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Optimal Allocation of Solar PV Systems for Enhancing Radial Distribution System Performance Using TLBO Algorithm

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Abstract

Placement of distributed generation (DG) sources in a distribution network has the potential to provide improved system performance such as reduced losses and improved voltage profile, while also providing nontechnical benefits like reduced emissions. The technical impact of DG sources can be positively or adversely affected by the location and sizing of the DG sources. Therefore choosing the location and size of DG sources is of utmost importance. This paper considers the placing and sizing of photovoltaic (PV) systems, which are DG sources providing active power, using a hybrid of Loss Sensitivity Factors (LSF) and Teaching Learning Based Optimization (TLBO) algorithm, by considering the minimization of losses as the objective function. The performance analysis of the proposed method in terms of real power loss and static voltage stability is carried out with standard IEEE 33-bus and standard IEEE 69-bus test systems. The proposed approach has given better results than many existing techniques and shows its adaptability to real time applications.

Keywords

Photovoltaic (PV) Systems, Placing and Sizing, Loss Sensitivity Factors, TLBO Algorithm

Introduction

Distributed Generation (DG) sources are small generation units situated at or near load sites in the distribution network. The increasing penetration of these sources can be attributed to the steadily increasing trend in energy demands, fast depletion of conventional fuel resources and the push for clean energy sources. Being situated near to the consumer ends, DG sources provide technical benefits such as improved voltage profile, improved voltage stability, reduced distribution losses and reduced line congestion in the system. But appropriate selection of location and size of these sources is necessary to realize these benefits. DG sources can be classified as P type, Q type or PQ type depending on the type of power provided by them. P type sources provide only active power, Q type sources provide only reactive power and PQ type provides active power, but may provide or consume reactive power. Solar photovoltaic systems are one of the most popularly used P type DG source. As per the status report (Jäger-Waldau, 2017) photovoltaic (PV) systems have the largest share of investments among renewable technologies and represent almost 50 % share among the renewable power capacity. With such a growth rate there has been a continued interest in deriving maximum benefits through optimal positioning and sizing of these sources. In literature the problem of DG allocation has been solved with different approaches such as analytical approaches, classic approaches such as linear and nonlinear programming optimization algorithms and heuristic approaches. In (Hung et al., 2010), the authors have proposed a method using analytical expressions to place multiple DG units of multiple DG types. An analytical approach using loss sensitivity factor to prioritize bus locations for DG placement has been proposed in (Acharya et al., 2006). In (Mahmoud et al., 2016), an efficient analytical (EA) method to optimally allocate a mix of DG types has been proposed. In addition a combined method involving EA and Optimal Power Flow algorithm has also been proposed by the same authors. A sequential quadratic programming method has been used to solve the DG sizing problem in (Sfikas et al., 2015). Linear programming has been used to find the optimal DG sizes and sites in (Keane and O' Malley, 2005). Due to computational ease, heuristic algorithm based solutions have found wide acceptance in literature for the DG allocation problem. Some of these methods are: Cuckoo Search Algorithm (Moravej and Akhlagi, 2013), Particle Swarm Optimization (PSO) based approach (Prakash and Lakshminarayana, 2016), Bat Algorithm (Sudabattula and Kowsalya, 2016), Hybrid Grey Wolf Optimizer (Sanjay et al, 2017), Water Cycle Algorithm (Abou El-Ela, 2018), Salp Swarm Algorithm (Sambaiah and Jayabarathi, 2019). Sensitivity index based approach has been employed to find optimal locations in (Murty and Kumar, 2015). Hybrid algorithms combining different heuristic techniques to optimize DG size and sites have also been proposed. In (Moradi and Abedini, 2012), a combination of PSO and Genetic Algorithm (GA) has been used to find optimal locations and sizes of DG sources. In this method the locations are searched using GA and the optimal sizes are calculated by PSO. A hybrid of Ant Colony Optimization to find candidate locations and Artificial Bee Colony Algorithm to optimize sizes has been proposed in (Kefayat et al., 2015). GA has been integrated with Tabu Search Algorithm to solve optimal DG placement problem in (Gandomkar et al., 2005). Heuristic methods have also been combined with sensitivity analysis to give faster solutions. The sensitivity factors narrow down the search space

