

Optimal placement and sizing of wind / solar based DG sources in distribution system

Wanlin Guan*, Niao Guo, Chunlai Yu, Xiaoguang Chen, Haiyang Yu, Zhipeng Liu, Jiapeng Cui

State Grid Heilongjiang Electric Power Company Limited Electric Power Research Institute, Harbin, Heilongjiang, 150030, China

*Corresponding author e-mail: wanlinguan@163.com

Abstract. Proper placement and sizing of Distributed Generation (DG) in distribution system can obtain maximum potential benefits. This paper proposes quantum particle swarm algorithm (QPSO) based wind turbine generation unit (WTGU) and photovoltaic (PV) array placement and sizing approach for real power loss reduction and voltage stability improvement of distribution system. Performance modeling of wind and solar generation system are described and classified into PQ\PQ (V)\PI type models in power flow. Considering the WTGU and PV based DGs in distribution system is geographical restrictive, the optimal area and DG capacity limits of each bus in the setting area need to be set before optimization, the area optimization method is proposed. The method has been tested on IEEE 33-bus radial distribution systems to demonstrate the performance and effectiveness of the proposed method.

1. Introduction

Distributed generation (DG) in power system networks has rapidly increased as the demand of power system is growing exponentially. DG is small-scale power generation and usually located in distribution network [1]. DG units are mainly energized by wind, solar and fuel cell and have many advantages over centralized power generation. The optimum DG placement and sizing at planning stage of distribution system is necessary to achieve the reduction of power system losses and improved voltage profile [2]. However, installing DG units at non-optimal place may get an opposite effect to what is desired. Selecting the best places for installing DG units and their preferable sizes in large distribution systems is a complex combinatorial optimization problem.

The optimal placement and sizing of DG in distribution networks has been continuously studied in order to achieve the maximum benefits. J.O. Kim [3] presented the improved Hereford Ranch algorithm to solve the DG allocation problem and getting significant effect. An analytical approach put forward by A Naresh to allocate DG for minimizing the total power losses in primary distribution network [4], DG is placed one by one in the network to obtain minimum power loss of the system. Authors in [5] considered a simple conventional iterative search technique along with NR (Newton Raphson) method of load flow study is implemented. But the analytical approach is not suitable for the large scale network for its large amount of calculation. GA [6] and PSO [7] algorithm, as the representative of the artificial intelligence algorithm, are applied to optimal the place and size of DG. Ref. [8] combined discrete



enabled PSO and GA optimization methods to perform optimal location and DG size. However, in the later stage of evolution, the two algorithms are easy to fall into local optimal solution or stagnant state.

In [9], the voltage stability was considered as an objective function when dealing with optimum location of DG units for minimizing overall cost. Kumar and Banerjee [10] have studied about sizing and sitting of PV module and biomass gasifier based DG in isolated power system for distribution loss reduction only. The two objectives, minimization of total installation and operational costs, and minimization of the risk factor have been taken into account for system planning in Ref [11]. Considering the interests of power supply and users, minimization of power losses and maximization of voltage stability due to finding weakest voltage bus as well as due to weakest link in the system are considered in fitness function [12].

However, in most of them, DGs are treated as PQ model type only (the real and reactive power output of DG is constant). In actually, power generation of wind unit and solar power need be detailed modeled based on their mechanism of generation. Wind and solar power DG have their operation modes and control characteristics, so handle DG as PQ model in power flow is not accurate.

Partha Kayal, et. [13] realized the sitting of the wind and solar based DG, but the sizing optimum of DG was not considered. Though Ref. [14] presented an approach to find the optimum size of DG of three types at optimal power factor, the optimum placement of DG is also not solved. So optimal sitting and sizing of wind and solar based DG in distribution system simultaneously is necessary and impendency.

