Dispatchable Wind Power Generation Planning for Distribution Systems

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***Abstract*—In this paper, a set of new planning strategies are proposed to optimally accommodate aggregated capacity of wind farms with special switching arrangements to make these dispatchable. The goal is to mitigate the issues of intense renewable power penetration on distribution systems such as wind power curtailment, reverse power flow problem, high voltage problem etc. The proposed model is investigated on a standard 33-bus radial distribution system and genetic algorithm is used to solve it. The simulation results of proposed model are compared with the same obtained by conventional planning models, which shows that the proposed approach is promising.**

***Keywords*—Distributed generation, distribution systems, genetic algorithm, mixed-integer, wind power.**

I. Nomenclature

A. Indices and sets

h	hours.
i, j	System buses.
N	Set of buses in the system ($i, j \in N$).
T_p	Set of DG life (years) ($y \in T_p$).
u	Wind turbines in a wind farm.
y	Years.

B. Parameters and variables

C_E^h	Grid energy price in hth hour (\$/kWh).
$C_{Inv.}^{WT}$	Turnkey cost of a WT (\$/kVA).
C_{OM}^{WT}	O & M cost of a WT (\$/kWh).
d	Discount rate.
f	Rate of annual load growth.
I_{ij}^h	Current in the branch between bus 'i' and 'j' in hth hour (Amp.).
I_G^h	The current in the secondary winding of grid substation transformer in hth hour.
$I_{DC_{h,u}}^{WT}$	DC current injected by uth WT in hth hour (Amp.).
I_{ij}^{Max}	Maximum current carrying capacity of the branch connecting node 'i' and 'j' (Amp.).
k_i^{WT}	Total number of WTs installed at bus 'i'
n_i^h	Number of WTs operated at bus 'i' in hth hour.
$P_{D_i}^0$	Nominal real power demand of bus i (kW).
P_r^{WT}	Rated real power output of a WT (kW).
P_{Max}^{WF}	Maximum allowable wind farm capacity limit.
S_D^{Peak}	Peak demand of the system.
S_r^T	The nameplate rating of the grid substation transformer.
$v_{h,i}$	Wind speed in hth at bus 'i' (m/s).
v_{cutin}	Cutin wind speed of a WT (m/s).
v_{cutout}	Cutout wind speed of a WT (m/s).
v_r	Rated wind speed of a WT (m/s).
$V_{DC_{h,i}}^{WT}$	DC bus voltage at bus 'i' in hth hour (p.u.).
V_i^h	Voltage magnitude at bus 'i' in hth hour
V_{maxS}	Maximum specified voltage at the bus.
V_{minS}	Minimum specified voltage at the bus.
Y_{ij}	Element of Y-bus matrix.
λ_i^h	Load multiplying factor in hth at bus 'i'
η_C	DC-AC converter efficiency.
η_T	Coupling transformer efficiency.
σ_i^{WT}	Binary decision variable for WT installation at bus i.
δ_i^h	Voltage angle of bus i in hth hour.
θ_{ij}	Impedance angle of the branch connecting bus 'i' and 'j'.
ϕ	Daily to annual cost conversion factor.

II. Introduction

Numerous potential advantages of renewable energy resources over depleting conventional resources has led to the large-scale deployment of intense renewable power generation in modern power system, specially in distribution systems. However, many counter-productive effects of high renewable penetration may be observed in distribution systems such as high power losses, node voltages, fault currents, system instability etc. Alternatively, an optimally accommodated Distributed Generations (DGs) may provide reduced power/energy losses [1]–[5], voltage deviation [2]–[5] with improved stability [3]–[5] and reliability [6] etc.

