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Techno-economic Study by Teaching Learning-based Optimization Algorithm for Optimal Placement of DG Units in Distribution Systems

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A significant improvement in system performance can be achieved by placing Distributed Generator (DG) units of the optimal size in optimum network of radial distribution locations. In order to maximize the economic and technological benefits, it is necessary to reduce yearly economic losses. These losses include expenditures associated with installation and operation of the buses as well as power loss and voltage difference between buses. In view of these multi-objective frameworks, the current problem is assessed and the best compromise solution also referred as the Pareto-optimal solution is provided. In the framework of the multi-objective optimization problem, specific equality as well as inequality constraints is investigated. It is shown in this study that a Multi-Objective Teaching-Learning Based Optimization (MOTLBO) algorithm has been proposed to solve the multi-objective problem. For the purpose of evaluating its performance, the proposed method is being deployed on IEEE-33 and IEEE-69 System of radial bus distribution. A comparison with other recent multi-objective algorithms such as OCDE, KHA and LSFSA is also included in this study. It has been revealed that the algorithm proposed can offer superior outcomes concerning power loss, annual economic loss mitigation and voltage profile enhancement.

Keywords: Distributed generation location, Distribution radial system, Economic loss analysis, Loss mitigation, Simultaneous DG placement

Introduction

The energy sector is being forced to study small, localized nonconventional energy sources due to the rapid depletion of non-renewable, substantial environmental repercussions including growing generation & distribution losses in existing power systems. On top of all that, as a result of excessively rapid scientific improvements in this sector, the cost per unit of power generated by non-conventional resources has dropped considerably over the previous two to three decades. As a result, these Distributed Generation (DG) systems units are becoming popular. Small scale DG units should typically have a power capacity of less than 5 MW.[1] There are two types of DG units: intermittent and non-intermittent.

Several research studies in this area have been published in the literature in recent years. Different authors have used a variety of classical and heuristic strategies to address Optimal DG Positioning (ODGP) issues. A technique based on Genetic Algorithm (GA) for location and sizing of different kinds of DG units has previously been presented to reduce the daily average cumulative actual power losses along enhancements to voltage profiles.[2] GA was applied by Singh *et al.*[3] to investigate placement effects of several variants of DGs running at various power factors also among various models of load.

Vatani *et al.*[4] coupled GA with an analytical technique to address the problem of ODGP by reducing losses of the system by taking into account the DGs' operating power factor.

For the DG allocation problem, the Genetic Algorithm was integrated with Tabu search[5], Particle swarm optimization (PSO)[6] & graph theory[7] as an evolutionary strategy. A basic PSO approach[8] was applied to minimize power loss while simultaneously optimizing voltage stability for the optimal DG location challenge. Using the clonal differential evolution technique, Madihah *et al.* introduced an algorithm to determine the best location and size for renewable energy-based DGs taking into consideration unpredictability and practicality components to cut costs.[9] There are also alternative soft computing approaches featuring Tabu search[10], Krill Herd Algorithm (KHA)[11], Bacterial Foraging

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Optimization (BFO)[12], Ant Colony Optimization (ACO)[13], Augmented Lagrangian Genetic Algorithm (ALGA)[14], Cuckoo Search (CS)[15], Whale Optimization Algorithm[16,17] Stud Krill Herd Algorithm (SKHA)[18], Ant-Lion Optimization Algorithm[19], Flower Pollination Algorithm[20] , Elephant herding optimization algorithm[21] etc. have successfully applied by several researchers to solve the problem of ODGP. Teaching-Learning Based Optimization (TLBO) was proposed by Venkata rao *et al.*[22] The typical IEEE-33 bus distribution system of radial type[23,24] is taken into account in this study.

In order to assess how the quantity of appropriately assigned shunt capacitors impacts both the technical and financial benefits, Okelola *et al.*[25] have developed a novel technique known as the Whale Optimization Algorithm (WOA). Particle swarm optimization is a method for DG unit sizing and placement optimization that Jumaa *et al.*[26] has proposed.

