Distribution Network Hosting Capacity Maximization using Demand Response

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ABSTRACT

Distribution network operators (DNOs) are willing to maximize the share of renewable energy sources (RESs). This means that DNOs identify the best locations and capacities of RESs that can be installed in the network, while ensuring that it does not violate the technical constraints of the networks. Technical issues that limit RESs hosting capacity (HC) of distribution networks are mainly include the thermal ratings of the network components, voltage regulation, short circuit level and power quality considerations. Due to the regulatory issues as well as the stochastic nature of RESs the DNO is not able to interfere with active power schedule of these units. Hence, in order to relax the RESs capacity limiting constraints and hence increase the HC of the networks, DNOs can apply several practices. In this paper, two effective practices are utilized, namely demand response (DR) in the context of smart grids and scheduling of switchable capacitor banks in the distribution feeder. Thus, the decision variables are DR schedules and the switching pattern of capacitor banks for a given horizon. It is demonstrated that DR and optimal switching of capacitor banks are effective tools for a DNO to increase the HC of RESs. In order to quantify the benefits of the proposed method, the evaluation of the proposed approach is carried out by applying it on IEEE 33-bus distribution network.

INTRODUCTION

Over the last years, significant efforts have been made towards more utilization of renewable energy sources (RES) and the integration of such resources to the electricity networks, especially distribution networks. This integration requires specific attention regarding the technical conditions of the distribution networks. Hence, there are new challenges that Distribution network Operators (DNO) are faced with.

The main role of DNO is to maintain the efficiency and security of the network. The regulatory frameworks in electricity markets do not usually allow the DNO to interfere with the operating schedule of RES. The power outputs of RES are mainly determined based on the weather condition.

One of the well-known indices to indicate the efficiency of the distribution network is the hosting capacity (HC). The HC is defined as the maximum capacity which a RES harvesting network can absorb without violating the steady sate operational constraints such as line flow and voltage limits. Absorbing more RES not only increases the benefits of DNO (due to the incentives it may receive) but also the positive environmental impacts are achieved.

Wind power is the most popular and cost-effective form of RES, which is a meritorious alternative to the commonly used fossil fuels driven energy producers. Reference [1] provides a complete survey for worldwide HC of distributes energy resources. Reference [2] addresses how with the wind farm voltage control provision, constraints such as steady-state bus voltage limits may be overcome and the local HC can be increased. A model based on cost-benefit analysis is proposed in [3] for determining the optimal wind power HC of a distribution system using active-management strategies (AMSs). In[6]–[4] probabilistic approaches were proposed for determination of maximum DG penetration in medium voltage distribution networks. In [7] curtailment is used to allow more wind or solar power to be connected to a distribution network when over-current or over-voltage occurs. As it is mentioned in [1], replacement of fixed capacitor banks on the feeder with switchable ones, and Demand Response (DR) are potential possibilities and effective tools for maximizing the HC in the future distribution systems.

Hence, this paper proposes a multi-period OPF model in order to increase the HC of wind power in the distribution networks. The decision set for accomplishing this aim is demand response (DR), and switching of multi-stage shunt capacitors. The technical constraints of the DR, capacitor banks switching steps and the network power flow constraints, along with feeders' capacity limits and load points' voltage limits are considered. It is assumed that a predefined percentage of demand can be shifted to other time step (shift-able demands). The conducted analysis considers a pre-specified wind and load patterns in different areas of the network. The wind power curtailment option is modeled in the problem formulation, in order to prevent over voltage at the light loading condition.

PROBLEM FORMULATION

Nomenclature

NW	The set of candidate nodes for wind power hosting.
NB_k	The set of nodes directly connected to node *k*.
k, j	Index of distribution network nodes.
t	Index of operating periods.
$(P/Q)^{net}_{k,t}$	Net active/reactive power injection to node i for time interval *t*.
$(P/Q)^{inj}_{k,t}$	Injected active/reactive power injection to node i for time interval *t*.