In existing literature, many DG planning models have been proposed and investigated to maximize the integration benefits of Distribution Network Operator (DNO), DG owner and consumer. A harmony search optimization based optimal DG allocation problem is investigated in [2] to minimize the power loss in distribution systems. In [3]–[5], multiobjective DG allocation problems have been investigated to improve the system performance using improved elephant herding optimization, Taguchi method and hybrid Genetic Algorithm (GA)-particle swarm optimization respectively. Joydeep et al. [6] developed a simulated annealing based mixed and multiple DG allocation model to improve the reliability of distribution systems. In [7], a multi-year optimization framework has been developed to maximize the Net Present Value (NPV) of DNO and DG owner simultaneously using differential evolution algorithm. The above discussed literature deals the DG planning problem in deterministic environment without considering the generation, demand, energy price, system uncertainties etc.

In [1], [8], optimal renewable power generation planning problem is developed in stochastic framework to maximize the NPV of the investment using mixed-integer programming and GA respectively. In [9], a Monte Carlo simulation-embedded GA-based approach is employed to solve the optimal siting and sizing problem of DGs considering generation, demand and price uncertainties. A probabilistic framework is developed in [10] to obtain the optimal sites and sizes of wind power generation for annual energy loss minimization. A fuzzy stochastic programming based reactive power compensation is achieved in [11] to minimize the total cost of newly located/sized capacitors and the annual energy loss in a distribution systems. Although, the above discussed literature deals with the uncertainties of renewable power generation and load demand however, the optimal DG planning models which can reveal the dispatchable arrangements of renewable power generation may be somewhat missing.

In practice, the DG owners have to sign a contract with DNOs that renewable generation must be curtailed if it any system security constraint is violated. The power curtailment cost may be high which can also affect the annual revenue and NPV of the project. Therefore, some amount of dispatchable DGs [8] or energy storage [12] may be installed with renewable power generation. However, the high cost of investment, operation and maintenance with lesser life span of battery energy storage may not be economical.

In this paper, a strategic frameworks is introduced to utilize the wind power generation as a dispatchable power generation comprising the modular availability of disperse power generation technologies. The objective is to maximize the NPV of the investment considering the cost of investment, operation & maintenance, grid energy transaction etc. while satisfying various system security constraints. The proposed DG planning model is implemented on a standard 33-bus test distribution system. The simulation results are compared with the same obtained from conventional DG planning models and found to be promising. The proposed DG planning model is significantly reduced the cost of wind power curtailment, annual energy loss, investment, operation and maintenance while improving the node voltage profile of the system.

III. Proposed Generation and Load Modeling

The renewable power generation and load demand is varying with the time. Therefore, an ad-hoc model of hourly power generation and load demand may be advantageous to investigate the planning and operational issues of renewable power generations. However, a deterministic modeling of generation and load demand has been used rather a stochastic modeling, which is out of the scope of this work since the theme is to investigate the effect of modular power generating units. The individual modeling of WT power generation comprising of wind speed are given below followed by hourly load demand.

A. Wind Power Generation Modeling

The wind speed is highly uncertain that causes fluctuation in wind power generations. The real power produced by WTs is the cubic function of wind speed; therefore, wind speed is then combined with the wind turbine parameters in order to evaluate the hourly electrical power generation. However, parameters such as air density, pitch angle, swapping area etc. may assumed to be constant except wind speed. If appropriate transformation is used, wind speed can be converted into the real power as a cubic function of wind speed as expressed below

$$P_{h,u}^{WT} = f(v^3) \qquad \forall\ u, i, h \tag{1}$$

using (1), the wind speed at bus 'i' can be converted into real power generation as

$$P_{DC_{h,u}}^{WT} = \begin{cases} 0, & \text{if } v_{h,i} < v_{cutin} \text{ or } v_{h,i} \geq v_{cuout}; \\ P_r^{WT} \times v_{h,i}^3 \big/ v_r^3, & \text{if } v_{cutin} \leq v_{h,i} < v_r; \\ P_r^{WT} & \text{if } v_r \leq v_i^h < v_{cutout}; \end{cases} \tag{2}$$

