

Optimal Integration of Wind Power Resources in Distribution Networks Considering Demand Response Programs

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Abstract— distribution network operators (DNOs) tend to supply electrical energy to its customers in an economical and reliable manner. If wind power generation (WPG) units are planned with a suitable way, they will be the best option to reduce costs and increase the distribution network reliability. This paper proposes a WPG units planning model to determine technology type, capacity and location of WPG units to reduce power losses and improve reliability and voltage profile in network. In this model, DNO has been considered to study the effect of demand response programs (DRP) on total cost function, where the time-of-use rates of demand response programs have been modeled and consequently its influence on load profile has been discussed. Objective function is a cost function which minimizes the investment and operation cost of DGs, purchase costs of the upstream network, defined cost to reliability index and the energy losses. In this study, electrical load is time variable and model is simulated on a typical radial network, successfully.

1. INTRODUCTION

One of the most promising distributed generation (DG) technologies is wind power generation (WPG) among the renewable resources owing to the environmental friendly characteristics. Environmental, economic and technical factors have played an important role in WPG development. These units are a good choice for distribution network operators (DNO) to supply their customers' needs. So still there is this incentive be studied the different methods of WPG planning included its various technologies. Among these renewable energy, wind technology developed rapidly in the last decade and reduce investment costs and well wind power have entered competition with traditional generation units. Renewable energy such as wind with respect to their main source of energy has special features. The source of wind power that is wind is not constant during the operation of wind turbines and depending on the weather conditions of its installation location changes, constantly. Therefore power output changes proportional to the wind speed. WPG units can have various benefits for DNO. Among them postponing investment in network [1], reducing environmental pollution [2], increasing reliability [3,4] and reducing network losses [5,6], which also led to a reduction in operating costs of the network could be named. Benefits from WPG units depend greatly on the capacity and location of installed in networks. In the WPG planning issue consider technical constraints such as the voltage range, feeders' capacity and WPG penetration level. Also in this debate, there is regulatory that possible the potential benefits of WPG units change to DNO. These regulations can be set in the two main categories:

First, network administrators are the WPG owners and in the latter the private sector is responsible for the DG units' installation in the network [7]. In the first category, DNO can be a good decision to install wind turbines based on increasing its benefit. In the second category, the DNO refuses of WPG, and the investment and operation of WPG is performed by the Private sector (or DG owners). However, because purpose is maximizing the network operator profit or the WPG owner, DNO can identify the convenient location and capacity of WPG units and provide necessary guidance for DG investors [8]. In this study, with respect to mentioned advantages, wind turbines have been also used in the DG units planning.

Despite the advantages (or defects in some instances) of DG units, load growth rate will cause these resources existence inadequate to reliability enhancement. One of the proposed solutions in this paper is applying demand response programs (DRPs). DRP is defined as changes of customer loads from nominal value in response to incentive payments of operator or reliability problems [9], [10]. Application of DRP in enhancing frequency stability of power system studied in [11] and [12]. In [13], DRP is accomplished by developing time of day energy pricing schemes that provide incentives for customers to shift all or part of their load demand from peak to other load periods. In [14] are developed different mathematical nonlinear models for DRPs and extracted the most conservative and non-conservative time of use (TOU) models. These models have been developed based on price elasticity of demand.

The both technical purpose of losses reduction and reliability improvement are considered for optimum DG planning in the distribution network. In this paper, a cost based objective function is assumed to minimize the investment and operation cost DG, purchased energy costs from the upstream network, the defined cost for reliability and energy losses cost and minimize the energy losses. The main contribution of this paper can be categorized as follows:

- Time variant load modeling based on time-of-use rates demand response programs.
- Presenting a cost function which considers the impact of reliability and losses, simultaneously.

The rest of paper is arranged accordingly: The section two covers the problem formulation. The sample system and the problem assumptions are presented in the Section three. The results of the study are provided in the section four. Conclusion is ultimately presented in the last section.