increasing computational speed. Loss sensitivity factor (LSF) defined as, sensitivity of the system losses to an increase in effective power load at a bus has been combined with heuristic algorithms to find optimal placement of DG sources (Imran and Kowsalya, 2014; Prabha and Jayabarathi, 2016; Shukla et al., 2010).
The review of literature shows that effective combination of approaches can successfully identify locations and calculate sizes of DG to reduce losses and improve performance of a distribution system. In this paper a new hybrid approach has been proposed to determine the optimal locations and sizes of PV sources using loss sensitivity factors (LSF) and a recent optimization algorithm, teaching learning based optimization (TLBO), considering minimization of losses as the objective function. The performance of the system with optimally allocated PV systems is calculated in terms of reduction in losses, improvement in voltage stability index and improvement in voltage profile. Though the use of TLBO for optimal allocation can be found in (Mohanty and Tripathy, 2016) it has not been considered in conjunction with loss sensitivity analysis. Also the locations and sizes in the paper have been determined with the objective of maximizing voltage stability.

Loss Sensitivity Factor

Loss Sensitivity factor (LSF) is used to find the sensitivity of system losses to a change in active or reactive power at a bus (Prakash and Sydulu, 2007). Consider a distribution line k connected between nodes p and q as shown in Fig. 1. P_{eff}, is the total of active power supplied to all nodes beyond node q and the power supplied at node q. Similarly, Q_{eff} is the total of reactive power supplied to all nodes beyond node q and the reactive power supplied at node q. Active power loss in the line k are given by (1). LSFP calculated as in (2) gives the sensitivity of losses to active power increment at a bus and LSFQ calculated as in (3) gives the sensitivity of losses to reactive power increment at a bus.

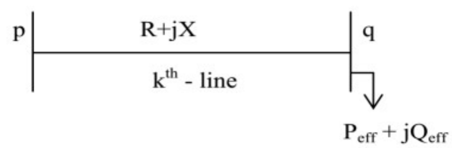

Fig. 1: Representative Branch in a Distribution Network

$$P_{loss}[k] = \frac{\left(P_{eff}^2 + Q_{eff}^2\right) \times R}{V[q]^2} \tag{1}$$

$$LSFP = \frac{\partial P_{loss}}{\partial P_{eff}} = \frac{2 \times P_{eff} \times R}{V[q]^2} \tag{2}$$

$$LSFQ = \frac{\partial P_{loss}}{\partial Q_{eff}} = \frac{2 \times Q_{eff} \times R}{V[q]^2} \tag{3}$$

The locations with high values of LSFP or LSFQ are considered as candidate locations for placement of PV systems. This narrows down the search space while identifying the optimal locations and sizes of the PV systems.

Problem Formulation

With the aim of maximizing loss reduction with the placement of PV systems, the objective function is formulated as in (4) subject to the constraints (5) and (6).

$$OF = min\left\{\sum_{k=1}^{nbr} I_k^2 R_k\right\} \tag{4}$$

where, *nbr* is no: of branches, I_k is the current in the k^{th} branch and R_k is the resistance of k^{th} branch.

$$\Delta X_{j,k} = r_i\left(X_{j,kbest} - T_F M_j\right) \tag{5}$$

$$\sum_{i=1}^{N_{dg}} DG_i = Pt \times \sum_{i=1}^{N} P_i \tag{6}$$

where, N_{dg} is no: of buses with PV systems, *Pt* is penetration level and *N* is total no. of buses and P_i is the load at a bus.

Voltage Stability Index

Voltage stability indices predict the nearness of a system to voltage collapse. Optimal Placement of DG sources improves voltage profile and enhances the voltage stability. Improvement of voltage stability can be analyzed with voltage stability indices. Several researchers have made their contribution in formulating voltage stability indices. The voltage stability index (VSI) as proposed in (Chakravorty and Das, 2001) is used for stability calculations in this paper and is given by (7). P and Q are the active and reactive powers at the receiving node for a line connected between nodes i and j. R_{line} and X_{line} are resistance and reactance of the line. V is the voltage at sending end node i.

$$SI_j = \left|V_i^4\right| - 4\times\left(P_j\times X_{line} - Q_j\times R_{line}\right)^2 - 4\times\frac{P_j\times R_{line}+Q_j\times X_{line}}{V_i^2} \tag{7}$$

Teaching Learning based Optimization (TLBO) Algorithm

TLBO is an efficient optimization technique introduced in (Rao et al., 2011). The algorithm is based on the effect of influence of a teacher as well as peers on the learning of students. The group of learners is the population, subjects form the design variables and the learners' result forms the fitness value of the problem. The algorithm involves two phases, the teacher phase which takes into account influence of teacher and the learner phase which takes into account influence of peers on the result of a student.