Salkuti *et al.*[27] offers an innovative approach to determine the appropriate location and sizing for shunt capacitors for reactive power compensation in power distribution systems with scattered generating. The location of the shunt capacitors is chosen in this case using the loss sensitivity factor technique. Nguyen *et al.*[28] provide a method that is based on Enhanced Sunflower Optimization (ESFO) for optimizing the size and placement of DG in the distribution system to minimize power loss.

In this study, the capacity and DG source locations are optimized such that the overall cost and energy losses of the system are minimized when bus voltages improve. When the system's lifespan is considered as well as the cost of energy distribution losses, the system's cost is directly related to the investment in DG sources. In majority of the research on DG placement, Cost reduction, loss reduction, or voltage deviation reduction are all taken into account, separately. Conversely, as per best of our knowledge, no one has evaluated all of the objectives at the same time, including maximization of economic advantages, minimization of power loss, and minimization of voltage deviation. Consequently, under altered power conditions simultaneous evaluation of all of the aforementioned objectives is a requirement for corporate viability. This work is unique as it uses a multi-objective framework to consider all of the above goals. The MOTLBO approach is employed in this paper. The efficacy of the above-mentioned approach is validated using IEEE 33 and IEEE 69 bus test systems. When compared to other meta-heuristic methods, the proposed method appears to be capable of producing superior results.

Problem Identification

Multi-objective ODGP's primary goal is to maximize annual profit while reducing power loss and increasing bus voltages hence improving performance and dependability of the system. The cost of the overall system is mostly influenced by network system losses and the value of DG units post penetration. As a result, one of the aims is to mitigate power loss while another is to mitigate the system's annual economic loss (AEL).

The annual economic loss without DG ($\mathrm{AEL}_{\mathrm{woDG}}$) reflects energy loss owing to power distribution costs while the DG's annual economic loss ($\mathrm{AEL}_{\mathrm{wDG}}$) reflects the yearly economic loss because of Losses in power distribution with existence of DG as well as annual additional cost caused by DG integration.

The difference between $\mathrm{AEL}_{\mathrm{woDG}}$ and $\mathrm{AEL}_{\mathrm{wDG}}$ indicates the entire annual cost savings as a result of optimal DG penetration. All of these goals are outlined in the sections that follow:

Loss of Real Power

When compared to transmission systems, distribution systems have larger losses due to low voltage. Copper losses are the most common in the distribution system and can be estimated as follows:

$$P_{loss} = \sum_{i=1}^{n} I_i^2 R_i \qquad \ldots (1)$$

Here 'I_i' represents current, 'R_i' represents resistance, and 'n' represents the number of buses. The goal of this paper is to minimize real power loss. The voltage limitation is set between 0.9 and 1.05. DG's size ranges from 60 to 3000.

Annual Economic Loss (AEL)

Whenever a DG or several are installed in a network, the overall loss of active power is lower than when the network is not equipped with DGs. As a result, the total annual economic loss without any DG (AEL_{woDG}) is given by

$$\mathrm{AEL}_{woDG} = PL^{woDG} \times C_e \times 8760 \qquad \ldots (2)$$

where, C_e = Cost of energy loss per kWh in \$, P_L^{woDG} is loss of total real power without DG.

Total annual economic loss due to DGs including DG cost ($\mathrm{AEL}_{\mathrm{wDG}}$) will be

$$AEL_{wDG} = P_L^{wDG} \times C_e \times 8760 + \frac{C_{DG} \sum_{i=1}^{N_{DG}} P_{DGi}}{L_{DG}} \quad \dots (3)$$

where, 'N_{DG}' is Number of DGs installed; 'P_L^{wDG}' is total real power loss with DG; 'C_{DG}' is DG cost per kW supplied which includes DG capital expenditure as well as cost of installation; operating and maintenance; 'L_{DG}' is Years of DG life total.