2. PROBLEM FORMULATION

In this section, a model for the distribution network scheduling in the presence of WPG units is presented. This model is based on optimal power flow and minimizes the energy costs of DisCo for a

long-term period. In the proposed model for the objective function, DisCo is assumed the owner of WPG units. Therefore, planning and dispatch of these units is done by DisCo. This model is based on the variation of the daily load curve.

2.1. Load & electricity price model

As we know the precise optimization of objective function can be as a result the correct analysis of the input data. One of the most important input data is the definition of electrical load. The system load is changing during a day. Figure (1) shows the forecasted values of the system load demand and the electricity price for 24 hours of the day. The other hand, the annual load curves is similar to the daily electrical load. To avoid complexity of the annual load curve, the daily electrical load is repeated 365 times during the year. In addition demand is not constant every year in comparison with other year and will be faced to growth rate α percent.

According to following relations $P_{i,h}^l$ and $P_{i,t,h}^l$ indicate active load each node in every hours of the day and the annual active load demand, respectively.

$$P_{i,t,h}^l = \sum_{dy=1}^{N_{day}} P_{i,h}^l \times (1 + \alpha)^t, P_{i,h}^l = P_{i,h}^{base} \times \mu_{i,t,h}^d \quad (1)$$

$$Q_{i,t,h}^l = \sum_{dy=1}^{N_{day}} Q_{i,h}^l \times (1 + \alpha)^t, Q_{i,h}^l = Q_{i,h}^{base} \times \mu_{i,t,h}^d \quad (2)$$

The price of energy purchased from the main grid is not considered identical for different demand levels. Hence generally we assume that the price of electricity in h^{th} demand level can be determined as follows [15]:

$$\lambda_h = \rho \times PLF_h \quad (3)$$

where ρ is base price and PLF_h is h^{th} price level factor. For simplicity, we assume that for load levels, PLF_h curve is considered such as DLF_h curve.

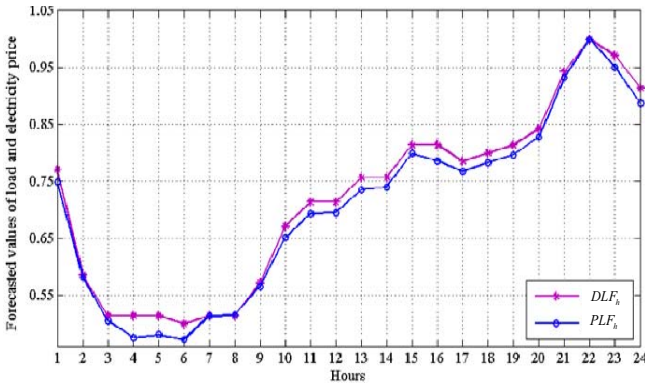


Figure 1: Demand level factor for daily short-term period

2.2. Demand response based load modeling

By performance demand response programs, the DisCo shifts their consumers load from costly periods to inexpensive periods in order to decrease its costs. It should be noted that in this paper, it is considered that the costumers only participates in TOU programs. It is worth mentioning that the costumers have a limited capability of shifting their demand. For example, their maximum capability may be assumed to be 15 percent of total demand. ($DR_{max}=15\%$). The DRP can be modeled as Figure.2.

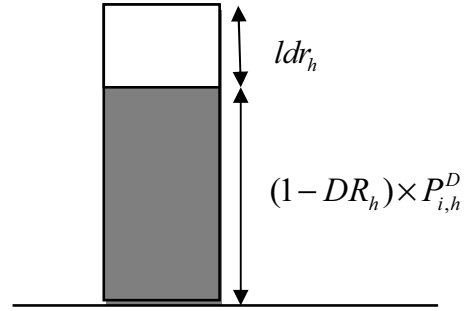


Fig. 2: Load modeling with DRP

The dashed part of load in Figure.2 is the section which doesn't participate in DRP and the other section is able to shift from one period to others due to price differences. Figure.2 can be defined mathematically as follows:

$$P_{i,h}^D = (1 - DR_h) \times P_{i,h}^D + ldr_h \quad (4)$$

$$P_{i,h}^D - P_{i,h}^{DR} = ldr_h = DR_h \times P_{i,h}^D \quad (5)$$

where $P_{i,h}^D$ is the initial load at time period h , and $P_{i,h}^{DR}$ is load after DRP implementation in the same period. ldr_h is the shifted load value by DR programs at level h . DR_h factor shows the costumers participation in DRP.