$(P/Q)_{k,t}^{W}$	Active/reactive power generation of wind turbine in node i for time interval *t*.
CW_k	Installed wind power capacity in node *k*.
$tg(\varphi_k)$	Wind turbine-generator minimum power factor
$P_{k,t}^{C}$	Curtailed active power in node i for time interval *t*.
Q_k^{Cap}	Capacity of each step of capacitor bank installed at bus *k*.
$U_{k,t}$	Denotes switching step of capacitor banks connected to bus k at time interval *t*.
$(\bar{P}/\bar{Q})_{k,t}^{D}$	Forecasted active/reactive power load of bus *k* at time interval *t*.
$(P/Q)_{k,t}^{D}$	Active/reactive power load of bus k at time interval *t*.
$\xi_{k,t}$	Forecasted (expected) power generation of wind turbine for time interval t in node *k*.
$\lambda_{k,t}$	maximum percentage of allowed wind energy curtailment at node k and time interval t.
$I_{(kj),t}$	Current magnitude of line between nodes *i* and *j* for time interval *t*.
$(V/\theta)_{k,t}$	Magnitude/angle of bus k voltage at time interval *t*.
$Y_{kj}\angle\gamma_{kj}$	*kj*-th element of the system Y_{BUS} matrix
Δ_t	Duration of time interval *t*.
$\alpha_{DR_k}^{\max/\min}$	Maximum/minimum limit (flexibility) of demand response in node *k*.

The objective function (OF) of wind power HC maximization problem is as follows.

$$\max\ OF = \sum_{i\in NW} CW_i \tag{1}$$

The above OF is maximized subject to the following load flow and operational constraints.

$$P_{k,t}^{net} = P_{k,t}^{inj} \tag{2}$$

$$Q_{k,t}^{net} = Q_{k,t}^{inj} \tag{3}$$

where, for the supply (or slack) bus,

$$P_{k,t}^{net} = P_{k,t}^{G} - P_{k,t}^{D} \tag{4}$$

$$Q_{k,t}^{net} = Q_{k,t}^{G} - Q_{k,t}^{D} \tag{5}$$

And, for the remaining load buses,

$$P_{k,t}^{net} = P_{k,t}^{W} - P_{k,t}^{D} - P_{k,t}^{C} \tag{6}$$

$$Q_{k,t}^{net} = Q_{k,t}^{W} + Q_k^{Cap} U_{k,t} - Q_{k,t}^{D} \tag{7}$$

also,

$$P_{k,t}^{inj} = \sum_{j\in NB_k} V_{k,t} V_{j,t} Y_{kj} \cos(\theta_{k,t} - \theta_{j,t} - \gamma_{kj}) \tag{8}$$

$$Q_{k,t}^{inj} = \sum_{j\in NB_k} V_{k,t} V_{j,t} Y_{kj} \sin(\theta_{k,t} - \theta_{j,t} - \gamma_{kj}) \tag{9}$$

And the wind power generation pattern for the entire results:

$$P_{k,t}^{W} = \xi_{k,t} CW_k \tag{10}$$

Also the following operational limits are considered:

$$0 \le P_{k,t}^{W} + P_{k,t}^{C} \le CW_k \tag{11}$$

$$0 \le P_{k,t}^{C} \le \lambda_{k,t} CW_k \tag{12}$$

$$-tg(\varphi_k) P_{k,t}^{W} \le Q_{k,t}^{W} \le tg(\varphi_k) P_{k,t}^{W} \tag{13}$$

$$V_k^{\min} \le V_{k,t} \le V_k^{\max} \tag{14}$$

$$0 \le \left(I_{(kj),t} = \left| Y_{kj} \left\{ (V_{k,t}\angle\theta_{k,t}) - (V_{j,t}\angle\theta_{j,t}) \right\} \right| \right) \le I_{kj}^{\max} \tag{15}$$

And at the buses where the switchable capacitor banks are installed, the corresponding switching steps limited as follows.

$$0 \le U_{k,t} \le U_k^{\max} \tag{16}$$

Also, at the buses where DR allowed, the following constraints are considered.

$$\bar{P}_{k,t}^{D}\left(1-\alpha_{DR_k}^{\min}\right) \le P_{k,t}^{D} \le \bar{P}_{k,t}^{D}\left(1+\alpha_{DR_k}^{\max}\right) \tag{17}$$

$$\bar{Q}_{k,t}^{D}\left(1-\alpha_{DR_k}^{\min}\right) \le Q_{k,t}^{D} \le \bar{Q}_{k,t}^{D}\left(1+\alpha_{DR_k}^{\max}\right) \tag{18}$$

Since, the DR is in the form of load shifting, thus the following constraints should be satisfied.

$$\sum_{\forall t}\left(P_{k,t}^{D}\ \Delta_t\right) = \sum_{\forall t}\left(\bar{P}_{k,t}^{D}\ \Delta_t\right) \tag{19}$$

$$\sum_{\forall t}\left(Q_{k,t}^{D}\ \Delta_t\right) = \sum_{\forall t}\left(\bar{Q}_{k,t}^{D}\ \Delta_t\right) \tag{20}$$