In this paper, a QPSO methodology is proposed to optimal placement and sizing of wind and solar based DG sources for real power loss reduction and voltage stability improvement of distribution system. The paper is organized as follows. In first section, double objective formulation is found as problem formulation for optimum DG placement and sizing. Second section is composed of performance modeling of wind and solar power generation system. In third section, area optimization method of DG units is proposed. Section fourth, basic mechanism of QPSO is presented, and also states the procedure to select appropriate locations and size for DG units using QPSO method. In fifth section, the method this paper put forward is tested in IEEE33-bus distribution systems. Finally some relevant conclusions are drawn.

2. Problem Formulation

Considering the interests of power supply and users, effectively combining the economy and safety, minimization of real power losses, maximization of voltage stability are considered as double objective formulation for optimum DG placement and sizing.

2.1. Real Power Losses Formulation

Considering N bus distribution system, the objective function for the minimization of real power loss is described as

$$f_{ploss} = \sum_{i=1}^{N-1} k_i r_i \frac{P_i^2 + Q_i^2}{U_i^2} \quad (1)$$

Where r_i is the resistance of the i_{th} branch; U_i is the voltage magnitude at bus i ; P_i , Q_i are the active and reactive power inject bus i .

2.2. Voltage Stability Formulation

An improved distribution system voltage stability index is adopted. This index takes power flow solution as its criterion, the detailed description is as follows.

$$U_{stab,k} = 4 \left[(XP_j - RQ_j)^2 + (XQ_j + RP_j)U_i^2 \right] / U_i^4 \quad (2)$$

Where U_{stab} , k is the voltage stability index of line k (eg. bus i and j are start bus and end bus); R and X , are the resistance and reactance of line k respectively, P_j and Q_j are the active power and reactive power injected into bus j respectively; U_i is the voltage amplitude of bus i .

When the system is stable, all branch voltage stability of all branches values must be less than 1.0. However, when the system trend to crash, the crash bus must be the weakness point. So we can analyze the voltage stability of the system according to the distance between U_{stab} and 1.0.

The maximum voltage stability index value is the $f_{U_{stab}}$ of the whole system and follows that

$$f_{U_{stab}} = \max \{U_{stab,1}, U_{stab,2}, \dots, U_{stab,N}\} \quad (3)$$

Where N is the bus number of network; $U_{stab,1}, U_{stab,2}, \dots, U_{stab,N}$ are the voltage stability of branch 1, 2, ..., N respectively.

2.3. Double objective formulation

Weight coefficient method is used to convert real power loss reduction and voltage stability improvement into a single Double objective formulation.

$$\min f = aw_1 \frac{f_{ploss}}{ploss_{init}} + bw_2 \frac{f_{ustab}}{U_{stab}_{init}} \quad (4)$$

Where f is the double objective optimization function; $ploss_{init}$, U_{stab}_{init} is the initial real power loss and voltage stability index, by this time DG is not access to the network. a and b are the penalty factors of active loss and static voltage stability index respectively; w_1 , w_2 are the weighting factors of active loss and static voltage stability index respectively, however, $w_1 + w_2 = 1$. If $w_1 = 1$, $w_2 = 0$, the single objective optimization is real power loss. Otherwise, the voltage stability index is treated as the single objective optimization.

a and b are defined as follows;

$$a = \begin{cases} N & \frac{f_{ploss}}{ploss_{init}} \geq 1 \\ 1 & \text{else} \end{cases} \quad (5)$$

$$b = \begin{cases} N & \frac{f_{ustab}}{U_{stab}_{init}} \geq 1 \\ 1 & \text{else} \end{cases} \quad (6)$$

If the optimization of the real power losses greater than its initial (without DG) value, then $a = N$, N is a big positive value, which can increase the f value and give up this solution. According to this strategy, the objective function can toward to the optimal solution direction. Otherwise, $a = 1$. Update rule of b is same with a .

Subject to

- (I) System power flow equations must be satisfied.
- (II) Branch capacity and bus voltage constraints:
- (III) DG capacity constraint

3. Performance modelling of wind and solar generation system

Power generation of Wind Turbine Generation Unit (WTGU) and PV array depends on their model and resource such as wind speed, solar radiation and ambient temperature. In this section modeling of WTGU and PV array is discussed.