2.3. Wind power generation:

Generation scheduling the wind turbine depends largely on wind speed at the site and it is calculated by using the equation (6) [16].

$$P_{i,t,h}^w = \begin{cases} 0 & \text{if } v < v_{in}^{cut}, v > v_{out}^{cut} \\ \frac{v - v_{in}^{cut}}{v_{rated} - v_{in}^{cut}} \times P_{i,w}^{max} & \text{if } v < v_{in}^{cut}, v > v_{out}^{cut} \\ P_w^{max} & \text{if } v_{rated} \leq v < v_{out}^{cut} \end{cases} \quad (6)$$

The wind velocity curve is considered as Figure 3 [16].

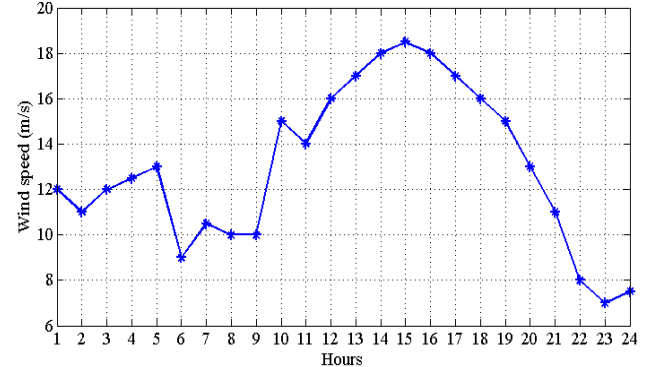


Figure 3: wind velocity curve for the daily period.

2.4. Objective function

In this section, objective function is modeled the network costs view point and studied. In this model assumes that DNO is responsible for the customer energy demand provision, investment and operation of DG units and distribution network management. All these responsibilities will be based on reduce costs, energy losses and improve the network reliability.

- Investment cost of DG units:

The investment cost of the renewable and nonrenewable DG units is calculated using equation 7.

$$DGIC = \sum_{i=1}^{N_{DG}} (S_{max}^w \times IC_w) \times \left(\frac{1 + InfR}{1 + IntR} \right)^t \quad (7)$$

- Operation cost of the DG units:

In this paper operating costs for the wind turbine is considered zero. Energy purchased from upstream network is also calculated as follows.

$$GC = \sum_{t=1}^T \sum_{h=1}^{N_h} P_{t,h}^{SS} \times \rho_h \times \tau_h \times \left(\frac{1 + InfR}{1 + IntR} \right)^t \quad (8)$$

- Energy not supplied costs calculation:

Several reliability indices based on customer load is defined and used in evaluation of the electricity industry performance. It shall be noted that when a fault occurs in the main feeder, each branch is separated from network by an isolator switch and all the customers who are connected to it feeder, will be faced with power outage. Within a few minutes, remote controllable switches the will be isolated fault from the network. To purpose of showing the outage importance in the distribution network, energy not supply (ENS) index is studied. This index reflects the total energy not supply in the network in time range of fault occurrence. This reliability analysis is implemented by analytical approach. So power outage costs value as equation (9) will be described [17]:

$$C_{ENS} = \sum_{t=1}^T \sum_{b=1}^{N_{br}} \rho_{ENS} \times \lambda_b \times l_b \times \left(\sum_{res=1}^{N_{res}} P_{res} \times t_{res} + \sum_{rep=1}^{N_{rep}} P_{rep} \times t_{rep} \right) \quad (9)$$

