Mahesh Kumar[1*], Perumal Nallagownden[2], Irraivan Elamvazuthi[3]

J. Electrical Systems 13-2 (2017): 322-331

JES Journal of Electrical Systems

Regular paper

Multi-objective PSO based optimal placement of solar power DG in radial distribution system

Ever increasing trend of electricity demand, fossil fuel depletion and environmental issues request the integration of renewable energy into the distribution system. The optimal planning of renewable distributed generation (DG) is much essential for ensuring maximum benefits. Hence, this paper proposes the optimal placement of probabilistic based solar power DG into the distribution system. The two objective functions such as power loss reduction and voltage stability index improvement are optimized. The power balance and voltage limits are kept as constraints of the problem. The non-sorting pareto-front based multi-objective particle swarm optimization (MOPSO) technique is proposed on standard IEEE 33 radial distribution test system.

Keywords: Distributed generation, solar PV module, distribution system, multi-objective PSO.

Article history: Received 19 March 2017, Accepted 11 May 2017

1. Introduction

Worldwide, the demand for electricity, risk for fossil fuel depletion and environmental issues are increasing. Hence, the renewable based power generation (i.e. wind turbine, solar PV, biomass, micro-turbine etc.) are feasible options in the distribution system. Among the renewable based power generation, there is an increasing trend of power generation from solar based DGs. Because it is non-exhaustible and freely available in nature. It is also noticeable that distribution system is radial in nature, which possesses high resistance to reactance ratio and draws more power loss and decreases the voltage quality of the system [1, 2]. In this case, optimal integration of solar DG advances many benefits, i.e. increase the power losses reduction, improve voltage profile and voltage stability index [3]. It also reduces the greenhouse gas effects and defers the network upgradation.

Many positive benefits can be claimed from DG integration. However, the integration of distributed generation in distribution system witnesses to change the operational and control behaviour of the distribution network. Such as non-optimal placement may worsen the situation than existing one. Hence, an efficient optimal placement method is required to overcome these complexities and improve the system performance [4].

In literature, many optimization algorithms are used to overcome these operational complexities and optimally fit the DGs into the distribution system. Among them, analytical, numerical and heuristic based optimization algorithms are most effectively utilized [5]. Author [6, 7] uses the analytical expressions for optimal placement and sizing of distributed generation for power loss reduction and voltage profile improvement in the radial distribution system. The author [8, 9] uses the linear and non-linear programming to optimize the system

[*] Corresponding author: Mahesh Kumar, Department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia.
[1]Department of Electrical Engineering, Mehran University of Engineering and Technology Jamshoro, Sindh, Pakistan. E-mail: rathii.mahesh@gmail.com; Tel.: +60-149851338.
[123]Department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia.

parameters in the distribution system. The GA, PSO and GA/PSO based multi-objective optimization for power loss reduction and voltage stability improvement are suggested by the author [10]. Flower pollination optimization algorithm [11], big bang crunch based [12], GA and backtracking search optimization algorithm based optimization algorithm [13] for optimal DG integration were proposed in the literature. Among, the author [8, 14] uses the solar based distributed generation in distribution system using non-linear and flower pollinating based optimisation algorithm. However, this paper proposes an advance, pareto-front non-dominated sorting based multi-objective PSO optimization for power loss reduction and voltage stability improvement. The proposed model is tested and verified against many literature methods with standard IEEE 33 test system.

The reminder of the paper is structured as, Section II presents the problem formulation, section III presents the output power form solar power DG, Section IV presents the multi-objective PSO optimization algorithm, Section IV present the case study, results and discussion and Section V presents the conclusion.

2. Problem formulation

The main objective function this study is to optimally allocate the solar power DG into the radial distribution system. The two main objective functions such as power loss reduction and voltage stability index improvement are optimized. Furthermore, the study considers the power balance and minimum and maximum voltage magnitudes as constraints of the problem.

