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Optimal Location of WT based Distributed Generation in Pool based Electricity Market using Mixed Integer Non Linear Programming

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Abstract

In this paper, analysis a Mixed Integer Nonlinear Programming (MINLP) approach has been utilized for determining optimal location and number of distributed generators considering minimization of fuel cost of conventional and Wind turbine power. The pattern of nodal real and reactive power prices have been obtained with and without Wind turbine integration. The results are also obtained for, loss reduction, fuel cost saving and voltage profile. The impact of different load models as PQ load and Zip load model has been studied. The proposed MINLP based optimization approach has been applied for IEEE24 bus reliability test system.

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Keywords: Mixed Integer Nonlinear Programming (MINLP) approach, Nodal price, optimal location, WT- based Distributed generator;

1. Introduction

The next five years, renewable energy will represent the largest single source of electricity growth and its driven by falling cost and aggressive expansion in emerging economies [1]. There are many renewable energy resources available in market like wind, solar and biomass etc. In all renewable energy resources the most popular source is wind power because it's clean, free and continuous source of energy but it has some demerits also like its volatile and uncertain nature. The wind power source is the most popular source in comparison to other renewable energy

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sources [2]. In recent years, all researchers focused on characteristics of distributed generation (DG) and its effects on electrical power system. Because distributed generation are the best alternative solution for power market, it produces electricity near the consumption place which improves the reliability of grid, reduces the transmission losses, improves the power quality and voltage profile and also uses renewable source for DGs to provide the pollution free, clean and efficient energy. Distributed generation fulfil the electricity demand for the growing population [3, 4]. When DGs are connected to the power networks, it raises a number of impacts on the systems like (i) environmental impacts of DG, (ii) economical impacts of DG, (iii) technical impacts of DG. The optimal size and location of the DGs in the power networks plays the most important role. When the optimal size and location is not proper than there will be more power loss, no reliability of the system, no stability of the system and overall cost will increase making it non economical system [5-8]. Thus the optimal sizing and location are very important part of system. Number of technique and methods are available for optimal size and optimal location of DG. According to literature its categorized as: (a) analytical techniques (in this included Eigen-value based analysis (EVA)[9], index method(IMA)[10], sensitivity based method(SBM)[11]) , (b) classical optimization techniques(in this included linear programming [9], mixed non linear programming [12, 13], dynamic programming [14], optimal power flow [15], continuous power flow [16]) , (c) artificial intelligent techniques (Fuzzy logic and genetic algorithm [17,18], particle swarm optimization [19], ant colony search algorithm [20]) and (d) miscellaneous techniques(Monte Carlo simulation[21], Encoded Markov cut set algorithm [22]).

In this paper, the main contributions are: (i) Mixed integer nonlinear programming (MINLP) approach for determining optimal location and number of distributed generators considering minimization of fuel cost of conventional generator and cost of distributed generators in pool electricity market, (ii) impact of wind power output on nodal prices of real and reactive power with wind power variation during 24 hours. The proposed MINLP based optimization approach has been applied for IEEE 24 bus reliability test system. The proposed MINLP based optimization approach has been applied for IEEE 24 bus reliability test system.

2. Wind Turbine Generation Pattern Modeling and Cost Function

The wind speed in the site are main factor for generation of power by Wind turbine and various methods to model wind behavior like time-series model [23], data mining algorithm and clustering approach [24]. In this work, the variation of wind speed, i.e, v, is modeled as a Weibull PDF and its characteristic function which relates the wind speed and the output of a WT as follows:

$$PDF(v) = \left(\frac{i}{c}\right)\left(\frac{v}{c}\right)^{(i-1)} \exp\left[-\left(\frac{v}{c}\right)^{i}\right] \tag{1}$$

$$i = \left(\frac{\overline{\sigma}}{\mu}\right)^{-1.086} \tag{2}$$

$$c = \frac{\overline{\mu}}{\Gamma\left(\frac{1}{i}+1\right)} \tag{3}$$

Where i and c are the shape and scale factor of the Weibull PDF of wind speed $\overline{\sigma}$ and $\overline{\mu}$ are mean m/s and standard deviation m/s, we used the data for the hourly mean with speed during the month of May over the first twelve year (1994-2005) [23]. The hourly wind speed sample has been obtained by using the Monte Carlo simulation (MCS).

The generated power of the Wind turbine is determined using its speed-power curve as follows:

$$P_k^w = \begin{cases} 0 & , if v \le v_{in}^c or v \ge v_{out}^c \\ \dfrac{v - v_{in}^c}{v_{rated}^c - v_{in}^c} P_{k,r}^w & , if v_{in}^c \le v \le v_{rated}^c \\ P_{k,r}^w & , else \end{cases} \quad (4)$$

$P_{k,r}^w$: is the rated power of Wind turbine install in bus- k, P_k^w : is the generated power of WT in bus- k, v_{out}^c : is the cut-out speed, v_{in}^c : is the cut-in speed, v_{rated}^c : is the rated speed of the Wind turbine.

The speed-power curve of each Wind turbine (turbine 1, turbine 2, and turbine 3) has been obtained. The technical data is given in Table 1 [25].

Table 1. Technical characteristic of Wind turbine.