Yearly cost savings = $AEL_{woDG} - AEL_{wDG}$ … (4)

Multi-Objective Formulation:

This paper discusses the multi-objective index (MOI) which takes into account all of the objectives listed above in order to retain the impacts on techno-economic analysis in general. The objective function's components are weighted normalized indices. The weighting variables' values are carefully chosen for DG penetration, such that their weights provide the appropriate relevance. So the basic aim of this analysis is to decrease MOI while satisfying with a number of constraints on equality and inequality. MOI can be stated mathematically as:

$$Minimise\ MOI = (w_1.P_{loss} + w_2.AEL_{wDG}) \quad \dots (5)$$

where, $\sum_{i=1}^{2} W_i = 1.0; \wedge W_i \in (0, 1)$ … (6)

To decrease MOI, several limitations are examined and their limits rigidly maintained including power conservation, bus voltage min–max, line power flow limits.

Algorithm for Teaching-Learning Optimization

All optimization methods based on evolutionary and swarm intelligence have control elements include the population size, the generations number, the size of the elite and so on. Algorithms, in addition to the normal control parameters, require its own set of parameters. This problem is addressed by teaching learning based optimization (TLBO), which avoids the use of algorithm-specific variables.

The algorithm of TLBO considers how a teacher's instruction affects students. When compared to other algorithms, it is straightforward because it does not require the usage of any parameters throughout its operation. It necessitates less computational and memory effort. It gained popularity as a result of its ease of use when it comes to tackling optimization problems. TLBO was proposed by Venkata rao *et al.*[22]

TLBO algorithm mainly consists of two stages.

- Teaching Phase
- Leaning Phase

The teachers encourage and improve the student's knowledge, and the teachers share their knowledge with the students. Students will interact with one another in order to enhance their skills.

Thus, based on the teacher's teaching quality and student interaction, the teacher will improve the student's quality and knowledge. Different design variables correspond to various courses, while population indicates the number of students. There are two sections to the TLBO: (i) teacher phase (ii) learner phase. Below is a description of how both phases work.

Teaching Phase:

The class's overall performance will increase as students knowledge improvement. The quality of the teacher's instruction will determine how well the class performs. Everyone's new position is determined by the

$$X_{new,k} = X_{old,k} + r_k(X_{teacher} - T_F M_K) \quad \dots (7)$$

$$T^F = round\ \{1+random\ [0, 1]\ (2-1)\} \quad \dots (8)$$

Here, $X_{old,k}$ represents the student k's previous position, from which he or she has to learn from the teacher to boost their level of knowledge. $X_{new,k}$ is student k's new position. The letter M represents the number of courses. $X_{teacher}$ is the best position for a student who strives to improve the average grade in the class. Teaching factor, random number and mean value of the outcomes represented by T_F, r and M_K respectively. The new value of each student is only evaluated if it is higher than the prior value.

Learning Phase:

Students collaborate to increase their knowledge throughout this period. An arbitrary student knowledge level is used to decide the incoming student's position. Each student learns knowledge by interacting with a student who has a higher level of skill who is picked at random. Every student is assigned to a new role.

$$x^{new,} = x^{old,} + rand x^{old,} - , \quad \dots (9)$$

where, $x^{new,a}$ is position 'a' for new student; $x^{old,a}$ is position 'a' for old student; $x^{old,b}$ is a randomized student's 'b' previous position

Only if the new position is superior does the new value stay. A population-based algorithm called TLBO simulates the teaching-learning process in the classroom. There are no control settings specific to the algorithm in this approach, only standard control variables like population size & generation number. The TLBO algorithm is depicted in the above Fig. 1.