2.1. Power loss reduction

It is fact that distribution system consists of about thirteen percent power losses from the total power generation as reported in [15]. Hence, the first objective of this study is to reduce the power losses. A backward forward power flow is utilized to calculate the diffident electrical parameters [16]. The power loss reduction using optimal integration of solar power DG can be formulated as following.

$$f_1 = \min\left(\sum_{i=1}^{i=nb-1} P_{i\,loss}\right) \tag{1}$$

where P_{iloss} is the real power loss of branch i, nb is total number of branches of the system.

2.2. Voltage Stability index

The voltage stability index (VSI) is an indicator, which shows the stability of the system or in other terms it can be explained as when the load in the distribution system increases, it reduces the voltage profile of the system. Hence, it is ought to maintain the VSI index in the permissible limit. A lower value of VSI (i.e. lower than the base case) indicates the abnormality in the system, whereas greater values indicate the maximum stability in the system [17]. The voltage stability index for two buses m1 and m2 can be formulated as follows given in Figure 1:

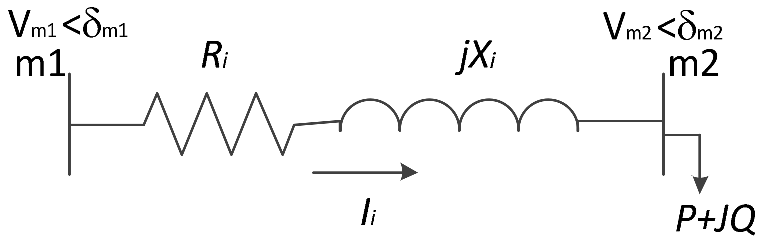

Figure 1. One-line diagram of the two-bus radial distribution system.

$$VSI_{m2} = |V_{m1}|^4 - 4.0\begin{Bmatrix} P_{m2} \times X_i - \\ Q_{m2} \times R_i \end{Bmatrix}^2 - 4.0\{P_{m2} \times R_i + Q_{m2} \times X_i\}|V_{m1}|^2 \quad (2)$$

$$f'_2 = \max \sum_{mi}^{Nb} (VSI_{mi}) \quad (3)$$

where VSI_{m2} is the voltage stability index for bus number 2, VSI_{mi} is the voltage stability index for all buses that are connecting the system such as $(mi = 2, 3, 4 \ldots Nb)$, Nb is the total number of buses. The voltage stability index is kept as second objective function for this paper. The objective function can be written as:

$$f_2 = \left(\frac{1}{f'_2} \right) \quad (4)$$

2.3. Network Constraints

The Equations (5)–(8) represents the equality and non-equality constraints of the proposed model.

2.3.1. Power Balance

$$P_{substation} + \sum P_{DG} = \sum P_{loss} + \sum P_{load} \quad (5)$$

$$Q_{substation} + \sum Q_{DG} = \sum Q_{loss} + \sum Q_{load} \quad (6)$$

where $P_{substation}$ and $Q_{substation}$ are the total real and reactive power injection by substation in to the network. ΣP_{DG} and ΣQ_{DG} are the total real and reactive power, injected by DG. ΣP_{loss} and ΣQ_{loss} are the total real and reactive power loss in the network. ΣP_{load} and ΣQ_{load} are the total real and reactive power losses of the network respectively.

2.3.2 Position of DG

Bus 1 is the substation or slack bus, so the position of the DG should not be used at bus 1.

$$2 \le DG_{position} \le n_{buses} \quad (7)$$

2.3.2 Voltage Profile

For maintaining proper voltage magnitudes of the whole bus system. It is very important that all distribution system node follow the following constraints:

$$V^{\min} \leq V \quad \leq V^{\max} \tag{8}$$

3. Output power from Solar power DG

An hourly, 15 years real time data for solar irradiance is chosen from the 29°19′8″N 71°49′25″E co-ordinates. The intermittency of solar irradiance are further processed with Beta probability distribution function for each hour, which is describe in Equation 9, detail given in Ref [8, 18].

