A PSO-TVAC for optimal installation of multiple distributed generations in a radial distribution system

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ABSTRACT

The integration of distributed generations (DGs) into distribution system networks has seen a significant increase owing to the depletion of conventional energy resources and the growing power demand. However, a high penetration of DGs can adversely affect the stability of the distribution networks due to the intermittent nature of their generation capabilities. Hence, it is crucial to design DGs optimally to support grid voltage regulation and improve distribution networks performance. This study utilizes a particle swarm optimization (PSO) with time-varying acceleration coefficients (PSO-TVAC) technique to optimize the location and size of various distributed generation units while minimizing the total active power loss. The initial system power loss was determined using a distribution load flow analysis based on the backward-forward technique. The PSO-TVAC algorithm was then employed to identify the optimal placement and sizing of DGs within the standard IEEE 33-bus radial distribution network. To assess the proposed algorithm's effectiveness, photovoltaic (PV) and wind turbine (WT) were considered as the DGs. In comparison with other algorithms, PSO-TVAC achieved the lowest power loss, measuring 72.79 [kW] and 12.14 [kW] for 3-PV and 3-WT installations, respectively. Furthermore, the optimal installation of 3-PV and 3-WT improved the distribution system performance by 65.49% and 94.25%, respectively.

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1. INTRODUCTION

Electricity is distributed to individual customers through a distribution network, which is the last stage of an electrical supply system. The heat produced by current flow during power distribution could result in power loss [1]. For a large-scale distribution network, the total power loss of the system may be significant. According to a previous research, distribution network system losses accounted for 70% of total power system network losses, while transmission and sub-transmission line losses accounted for 30% [2]. In accordance with the losses issue, one of the techniques that can be utilised to reduce power loss in a power system network is by installing distributed generations (DGs) near to load centers [3]. Additionally, integrating renewable DGs units as alternative sources for conventional power plants will significantly help in addressing the rapidly increasing load demand issues [4]–[6]. The DGs use smaller generating units, ranging from 25 [kW] to 100 [MW] [7], which allow for more flexible power supply as the system can be easily disconnected for inspection if a fault occurs. Furthermore, DGs are more reliable than large power grids, which are more prone to faults. Additionally, DGs help to improve the voltage profile, power quality, and overall grid reliability [8]. Despite the previously mentioned benefits of DGs, improper placement and sizing of the units in distribution networks may result in significant technical issues. These technical issues would have a negative impact on voltage reduction, power supply dependability, system stability, power losses, protection system, and undesirable islanding [9]. Integrating DGs into existing power networks may result in several drawbacks since conventional electrical grids have always been built to supply load demand from the generation side [10]. However, the power flow will be bidirectional if the DGs are connected to the system as the surplus power produced is fed back to the generation side.

In a distribution network, selecting the optimal location and size for DGs involves complex optimisation problems [11]–[15]. To ascertain adequate placement and size of DGs in the distribution network, various meta-heuristic optimisation techniques have been proposed. Crow search optimisation (CSO) was employed to determine the optimal sizing and placement of distribution generation for an actual radial distribution system in Egypt [16]. Furthermore, the hybrid lightning search algorithm-simplex method (LSA-SM) [17] and flower pollination algorithm (FPA) [18], [19] were used to optimise the distributed generation systems. Another method of determining the optimal location of DGs was based on the firefly algorithm (FA), which mimics the attractiveness of the firefly as a function of the light intensity seen by adjacent fireflies [20]. The optimal positioning and sizing of grid-connected DGs in radial distribution networks can be accomplished through the application of a well-established optimization technique, particle swarm optimization (PSO) [21]. Another study Halim *et al.* [22] employed the moth flame optimization (MFO) algorithm, which incorporates distinct spiral courses, to determine the most favorable placement and sizing of DGs in the IEEE 12 and 33-bus radial distribution networks. A new technique for optimal sizing and placement of DGs consisting of photovoltaic (PV) and wind turbine (WT) in a radial distribution network was proposed in this work. To minimise active power losses and improve the voltage profile, particle swarm optimisation with time-varying acceleration coefficients (PSO-TVAC) technique was used to solve the optimisation problem while taking equality, inequality, and security constraints into account. The algorithm has proven its ability to provide consistent and robust solutions to a variety of power system optimisation problems.

2. METHOD

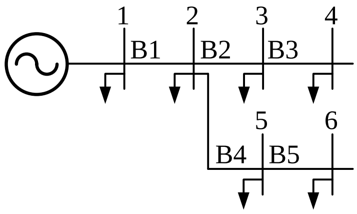
The following sub sections discuss the methodologies involved in this study. The first procedure was related to the formulation of a distribution system based on the standard IEEE 33-bus radial system network. The next procedure involved the implementation of a meta-heuristic algorithm, known as particle swarm optimisation with time-varying acceleration coefficients to determine the best location and sizing of DG installation in the 33-bus radial distribution system network.