Features	Turbine1	Turbine2	Turbine3
Rated power(MW) $P_{k,r}^w$	1.1	2	3
Cut-in speed(m/s) v_{in}^c	3	3	3
Rated speed(m/s) v_{rated}^c	14	15	15
Cut out speed(m/s) v_{out}^c	24	25	25

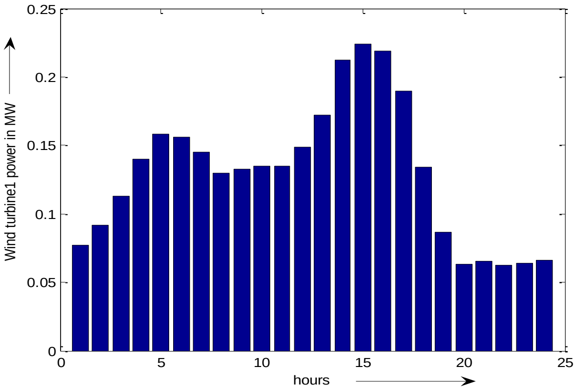

Fig. 1. Wind turbine1 24 hours power generation pattern

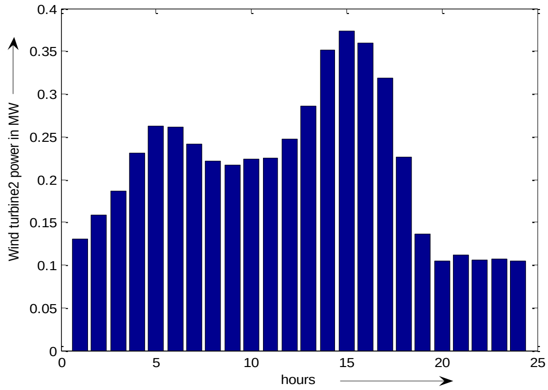

Fig. 2. Wind turbine2 24 hours power generation pattern

In this work, the average value of active and reactive power generation of each turbine and 24 hours power generation pattern of each wind turbine (turbine1, turbine2 and turbine3) shown in Figure 1, 2 and 3 respectively are considered as for turbine1 active power is 0.2171 MW and 0.0309 MW are reactive power, turbine2 active power is 0.1308 MW and reactive power is 0.0186, and turbine3 active power is 0.3254 MW and 0.0464 are the reactive power of the turbine.

$$P(C_{WT}) = a_{WT} + b_{WT} P_{WT} + c_{WT} P_{WT}^2 \quad (5)$$

Where $P(C_{WT})$ is the cost function of WT-based DG and P_{WT} is the generated power in MW. The a_{WT}, b_{WT}, c_{WT} are cost coefficient of Wind turbine in \$, \$/MWh, \$/MWh^2 . In Wind turbine1 cost function (a_{WT} = 4.44\$, b_{WT} =17.23 \$/MWh, c_{WT}= 0.0026 \$/MWh^2) , Wind turbine2 cost function (a_{WT} = 4.45\$, b_{WT} =17.54 \$/MWh, c_{WT}= 0.0028 \$/MWh^2) and Wind turbine3 cost function (a_{WT} = 4.46\$, b_{WT} =17.83 \$/MWh, c_{WT}= 0.0027 \$/MWh^2) are refer to [26].

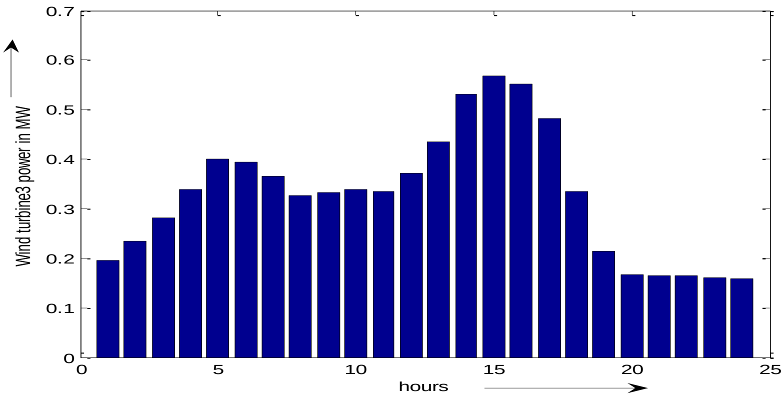

Fig. 3. Wind turbine3 24 hours power generation pattern

3. General OPF Formulation

A general mathematical model minimizing fuel cost of conventional generators and the cost function of WT-based power source has been considered subject to satisfying the equality and inequality constraints is:

$$\text{Min } F\left(h, g, \xi^{\text{int}}\right) \tag{6}$$

Subject to equality and inequality constraints defined as

$$x\left(h, g, \xi^{\text{int}}\right) = 0 \tag{7}$$

$$u\left(h, g, \xi^{\text{int}}\right) \leq 0 \tag{8}$$

Where,
h is state vector of variables V, δ;
g are the control parameters, P_{gk},Q_{gk}, P_{WTk}, Q_{WTk};
ξ^{int} is an integer variable with values {0, 1}. The zero value means without and one value mean with distributed generator in the network.
Objective function F with only cost function of conventional generators is

$$\text{Min } \quad F\left(h, g, \xi^{\text{int}}\right) = \left\{ \sum_{k \in N_g} \left(a_{gk} + b_{gk} P_{gk} + c_{gk} P_{gk}^2\right) \right\} \tag{9}$$

The objective function is the total fuel cost of conventional generators only in equation (9).
The objective functions of combined cost (fuel cost of convectional generators+ WT-based DG cost) in equation (10).

$$F\left(h, g, p, \xi^{\text{int}}\right) = \left\{ \sum_{k \in N_g} \left(a_{gk} + b_{gk} P_{gk} + c_{gk} P_{gk}^2\right) + \xi_k^{\text{int}} * \sum_{k \in NWT} \left(a_{WTk} + b_{WTk} P_{WTk} + c_{WTk} P_{WTk}^2\right) \right\} \tag{10}$$

The line flows from bus-*k* to bus-*j* and bus-*j* to bus-*k* are given as:

$$P_{kjl} = V_k^2 G_{kj} - V_k V_j \left(G_{kj} \cos\left(\delta_k - \delta_j\right) + B_{kj} \sin\left(\delta_k - \delta_j\right)\right) \tag{11}$$

$$P_{jkl} = V_j^2 G_{kj} - V_k V_j \left(G_{kj} \cos\left(\delta_k - \delta_j\right) - B_{kj} \sin\left(\delta_k - \delta_j\right)\right) \tag{12}$$