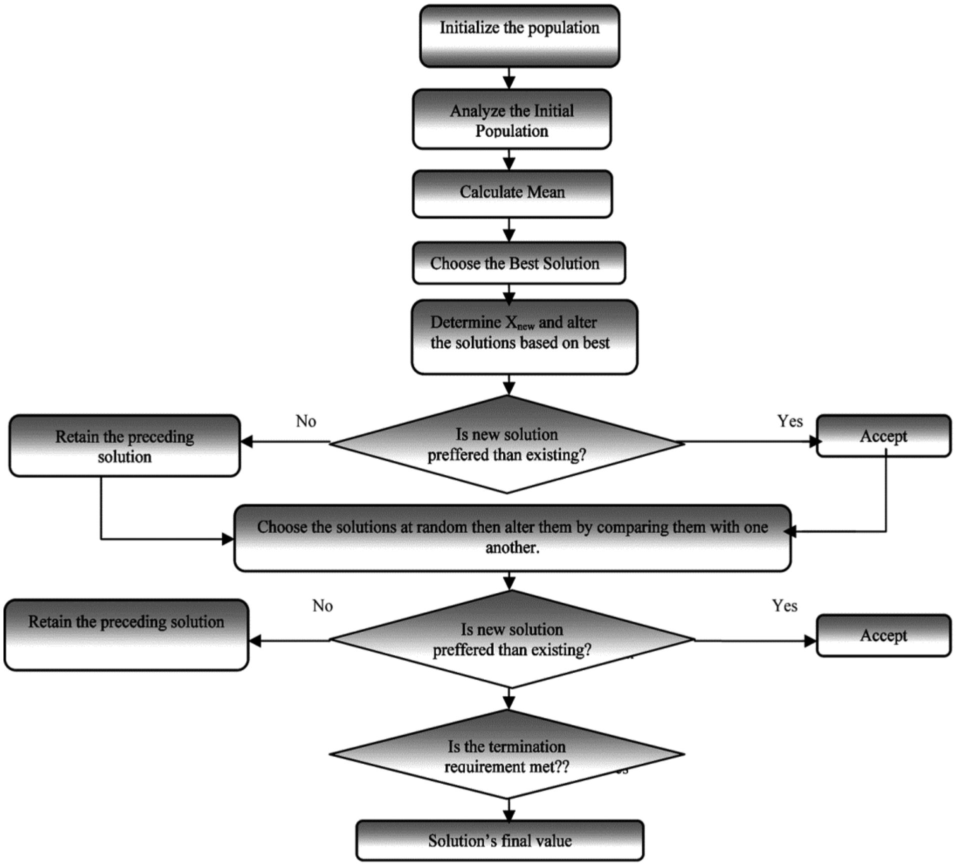

Fig. 1 — The TLBO algorithm's flowchart

Results and Discussion

The proposed technique's effectiveness is assessed using conventional IEEE-33 as well as IEEE-69 bus systems with varying levels of penetration. To put it differently for better economic and technological advantages, one or several DGs were installed in each test systems. Except for the slack bus, all of the buses are considered likely candidates for DG placement. The highest and lowest limits of bus voltages are 1.05 & 0.95 p.u., respectively. For maximum capacity utilization, the power factor of the DGs is considered to be unity resulting in the most possible benefit from DGs.

Because the entire DG's life is expected to be ten years, the combined system planning time will be ten years as well in order to illustrate the long-term influence of the ODGP. The cost of DG energy injection is $30.00 per kW, which covers the DG unit's capital investment along with installation, operating, and maintenance expenditures. Energy loss is estimated to cost $0.05 per kWh.[18] NP is taken to be 50 in all cases. On the MATLAB R2020a edition, the proposed algorithm is enacted. In a multi-objective scenario, other well-known algorithms are compared to the proposed MOTLBO.

Case Study 1 (IEEE-33 System Bus)

The typical IEEE-33 bus distribution system of radial type[23,24] is taken into account in this scenario. The substation base MVA and base voltage for this system are 100 MVA and 12.66 kV. It requires 3.715 MW of real power and 2.3 MVAr of reactive power. Prior to DG installation, for the typical system, overall actual and reactive losses are 210.9970 kW and 143.0320 kVAr, respectively. At bus number 18, the minimum voltage is found to be 0.9423 p.u. without any DG installation. Total loss of real power is equated to its approximate annual economic loss (AEL_{woDG}) for cost analysis, which is 92418 $.