B. System Demand Modeling

The system demand is also varying with the time, therefore, hourly system demand may be used to investigate the planning and operational issues of distribution system. In this section, the demand is modeled as the fraction of annual peak demand. The hourly load demand for node 'i' can be expressed as

$$P_{D_i}^h = \lambda_i^h \times P_{D_i}^0 \qquad \forall\ i, h \tag{3}$$

IV. Proposed Approach for Wind Power Generation Control

The renewable power generation is highly uncertain and intermittent by the nature therefore, installation of high renewable penetration may causes threat to the system security. Alternatively, the ambitious goals of renewable energy and environmental protection agencies or bodies are aiming to maximize the share of clean energy generation across the globe. However, both the objectives are conflicting in nature. In order to achieve both the goals, a maximum capacity of renewable power generations has to be deployed in distribution systems but DG owners have to sign contract with the utilities. According to the contract, '*the power producers have to curtail the renewable power generation if system violates any constraint or the system is found to be at the risk*'. However, the curtailed amount of power causes annual revenue loss to the DG owner.

In this paper, a new renewable power generation planning model is proposed to transform the renewable power generation into dispatchable power generation sources. The goal is to determine the optimal aggregated hosting of WTs to maximize the NPV of the investment. In order to achieve this, the knowledge of modular DG units is taken into the account unlike, in traditional planning models. In this paper, the word 'traditional/conventional DG planning models' will be referred to the models in which, multiple DGs are deployed at multiple nodes but each node has a big-sized DG unit [1]–[12]. In this paper, multiple WT units will be installed at a single node called as Wind Farm (WF). Further, multiple WFs are deployed in the system. The basic configuration of a WF deployed at a bus which consists multiple WTs is shown in Fig.1. The knowledge of information and communication technologies have been used to control the dispatch/switches of WTs.

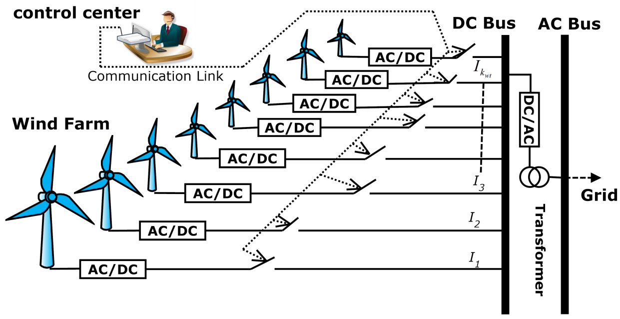

Fig. 1. Proposed scheme for power generation control

Using (2), the total DC power generated from the WF deployed at bus 'i' will be the algebraic sum of powers generated from each WT installed in that WF as expressed below.

$$P_{DC_{h,i}}^{WT} = V_{DC_{h,i}}^{WT} \times \sum_{u=1}^{n_i^h} I_{DC_{h,u}}^{WT} = \sum_{u=1}^{n_i^h} P_{DC_{h,u}}^{WT} \quad \forall\, i,h \quad (4)$$

In order to control the dispatch of the WF deployed at bus 'i', the n_i^h number of switches which has to be closed in hour 'h' should be determined optimally. The DC power is converted into AC power using a high power rated DC-AC converter followed by a coupling transformer to match with the grid voltage. The power output of the transformer can be expressed as

$$P_{h,i}^{WT} = \eta_T \eta_C P_{DC_{h,i}}^{WT} \qquad \forall\, i,h \quad (5)$$

V. Problem Formulation

In general, DNOs have to perform many duties in order to maximize it's operational benefits while satisfying numerous operating constraints. It may have been observed that DNOs are spending a major amount of money on annual energy purchase from the transmission grid. Therefore, in order to maximize the profit of DNO, the annual cost of grid energy purchase, operation and maintenance along with various annual investments may be minimized.