3.1 Equality Constraints

(a) The presence of distributed generation for all buses, modified equality constraints of real and reactive power flow equations as

$$P_k = P_{gk} + \xi_k^{\text{int}} * P_{WTk} - P_{dk} \ \forall k = 1,2,\ldots N_b \tag{13}$$

$$Q_k = Q_{gk} + \xi_k^{\text{int}} * Q_{WTk} - Q_{dk} \forall k = 1,2,\ldots N_b \tag{14}$$

$$P_k = \sum_{j=1}^{N_b} V_k V_j \left[G_{kj} \cos(\delta_k - \delta_j) + B_{kj} \sin(\delta_k - \delta_j)\right] \quad \forall k = 1,2,\ldots N_b \tag{15}$$

$$Q_k = \sum_{j=1}^{N_b} V_k V_j \left[G_{kj} \sin(\delta_k - \delta_j) - B_{kj} \cos(\delta_k - \delta_j)\right] \quad \forall k = 1,2,\ldots N_b \tag{16}$$

(b) System real and reactive power balance equations: Define total power generation real and reactive (P_{GT},Q_{GT}), total power demand real and reactive (P_{DT},Q_{DT}), and total real and reactive power loss (P_{LT},Q_{LT}), the system real and reactive power balance equations can be written as:

$$P_{GT} - P_{LT} - P_{DT} = 0 \tag{17}$$

$$Q_{GT} - Q_{LT} - Q_{DT} = 0 \tag{18}$$

Using general loss formula, total real and reactive power loss can be expressed as [27]:

$$P_{LT} = \sum_{k=1}^{N_b} \sum_{j=1}^{N_b} \left[\alpha_{kj}(P_k P_j + Q_k Q_j) + \beta_{kj}(Q_k P_j - Q_j P_k)\right] \tag{19}$$

$$Q_{LT} = \sum_{k=1}^{N_b} \sum_{j=1}^{N_b} \left[\gamma_{kj}(P_k P_j + Q_k Q_j) + \xi_{kj}(Q_k P_j - Q_j P_k)\right] \tag{20}$$

$$\alpha_{kj} = \frac{R_{kj}}{|V_k V_j|} \cos(\delta_k - \delta_j) \tag{21}$$

$$\beta_{kj} = \frac{R_{kj}}{|V_k V_j|} \sin(\delta_k - \delta_j) \tag{22}$$

$$\gamma_{kj} = \frac{X_{kj}}{|V_k V_j|} \cos(\delta_k - \delta_j) \tag{23}$$

$$\xi_{kj} = \frac{X_{kj}}{|V_k V_j|} \sin(\delta_k - \delta_j) \tag{24}$$

3.2 Inequality constraints

(a) Real power generation limit of generators at bus-k

$$P_{gk}^{\min} \le P_{gk} \le P_{gk}^{\max}, k = 1,2,\ldots N_g \tag{25}$$

(b) Reactive power generation limit of generators and other reactive sources at bus-*k*

$$Q_{gk}^{\min} \le Q_{gk} \le Q_{gk}^{\max}, k = 1,2,\ldots N_q \tag{26}$$

(c) Voltage limit at bus-k

$$V_k^{\min} \le V_k \le V_k^{\max}, k = 1,2,\ldots N_b \tag{27}$$

(d) Phase angle limit at bus-k

$$\delta_k^{\min} \le \delta_k \le \delta_k^{\max}, k = 1,2,\ldots N_b \tag{28}$$

(e) Line flow limits: These constraints represent maximum power flow in a transmission line and are based on thermal and stability considerations.

$$\left|S_{kj}\right| \leq S_{kj}^{\max} \tag{29}$$

(f) two new inequality constraints are added in an OPF model with WT- based distributed generation.

3.3 Power generation limit

This includes the upper and lower real power generation limit of generators at bus-*k*

(a) Real power generation limit

$$P_{WTk}^{\min} \leq P_{WTk} \leq P_{WTk}^{\max}, k = 1,2,\ldots N_{WT} \tag{30}$$

(b) Reactive power generation limit

$$Q_{WTk}^{\min} \leq Q_{WTk} \leq Q_{WTk}^{\max}, k = 1,2,\ldots N_{WT} \tag{31}$$

(c) Optimal number of distributed generators: This includes the limit on number of maximum distributed generators in the network.

$$N_{WT} = \sum_{k=1}^{Nwt} \xi_k^{\text{int}} \leq N_{WT}^{\max} \tag{32}$$

4. Zip Load Model

The load is modeled as polynomial load [28, 29] as:

$$P_{dz} = P_o(A_p V^2 + B_p V + C_p) \tag{33}$$

$$Q_{dz} = Q_o(A_q V^2 + B_q V + C_q) \tag{34}$$

$$(A_p + B_p + C_p) = (A_q + B_q + C_q) \tag{35}$$

Where, *V* is the p.u. value of the node voltage; P_o, Q_o are the real power and reactive power consumed at the specific node under the reference voltage; A_p, A_q are the parameters for constant impedance (constant *Z*) load component; B_p, B_q are the parameters for constant current (constant *I*) load component; C_p, C_q are the parameters for constant power (constant *P* and *Q*) load component. The values of A_p, A_q , B_p, B_q and C_p, C_q are determined for different load types in distribution systems. n the case of zip load, the different possible values of zip load coefficient are taken at each bus.