Case I (P_L Minimization)

For the sake of simplicity and comparison, the only objective function for DG allocation optimization is power loss minimization. The findings obtained using the proposed TLBO method is given in Table 1. It also compares the results of existing approaches such as OCDE[18], KHA[11] and LSFSA[20] to the proposed method for a comparative study. When a single DG is considered, the proposed method's optimal loss is 111.03 kW. When many DGs are placed, real power losses are also shown in Table 1. After installing three and four DGs, the losses in real power are now 72.78 and 67.64 kW, respectively. These losses are marginally better than the previous ones reported in the literature by other approaches. Cost comparison for various penetration levels is shown in Table 2. Since, higher penetration lowered line power loss, annual economic losses decreased as well resulting in a significant rise in annual total savings as shown in Table 2.

Case II (P_{Loss} & AEL_{wDG} Minimization)

P_{Loss} and AEL_{wDG} are two objectives that should be minimized in this case and the DGs number is fixed to three. The case II section in Table 3 contains the best compromised solution for this issue using the suggested MOTLBO technique. According to this analysis, three DGs with capacities of 707.6 kW, 1015.9 kW and 748.9 kW may be positioned at bus numbers 25, 30, 14 for simultaneous minimal P_{Loss} and AEL_{wDG}. The value of AEL_{wDG} is decreased to USD 40029 from USD 40722 by sacrificing in P_{Loss} which is enhanced to some extent from 72.78 kW to 74.46 kW with ideal placements. When both goals are considered savings increase.

The voltage profile of 33 bus system was depicted in Fig. 2, with increasing DG units from 1, 3 and 4 respectively. The voltage profile with 4 DG units is better when compared to others. The total yearly economic loss and yearly savings is depicted in Fig. 3.

Table 1 — 33 bus system's results for single objective

DG unit no.(s)	Techniques^{Ref}	DG siting@ Bus no.	DG's capacity (kW)	The worst bus	Voltage on the bus (min) (p.u.)	Total loss@ Active power (kW)
1	Proposed TLBO	6	2590.2	18	0.9424	111.03
3	OCDE[18]	13	801.84	33	0.9686	72.848
		24	1091.46			
		30	1046.58			
	KHA[11]	13	810.7	18	0.9610	75.412
		25	836.8			
		30	841.0			
	LSFSA[20]	6	1112.4	14	0.9677	82.03
		18	487.4			
		30	867.9			
3	Proposed TLBO	24	1091.3	33	0.9687	72.78
		13	801.7			
		30	1053.7			
4	OCDE[18]	6	926.69	18	0.9702	67.74
		14	646.78			
		24	967.34			
		31	679.38			
4	Proposed TLBO	14	646.78	18	0.9703	67.73
		25	782.53			
		6	975.38			
		31	686.41			

Table 2 — Cost analysis of 33 test bus system for single objective

DG unit no.(s)	Annual economic loss in total (USD)	Total yearly saving (USD)
0	92418	0
1	56404	36014
3	40722	51696
4	38947	53471

Table 3 — 33 bus system results for Multi-objective

Technique	Case	DG no's	Size of DG/ Placement [Kw/Bus No.]	Voltage $_{@bus[min]}$ (V_{pu})/Worst bus	loss of active power $_{[kw]}$	Total Annual economic$_{[\$]}$loss	Annual Savings Total $_{[\$]}$
OCDE [18]	Case: II (*Minimization of P_L & YELwDG*)	3	758.39/14 986.52/24 1032.32/30	0.9671/33	73.08	40338.942	51649.201
Proposed TLBO	Case: II (*Minimization of P_L & YELwDG*)	3	707.6/25 1015.9/30 748.9/14	0.9687/33	74.46	40029	52389