$$f^t(s) = \begin{cases} \dfrac{\Gamma(\alpha^t + \beta^t)}{\Gamma(\alpha^t) \times \Gamma(\beta^t)} \times (s^t)^{\alpha^t - 1} \times (1 - s^t)^{\beta^t - 1} \\ , \ 0 \leq s \leq 1; \alpha, \beta \geq 0 \\ 0, \qquad\qquad\qquad\qquad otherwise \end{cases} \tag{9}$$

where $f^t(s)$ the beta probability distribution is function for solar irradiance at tth hour, S is the solar irradiance. α and β are the further statistical parameters of $f^t(s)$, and can be solved as follows:

$$\alpha^t = \frac{\mu^t \times \beta^t}{(1 - \mu^t)} \tag{10}$$

$$\beta^t = (1 - \mu^t) \times \left(\frac{\mu^t (1 + \mu^t)}{(\sigma^t)^2} - 1 \right) \tag{11}$$

where μ^t and σ^t is the mean and standard deviation of solar irradiance at time t hour. As, the solar irradiance are intermittent in nature. Hence this paper divides each hour with different states (for this paper 15 states per hour) and form the probability of solar radiation of any specific hour, the formulation is given as follows:

$$P(s_p^t) = \begin{cases} \displaystyle\int_0^{\frac{(s_p^t + s_{p+1}^t)}{2}} f^t(s) \ . \ ds, \ for \ p = 1 \\ \displaystyle\int_{\frac{(s_{p-1}^t + s_p^t)}{2}}^{\frac{(s_p^t + s_{p+1}^t)}{2}} f^t(s) \ . \ ds, \ for \ p = 2 \ldots (nbs, s - 1) \\ \displaystyle\int_{\frac{(s_{p-1}^t + s_p^t)}{2}}^{\infty} f^t(s) \ . \ ds, \ for \ p = nbs, s \end{cases} \tag{12}$$

The power output from solar PV can be obtained, using the probability of solar irradiance (as found above) and from solar PV module characteristics, which is given as:

$$T_{C_P} = T_A + S_{ap}\left(\frac{N_{OT}-20}{0.8}\right) \tag{13}$$

$$I_p = S_{ap}\left[I_{sc} + K_i(T_c - 25\right] \tag{14}$$

$$V_p = V_{oc} - K_v T_{C_P} \tag{15}$$

$$FF = \left(\frac{V_{MMP} \times I_{MMP}}{V_{oc} \times I_{sc}}\right) \tag{16}$$

$$PDG_{solar,p} = N \times FF \times I_p \times V_p \tag{17}$$

where T_{C_P}, T_A and N_{OT} are the temperatures measured in degree C. I_p and V_p, I_{sc} and V_{oc} and K_i and K_v are the electrical parameters. I_{MMP} and V_{MMP} are the current and voltage at maximum power point and N is the total number of PV module. Hence the output power at each hour can be obtained as:

$$\boldsymbol{P^t_{solar}} = \sum_{\boldsymbol{p=1}}^{\boldsymbol{nbs,s}} \boldsymbol{PDG_{solar,p}} \times \boldsymbol{P(s^t_p)} \tag{18}$$

where P^t_{solar} is the output power of solar PV module at time t hour.

4. Multi-objective PSO optimization algorithm

The particle swarm optimization algorithm (PSO) was introduced by [19] in 2001. The drawback of this conventional PSO is that it can't handle more than one objective function at one run. Hence, the multi-objective PSO (MOPSO) is the extended version, which was introduced by [20] in 2004. The optimal integration of solar based power generation in the distribution system is the multi-objective problem in nature. Therefore, this paper considers two objective functions such as power loss reduction and voltage stability improvement. The complete flow chart is mentioned in Figure 2 and follows the subsequent steps.