3.1. Performance model of WTGU

Direct driven synchronous wind turbines are usually connected to grid by transducer which can control generator's active power output and reactive power respectively. So the direct driven synchronous and doubly fed wind turbines may be described as PQ model in flow calculations as well as power factor controlled combined heat and power generators. The type of DG is capable of injecting both real and reactive power.

Fixed speed and slip controlled asynchronous wind turbines which absorb reactive power from power system to build the magnetic field, don't have the ability of voltage regulation and this will lead to the increasing of network real power losses. Generally, compensative capacities are used to supply the reactive power which asynchronous generator need [15].

3.2. Performance model of PV array

Generally photovoltaic system is connected to power system by current controlled inverter. Photovoltaic system only supplies active power to power system. If photovoltaic system equipped with current inverter, the current output is constant. The corresponding compensative reactive power can be gotten by Eq. (7).

$$Q^{k+1} = \sqrt{|I_m|^2 (e_k^2 + f_k^2) - P^2} \quad (7)$$

Where Q^{k+1} is the reactive power of DG in the $(k+1)$ iteration; e_k and f_k are the real part and imaginary part of voltage in the k iteration respectively; I_m is the current magnitude of DG; P is the active power of DG.

3.3. Power flow model type of WTGU and PV array

According to the Section 2.1 and 2.2, the WTGU and PV model DG will be classified into three type model in power flow, and described in Tab. 1.

Table 1. The classification of DG in power flow.

DG type	Classification	Model type in power flow
WTGU	Direct driven synchronous wind turbines	PQ
	Doubly fed wind turbines	PQ
	Fixed speed and slip controlled asynchronous wind turbines	PQ(V)
PV	photovoltaic system equipped with current inverter	PI

4. Area optimization method

Installing WTGU and PV based DGs in distribution system is geographical restrictive. As the storage of the local wind and solar power in distribution system are not identical, some areas are not suitable for installing WTGU or PV based DGs. So the optimal area and DG capacity limits of each bus in the setting area need to be set before optimization.

Based on this idea, this paper presents the area optimization method and describing as follows:

Two matrices are defined: Area optimization Matrix NDG , DG capacity limit Matrix M . The size of NDG is $1 * N$, The size of M is $2 * N$, and N is the bus number of the optimal area. NDG records the optional installation buses of the optimization area, but not mean all the buses need to be installed DG. M records the lower and upper limit of DG capacity in the optimal area. If the DG capacity less than the lower limit of DG, this bus will not be installed DG.

5. Optimal placement and sizing of DG

5.1. Overview of QPSO

Aiming at the shortcomings of PSO, Sun et al. proposed quantum particle swarm algorithm (QPSO) in 2004[16], QPSO improves the classic particle swarm optimization (PSO), combing the idea of quantum physics and key consideration of each particle's current local optimum information and global optimum location information. QPSO bases on DELTA, considering that the particles have quantum behavior. In quantum space, the particles make stochastic optimization search in the whole feasible solution space, so QPSO has stronger global optimization capability than standard PSO [17]. QPSO algorithm makes use of the wave function $\psi(X, t)$ to describe the state of the particles, obtains probability density function particles appear in a certain point by solving the Schrödinger Equation and gets particles position Eq. (8) as follows through Monte Carlo random simulation:

$$X(t) = p \pm \frac{L}{2} \ln\left(\frac{1}{u}\right) \quad (8)$$

Where

$$L(t+1) = 2 * \beta |mbest - X(t)| \quad (9)$$

QPSO algorithm evolutions are as follows:

$$mbest(t) = \frac{1}{M} \sum_{i=1}^M P_i(t) = \left[\frac{1}{M} \sum_{i=1}^M P_{i1}(t), \frac{1}{M} \sum_{i=1}^M P_{i2}(t), \dots, \frac{1}{M} \sum_{i=1}^M P_{iD}(t) \right] \quad (10)$$

$$P_{id}(t) = \varphi * P_{id}(t) + (1 - \varphi) * P_{gd}(t) \quad (11)$$

$$X_{id}(t+1) = P_{id}(t) \pm \beta * |mbest(t) - X_{id}(t)| * \ln\left(\frac{1}{u}\right) \quad (12)$$