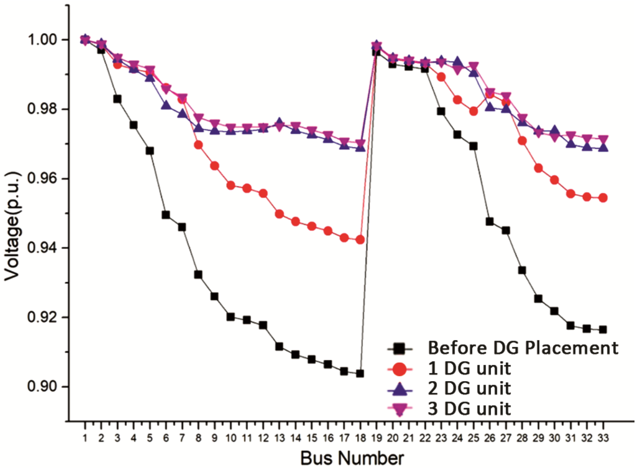

Fig. 2 — 33 bus system voltage profile

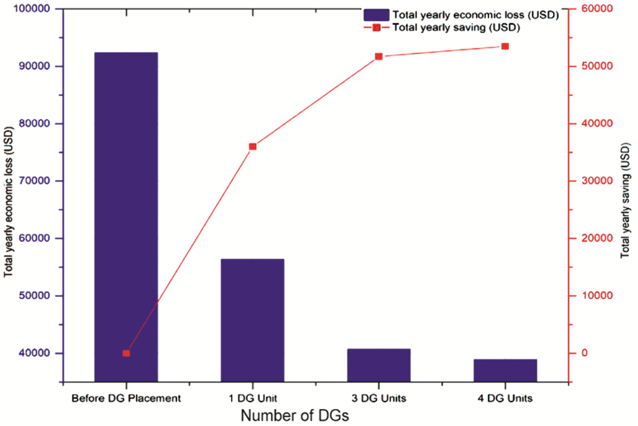

Fig. 3 — Total Yearly economic loss and yearly savings of 33 bus

The convergence characteristic of the 33 bus is depicted in Fig. 4.

Case Study 2 (IEEE-69 bus system)

This scenario considers the IEEE-69 bus larger distribution radial system. 12.66 kV is the substation base voltage for this system. 3.8022 MW and 2.6946 MVAr are the real and reactive loads, respectively. The active and reactive losses, according to the load flow study are 225 kW and 102.1321 kVAr respectively. Total real power loss without DG is converted to its equivalent yearly economic loss (YELwo$_{DG}$) for cost analysis, which in this scenario is 98550$. At bus number 65, 0.9092 p.u. is the minimum bus voltage when no DG is present.

Case I (P_{Loss} Minimization)

For the sake of simplicity and comparative performance comparison in this case study, the sole objective function is the power loss. The TLBO suggested method can only decrease system power loss and the results comparison is made to those obtained using other strategies such as OCDE[18], KHA[11] and LSFSA[20]. The outcome of the proposed strategy is displayed in Table 4. The annual economic losses & savings before and after DG installation is presented in Table 5. The overall annual savings increase as the penetration level increases, but the rate of increase slows after 2 to 3 DGs are installed.