Initialization: initialize the particle position, velocity and random location of the distribution system.

a. For $i = 1\ to\ Max$
b. Start the load flow and calculate the base case objective functions values for each particle in the swarm.
c. Update the personal best $pbest$.
d. Choose the global best from repository REP file of each particle.
e. Select the leaders from REP.
f. Update the velocity of each particle.

$$POP(i).Vel = w \times POP(i).Vel + C_1 \times rand() \times (POP(i).Pbest - POP(i))$$
$$+ C_2 \times rand() \times (REP(h) - POP(i))$$

g. Update the position of each particle in the swarm.

$$POP(i).Position = POP(i).Position + POP(i).Vel$$

h. Apply the mutation factor.

i. Start the load flow and calculate the final objective functions values for each particle in the swarm.
j. Select the optimal trade-off values using fuzzy decision form a pereto-front non-dominated solution.
k. Present the final objective function values.

5. Case study

The optimal placement of solar based distributed generation is carried out using MOPSO optimization technique. The proposed method is tested on standard IEEE 33 distribution system as shown in Figure 3. The total real and reactive power demand on this distribution system is 3.715 MW and 2.3 MVar respectively. The bus and line parameters are taken from [21, 22]. The distribution system is mostly operated in populated areas. Hence, considering the land limitation, only 3 solar farms are suggested in this system. Each solar farms have 4 subdivided solar PV arrays, which gives the yearly average output power through all seasons as 783.28 kW. It is further assumed that this power is constantly supplied by solar PV when there is sun light whereas additional power is adjusted through battery storage when there is no sunlight.