A. Objective Function

In this work, the NPV of DG investment is maximized. The NPV calculation includes the cost of annual energy transactions between utility and transmission grid, DG investment, operation and maintenance etc. The proposed objective function can be expressed as

$$\max\ NPV = C_{Out}^{b} - C_{Out}^{a} \quad (6)$$

where,

$$C_{Out}^{b} = \sum_{y=1}^{T_p} \frac{\phi}{(1+d)^y} \left(\sum_{h=1}^{24} C_E^h \sum_{i=1}^{N} (1+f)^{y-1} P_{D_i}^h \right) \quad (7)$$

$$C_{Out}^{a} = \left(C_{Inv}^{WT} \sum_{i=1}^{N} \sigma_i^{WT} P_i^{WT} \right) ⓐ + \sum_{y=1}^{T_p} \frac{1}{(1+d)^y} \times \Bigg[\left(\phi \sum_{h=1}^{24} C_E^h \sum_{i=1}^{N} (1+f)^{y-1} (P_{D_i}^h - P_{G_i}^h) \right) ⓑ + \left(\sum_{i=1}^{N} \sigma_i^{WT} C_{OM}^{WT} P_i^{WT} \right) ⓒ \Bigg] \quad (8)$$

$$P_{G_i}^h = \sigma_i^{WT} (n_i^h \times P_{h,i}^{WT}) \quad (9)$$

$$P_i^{WT} = k_i^{WT} \times P_r^{WT} \quad (10)$$

where, C_{Out}^b and C_{Out}^a are representing the net present cash outflows of the utility before and after DG integrations respectively. It may be observed that net present cash outflow before DG integration is mainly spending on grid energy purchase as expressed in (7). The total net present cash outflow after DG integration may include many annual costs such as DG investment, grid energy transactions, operation and maintenance of DGs represented by ⓐ, ⓑ and ⓒ respectively in (8). Eqn. (9) and (10) are representing the power dispatch of hour 'h' and total installed capacity of WF at bus 'i' respectively.

B. Constraints

The objective function expressed in (6) is subjected to the following constraints:

1) Nodal Power Balance Constraints:

$$P_{G_i}^h - P_{D_i}^h = V_i^h \sum_{j=1}^{N} V_j^h Y_{ij} \cos(\theta_{ij} + \delta_j^h - \delta_i^h) \quad \forall\, i,h \quad (11)$$

$$Q_{G_i}^h - Q_{D_i}^h = -V_i^h \sum_{j=1}^{N} V_j^h Y_{ij} \sin(\theta_{ij} + \delta_j^h - \delta_i^h) \quad \forall\, i,h \quad (12)$$

2) Voltages Limit Constraints:

$$V_{\text{minS}} \le V_i^h \le V_{\text{maxS}} \qquad \forall\, i,h \quad (13)$$

3) DG Units Limit Constraints:

$$P_i^{WT} \le P_{Max}^{WT} \qquad \forall\, i \quad (14)$$

4) Maximum DG Penetration Limit Constraint: Maximum DG penetration in the system must be limited to the nameplate kVA rating (S_r^T) of the respective transformer [13] or peak demand (S_D^{Peak}) of the system.

$$\sum_{i=1}^{N} \sigma_i^{WT} P_{r,i}^{WT} \leq min\langle S_r^T, S_D^{Peak} \rangle \tag{15}$$

5) Feeders Thermal Limit Constraints:

$$I_{ij}^h \leq I_{ij}^{Max} \qquad \forall\ h, i, j \tag{16}$$

6) Reverse Power Flow Constraint: The reverse power flow should be constrained to avoid some protection issues. In [14], it has been suggested that the reverse power flow should not be occurred during more than 5% of the hours in one year. Therefore, a counter is used to count the number of hours in which, the reverse power flow occurs. The counter is expressed as

$$Count(h) = \begin{cases} 1, & \text{if } I_G^h < 0; \\ 0, & \text{if } I_G^h \geq 0; \end{cases} \tag{17}$$

Considering above discussed facts, following reverse power flow constraint has been proposed in this paper.

$$\sum_{h=1}^{24} Count(h) \leq 2 \qquad \forall\ y \tag{18}$$

VI. Optimal Aggregated Wind Power Generation Planning using Genetic Algorithm

The proposed optimal aggregated wind power generation planning problem is a complex, non-linear and non-convex optimization problem which requires a powerful optimization technique to obtain the global optimal solution. In this paper, an improved variant of GA has been adopted from [15] since the exploration of optimization techniques is out of the scope of this work. The GA is a powerful optimization method inspired from the process of natural selection which already proven it's ability to solve similar power system problems in the literature [4], [8], [9], [15]. The structure of individuals used in adopted GA is shown in Fig. 2 which contains the WF locations and number of WTs in a WF as decision variables.