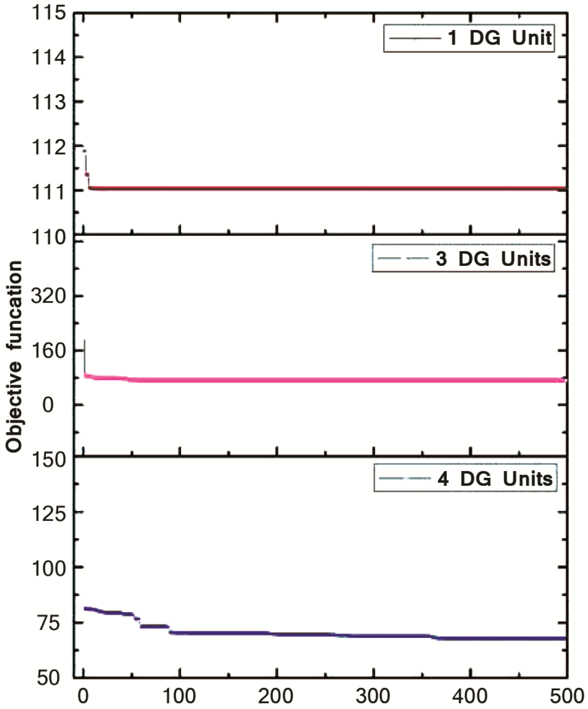

Fig. 4 — Convergence characteristics of 33 bus

Case II: Minimization of P_{Loss} & AEL_{wDG}

Three DGs were placed in this scenario so that the values of both PL and AEL$_{wDG}$ reached simultaneously their lowest points. Because the two objectives are fundamentally irreconcilable, we must choose the best compromise option for each.

After three DGs are installed, the loss is 71.67 kW, slightly greater than the value achieved in Case I. However, AEL$_{wDG}$ falls from 38288 USD to 37857 USD, bringing total annual savings to 60693 USD. The best results are shown in Table 6 along with the DG sizes and placements. When both goals are considered savings increase.

The 69 bus system voltage profile is shown in Fig. 5 with increasing DG units from 1, 2 and 3 respectively. The voltage profile with 3 DG units is better when compared to others. Total yearly economic loss and yearly savings of 69 bus is depicted in Fig. 6.

The convergence characteristic of 69 bus sytem is depicted in Fig. 7.

Table 4 — 69 bus system results for single objective

DG unit number(s)	Techniques	DG's placement (@Bus no.)	DG's @Size$_{[KW]}$	Voltage @bus[min] [V_{pu}]	The worst $_{Bus}$	Total active loss $_{[KW]}$ of power
1	Proposed TLBO	61	1872.8	0.9683	27	83.2
2	OCDE[18]	17	530.99	0.9789	65	71.68
		61	1781.34			
	Proposed TLBO	61	1781.5	0.9789	65	71.67
		17	531.5			
3	OCDE [18]	11	525.93	0.9790	65	69.436
		18	380.18			
		61	1718.96			
	KHA [11]	12	496.2	0.9790	65	69.563
		22	311.3			
		61	1735.4			
	LSFSA [20]	18	420.4	0.9811	61	77.1
		60	1331.1			
		65	429.8			
4	Proposed TLBO	18	380.3	0.9790	65	69.43
		61	1719			
		11	526.8			

Table 5 — Cost analysis of 69 test bus system for single objective

DG unit no.(s)	Total yearly@annual economic loss (USD)	Total yearly saving (USD)
0	98550	0
1	42071	56479
2	38334	60216
3	38288	60262

Table 6 — 69 bus system results for Multi-objective

Technique	Case	DG Nos	Size of DG /Placement [Kw/Bus No.]	Voltage $_{@bus[min]}$ (V_{pu})/ Worst bus	loss of active power $_{[kw]}$	Annual economic$_{[\$]}$ Total loss	Annual Savings Total $_{[\$]}$
OCDE [18]	Case: II (*Min. of P_L & YELwDG*)	3	406.46/12 314.68/21 1707.25/61	0.9775/65	69.78	37847.325	60672.2
Proposed TLBO	Case: II (*Minimization of P_L & YELwDG*)	3	459.2/18 1406.5/61 289.6/64	0.9790/65	71.67	37857	60693