(a)Without WT-based DG, power balance equations are:

$$P_k = P_{gk} - P_{dzk} \, \forall k = 1,2,\ldots N_b \tag{36}$$

$$Q_k = Q_{gk} - Q_{dzk} \forall k = 1,2,\ldots N_b \tag{37}$$

(b) With WT-based DG

With distributed generation the real and reactive power constraints are modified in the presence of zip load as:

$$P_k = P_{gk} + \xi_k^{\text{int}} * P_{WTk} - P_{dzk} \, \forall k = 1,2,\ldots N_b \tag{38}$$

$$Q_k = Q_{gk} + \xi_k^{\text{int}} * Q_{WTk} - Q_{dzk} \forall k = 1,2,\ldots N_b \tag{39}$$

The spot price of real and reactive power has been obtained without and with Wind turbine in pool based electricity market model. The general form of Lagrange equation can be written as:

$$L(X, \lambda, \mu) = F(X) + \sum_{k=1}^{m} \lambda_k h_k(X) + \sum_{j=1}^{n} \mu_j g_j(X) \tag{40}$$

At the optimal point, the following conditions must be satisfied as:

$$\left.\frac{\partial L}{\partial \mu_k}\right|_{\underline{x}^*,\underline{\lambda}^*,\underline{\mu}^*} = 0, \quad \mu \geq 0 \quad if \quad g_j(\underline{x}^*) = 0 \quad and \quad \mu_k = 0 \quad if \quad g_j(\underline{x}^*) < 0 \tag{41}$$

Inequality constraints will be active only if the gradient of the function and constraints are opposite as: $(\nabla F)^T \nabla g \leq 0 \Rightarrow \mu_k \geq 0$

Where, X are the variables, λ_k are the Lagrange multipliers corresponding to all equality constraints, and μ_k are the Lagrange multipliers corresponding to inequality constraints. In (42), these Lagrange multipliers have been represented with different symbols for each equality and inequality constraints for distinction. The Langrangian function for the nodal price determination can be written as a function of $P_k$and Q_k as:

$$\begin{aligned} L(P_k, Q_k) = &\sum_{k \in N_g} C_k(P_k) + \\ &\sum_{k \in N_b} (\lambda_{pk}) \left[P_k - \sum_{j=1}^{N_b} V_k V_j \left[G_{kj} \cos(\delta_k - \delta_j) + B_{kj} \sin(\delta_k - \delta_j) \right] \right] + \sum_{k=1}^{N_b} (\lambda_{qk}) \left[Q_k - \sum_{j=1}^{N_b} V_k V_j \left[G_{kj} \sin(\delta_k - \delta_j) - B_{kj} \cos(\delta_k - \delta_j) \right] \right] \\ &+ \vartheta_{pl}(P_{GT} - P_{DT} - P_{LT}) + \vartheta_{ql}(Q_{GT} - Q_{DT} - Q_{LT}) + \sum_{k=1}^{N_g} \mu_k^{\max}(P_k^{\max} - P_k) + \sum_{k=1}^{N_g} \mu_k^{\min}(P_k - P_k^{\min}) + \\ &\sum_{k=1}^{N_q} \eta_k^{\max}(Q_k^{\max} - Q_k) + \sum_{k=1}^{N_q} \eta_k^{\min}(Q_k - Q_k^{\min}) + \sum_{k=1}^{N_b} \gamma_k^{\max}(V_k^{\max} - V_k) + \sum_{k=1}^{N_g} \gamma_k^{\min}(V_k - V_k^{\min}) + \sum_{k=1}^{N_b} \zeta_k^{\max}(\delta_k^{\max} - \delta_k) \\ &+ \sum_{k=1}^{N_g} \zeta_k^{\min}(\delta_k - \delta_k^{\min}) + \sum_{l=1}^{N_l} \psi_l (S_l^{\max} - S_l) \end{aligned} \tag{42}$$

Knowing Lagrangian function, real and reactive power nodal price at any bus-k can be determined as the partial derivative of the Lagrangian function with respect to injected real and reactive power equated to zero as; $\frac{\partial L}{\partial P_k} = 0$, $\frac{\partial L}{\partial Q_k} = 0$. The marginal price of real and reactive power at each generator node can be obtained as:

$$\lambda_{pk} = \frac{\partial \left(\sum_{k \in N_b} C_k(P_k) \right)}{\partial P_k} + \mu_k^{\max} - \mu_k^{\min} + \vartheta_{pl}\left(1 - \frac{\partial P_{LT}}{\partial P_k}\right) - \vartheta_{ql}\left(\frac{\partial Q_{LT}}{\partial P_k}\right) \tag{43}$$

$$\lambda_{qk} = \eta_k^{\max} - \eta_k^{\min} - \vartheta_{pl}\left(\frac{\partial P_{LT}}{\partial Q_k}\right) + \vartheta_{ql}\left(1 - \frac{\partial Q_{LT}}{\partial Q_k}\right) \tag{44}$$

The results have been obtained by solving mixed integer nonlinear programming problem in GAMS using a discrete continuous optimization package (DICOPT) solver. The interfacing of MATLAB and GAMS environment to obtain the solution has been utilized and the interfacing.

5. Results and Discussion

The proposed approach for an optimal distribution generation location has been applied to IEEE 24-bus reliability test system [30]. The results have been obtained for fuel cost, losses, power generation schedule for conventional and distributed generators in the presence of WT-based DGs. Four different cases have been considered for analysis. The results have also been obtained without and with presence of WT-based DGs for comparison. The maximum number of WT-based DGs is defined in the optimization problem for the different cases. The results are also obtained with zip load considering variation of ZIP load at each bus for comparison. The results are given in tabular form in Tables 2 to 5. The results have been obtained considering different cases with different number of distributed generators.

Case 1: (without WT- based distributed generator)
Case 2: (with one WT-based distributed generator)
Case 3: (with two WT-based distributed generators)
Case 4: (with three WT- based distributed generators)

5.1. Results without and with WT based DG with Constant P, Q and Zip Load Model

The results have been obtained without and with WT- based DG considering the cost of both conventional generators and DGs. The results have also been obtained without consideration of cost of Wind turbine for comparison and also constant P,Q and ZIP load model are presented.