Where M is the number of particles in the population; D is the particle dimension; u and φ are the uniformly distributed random number in $[0,1]$ respectively; $P_{id}(t)$ is the current optimum position of particle i in the iteration t ; $P_{gd}(t)$ is the globally optimum position of particle i in the iteration t ; $mbest(t)$ is population average optimum position of all particles in the iteration t ; $P_{id}(t)$ is a random point between $P_{id}(t)$ and $P_{gd}(t)$. β is the contraction and expansion coefficient, it is an important parameter of QPSO. For better optimization effect, β dynamic changes with the number of iterations as follow:

$$\beta = m - (m - n) * \frac{t}{MaxIters} \quad (13)$$

Where, $MaxIters$ is the maximum number of iterations. β increases from n to m with the iterations linearly, usually $m=1, n=0.5$.

5.2. The procedure for Optimizing placement and sizing of DGs

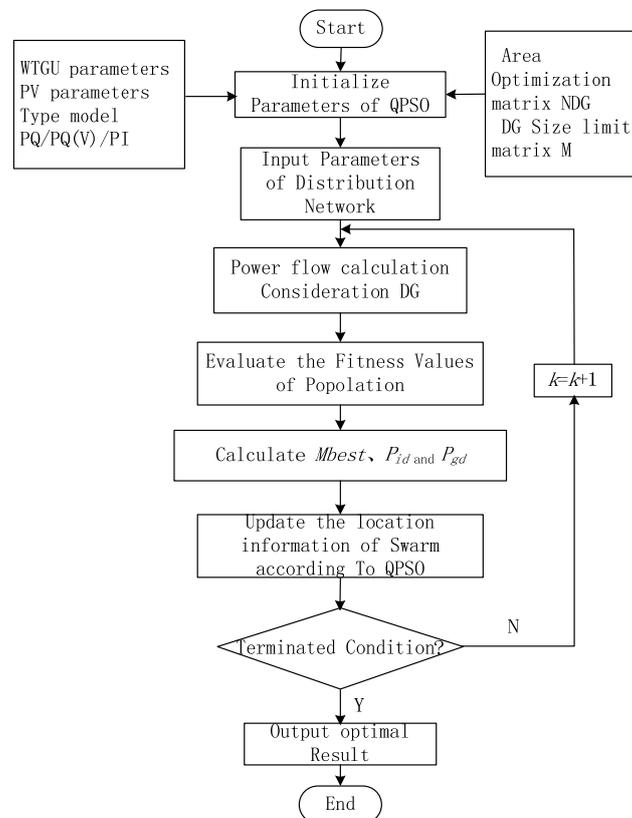


Figure 1. The flow chart of optimal placement and sizing of wind / solar based DG sources using QPSO.

6. Experiment results

The proposed method is tested on IEEE33-bus radial distribution systems, and results are obtained to evaluate its effectiveness. The substation voltage is considered as $1p.u$, Assume P_{loss} is the real power losses of network; U_{stab} is the voltage stability index. V_{min} is lowest voltage of all buses. IEEE33 bus system is shown in Fig.2.