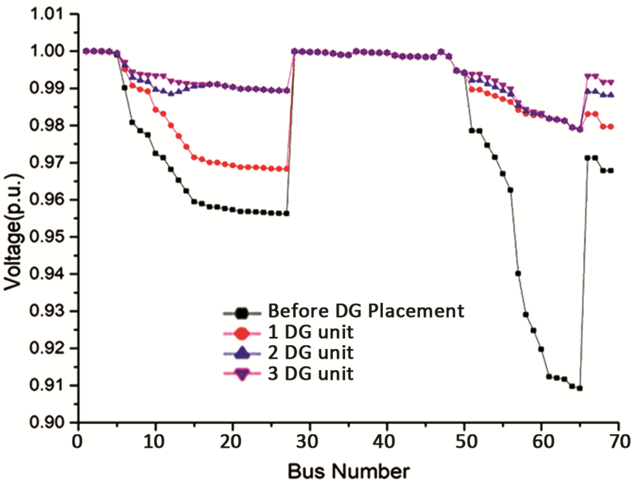

Fig. 5 — voltage profile of the 69 bus system

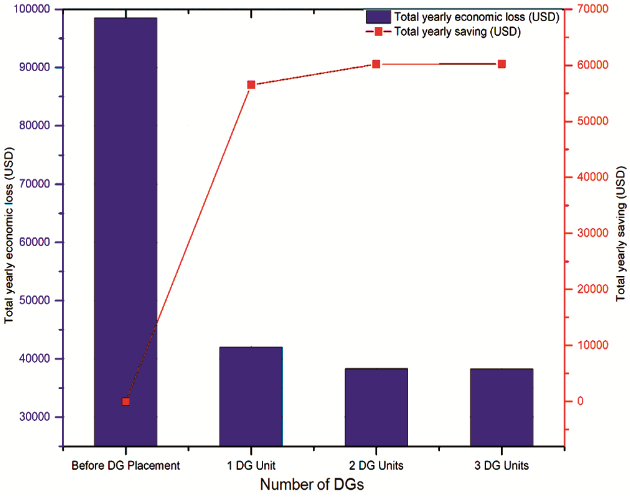

Fig. 6 — Total Yearly economic loss and Yearly savings of 69 bus

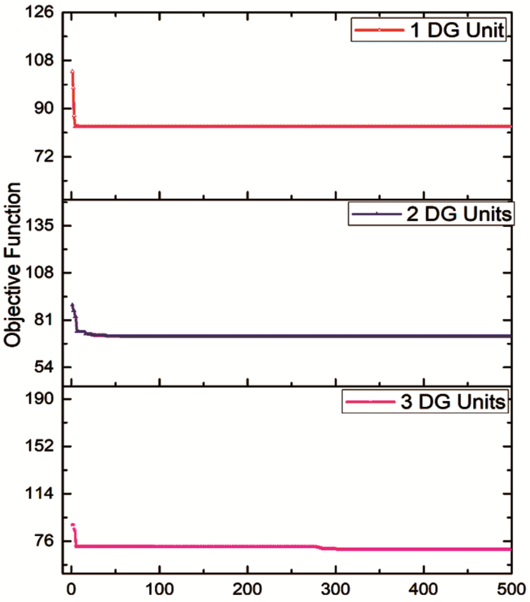

Fig. 7 — Convergence Characteristics of 69 bus

Conclusions

This paper discusses a novel multi-objective Teaching learning-based optimization technique for deploying optimal DGs in optimal locations with the objective to optimize overall annual savings by reducing total economic loss, actual power loss, and improving voltage profile. By placing optimal-sized DGs in Reduced optimal sites, real power loss, annual economic loss and the voltage profile is improved. Annual economic benefit grows as annual economic loss decreases. Its results are compared to other methodologies. The proposed method has been shown to be superior. In comparison to existing algorithms like OCDE, KHA, and LSFSA, the new MOTLBO algorithm outperforms them all in terms of precision and diversity. For 33 bus, three DGs with capacities of 707.6 kW, 1015.9 kW and 748.9 kW are positioned at bus numbers 25, 30, 14 for simultaneous minimal P_{Loss} and AEL_{wDG}. The value of AEL_{wDG} is decreased to USD 40029 from USD 40722 bringing total annual savings to 52389 USD. For 69 bus, after three DGs are installed AEL_{wDG} falls from 38288 USD to 37857 USD, bringing total annual savings to 60693 USD. So, the proposed method is appropriate for choosing the ideal locations and DG sizes in a distribution network. The multi-objective TLBO technique employed to integrate DGs optimally assisted in lowering the overall real power losses and the energy cost losses. Future studies can look into economic analysis to find the lowest temporal relationship between technical loss minimization, profits & the costs associated with setting up, and operating & maintaining distributed generation units while taking a variety of demand conditions into account.

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