Teacher Phase

The teacher is considered the best performer of the class. Therefore the teacher tries to steer the students towards his performance by increasing the mean result of the class towards his performance. Let j denote j^{th} design variable (subject), k denote k^{th} learner, $X_{j,k}$ the value of j^{th} variable for k^{th} learner, $X_{j,kbest}$ the value of j^{th} variable of the best learner, M_j the mean value of all learners for the j^{th} variable. The difference between the existing mean result of each subject and the corresponding result of the teacher for each subject is given by (8).

$$\Delta X_{j,k} = r_i\left(X_{j,kbest} - T_F M_j\right) \tag{8}$$

where, T_F is teaching factor and r_i is a random number between 0 and 1. The performance of each learner in a subject is then modified as (9).

$$X'_{j,k} = X_{j,k} + \Delta X_{j,k} \tag{9}$$

If the function result is better than the previous result, the modified value is retained. Otherwise it is discarded and the previous values of design variables are retained. The accepted design variable values become the input to the learner phase.

Learner Phase:

In the learner phase the learners interact among themselves to increase the knowledge. If there are two learners, p and q then for a minimization problem, the modification for learner p is given by equation (10) if the result of learner p is less than result of learner q and by (11) if result of learner q is less than result of learner p. For a maximization problem, the modification is given by (12) if result of learner p is greater than result of learner q and by (13) if result of learner q is greater than result of learner p,

$$X'_{j,p} = X_{j,p} + r_i\left(X_{j,p} - X_{j,q}\right) \tag{10}$$

$$X'_{j,p} = X_{j,p} + r_i\left(X_{j,q} - X_{j,p}\right) \tag{11}$$

$$X'_{j,p} = X_{j,p} + r_i\left(X_{j,p} - X_{j,q}\right) \tag{12}$$

$$X'_{j,p} = X_{j,p} + r_i\left(X_{j,q} - X_{j,p}\right) \tag{13}$$

The procedure to implement the algorithm to the problem of DG allocation can be described with the flowchart in Fig. 2.