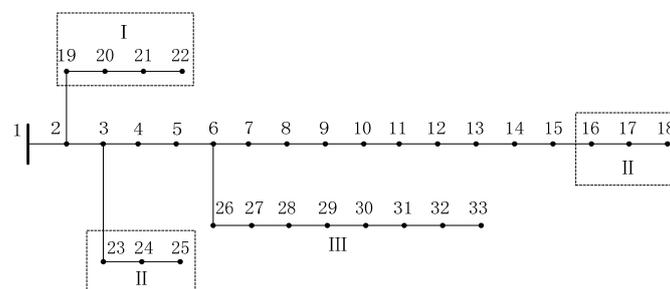


Figure 2. IEEE33 bus system

According to section 3, assume place DGs in three areas, these areas are defined as below. Area I: $NDG=[19,20,21,22]$; Area II: $NDG=[16,17,18,23,24,25]$; Area III: $NDG=[26,27,28,29,30,31,32]$. The total real and reactive power loads of the system are 3715kW and 2300kvar respectively. The size of population is 50 and maximum number of iteration is 100 for all algorithms. Initial real power losses

(P_{loss}) is 202.6463kW, voltage stability index (U_{stab}) is 0.0792, and the lowest voltage of all buses (V_{min}) is 0.9183pu.

Multiple asynchronous wind turbine (WTGU) and photovoltaic power generation (PV) type DGs will be placed in area I and II.

Install asynchronous wind turbines (WTGU) and photovoltaic system (PV) type DGs in area I and II. According to section 2, asynchronous wind turbines and photovoltaic power generation will be processed as PQ (V) model and PI model in power flow calculation respectively.

This experiment is divided into six schemes, and defined as Table 1.

Table 2. Description of six schemes

Scheme Number	DG model	Upper limit/kW	Lower limit/kW
1	PQ(V)	2400	300
2	PQ(V)	2400	300
3	PQ(V)	600	300
4	PI	2400	300
5	PI	2400	300
6	PI	600	300

As WTGU and PV model DG have lower capacity limit, if the capacity of DG is less than the lower limit, the bus is not suitable for locating DG. The results are shown in Tab. 3. Fig.3 displays the convergence characteristics of scheme 2 and 5; Comparison voltage magnitude of scheme 2 and 5 is shown in Fig.4

Table 3. Optimal allocation results of WTGU and PV model DGs

Scheme	Area	DG type	Placement(Sizing/kW)	f	P_{loss}/kW	U_{stab}	$V_{min}/p.u.$
1	I	PQ(V)	19(876.5);20(300);21(0);22(0)	0.9924	200.0077	0.0790	0.9139
2	II	PQ(V)	16(787.8);17(0);18(0); 23(825.2);24(0);25(422.7)	0.8175	158.1729	0.0677	0.9293
3	II	PQ(V)	16(404.4);17(371.2);18(0); 23(443.8);24(382.3);25(362.4)	0.8197	158.5534	0.0679	0.9290
4	I	PI	19(1089.5);20(0);21(0);22(0)	0.9851	197.0910	0.0790	0.9142
5	II	PI	16(501.3);17(0);18(0); 23(1080.8);24(0);25(557)	0.5842	88.4414	0.0580	0.9366
6	II	PI	16(500.6);17(0);18(0); 23(521.2);24(524.6);25(593.2)	0.5846	88.6169	0.0580	0.9365

Scheme1 plans to optimal placement and sizing of WTGU DG in area I. The optimization results show that bus 19 and 20 allocate DG of 876.5kW and 300kW respectively. However, bus 21 and 22 is not suitable for allocate DG. Assuming Rated power of WTGU is 300kw, so the bus 19 and 20 will be located 3units and 1 unit WTGU respectively.

Scheme2 plans to optimal placement and sizing of WTGU DG in area II. The optimization results show that bus 16 allocates DG of 787.8kW.

WTGU absorbs reactive power of 540.4kvar. According to the automatic switching program of parallel capacitor group of reactive power, 6 groups of parallel capacitor need to be accessed, the power factor of the WTGU increased from 0.8246 to 0.8246 and meets the demand of power factor. The actual compensation reactive power is 217.8kvar. However, WTGU also need absorbs 338.5kvar reactive power from the system.

After optimization, P_{loss} decrease from 202.6463kW to 158.1729kW, and reduction rate is 21.94%. U_{stab} decrease from 0.0792 to 0.0677, and reduction rate is 14.52%.