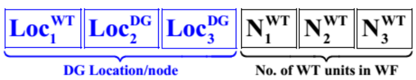

Fig. 2. Individual's structure used in GA

VII. Case Study

The proposed DG planning model is implemented and investigated on a benchmark 33-bus distribution system, which is a 12.66 kV radial distribution system with nominal real and reactive power demands of 3715 kW and 2300 kVAr respectively. The other detailed information about the system can be obtained from [16]. The monetary parameters used in the study are summarized in Table I. Moreover, all monetary parameter are assumed to be increased at a annual rate of 6% as suggested in [1]. In this paper, three pre-specified number of WFs are assumed to be installed at three different sites as suggested in literature [2], [3], [5], [8], [12]; therefore, the task is to determine the optimal nodes and aggregated hosting capacities of WFs such that the project NPV is maximized.

TABLE I
Study Parameters

Parameter(s)	Value(s)
Planning horizon (T_p)	20 years
Annual discount rate (d)	5%
Daily to annual cost conversion factor (ϕ)	365 days
Annual load growth rate (f)	3%
Investment cost of WTs (C_{Inv}^{WT})	1882 \$/kW
Annual operation and maintenance cost of WTs (C_{OM}^{WT})	87.60 \$-kW

TABLE II
Wind Turbine Parameters used in Proposed Model

Parameter(s)	Value(s)
Nominal power output (P_r)	250 kW
Cut-in wind speed (v_{cutin})	2.5 m/s
Rated wind speed (v_r)	7.5 m/s
Cut-out wind speed (v_{cutout})	25 m/s,
Survival wind speed	59.5/52.5 m/s

The parameters of small sized WTs used in the proposed DG planning model are given in the Table II. For both conventional and proposed DG planning models, a maximum of 2 MW of DG/WF hosting capacity is permitted to install at single node. Therefore, in conventional DG planning model, a single unit of DG is generally installed at a node [2], [8]. Whereas, in proposed planning model, a maximum aggregated hosting capacity of 2 MW wind farm is allowed to be installed at a single node; therefore, eight small-sized WTs given in Table II may be installed at a node. Without loss of generality and simplicity of the DG planning model, the hourly wind speed is assumed to be identical across all nodes since distribution system is assumed to be spreaded in small geographical area. Moreover, identical WTs are considered for all three WFs/buses with assuming the lossless DC-AC converters and coupling transformers. The wind power generation as a fraction of it's rated power output, load multiplying factor as a fraction of nominal load demand and hourly grid energy price are shown in Fig. 2(a), 2(b) and 2(c) respectively.

Now, the proposed and conventional DG planning problems are solved for the study system using GA and the simulation results are summarized in Table III. The table summarizes the information of optimal DG nodes, sizes and NPV of the investment. The comparison of simulation results show that proposed DG planning model is significantly increased the integration benefits of the renewables as compared to conventional DG planning models due to the control of WTs. It may be observed that the total hosting capacities of WTs obtained by proposed DG models are found to less as compared to conventional DG planning models.