In the above model, (1) is the OF, which is maximized, (2)-(9) are AC load flow equations, (10)-(13) are the constraints of wind power generation which shows the limits on the injected and curtailed wind powers. Also, (14) and (15) are bus voltages and current limits of feeders. Equation (16) reveals the minimum and maximum limits on the switching steps of capacitor banks. Besides, (17) and (18) gives the relation between the actual active/reactive load powers. Finally (19) and (20) means that the DR is in the form of load shifting, and the consumed by loads remains constant in the entire studied horizon.

CASE STUDY AND SIMULATION RESULTS

The proposed model is implemented in GAMS [8] environment and solved by DICOPT solver [9]. It is applied to the IEEE 33-bus distribution system. The power factor limit of each wind turbine is assumed to be $\cos(\varphi_k) =$ 0.95 (lag/lead). The maximum percentage of allowed wind energy curtailment ($\lambda_{k,t}$) in (16) is assumed to be 10% ($\forall k \in NW$, $\forall t$). It is assumed that candidate connection points of wind power are known as depicted in Fig. 1. The candidate wind connection nodes are as follows: wind sites in nodes 6 and 18 follow the wind pattern 1 ($\xi 1_{k,t}$), while the wind sites in nodes 12, and 33 follow the wind pattern 2 ($\xi 2_{k,t}$) as described in Table 1[10]. It is also assumed that all nodes can participate in demand response program. The demand flexibility ($\alpha_{DR_k}^{\max/\min}$) is assumed to be the same for all nodes and equal to 20%. Also, it is assumed that multi-step capacitor banks are installed at the following buses: 7, 24 and 30, as depicted in Fig. 1. The capacitor bank in each node consists of 10 equal steps, in which each step is 5, 10 and 30 kVAR, respectively for the above buses.

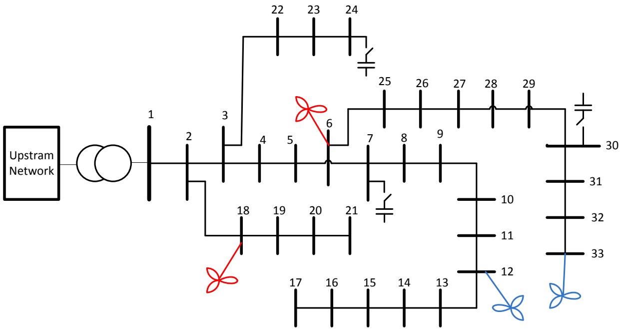


Fig. 1. Single line diagram of the IEEE 33-bus network.

Table 1. Wind-demand patterns in different time intervals

Time	Demand	w1	w2	Duration	Time	Demand	w1	w2	Duration
t1	0.3	0	0	1	t29	0.7	0.1	0.3	362
t2	0.3	0	0.1	9	t30	0.7	0.3	0.3	310
t3	0.3	0.1	0.1	50	t31	0.7	0.3	0.5	429
t4	0.3	0.1	0.3	13	t32	0.7	0.5	0.5	168
t5	0.3	0.3	0.3	7	t33	0.7	0.5	0.7	334
t6	0.4	0.3	0.5	20	t34	0.7	0.7	0.7	127
t7	0.4	0.5	0.5	5	t35	0.8	0.7	0.9	377
t8	0.4	0.5	0.7	2	t36	0.8	0.9	0	14
t9	0.3	0.7	0.7	1	t37	0.8	0.9	0.9	668
t10	0.3	0.9	0.9	2	t38	0.8	0.9	1	274
t11	0.5	0	0	148	t39	0.8	1	0.9	185
t12	0.5	0	0.1	113	t40	0.8	1	1	45
t13	0.5	0.1	0.1	875	t41	0.8	0	0	41
t14	0.5	0.1	0.3	241	t42	0.9	0	0.1	14
t15	0.5	0.3	0.3	255	t43	0.9	0.1	0.1	195
t16	0.5	0.3	0.5	342	t44	0.9	0.1	0.3	60
t17	0.5	0.5	0.5	118	t45	0.9	0.3	0.3	35
t18	0.5	0.5	0.7	282	t46	0.9	0.3	0.5	60
t19	0.5	0.7	0.7	81	t47	0.9	0.5	0.5	23
t20	0.6	0.7	0.9	262	t48	0.9	0.5	0.7	62
t21	0.6	0.9	0	8	t49	0.9	0.7	0.7	11
t22	0.6	0.9	0.9	329	t50	0.9	0.7	0.9	76
t23	0.6	0.9	1	118	t51	0.9	0.9	0	11
t24	0.6	1	0.9	51	t52	0.9	0.9	0.9	123
t25	0.6	1	1	12	t53	0.9	0.9	1	40
t26	0.7	0	0	192	t54	0.9	1	0.9	43
t27	0.7	0	0.1	127	t55	0.9	1	1	5
t28	0.7	0.1	0.1	1003	t56	1	0.3	0.5	1