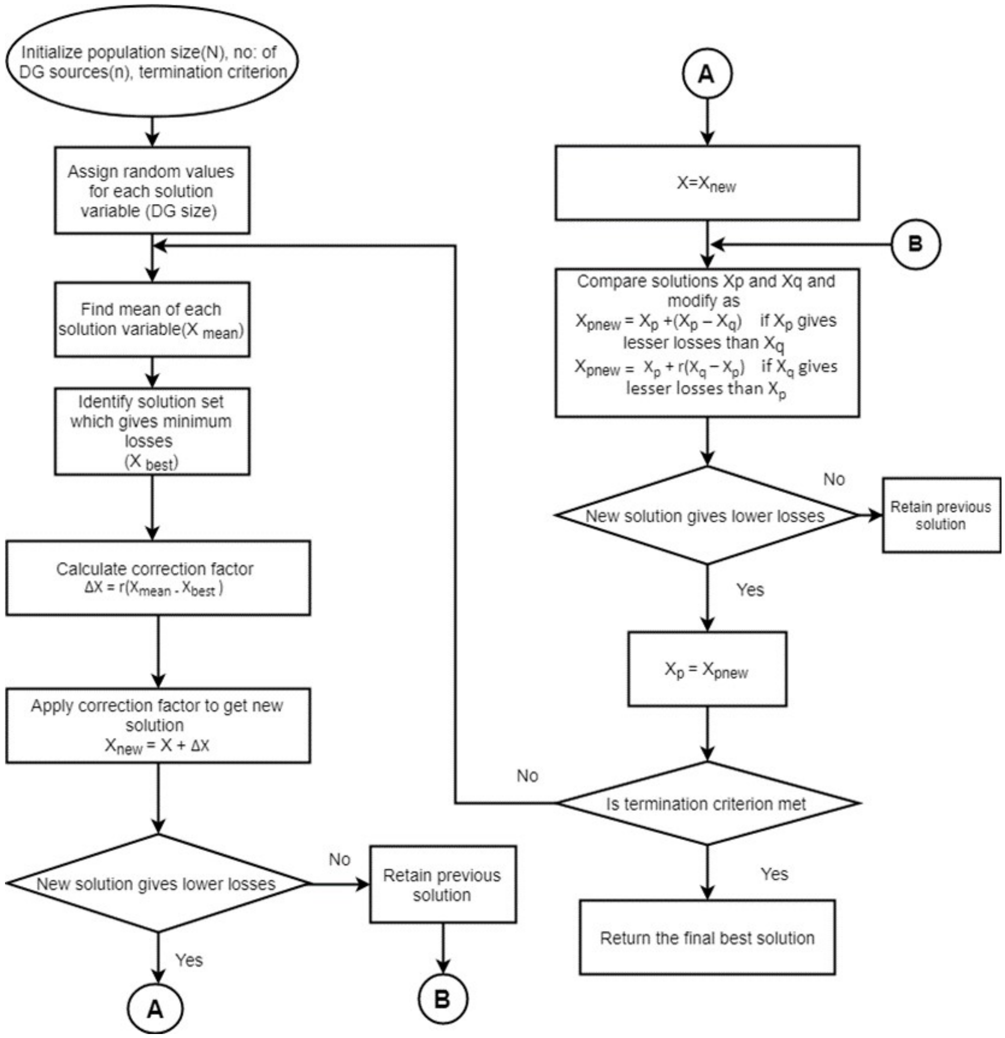

Fig. 2: Flowchart of TLBO Algorithm to allocate PV Units

Results and Discussions

The proposed methodology is tested on two test systems. The first system used in this paper is a 33 bus radial distribution test system with a total connected load of 3.715 MW and 2.3 MVar (Kashem et al., 2000) and the second test system is a 69 bus radial distribution test system with a total connected load of 3.802 MW and 2.69 MVar (Baran and Wu, 1989). The sizing of PV systems is assumed as continuous. The candidate locations are chosen by ranking the buses as per loss sensitivity factors LSFP, calculated using (2) and LSFQ, calculated using (3). The forward backward sweep method (Haque, 1996) has been used in the calculation of the loss sensitivity factors, distribution losses, voltage profile of the system and voltage stability index. Twenty percent of the total no. of buses based on both LSFP and LSFQ ranking are identified as possible locations for placement of PV systems and are tabulated in Table I for IEEE 33 bus and IEEE 69 bus system. The final optimal locations and sizes are then calculated using TLBO algorithm.

Results of 33 Bus System:

The total losses calculated for the system with base load is 210.07 kW. The voltage stability index is 0.6764 with a minimum voltage of 0.9069 at bus 18. The final locations and sizes of PV systems have been calculated considering search spaces obtained with LSFP, LSFQ and a combination of LSFP and LSFQ. The performance analysis with all the three cases are tabulated in Table II.

Table I: Candidate Locations Identified for PV Systems for IEEE 33 and 69 Bus Systems

Test system	Candidate locations based on LSFP	Candidate locations based on LSFQ	Candidate locations based on LSFP and LSFQ
33 bus	5,6,**8**,9,24,28,29	5,6,9,**13**,24,28,29	5,6,8,9,13,24,28,29
69 bus	2,3,6,7,14,**15**, 54,55,56, 57,58,59,60,61	2,3,6,7,14,**49**,54,55,56, 57,58,59,60,61	2,3,6,7,14,15,49,54,55,56,57 ,58,59,60,61

Table II: Comparison of Results with Different Sensitivity Factors for 33 Bus System

Factor	DG locations	DG sizes	Losses(kW)	Min voltage and location	VSI
LSFP	6,9,24,29	335.59,846.79, 682.76,846.79	76.5	0.9574(18)	0.8401
LSFQ	6,13,24,29	498.23,680.47,689.15,844.09	71.52	0.9634(33)	0.8614
LSFPQ	8,13,24,29	441.078,572.07, 761,929.79	70.87	0.9640	0.8636

Table III: Performance Analysis of 33 Bus System in the Presence of PV Systems

	Bus no:	DG size(kW)	Total DG size(kW)	% of penetration	Distribution losses(kW)
Without DG	…	…..	…..	…	210.07
Proposed method	**8**	**441.078**	**2711.9**	**72.99**	**70.87**
	13	**572.07**			
	24	**761**			
	29	**929.79**			
[14] GA	11	1500	2994.2	80.59	106.3
	29	422.8			
	30	1071.4			
[14] PSO	13	981.6	2988.1	80.43	105.3
	32	829.7			
	8	1176.8			
[17] LSF-BFOA	14	652.1	1917.7	51.6	89.9
	18	198.4			
	32	1067.2			
[9] BA	15	816.3	2721	73.24	75.05
	25	952.35			
	30	952.35			
[4] EA	13	798	2947	79.33	72.787
	24	1099			
	30	1050			
[4] (EA-OPF)	13	802	2947	79.33	72.79
	24	1091			
	30	1054			
[10] HGWO	13	802	2946	79.3	72.784
	24	1090			
	30	1054			