The difference of scheme 3 and 2 is the upper capacity limit. This scheme is set to analysis the capacity limit effect on the optimization results. The optimization results that the location of DG is different with scheme 2. Bus 18 is still not locate DG, the capacity of DG locating to the buses is between 300 and 600kw. As the upper limit of scheme 3 is less then scheme 2, the *Ploss* and *Ustab* are slightly bigger than scheme 2.

Scheme 4-6 plan to optimal placement and sizing of PV DG. As PV model DG do not need to absorb reactive power from the network, so *Ploss* and *Ustab* of scheme 4-6 is small then scheme 1-3. Compare with scheme 5 and 2, the placement of DG is same, it can be find that the DG model will not effect on the placement of DG so much. *Ploss* decrease from 158.1729kW (scheme 2) to 88.4414kW (scheme 5). *Ustab* decrease from 0.0677(scheme 2) to 0.0580(scheme 5).Scheme 6 and 3 also have the same rule.

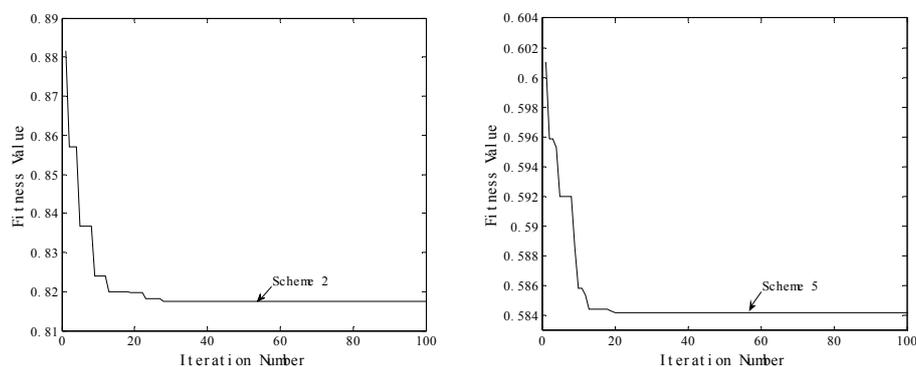


Figure 3. Convergence characteristics of scheme 2 and 5

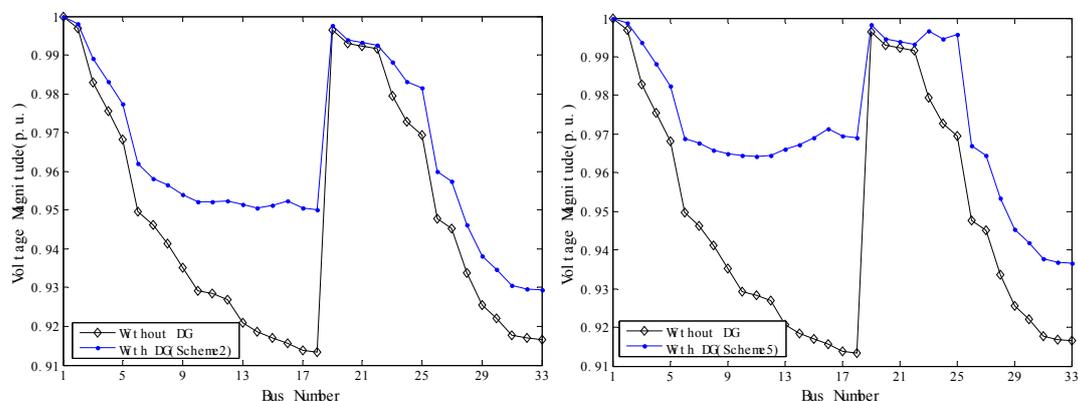


Figure 4. Comparison voltage magnitude of scheme 2 and 5 (With and without DG)