The average hourly demand flexibility versus time intervals is depicted in Fig. 2. This value is calculated based on demand values and their corresponding durations.

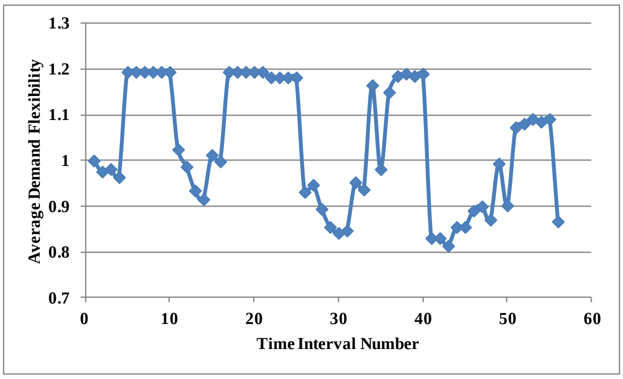


Fig. 2. Average hourly demand flexibility versus time intervals

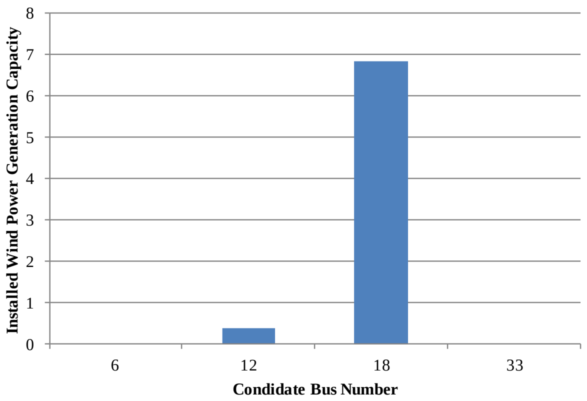


Fig. 3. The hosted wind power generation capacity at the candidate nodes

The variations of hosting capacity values for different cases are given in Table 2. The minimum value of HC occurs when the demand flexibility is 0% (no DR) and no capacitor switching is allowed and is equal to 5.7789MW. A sensitivity analysis is performed and the demand flexibility is increased to 20%. The maximum value of HC occurs when the demand flexibility is 20% and capacitor switching is allowed and is equal to 7.2059MW.

Table 2. HC (in MW) for different values of demand flexibilities and capacitor switching capability

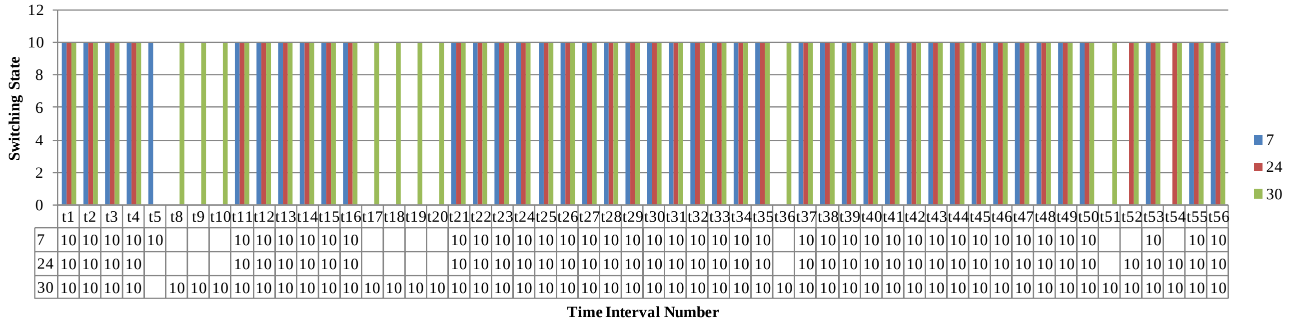
		Demand flexibility		
		0%	10%	20%
Capacitors	Considered	6.0604	6.755	7.2059
	Not Considered	5.7789	6.475	6.9196

Fig. 4. Shows the Switching states of capacitor banks at the installed buses in the case where DR & capacitor are considered (i.e. DR is 20% and capacitor switching is allowed). The voltage profile for an arbitrary bus (here bus 17) is shown in Fig. 5, for different cases.