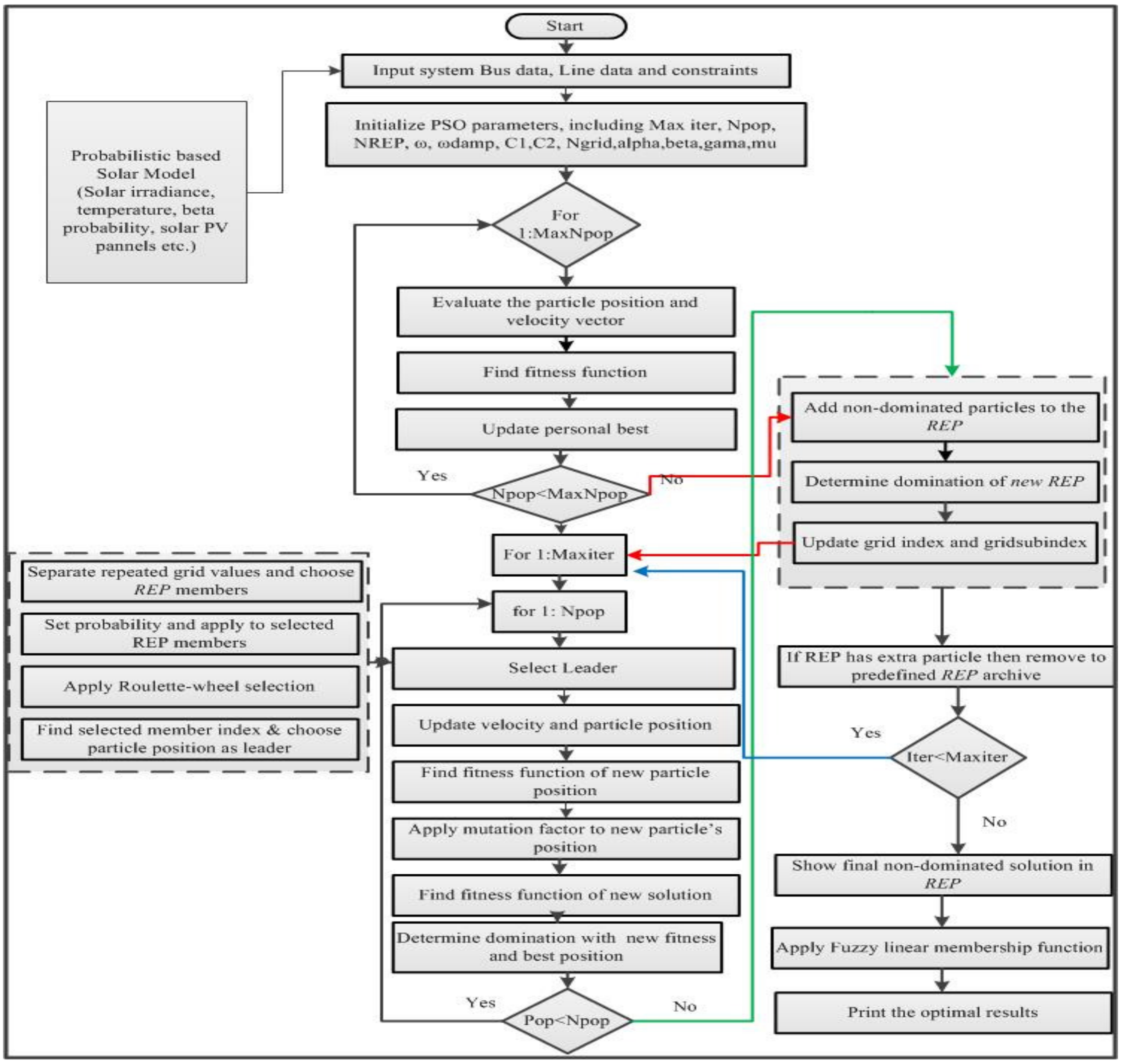

Figure 2. Flow chart for optimal placement of solar power DG using MOPSO.

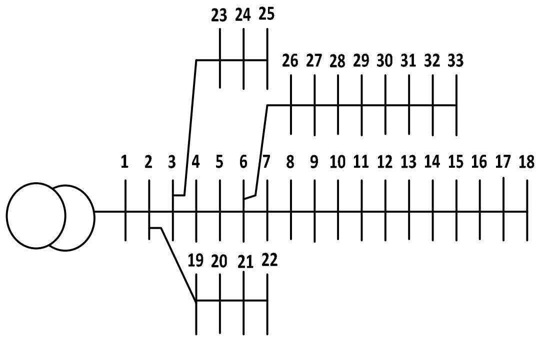

Figure 3. IEEE 33 radial distribution system.

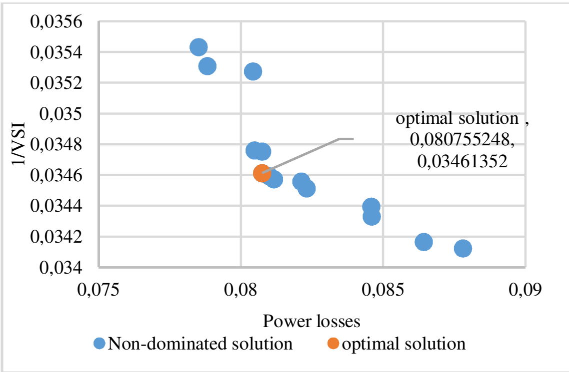

Figure 4. IEEE 33 radial distribution system.