5.1.1. Results with Wind turbine Cost Function

Table2. Results for minimization of combine cost with constant load.

	Case1	Case 2	Case 3	Case 4
Fuel cost+ DG (WT) cost($/h)	14625.4763	14623.5884	14623.4338	14624.4338
DG cost($/h)	0	38.5918	36.9290	41.6369
PLT(p.u.MW)	0.4559	0.4858	0.4756	0.4727
QLT(p.u.MVar)	-1.4134	-1.4278	-1.5007	-1.5090
Total load (p.u.MW)	28.5	28.5	28.5	28.5
Total load(p.u.MVar)	5.8	5.8	5.8	5.8
Optimal bus location of DG(WT)	0	10	3,10	3,6,10
Total DG(WT) size(p.u.MW)	0	0.3254	0.6508	0.8679
Total DG(WT) size(p.u.MVar)	0	0.0010	0.0474	0.0484
Pg(p.u.MW)	28.9559	27.7621	27.8046	27.6972
Qg (p.u.MVar)	4.3866	4.3685	4.2271	4.4271

Table3. Results for minimization of combine cost with Zip load.

	Case1	Case 2	Case 3	Case 4
Fuel cost+ DG (WT) cost($/h)	14620.2096	14619.7105	14614.0025	14614.8947
DG cost($/h)	0	17.8124	50.8135	58.5181
PLT(p.u.MW)	0.5108	0.5136	0.4936	0.4916
QLT(p.u.MVar)	-0.6854	-0.7963	-1.0636	-1.0877
Total load (p.u.MW)	28.2875	28.2877	27.9821	27.9833
Total load(p.u.MVar)	5.7567	5.7567	5.6947	5.6950
Optimal bus location of DG(WT)	0	10	3,10	3,6,10
Total DG(WT) size(p.u.MW)	0	0.3254	0.6508	0.8679
Total DG(WT) size(p.u.MVar)	0	0.0010	0.0474	0.0484
Pg(p.u.MW)	28.7984	28.2365	26.8644	26.6640
Qg (p.u.MVar)	5.0713	4.9586	4.4467	4.4244

The simulation of combined cost (fuel cost including DG cost) have been determined by solving nonlinear optimization problem as explained in section3. The effect of zip load is obtained from the modification given in section4 in the optimization problem that is the modified real and reactive power flow equations.Table2 contains the result of the minimization fuel cost including DG cost with constant load and Table3 contains the result of the same problem with zip load. Each table contains the value of fuel cost, DG cost, total active and reactive power loss, optimal location and size of DGs, and conventional generation schedule. The nodal price variations for both real and reactive power at each bus have been obtained without and with the presence of distributed generation for the different cases with and without Zip load. The marginal price variations are shown in Figure 4, 5, 6 and 7. In Figures 4 and 6 marginal prices for active power are shown with constant and zip load respectively. It is observed from Figure 4 and 6 that in the presence of WT-based DGs, the nodal prices have been considerably reduced and the variation of real power prices has also become uniform at all the buses. It is also observed that with zip load the nodal price are less than with the constant load. With constant load the minimum marginal price occur at bus 7 whereas with zip load minimum marginal price occur at bus 22. With the presence of WT-based DGs, it is observed that two price zones can be represented by single price zone. Thus, the consumers in both the zones will pay similar price.