7. Conclusion

This paper has presented quantum particle swarm algorithm (QPSO) based method for optimal placement and sizing of wind and solar based Distributed Generation (DG) units in distribution system. Double objective formulation including real power loss reduction and voltage stability improvement is proposed. Utilizing performance modeling, optimal location and size selection of WTGU and PV array in distribution system are discussed. WTGU and PV array are classified into PQ\PQ (V)\PI type models in power flow. Considering the WTGU and PV based DGs in distribution system is geographical restrictive, some areas are not suitable for installing WTGU or PV based DGs. So the optimal area and DG capacity limits of each bus in the setting area need to be set before optimization, the area optimization method is proposed. Area optimization matrix (*NDG*) and DG capacity limit matrix (*M*) are defined. The area optimization method can help make the optimization more accurate. Several

schemes have been experimented on IEEE33 bus radial distribution systems, the result show that proposed method is very helpful for optimizing placement and sizing of wind/solar based DG sources in distribution system.

References

- [1] Ackermann T, Andersson G, Soder L. Distributed generation: a definition. *Electric Power Syst Res* 2001; 57: 195-204.
- [2] AlRashidi MR, AlHajri MF. Optimal planning of multiple distributed generation sources in distribution networks: a new approach. *Energy Convers Manage* 2011; 52: 3301-8.
- [3] Kim J O, Nam S W, Park S K, et al. Dispersed generation planning using improved Hereford ranch algorithm. *Electric Power System Research* 1998; 47(1): 47-55.
- [4] Naresh A, Pukar M, Mithulananthan N. An analytical approach for DG allocation in primary distribution network. *Elec Power Energy Syst* 2006; 28: 669-78.
- [5] Ghosh S, Ghoshal SP, Ghosh S. Optimal sizing and placement of distributed generation in a network system. *Int J Elec Power Energy Syst* 2010; 32(8): 849-54.
- [6] Abou EI-Ela A A, Allam S M, Maximal optimal benefits of distributed generation using genetic algorithms. *Electric Power Systems Research* 2010, 80(7): 869-877.
- [7] Prommee W, Ongsakul W. Optimal multiple distributed generation placement in microgrid system by improved reinitialized social structures particle swarm optimization. *European Transactions on Electrical Power* 2011, 21(1): 489-504.
- [8] Moradi M H, Abedini M. A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems. *International Journal of Electrical Power & Energy Systems* 2012, 34(1): 66-74.
- [9] Hemdan N G A, Kurrat M. Distributed generation location and capacity effect on voltage stability of distribution networks,” in *Proc. Annu. IEEE Conf.*, 2008, 1-5,
- [10] Kumar MVM, Banerjee R. Analysis of isolated power systems for village electrification. *Energy Sust Dev* 2010;14: 213-22.
- [11] Ganguly S, Sahoo NC, Das D. Multi-objective particle swarm optimization based on fuzzy-Pareto-dominance for possibilistic planning of electrical distribution systems incorporating distributed generation. *Fuzzy Set Syst* 2013; 213: 47-73.
- [12] Aman MM, Jasmon GB, Bakar AHA, Mokhlis H. A new approach for optimum DG placement and sizing based on voltage stability maximization and minimization of power losses. *J Energy Convers Manage* 2013; 70: 202-10.
- [13] Partha Kayal, C.K. Chanda, Placement of wind and solar based DGs in distribution system for power loss minimization and voltage stability improvement, *Electrical Power and Energy Systems* 2013; 53: 795-809.
- [14] Kansal S, Kumar V, Tyagi B. Optimal placement of different type of DG sources in distribution networks. *Interational Journal of Electrical Power Energy Systems* 2013; 53: 752-760.
- [15] Guan WL, Tan YH, Zhang HX, Song JL. Distribution system feeder reconfiguration considering different model of DG sources. *International Journal of Electrical Power & Energy Systems*. 2015; 68: 210-221.
- [16] Sun J, Feng B, Xu W B. Particle swarm optimization with particles having quantum behavior. *Proceedings of Congress on Evolutionary Computation*. Portland: IEEE 2004: 325-331.
- [17] Jamalipour M, Gharib M, Sayareh R, Khoshahval F. PWR power distribution flattening using quantum particle swarm intelligence. *Annals of Nuclear Energy* 2013; 56: 143-150.