- Power losses cost:

The active power losses cost in the network can be calculated as follows:

$$LC = \sum_{t=1}^T \sum_{h=1}^{N_h} P_{t,h}^{loss} \times \rho_h \times \tau_h \times \left(\frac{1 + InfR}{1 + IntR} \right)^t \quad (10)$$

So the cost function can be written as follows:

$$OF = DGIC + GC + C_{ENS} + LC \quad (11)$$

The optimal size, location wind turbines are determined by minimising the total cost function in the distribution network. In this paper is used the GAMS software which is powerful optimization software to solve a nonlinear mixed integer programming (MINLP) problem.

2.5. Constraints and optimal power flow equations:

Power flow equations for i^{th} bus, h^{th} hours and t^{th} year is considered as follows.

$$P_{i,t,h}^G + \sum_{w=1}^{N_w} P_{i,t,h}^w - P_{i,t,h}^l = V_{i,t,h} \sum_j V_{j,t,h} (G_{ij} \cos \delta_{i,t,h} + B_{ij} \sin \delta_{j,t,h}) \quad (12)$$

$$Q_{i,t,h}^G + \sum_{gf=1}^{N_{gf}} Q_{i,t,h}^{GT} - Q_{i,t,h}^l = V_{i,t,h} \sum_j V_{j,t,h} (G_{ij} \sin \delta_{i,t,h} - B_{ij} \cos \delta_{j,t,h}) \quad (13)$$

The voltage of each bus in t^{th} year and h^{th} hours should be kept in the safe limits.

$$V_i^{\min} \leq V_{i,t,h} \leq V_i^{\max} \quad (14)$$

The DG units should be operated with considering the limits of their maximum installed capacity [16]:

$$P_{i,h}^{WPG} \leq P_{WPG}^{\max} \quad (15)$$

Active and reactive power received from the upstream network in each bus in t^{th} year and h^{th} hours should be formulated according to the HV substation capacity.

$$P_{sub}^{\min} \leq P_{t,h}^{sub} \leq P_{sub}^{\max} \quad (16)$$

$$Q_{sub}^{\min} \leq Q_{t,h}^{ss} \leq Q_{sub}^{\max} \quad (17)$$

The transmission power of the line between nodes i and j in t^{th} year and h^{th} hours should be limited to a maximum limit.

$$S_{ij,t,h} \leq S_{ij}^{\max} \quad (18)$$

The moveable demand has variable size in each period which is defined by DR_h and represented by (19). DR_h factor shows the customer participation in DR programs.

$$\sum_{h=1}^{N_h} ldr_h = \sum_{h=1}^{N_h} DR_h \times P_{i,h}^D \quad (19)$$

Constraint (20) limits the maximum amount of DR_h in each period by “DR_{max}” which is considered 15% here.

$$DR_h \leq DR_{\max} \quad (20)$$

3. ASSUMPTIONS AND DESCRIPTIONS OF CASE STUDY

3.1. Assumption of problem

Capacity intended for the wind turbine is 2 MW which data about the wind turbines are given in Table 1. The investment and operation cost of DG units and other network data are also listed in Table 1.

Table 1: The data used in planning problem

parameter	value	parameter	value
T(year)	10	λ_b (f/km-year)	0.045
pr_{base} (\$/MWh)	70	t_{res} (hour)	1
IC_w (\$/MVA)	1350000	t_{rep} (hour)	8
ρ_{ENS} (\$/MWh)	170	$InfR$ (%)	4
V_i^{\min} (p.u)	0.9	$IntR$ (%)	5
V_i^{\max} (p.u)	1.1	α (%)	3
V_{in}^{cut} (m/s)	2	V_{out}^{cut} (m/s)	25
V_{rated} (m/s)	14	$P_{i,w}^{\max}$ (MW)	2

The proposed method have been used on a 9-bus radial network which shown at Figure 4 [17]. Distribution network includes high voltage substation 132–33 kV which feeds eight load points and each branch has been separated from network by a switch.