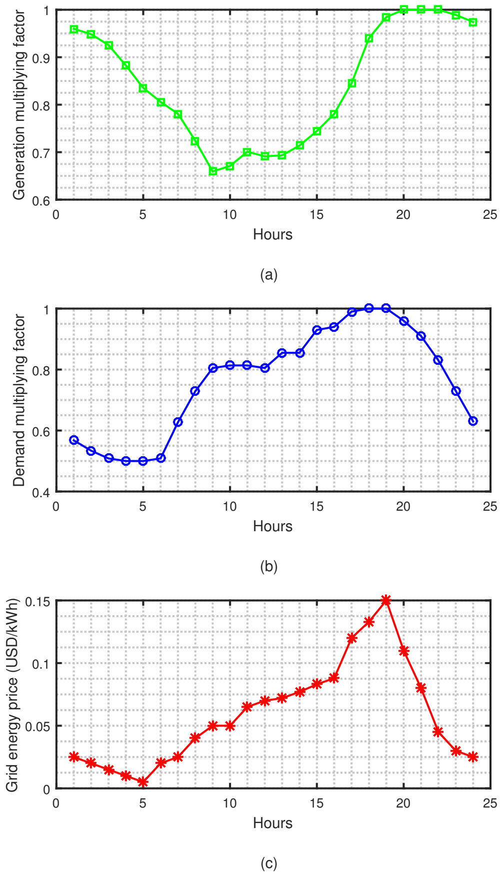

Fig. 3. Hourly shape multiplying factors used in the study for (a) wind power generation, (b) load and (c) grid energy price

TABLE III
OPTIMAL WIND FARMS SITES AND SIZES

Model	Optimal Nodes (DG Sizes in kW)	NPV (M$)
Conventional	02(1991), 11(1940), 31(1927)	19.372
Proposed	11(1750), 24(2000), 30(2000)	24.801

TABLE IV
OPTIMAL OPERATIONS OF WTS IN THE FIRST AND LAST YEARS OF PLANNING HORIZON

Year(s)	Hour(s)	Conventional Model			Proposed Model		
		n_2^h	n_{11}^h	n_{31}^h	n_{11}^h	n_{24}^h	n_{30}^h
y = 1	00:00	0*	0	1	0	7	2
	01:00	0	1	0	1	4	3
	02:00	0	1	0	3	4	1
	03:00	0	1	0	2	3	3
	04:00	0	0	1	3	1	5
	05:00	0	0	1	3	3	3
	06:00	0	0	1	3	6	3
	07:00	1	0	1	3	7	5
	08:00	1	0	1	6	6	6
	09:00	1	0	1	4	7	7
	10:00	1	0	1	3	8	6
	11:00	1	0	1	4	8	5
	12:00	1	0	1	5	7	6
	13:00	1	0	1	7	5	6
	14:00	1	0	1	4	8	7
	15:00	1	0	1	7	6	5
	16:00	1	0	1	6	7	4
	17:00	0	1	1	7	5	4
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	19:00	0	0	1	2	7	5
	20:00	0	0	1	0	8	6
	21:00	0	0	1	4	7	1
	22:00	0	0	1	3	5	3
	23:00	0	0	1	1	4	4
y = 20	00:00	0	1	1	4	4	7
	01:00	0	0	1	2	8	5
	02:00	0	0	1	5	6	3
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	17:00	1	1	1	8	8	6
	18:00	1	1	1	8	8	6
	19:00	1	1	1	8	8	6
	20:00	1	1	1	8	8	7
	21:00	1	0	1	8	7	7
	22:00	1	0	1	5	7	7
	23:00	1	0	1	7	5	5

–*Number of wind turbines operated in that WF.

The 1st and 20th years hourly operational status of WTs deployed in all WFs are presented in Table IV. The table shows that maximum wind power curtailment is observed in initial years of planning horizon, which is gradually reducing over the years. It may be observed that maximum power curtailment is found in conventional DG planning models due to single big-sized WT installation at a node. Whereas, the small-sized WTs are able to minimize the curtailment of wind power generation as compared to the conventional model.

