs at more appropriate places in terms of consumers' benefits and cost reduction taking into account network constraints. It also can be used as a tool for DNOs to evaluate the impact of wind and solar power penetration on a given network in terms of technical and economic effects.

Moreover, the proposed method allows the decision makers to understand the implications of various choices on technical and economic performances of the distribution system.

ACKNOWLEDGMENT

This work was supported in part by the Royal Academy of Engineering Distinguished Visiting Fellowship Grant DVF1617/6/45 and by the University of Bradford, UK under the CCIP grant 66052/000000.

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