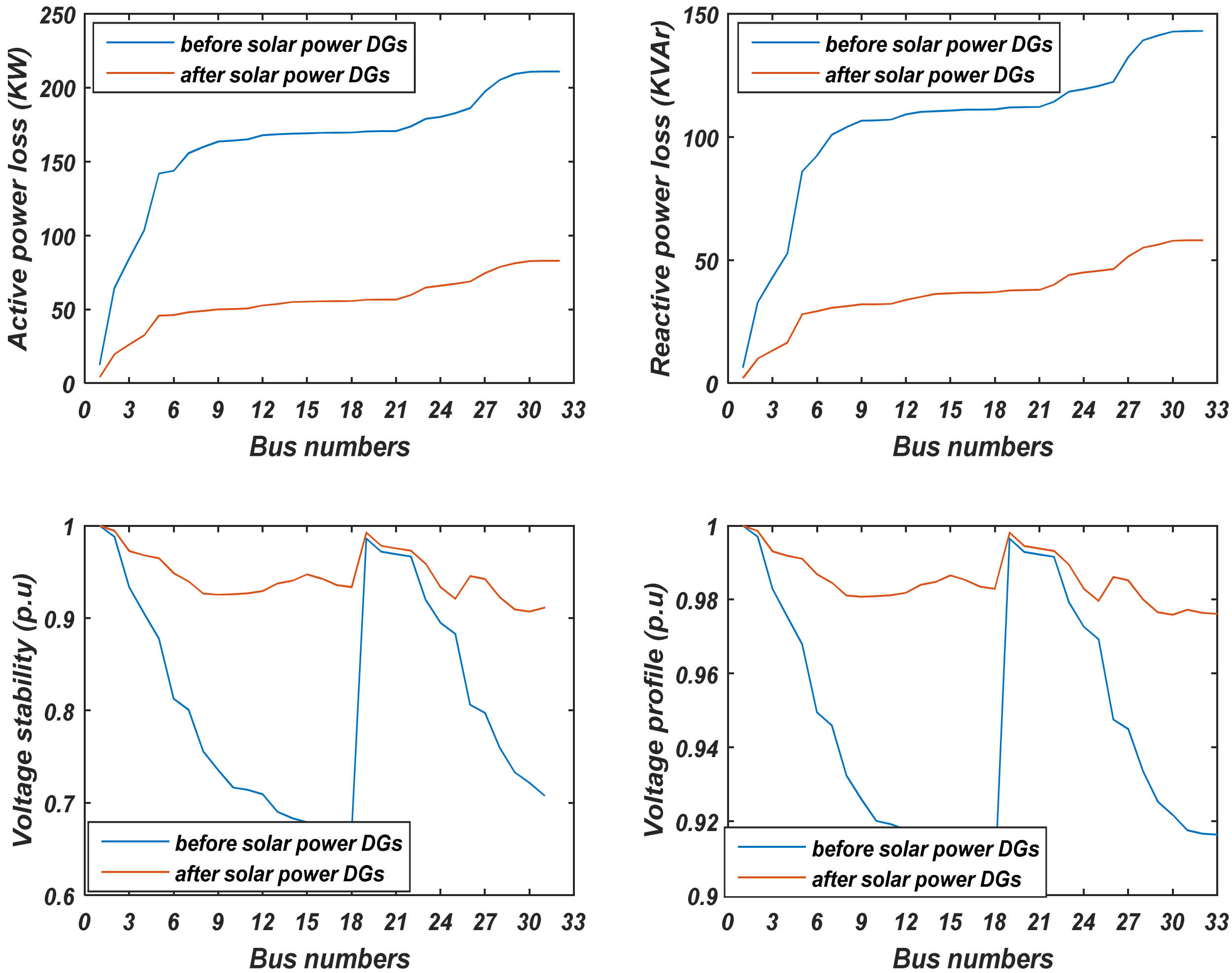

Figure 5. Power losses, voltage stability and voltage profile of each bus/branch before and after installation of solar power DG.

Table 1. Power loss and voltage stability before and after solar power DG.

Solar farm (MW)	Solar farm placement	Ploss (kW)	Qloss (KVar)	VSI
Base case	--	211	143	25.125
0.873	15			
0.873	31	82.8	58.1	29.3308
0.873	06			

Table 2. Minimum and maximum voltage profile and voltage stability before and after solar power DG.

Voltage				Voltage stability			
Before solar power DG		After solar power DG		Before solar power DG		After solar power DG	
Min (p.u)	Max (p.u)	Min (p.u)	Max (p.u)	Min (p.u)	Max (p.u)	Min (p.u)	Max (p.u)
0.9037 at bus 18	1.0 at bus 1	0.9759 at bus 18	1.0 at bus 1	0.667 at bus 18	1.0 at bus 1	0.9071 at bus 18	1.0 at bus 1

MOPSO algorithm is chosen to find the best optimal locations in the distribution system, where maximum power loss reduction and voltage stability index improvement is observed.