It is seen from the results that choosing the candidate locations based on both LSFP and LSFQ is more advantageous than choosing locations based on any one factor as it gives lower distribution losses. The total penetration of DG is distributed in four locations giving a total loss of 70.87 kW with a total reduction of 66.26 % as compared to the base case. The voltage constraint has also been realized with the minimum voltage being 0.9640 at bus no: 33. The voltage stability also shows considerable improvement with the index value (VSI) increasing to 0.8636. A comparative analysis of the results based on different methods is also given in Table III. The results show that the calculated losses are lowest with the proposed method. The DG sources are distributed in four locations but the penetration level is least at 73 %.

Table IV: Comparison of Results with Different Sensitivity Factors for 69 Bus System

Factor	DG locations	DG sizes	Losses(kW)	Min voltage and location	VSI
LSFP	7,15,55,60,61	321.454,483.397,70.38, 883.577,883.577	72.03	0.9783(65)	0.9159
LSFQ	7,14,49,59,61	187.5,525.2,188.3, 125.6,1615.9	70.61	0.9785(65)	0.9168
LSFP and LSFQ	14,15,49,59, 61	313.5,232,366.6, 114.7,1615.6	69.16	0.9789(65)	0.9184

Table V: Performance Analysis of 69 Bus System in the Presence of PV Systems

Method	Bus no:	DG size(kW)	Total DG size(kW)	% of penetration	Distribution losses
Without DG	…	….	….	….	224.79
Proposed method LSF-TLBO	**14**	**313.5**	**2642**	**69.48**	**69.16**
	15	**232**			
	49	**366.6**			
	59	**114.7**			
	61	**1615.6**			
[14] GA	21	929.7	2989.7	78.63	89
	62	1075.2			
	64	984.8			
[14] PSO	61	1199.8	2987.9	78.58	83.2
	63	795.6			
	17	992.5			
[17] LSF-BFOA	27	295.4	2088.1	54.9	75.238
	65	447.6			
	61	1345.1			
[11] WCA	61	775	2318	60.96	71.5
	62	1105			
	23	438			
[4] EA	61	1795	2642	69.48	69.62
	18	380			
	11	467			
[4] EA-OPF	61	1719	2626	69	69.43
	18	380			
	11	527			
[10] HGWO	11	527	2625	70.65	69.425
	17	380			
	61	1718			

Results of 69 Bus System:

The total losses calculated for the system with base load is 224.79 kW. The voltage stability index with base load is 0.6838 with a minimum voltage of 0.9093 at bus 65. The performance analysis of the system with the three different search spaces using only LSFP, LSFQ and both LSFP and LSFQ are listed in Table IV. It can be seen that as in the case of 33 bus system, for 69 bus system also, it is more advantageous to choose candidate locations based on both LSFP and LSFQ as the losses are lesser. With the 69 bus system, the total losses are found to be 69.16 kW with a total reduction of 69.23 % as compared to the base case. The voltage constraint has also been realized with the minimum voltage being 0.9789 at bus no: 65. The voltage stability also showed considerable improvement with the index value (VSI) increasing to 0.9184. A comparative analysis of the results based on different methods is also given in Table V. The results show lower losses as compared to other existing methods. Though five locations have been identified, the DG penetration is equal or lesser at 69.48 %.

Conclusion

The introduction of DG into the traditional distribution network plays a major role in reducing the losses in the system and improving the voltage stability. In this paper an optimization procedure based on loss sensitivity factor and TLBO algorithm has been developed to place and size PV systems which are active power producing DG sources to achieve improved voltage stability with reduced losses. The effectiveness of the procedure has been validated with results from two different test systems and has been compared with existing techniques. The results show that consideration of loss sensitivity to an increase in both active and reactive power at a bus are required for identifying proper candidate locations. TLBO has proved to be an effective algorithm in finalizing the optimal positions from the candidate locations and the sizes of the units to give minimum losses. The solutions obtained using the method result in lower losses as compared with existing methods.

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