The voltage profile for a given bus (17) is shown in Fig. 5. It can be seen that the minimum voltage in base case (no DR and no capacitor) is 0.9 pu. This value is increased to 0.955 in DR+ capacitor case.
As evidenced by simulation results, the following observations are made:

- The simulation results show that the HC can be increased without doing investment in network components.
- Using the DR will increase the HC. A cost benefit analysis can reveal the economic value of this increase and provide the appropriate economic signal to consumers which participate in demand response program.

- The capacitor switching makes the problem non-linear mixed integer which is hard to solve for large distribution networks.



	t1	t2	t3	t4	t5	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24	t25
7	10	10	10	10	10				10	10	10	10	10	10					10	10	10	10	10
24	10	10	10	10					10	10	10	10	10	10					10	10	10	10	10
30	10	10	10	10		10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

	t26	t27	t28	t29	t30	t31	t32	t33	t34	t35	t36	t37	t38	t39	t40	t41	t42	t43	t44	t45	t46	t47	t48	t49	t50	t51	t52	t53	t54	t55	t56
7	10	10	10	10	10	10	10	10	10	10		10	10	10	10	10	10	10	10	10	10	10	10	10	10			10		10	10
24	10	10	10	10	10	10	10	10	10	10		10	10	10	10	10	10	10	10	10	10	10	10	10	10		10	10	10	10	10
30	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

Fig. 4. The status of capacitors (installed in bus 7, 24 and 30) in different time periods.

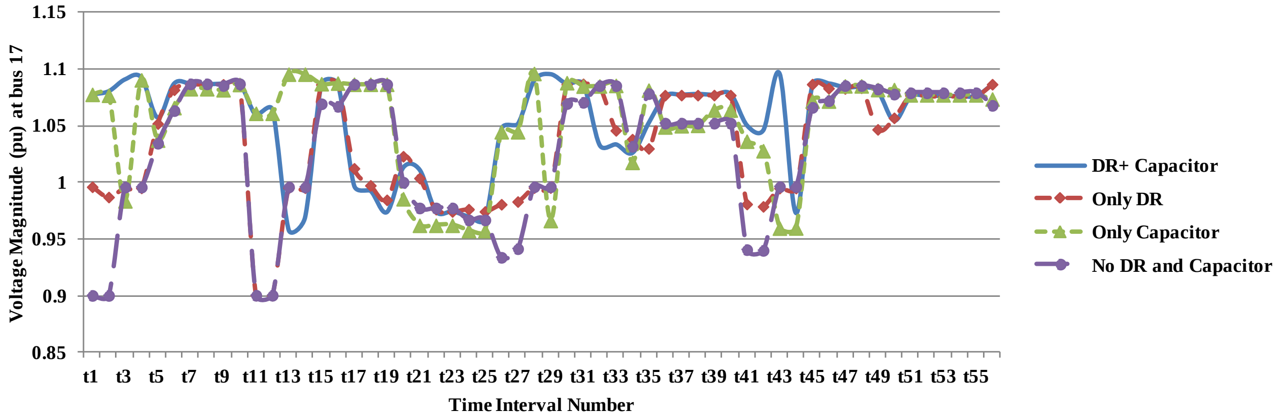


Fig. 5. Comparison of Voltage profile at bus 17, for different cases

CONCLUSION

In this paper, a general framework is presented which identifies the hosting capacity of distribution networks and tries to maximize it using the reactive power control of wind turbines, capacitor switching and demand response actions. The proposed framework considers the variations of wind power generation as well as demand values for a given horizon. The numerical results show that considering the demand response and capacitor banks switching are effective tools for maximization of HC. There are several ways on how future work can be based on the presented results as follows:

- The uncertainties of wind power generation pattern should be taken into account to provide more practical solutions. There are some techniques to handle these uncertainties such as stochastic methods [11], [12], information gap decision theory [13] or robust optimization [14].
- The decomposition techniques can be used to improve the computation performance.
- Current formulation only considers the demand shifting as the demand response option. The load curtailment option may further increase the hosting capacity of the network.
- The energy storage units can be used as the flexibility provider resource to increase the HC.

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