2.1. Power flow formulation of a distribution system

A power flow study is a common technique used in electrical engineering to optimise the operation of a power system network. The optimal operating condition for the electrical network can be determined by identifying the amounts of generation and consumption. The process of power flow analysis begins by identifying the system's elements including generator, transformers, and transmission lines. The network is modelled mathematically, and simulations of different power flow scenarios can be conducted to determine the bus voltage magnitude and phase angle, real and reactive power flow in different lines as well as the power loss due to the inefficiencies of the system. Thus, the power flow analysis can identify the potential ways to improve the efficiency of the system and reduce the amount of power loss such as the location of DGs installation and their sizing. In a radial distribution system, backward forward sweep (BFS) method is opted due to the special features of radial structure, high R/X ratio and unbalanced load [23]. In BFS algorithm, there are three major steps to calculate the power flow of radial distribution system as follows.

2.1.1. Three steps to calculate the radial power flow distribution algorithm of the BFS system

Step 1: Create bus-injection to branch-current (BIBC) matrix. The BIBC matrix is modified based on a 6-bus system as in Figure 1. Figure 1(a) shows the configuration of the 6-bus system while Figure 1(b) shows the BIBC matrix which represents the branch connection between buses of the network.



(a)

	I_2	I_3	I_4	I_5	I_6
B1	1	1	1	1	1
B2	0	1	1	0	0
B3	0	0	1	0	0
B4	0	0	0	1	1
B5	0	0	0	0	1

(b)

Figure 1. Modification of BIBC matrix; (a) 6-bus system configuration and (b) BIBC matrix

Step 2: Compute the currents using kirchhoff's current law (KCL) in backward sweep direction (from the farthest node to the source node). The equivalent current injection and the branch current are computed using (1) and (2) respectively.

$$I_i = \left(\frac{P_i + jQ_i}{V_i}\right)^* \quad (1)$$

$$[I_{branch}] = [BIBC][I_i] \quad (2)$$

Step 3: Compute the voltage using kirchhoff's voltage law (KVL) in forward sweep direction (starting from the source node). The line data for each branch is represented in a diagonal element in matrix *ZD* as in (3) and rearranged into BIBC matrix as in (4). The voltage of each bus is computed using (5).

$$ZD = \begin{bmatrix} Z_{B1} & 0 & 0 & 0 \\ 0 & Z_{B2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & Z_{Bn} \end{bmatrix} \quad (3)$$

$$[ZBIBC] = [BIBC]'[ZD][BIBC] \quad (4)$$

$$V_i = V_o - [ZBIBC] \times I_i \quad (5)$$

The computation of currents and voltages in Step 2 and Step 3 are repeated until the solution is converged. The currents and voltages for each bus computed by using BFS algorithm is used to determine the power flow of each branch and the total loss of the system. The complex power, S_{ij} from bus *i* to bus *j* and S_{ji} from bus *j* to bus *i* are calculated using (6) and (7) respectively. The branch loss and total loss of the system are calculated using (8) and (9) respectively.

$$S_{ij} = V_i I_{ij}^* \quad (6)$$

$$S_{ji} = V_j I_{ji}^* \quad (7)$$

$$L_{ij} = S_{ij} + S_{ji} \quad (8)$$

$$P_{loss} = \sum L_{ij} \quad (9)$$

2.2. PSO-TVAC for optimal installation of DG location and sizing

The installation of DGs with appropriate location and quantified sizing into the radial distribution system may reduce the system loss and increase the efficiency of the system. To determine the best location and sizing of DG installation, a meta-heuristic algorithm is an appropriate solution to be implemented. Random or improper selection of DGs location and sizing may lead to higher system loss and consequently reduce the system efficiency. Thus, PSO was implemented in this study to solve the optimal DGs location and sizing due to its ability of achieving a global optimum and robust solution. The PSO proposed by [24] is a common method used to solve the nonlinear functions in electrical power system problems. A modification was made to the conventional PSO to improve the performance of the algorithm. The flowchart of PSO-TVAC for optimal location and sizing of DG installation is presented in Figure 2.