In order to highlight the salient attributes of the proposed DG planning model, the individual factor/benefits observed in distribution system are summarized in Table V. It shows the Net Present Cost (NPC) of various factors over complete planning horizon such as energy loss, grid energy purchase, wind power curtailment cost etc. Here, the cost of power curtailment is calculated as the cost of energy not generated by the installed WT as per the current energy tariff. However, the total effective energy curtailment cost will be higher because that energy may produce other financial benefits if it would have generated. The NPC of energy supplied to the load is defined as the cost of energy purchased from the grid in the planning horizon if energy loss is zero. From the table, it may be observed that proposed approach is significantly reduces the NPC of grid energy purchase due to switchable/modular small WTs. Moreover, the initial investment, NPC of power loss and operation & maintenance are also found to be less as compared to conventional planning models. The proposed approach is also reduces the amount of energy curtailed.

Figures 4(a), (b) and (c) show the box plots of node voltage profile of the system observed over complete planning horizon

TABLE V
COMPARISON OF VARIOUS NET PRESENT COSTS

Factor(s)	Base case	Conventional	Proposed
NPC of energy loss ($)[a]	9225.464	4435.344	3504.085
NPC of wind power curtailment ($)[b]	0	202174.658	173379.403
NPC of energy supplied to load (M$)[c]	50.476	09.373	04.344
Initial investment (M$)[d]	0	11.025	10.822
NPC of operation & maintenance (M$)[e]	0	10.711	10.514
Total NPC (a + c + d + e) (M$)	50.485	31.113	25.684
NPV ($C^b_{Out} - C^a_{Out}$)	0	19.372	24.801

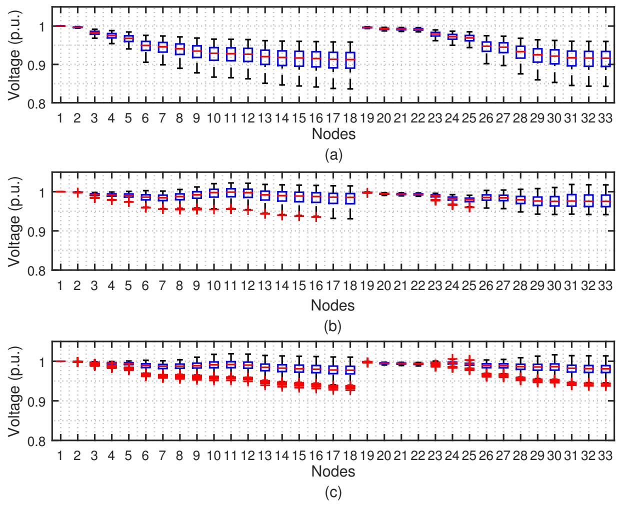

Fig. 4. Box plots of node voltage profiles of the system in 20 years for (a) base case (b) convention approach (c) proposed approach

for base case, conventional DG planning model and proposed DG planning model respectively. Each box contains the values of voltages appeared in complete planning for a given node. In each box, the central horizontal mark represents the median of values. The central box contains the 50% of solution set. The lower and upper boundary lines of the box indicate 25th and 75th percentiles respectively. The outliers are indicated individually using the '+' symbol [5]. It may be observed that both the planning models are significantly improved the node voltage profiles of the system as compared to base case. The node voltage profile produced by proposed planning model is better than the conventional approach because the box sizes are smaller. The smaller box sizes represents the lesser deviations in the node voltages over complete planning period. However, more outliers may be observed in proposed approach due to hourly connection and disconnection of WTs.

VIII. CONCLUSION

The paper presents a new wind power generation planning framework for distribution systems to convert the wind power generation into a dispatchable energy source. A set of switching arrangements based on communication and information technologies are suggested. The proposed planning model is successfully implemented on a standard 33-bus radial distribution system and the simulation results are compared with same obtained by conventional DG planning model. The comparison shows that the proposed model produces promising results as compared to the conventional planning model. Moreover, the approach is effectively converted the non-dispatchable renewable energy sources into dispatchable energy sources, which significantly reduces the cost of renewable power curtailment, energy loss, initial investment, operation and maintenance etc. while improving the node voltage profile of the system over the planning horizon.

In future, the proposed optimal DG planning model can be extended for other/mixed renewable energy resources to investigate the pros and cons of different renewable energy resources.

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