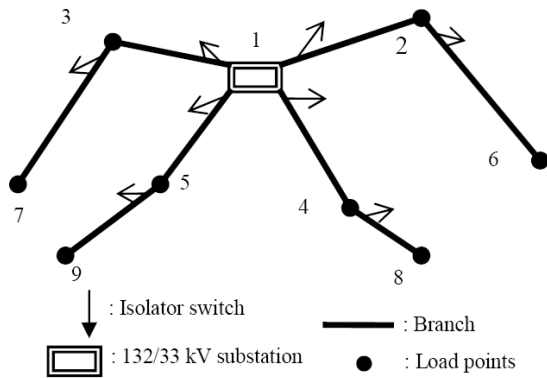


Figure 4: a single line diagram 9 bus system [17].

The maximum load demand is 65.7 MW that this demand value will reach to 88.29 MW at the end of planning period due to the intended load growth rate. Electrical load data and technical characteristics are adapted to [17].

3.2. Simulation results:

Simulations carried out on 9-bus distribution network shown in Fig. 4 and the objective function result is derived. Table 2 shows number, capacity, location wind turbines that should be installed in the network. In this study installation limits of the WPG units' number are not considered. Each the wind turbines has 2 MW capacity. For example with regard to the hypothetical capacity of network, at the load point 8 are installed 2 the wind turbine unit. It should be noted that the investment and operation cost of the DGs affect on the selected capacity. The installed capacity of wind turbines will change with implementation of DR program.

According to the results can be concluded that the DRP have effective role in improving network performance. In Table 3, a comparison between the made decisions by the DisCo for the network planning in different modes has been provided. According to the results of Table 3, by installing the WPG units in the network, the network operator costs 88.493 million dollars are saved. This value will reach to 115.21 million dollar in planning period with applying DRP. The total cost of ENS in the network calculated when the fault occurrence, will be different due to the reliability parameters value. In this study considering WPG, will improve 322,222 \$ in the planning period and this value will reach to 386,666 dollar in planning period with applying DRP. Reasonable WPG planning in the network will have a great impact on the active power losses so that after the installation of DG, losses were decreased 14.5 percent compared with prior and this value will reach to 33.9 percent with applying DRP.

Table 2: The WPG investments in the sample network

Without DRP		With DRP	
capacity(MVA)	node	capacity(MVA)	node
8	4	8	4
4	6	4	6
8	8	8	8
-	-	4	9

Figure 4 shows the positive effects of the WPG on the grid voltage. This figure indicates the voltage values (p.u) for 9 bus system during the planning periods for the load peak. In this study the load peak is assumed occurs at 22 o'clock. The voltage values has been set for 10 years and the voltage conditions with and out WPG compared with together. Voltage conditions have improved with the implementation

of the DR program. It is should be noted that the consumer load profile is changed. Figure 6 shows the load profile with and without considering DRP. As can be seen, the load profile (or demand level factor in per unit) become more flat with considering DRP.