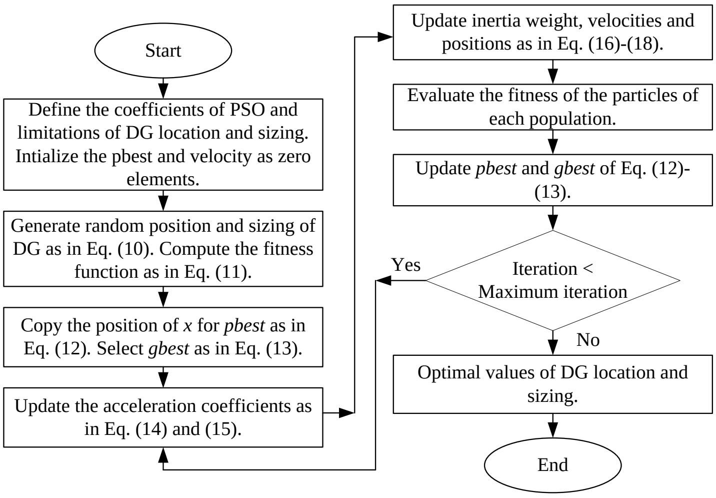


Figure 2. Flowchart of optimal DG location and sizing using PSO-TVAC

The algorithm of modified PSO with time-varying acceleration coefficients (PSO-TVAC) is further elaborated in the following steps:

Step 1: Generate *n*-population of random particles or solutions in a dimension, *d* and the fitness value for each set of random particles as in (10) and (11) respectively.

$$X_i = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1d} \\ x_{21} & x_{22} & \cdots & x_{2d} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nd} \end{bmatrix} \tag{10}$$

$$Y_i = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \tag{11}$$

Step 2: Select the best particles, *pbest* from the best fitness across all iterations for each population as in (12). However, *pbest* is directly taken for particles, *X* for the first iteration.

$$pbest = \begin{bmatrix} pbest_{11} & pbest_{12} & \cdots & pbest_{1d} \\ pbest_{21} & pbest_{22} & \cdots & pbest_{2d} \\ \vdots & \vdots & \ddots & \vdots \\ pbest_{n1} & pbest_{n2} & \cdots & pbest_{nd} \end{bmatrix} \tag{12}$$

Step 3: Select a global best particle, *gbest* from the best fitness of *pbest* of each population for every iteration as in (13).

$$gbest = [gbest_1 \quad gbest_2 \quad \cdots \quad gbest_d] \tag{13}$$

Step 4: Update the acceleration coefficients, c_1 and c_2 which varied with time as in (14) and (15).

$$c_1 = \left(c_{1,max} - c_{1,min}\right) \times (i/i_{max}) + c_{1,min} \tag{14}$$

$$c_2 = \left(c_{2,max} - c_{2,min}\right) \times (i/i_{max}) + c_{2,min} \tag{15}$$

Step 5: Update the time-varying inertia weight, *w* and velocity of the particles, *V* as in (16) and (17) respectively. Update the position of the *X* particles as in (18).

$$w_i = w_i \times (1 - \alpha) \tag{16}$$

$$V_i = w_i \times V_i + c_1 \times rand \times (pbest - X_i) + c_2 \times rand \times (gbest - X_i) \tag{17}$$

$$X_i = X_i + V_i \tag{18}$$

3. RESULTS AND DISCUSSION

The standard IEEE 33-bus radial distribution system was used as the test system as shown in Figure 3. The system consists of 33 buses with 32 branches. The total active and reactive loads are 3.715 [MW] and 2.3 [MVar] respectively. The bus and line data were based on the simulation data obtained in [25]. Table 1 presents the parameters of the algorithm and the operating constraints. To verify the performance of the proposed algorithm, two types of DG were considered. DG Type-I is denoted by PV, which only produces active power, *P*. Meanwhile DG Type-II is denoted by WT, which produces both active and reactive power.

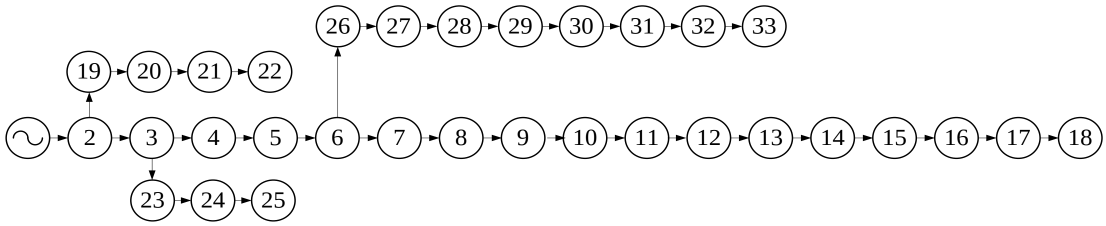


Figure 3. Schematic diagram of IEEE 33-bus radial distribution system

Table 1. Parameters and constraints for PSO-TVAC and DG installation

Parameters	Values
Size of population	50
Maximum iteration	100
DG limitations of active power generation	0.3 [MW] $\leq P_{DG,i} \leq$ 3 [MW]
DG limitations of power factor	$0.7 \leq P_{DG,i} \leq 1$