6. Results analysis and discussion

The three solar power DG, each of 0.873 MW was integrated through MOPSO, to find the best optimal location in IEEE 33 system. The main purpose of this research is to reduce the total power loss and improve system voltage stability as a multi-objective optimization problem. The power balance and voltage limits are kept as constraints. The backward forward load flow is performed for power flow analysis. The power losses, and voltage stability index without solar power was observed as 211 kW and 25.125 p.u respectively. Whereas, after installation of three solar power DG, the trade-off between power loss and voltage stability index comes to 82.8 kW and 29.33 p.u respectively. So it can be observed that with the integration of three solar power DG of 2.619 MW in total size, the power losses reduces to 60.75 percent, whereas the voltage stability index is improved as 28.47 percent. Furthermore, the bus numbers 15, 31 and 6 for these solar PV DGs are found as described in Table 1. Figure 4 shows the trade-off solution between power loss reduction and voltage stability index improvement. The results of active power losses, reactive power losses, and voltage profile and voltage stability of all buses before and after installation of solar power DGs are mentioned in Figure 5. It can be seen that a substantial amount of both active and reactive power is reduced. The same is true for voltage profile and voltage stability. Table 2 describes the minimum and maximum voltage profile and voltage stability of buses, before and after installation of solar power DG. It can be observed that with the installation of solar power DG a significant improvement is observed in power loss reduction, voltage profile improvement and voltage stability index.

7. Conclusion

This paper presents the optimal placement of solar power distributed generation in the distribution system. An hourly solar irradiance data of 15 years are chosen from 29°19′8″N 71°49′25″E. This solar data is further processed with 15 states of every hour for appropriate power output from it. The probabilistic nature of solar irradiance is handled with Beta probability distribution function. The non-sorting based multi-objective PSO optimization algorithm is used to improve the power loss reduction and voltage stability improvement. The two important constraints i.e. power balance and standard voltage limit are kept is a safe limit. The proposed model is tested on standard IEEE 33 radial test system. The efficacy and robustness of proposed model are tested with other literature optimization algorithms as given in our previous work [21]. Hence, it can be concluded that proposed model is best for integration of solar power DG into the radial distribution system.

Acknowledgement

The authors would like to thank Universiti Teknologi Petronas, Malaysia and Mehran University of Engineering and Technology Jamshoro Pakistan for providing an opportunity to conduct this research.

References

[1] K. Mahesh, P. A. Nallagownden, and I. A. Elamvazuthi, "Optimal placement and sizing of DG in distribution system using accelerated PSO for power loss minimization," in 2015 IEEE Conference on Energy Conversion (CENCON), 2015, pp. 193-198.

[2] K. Mahesh, P. Nallagownden, and I. Elamvazuthi, "Optimal Configuration of DG in Distribution System: An Overview," in MATEC Web of Conferences, 2016, p. 01007.

[3] P. Kayal and C. Chanda, "Placement of wind and solar based DGs in distribution system for power loss minimization and voltage stability improvement," International Journal of Electrical Power & Energy Systems, vol. 53, pp. 795-809, 2013.

[4] S. Kansal, V. Kumar, and B. Tyagi, "Optimal placement of different type of DG sources in distribution networks," International Journal of Electrical Power & Energy Systems, vol. 53, pp. 752-760, 2013.

[5] M. Ali, N. Zahirah, I. Musirin, S. I. Suliman, N. R. Hamzah, and Z. Zakaria, "Effect of Multi-DG Installation to Loss Reduction in Distribution System," Journal of Electrical Systems, vol. 12, 2016.

[6] D. Q. Hung, N. Mithulananthan, and R. Bansal, "Analytical strategies for renewable distributed generation integration considering energy loss minimization," Applied Energy, vol. 105, pp. 75-85, 2013.