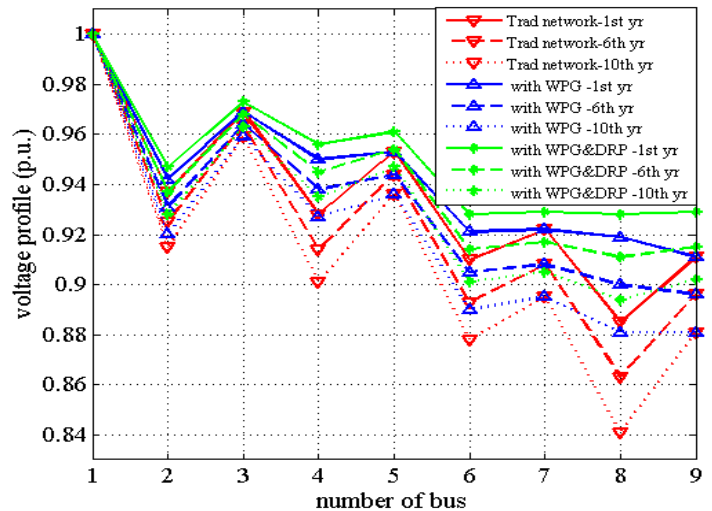


Figure 5: Voltage profile for the different operation modes in peak hour

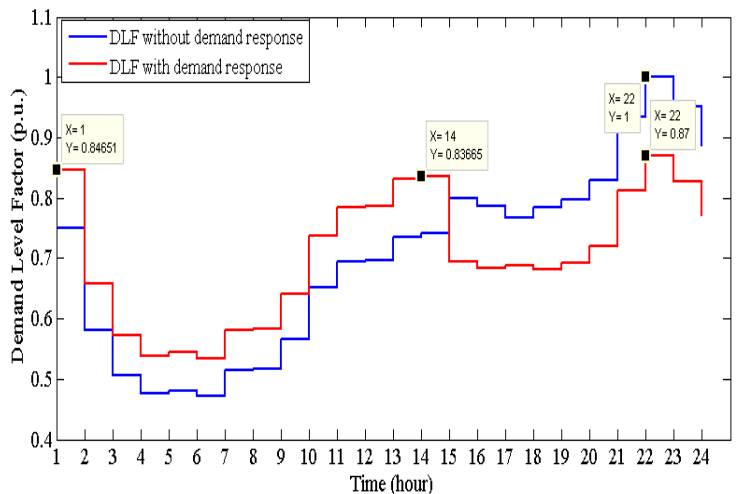


Figure 6. Demand level factor with and without DRP

4. CONCLUSION

This paper presents a multi-objective cost function with variable load model for wind power generation units planning. According to the paper results can be deduced which demand load value and its position in the network, WPG capacity installed in the network have significant impacts on energy losses and system reliability.

In this paper, consumers participate in TOU demands response programs. All of load points are considered flexible to applying DRP. It is shown that by participating in DR programs, the costs of operator is reduced because of load shifting from high price periods (peak) to other periods and flattens the load profile and decrease the maximum demand in each period. From studied results, also it has been derived that voltage profile and loss of the network are intensely depends on DRP. With the presence of WPG, the amount of energy purchased from the upstream grid and leads to power flow in the feeders is reduced.

Table 3: DG planning results without ESS

	Traditional system (no WPG)	System with WPG without DRP	System with WPG & DRP	DRP Benefit
Cost function (\$)	2.652991E+8	1.768062E+8	1.500890E+8	26.717 E+6
Total ENS cost (\$)	2242816.604	1920594.749	1856150.378	64,444
Total active losses cost (\$)	1.174160E+7	9551551.510	7585212.612	1.9633 E+6
Total P _{loss} (MWh)	223790.168	191207.784	147895.035	43312.7
Total Q _{loss} (MVarh)	370864.148	305405.995	243443.637	61962

Table 4: Technical report without ESS

Year	Traditional system (no WPG)		System with WPG without DRP		System with WPG & DRP	
	Power loss	ENS	Power loss	ENS	Power loss	ENS
1	16484.605	1215.401	15682.248	1015.691	12286.196	975.749
2	17362.063	1251.863	16093.872	1052.153	12558.750	1012.211
3	18291.515	1289.419	16546.315	1089.709	12866.742	1049.767
4	19276.348	1328.101	17042.262	1128.391	13212.506	1088.449
5	20320.210	1367.944	17584.596	1168.234	13598.541	1128.292
6	21427.034	1408.983	18176.416	1209.273	14027.528	1169.331
7	22601.067	1451.252	18821.061	1251.542	14502.347	1211.600
8	23846.897	1494.790	19522.127	1295.080	15026.090	1255.138
9	25169.498	1539.633	20283.495	1339.923	15602.084	1299.981
10	26574.264	1585.822	21109.355	1386.112	16233.908	1346.170

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