The performance of PSO-TVAC was evaluated by a comparison with PSO, backtracking search algorithm (BSA) [26], and bat algorithm (BA) [27] allocation and sizing of three DGs as in Table 2. Without the installation of DGs, the total power loss of the distribution system was 210.98 [kW]. It was observed that PSO-TVAC achieved the most minimum power loss of 72.79 [kW] and 12.14 [kW] for 3-PV and 3-WT installation respectively as compared to BSA, PSO and BA. Thus, the optimal installations of 3-PV and 3-WT were able to improve the performance of the distribution system at the highest by 65.49% and 94.25% power losses reduction.

Table 2. Optimal location and sizing of DGs installation by different algorithms

DG type	Method	Location (bus)	Size [kW]	Power factor	Power loss [kW]	Power loss reduction (%)
Without DG	-	-	-	-	210.98	-
3-PV	BSA	12	632	Unity	89.05	57.79
		28	487			
		31	550			
	PSO	14	691	Unity	74.09	64.88
		24	986.1			
		29	1277.3			
	BA	13	720	Unity	73.40	65.21
		24	1020			
		30	980			
	PSO-TVAC	30	1053.6	Unity	72.79	65.49
		13	801.8			
		24	1091.3			
3-WT	BSA	12	632	0.86	29.65	85.97
		28	487	0.71		
		31	550	0.70		
	PSO	13	537.8	0.669	19.63	90.70
		24	1058.9	0.786		
		30	967.7	0.758		
	BA	13	720	0.896	12.35	94.15
		24	1020	0.897		
		30	980	0.720		
	PSO-TVAC	13	710.6	0.883	12.14	94.25
		24	1004.2	0.701		
		30	1124.8	0.714		

Table 3 displays the results of allocating and sizing individual three, two, and one DGs for both PVand WT based on the proposed PSO-TVAC approach. As the number of DGs was increased, the power loss decreased from 111.02 [kW] and 87.17 [kW] to 72.79 [kW] for 1-PV, 2-PV, and 3-PV respectively. Similar reductions in the power loss were also observed for 1-WT, 2-WT and 3 WT of 67.86 [kW], 28.72 [kW] and 12.14 [kW] respectively. In comparison between two types of DGs, all three WT shows significantly higher power loss reduction with 67.84%, 86.39%, and 94.25% as compared to 47.38%, 58.68%, and 65.49% recorded by all three PV respectively. This is due to the reactive power compensated by WT in addition to the active power generated. Thus, the results show that the improvement of power factor by reactive power compensation also aid in the reduction of power loss of the overall distribution system.

Table 3. Results of optimal installation of DGs location and sizing by PSO-TVAC

DG Type	Location (bus)	Size [kW]	Power factor	Power loss [kW]	Power loss reduction (%)	Maximum voltage [p.u.]	Minimum voltage [p.u.]
Base case	-	-	-	210.98	-	-	-
1-PV	6	2590.2	Unity	111.02	47.38	1.0000	0.9424
2-PV	13	851.6	Unity	87.17	58.68	1.0000	0.9685
	30	157.6					
3-PV	30	1053.6	Unity	72.79	65.49	1.0000	0.9687
	13	801.8					
	24	1091.3					
1-WT	6	2553.1	0.819	67.86	67.84	1.0013	0.9581
2-WT	13	800.1	0.873	28.72	86.39	1.0021	0.9804
	30	1212.5	0.700				
3-WT	13	710.6	0.883	12.14	94.25	1.0013	0.9927
	24	1004.2	0.701				
	30	1124.8	0.714				

4. CONCLUSION

This study proposed PSO-TVAC technique for optimal placement and sizing of DGs in a radial distribution network. The proposed technique was tested on the 33-bus network with the integration of two different types of DGs, which are PVand WT. From the simulation results, it was proven that PSO-TVAC outperformed particle swarm optimisation, BSA and BA with the lowest simulated power losses of 72.79 kW and 12.14 [kW] for 3-PV and 3-WT installation respectively. Thus, the optimal installation of 3-PV and 3-WT is capable of improving distribution system performance by 65.49% and 94.25% power loss reduction. The power losses also reduced significantly as the number of DGs were increased, from 111.02 [kW] and 87.17 [kW] to 72.79 [kW] for 1-PV, 2-PV, and 3-PV, respectively. The findings also demonstrated that improving power factor through reactive power compensation helps to reduce power losses in the system.

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