[7] R. Viral and D. Khatod, "An analytical approach for sizing and siting of DGs in balanced radial distribution networks for loss minimization," International Journal of Electrical Power & Energy Systems, vol. 67, pp. 191-201, 2015.

[8] Y. Atwa, E. El-Saadany, M. Salama, and R. Seethapathy, "Optimal renewable resources mix for distribution system energy loss minimization," IEEE Transactions on Power Systems, vol. 25, pp. 360-370, 2010.

[9] C. Battistelli, G. Carpinelli, F. Mottola, D. Proto, and D. Zoppoli, "Distribution networks with linear and nonlinear loads: cost-based method for planning dispersed generation and capacitor units under uncertainty," Journal of Energy Engineering, vol. 137, pp. 44-58, 2011.

[10] M. H. Moradi, S. R. Tousi, and M. Abedini, "Multi-objective PFDE algorithm for solving the optimal siting and sizing problem of multiple DG sources," International Journal of Electrical Power & Energy Systems, vol. 56, pp. 117-126, 2014.

[11] A. Abdelaziz, E. Ali, and S. A. Elazim, "Flower Pollination Algorithm and Loss Sensitivity Factors for optimal sizing and placement of capacitors in radial distribution systems," International Journal of Electrical Power & Energy Systems, vol. 78, pp. 207-214, 2016.

[12] A. Y. Abdelaziz, Y. G. Hegazy, W. El-Khattam, and M. M. Othman, "A Multi-objective Optimization for Sizing and Placement of Voltage-controlled Distributed Generation Using Supervised Big Bang–Big Crunch Method," Electric Power Components and Systems, vol. 43, pp. 105-117, 2015.

[13] A. El-Fergany, "Multi-objective Allocation of Multi-type Distributed Generators along Distribution Networks Using Backtracking Search Algorithm and Fuzzy Expert Rules," Electric Power Components and Systems, pp. 1-16, 2015.

[14] S. K. Sudabattula and M. Kowsalya, "Flower Pollination Algorithm Based Optimal Placement of Solar Based Distributed Generators in Distribution System."

[15] A. Zeinalzadeh, Y. Mohammadi, and M. H. Moradi, "Optimal multi objective placement and sizing of multiple DGs and shunt capacitor banks simultaneously considering load uncertainty via MOPSO approach," International Journal of Electrical Power & Energy Systems, vol. 67, pp. 336-349, 2015.

[16] M. Haque, "Efficient load flow method for distribution systems with radial or mesh configuration," IEE Proceedings-Generation, Transmission and Distribution, vol. 143, pp. 33-38, 1996.

[17] M. Chakravorty and D. Das, "Voltage stability analysis of radial distribution networks," International Journal of Electrical Power & Energy Systems, vol. 23, pp. 129-135, 2001.

[18] P. Kayal and C. Chanda, "Strategic approach for reinforcement of intermittent renewable energy sources and capacitor bank for sustainable electric power distribution system," International Journal of Electrical Power & Energy Systems, vol. 83, pp. 335-351, 2016.

[19] E. R. Kennedy J, "Particle swarm optimization," presented at the Particle Swarm Optim, 1995.

[20] C. A. C. Coello, G. T. Pulido, and M. S. Lechuga, "Handling multiple objectives with particle swarm optimization," Evolutionary Computation, IEEE Transactions on, vol. 8, pp. 256-279, 2004.

[21] K. Mahesh, P. Nallagownden, and I. Elamvazuthi, "Advanced Pareto Front Non-Dominated Sorting Multi-Objective Particle Swarm Optimization for Optimal Placement and Sizing of Distributed Generation," Energies, vol. 9, DEC 2016 2016.

[22] R. Syahputra, I. Soesanti, and M. Ashari, "Performance Enhancement of Distribution Network with DG Integration Using Modified PSO Algorithm," Journal of Electrical Systems, vol. 12, 2016.