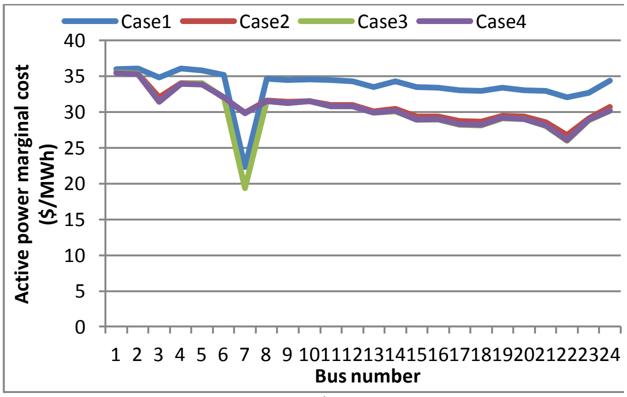

Fig.4. Active Power Marginal Cost ($/MWh) with Constant Load

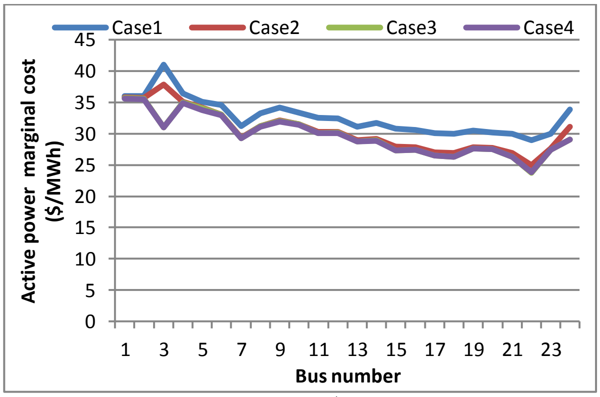

Fig.6. Active Power Marginal Cost ($/MWh) with Zip Load

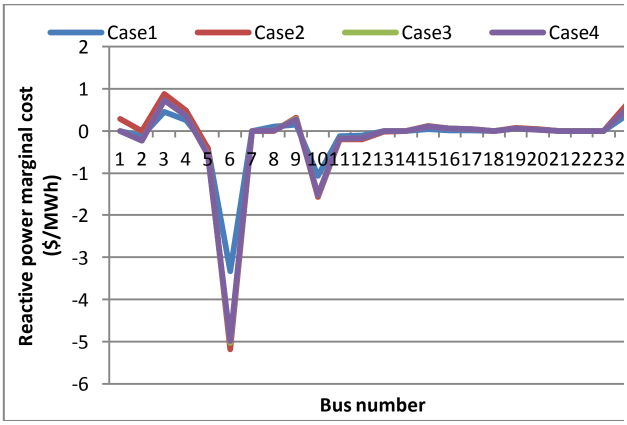

Fig.5. Reactive Power Marginal Cost ($/MWh) with Constant Load

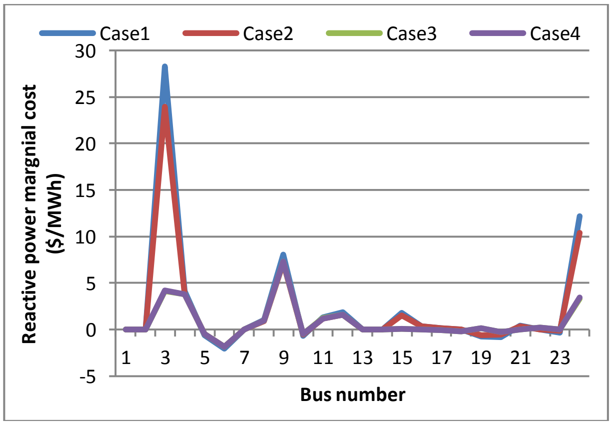

Fig.7. Reactive Power Marginal Cost ($/MWh) with Zip Load

The best results have been obtained in Case4 with three numbers of WT-based DGs. With more penetration of WT-based DGs in the network, the improvement in the result is found to be marginal. Figure 5 and 7 shows the reactive power price variation without and with WT-based DGs with constant and zip load respectively. It is observed from Figure.5 and 7 that the reactive power price is high at nodes 6 with constant load and with zip load as compared to other buses. Because at these nodes the reactive power absorption is quite high due to the presence of reactor and transformers.

5.1.1.1 Comparison of Constant and Zip Load with Combine Fuel Cost Case

The average nodal price variation for each case is shown in the Figure 8 for both load cases. It is observed that nodal price reduces considerably in the presence of WT-based DGs and become almost uniform. The data series written above is for the constant load and data series written below is for Zip load. For all the Cases average real power price with Zip load is less than with constant load. It is observed that with both load (constant load and Zip load) the Case4 (with three WT-based DGs) average nodal price are minimum (30.5603$/MWh at constant load and 29.7524$/MWh at Zip load). The fuel cost reduction in the presence of WT-based DGs with constant as well as zip load is shown in Figure.9. It can be seen that the saving in fuel cost of conventional generator is more with zip load than the saving with constant load for all the cases. Minimum fuel cost (14624.3309$/h at constant load) for Case 4 (with three WT-based DGs) and 14614.0025$/h at Zip load) is found for Case3 (with two WT-based DGs).

The impact on the real power loss in the presence of WT-based DGs is shown in Figure.10. The above data series is given for Zip load and below data se series is given for constant load. The system total loss Case1 (without WT-based DG) with constant load are 0.4559 (MW) and with Zip load total loss are 0.5108 (MW). In Case2 (with one WT-based DG) the system loss are 0.4858 MW (with constant load) and 0.5136 MW (with Zip load). In Case3 (with two WT-based DGs) the total real power loss are 0.4756 MW (with constant load) and 0.4936 MW (with Zip load). There is considerable reduction in losses in each case. In Case4 (with three WT-based DGs) the total real power loss are 0.4727 MW (with constant load) and 0.4916 MW (with Zip load). It is observed that losses are considerably reducing with WT-based DG and maximum reduction take place in Case4 (with three WT-based DG) for each load model. With Zip load losses are more as compared to the constant load.

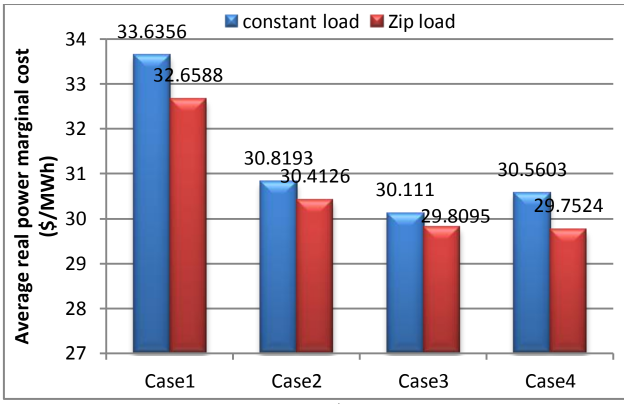

Fig.8. Average Power Marginal Cost ($/MWh) with Constant and Zip Load

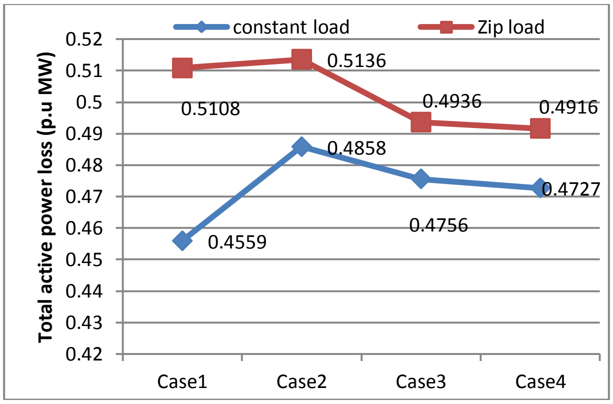

Fig.10. Total Active Power Loss (p.uMW) with Constant and Zip Load

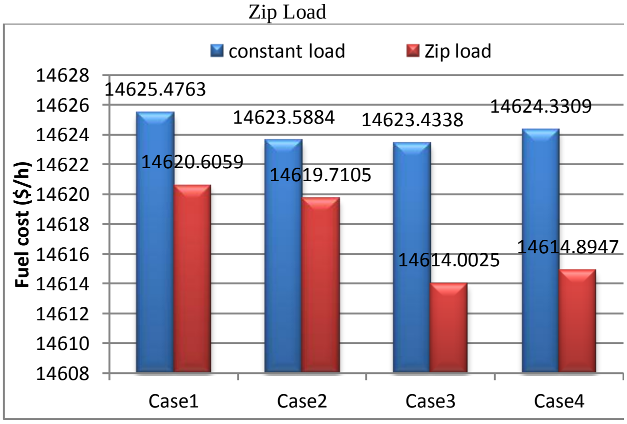

Fig.9. Combine (Convectional + DG) Generator Fuel Cost ($/hr) with Constant and Zip Load

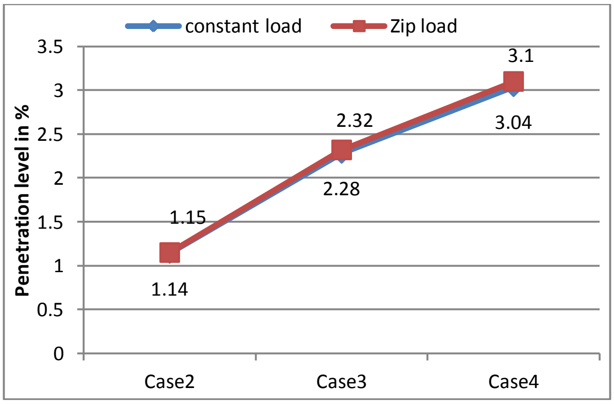

Fig.11. Penetration level in % with Constant and Zip Load

Figure 11 has been shown the distributed generation share for different cases. The below data series is given for constant load and above data se series is given for Zip load. In Case2 and Case3 the penetration level is more in case of Zip load than with constant load. In Case4 the penetration level is slightly more in case of Zip load than with constant load. It is observed that the saving is more with more penetrations. Optimal number of WT-based DGs required obtaining best results of fuel cost savings is found to be three with both constant as well as Zip load.

5.1.2. Results with Wind turbine DG without considering Cost of DGs

We have also obtained the results without and with WT-based DG without considering cost of DGs.Table4 contains the result of the minimization fuel cost of convectional generator without considering WT-based DG cost with constant load and Table5 contains the result of the same problem with Zip load. Each table contains the value of fuel cost, DG cost, total active and reactive power loss, optimal location and size of DGs, and conventional generation schedule.

Table4. Results for minimization of fuel cost of conventional generator only with Constant load.

	Case1	Case 2	Case 3	Case 4
Fuel cost+ DG (WT) cost($/h)	14625.4763	14620.9024	14603.4769	14599.1377
DG cost($/h)	0	6.6937	20.5243	27.2181
PLT(p.u.MW)	0.4559	0.4594	0.4718	0.4706
QLT(p.u.MVar)	-1.4134	-1.3689	-1.4142	-1.4171
Total load(p.u.MW)	28.5	28.5	28.5	28.5
Total load(p.u.MVar)	5.8	5.8	5.8	5.8
Optimal bus location of DG(WT)	0	6	3,10	3,6,10
Total DG(WT) size(p.u.MW)	0	0.1308	0.474	0.7816
Total DG(WT) size(p.u.MVar)	0	0.0010	0.0474	0.0484
Pg(p.u.MW)	28.9559	28.8286	28.3210	28.1890
Qg (p.u.MVar)	4.3866	4.4301	4.3384	4.3345

Table5. Results for minimization of fuel cost of conventional generator only with Zip load.

	Case1	Case 2	Case 3	Case 4
Fuel cost+ DG (WT) cost($/h)	14620.6059	14606.9727	14596.6541	14589.2703
DG cost($/h)	0	10.2622	20.5243	28.7824
PLT(p.u.MW)	0.5108	0.5036	0.5055	0.5036
QLT(p.u.MVar)	-0.6854	-0.7792	-0.8379	-0.8666
Total load (p.u.MW)	28.2875	28.1753	28.1743	28.1749
Total load (p.u.MVar)	5.7567	5.7340	5.7338	5.7339
Optimal bus location of DG(WT)	0	3	3,10	3,5,10
Total DG(WT) size(p.u.MW)	0	0.3254	0.6508	0.8679
Total DG(WT) size(p.u.MVar)	0	0.0464	0.0474	0.0484
Pg(p.u.MW)	28.7984	28.3535	28.0290	27.8106
Qg (p.u.MVar)	5.0713	4.9089	4.8485	4.48189

5.1.2.1. *Comparison of Constant and Zip Load with Convectional Generator Fuel Cost Case*

The average nodal price variation at each bus with constant and zip load for comparison is shown in Fig. 12. It is observed that nodal price reduces considerably in the presence of WT-based DGs and become almost uniform. The maximum reduction occurs in marginal price for Case4 (with three WT-based DGs), for constant (31.4331$/MWh) as well as zip load (30.0676$/MWh). For Case1, Case2, and Case3 average real nodal price with zip load is less than with constant load. In Figure13 has shown the fuel cost reduction in the presence of WT-based DGs with constant as well as zip load. It can be seen that the reduction in fuel cost of conventional generator is more with zip load than the reduction with constant load.

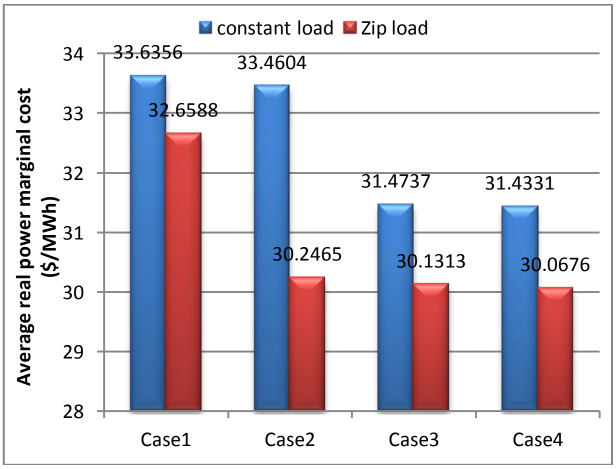

Fig.12. Average Real Power Marginal Cost ($/MWh) with Constant and Zip Load

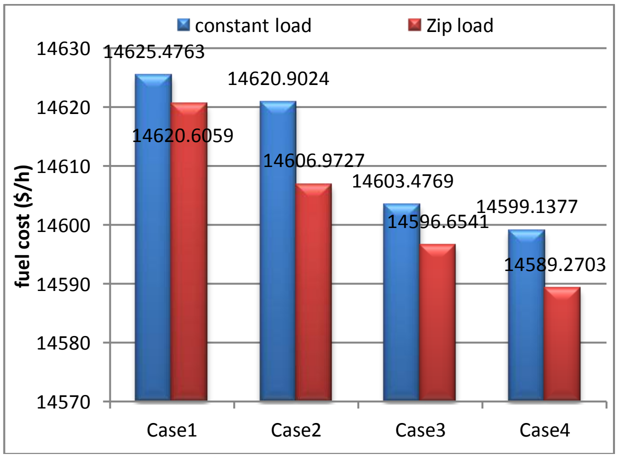

Fig.13. Fuel Cost ($/h) of Convectional Generator with Constant and Zip Load

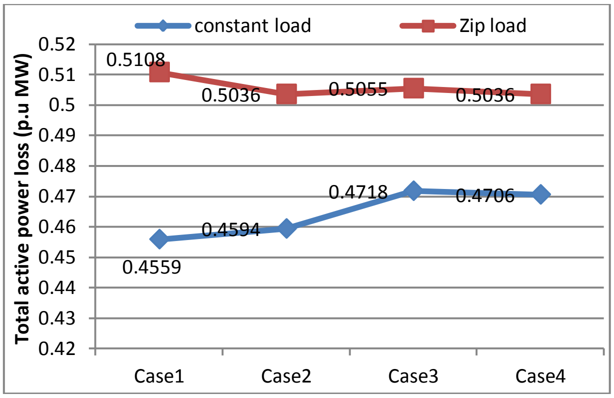

Fig.14. Total Active Power Loss (p.u MW) with Constant and Zip Load

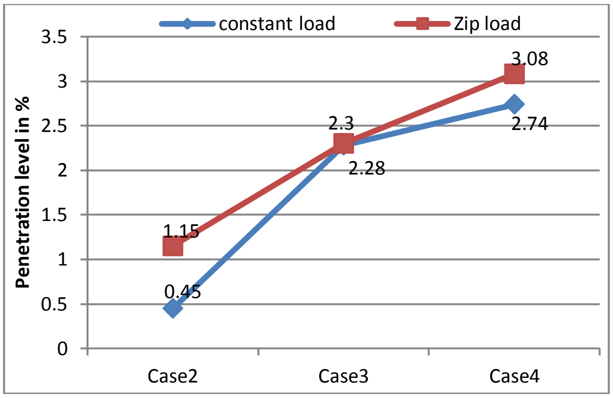

Fig.15. Penetration Level in % with Constant and Zip Load

The fuel cost reduces for all the cases. Minimum fuel cost (14599.1377$/h in constant load and 14589.2703$/h in Zip load) is found with four WT-based DGs in Case4. The impact on the real power loss in the presence of WT-based DGs is shown in Figure.14. The above data series are given for zip load and below data series is given for constant load. The total active power losses Case1 (without WT-based DG) are .4559 MW (with constant load) and .5108 MW (with zip load). In Case2 (with one WT-based DG) the system loss are 0.4594 MW (with constant load) and 0.5036 MW (with zip load). In Case3 (with two WT-based DGs) the total real power loss are 0.4718 MW (with constant load) and 0.5055 MW (with zip load). There is considerable reduction in losses in each case. In Case4 (with three WT-based DGs) the total real power loss are 0.4706 MW (with constant load) and 0.5036 MW (with zip load. It is observed that losses are considerably reducing with WT-based DG and maximum reduction take place in Case4 (with three WT-based DG) for each load model. With zip load Losses are more as compared to the constant load. The ratio of DG size to the total demand in the system is called the penetration level of the DGs. The distributed generation share for different cases has been shown in Figure 15. The penetration level is slightly more in case of zip load than with constant load. It is observed that the saving is more with more penetrations level of WT-based DGs. Optimal number of WT-based DGs required obtaining best results of fuel cost minimization is found to be three with both constant as well as zip load.

6. Conclusions

In this paper a mixed integer non-linear programming approach has been utilized for optimal location and optimal number of distributed generators. Pattern of real and reactive power nodal price, real power loss, and fuel cost have been determined for constant P, Q as well as zip load. Optimal number of WT-based DGs was found to be three for constant as well as zip load to obtain maximum fuel cost saving. Saving in fuel cost is more in case of zip load. The minimum fuel cost for without considering WT- based DG cost in Case4 (with three WT-based DG) of conventional generator14599.1377$/hr (with constant load) and 14589.2703$/hr (with Zip load) and for combined cost (fuel cost of conventional generator including DG cost) in Case3 (with two WT-based DG) it is 14623.4338$/hr (with constant load) and 14614.0025$/hr (with Zip load). It is observed that the nodal price reduces with DG for both load cases

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