Optimal Placement and Sizing of Renewable and Non-Renewable Resources in Smart Grid

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Abstract

Distributed Generators (DGs) play a key role in existing power distribution networks together with significant innovations in smart grid technology. It is now more essential to evaluate the various types of DGs within the system. Renewable energy types of DGs such as PV and wind promise low emissions and abundant availability. When it comes to the installation of DG, the size, location, and type of DG should be given high importance because improper placement of DG units leads to reducing the benefits of the distribution system and even endangers the entire system operation. If DG size exceeds a certain value limit, power loss at that bus becomes negative. This situation must be avoided. As a result, optimal DG placement aids in the reduction of losses, improvement of voltage profiles, reliability, and overall system efficiency. Considering this, in this paper, a Simultaneous Particle Swarm Optimization (PSO) algorithm is implemented for placement allocation and sizing of multiple types and multiple numbers of DGs in power distribution systems with the objectives of minimization of active and reactive power loss and enhanced voltage profile. Along with the meta-heuristic optimization algorithm, sensitivity techniques such as index vector, loss sensitivity factor,

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and voltage stability margin methods have been analysed. The outcomes are obtained using the aforementioned sensitivity-related methods on the IEEE 15, 33, 69, and 85-radial bus systems and compared with simultaneous PSO for efficacy.

Keywords: Renewable sources modeling, sensitivity methods, simultaneous PSO.

1 Introduction

Traditional electric power systems supply electricity through generator transformers from highly meshed transmission networks connected to large power plants through coordinated operations. The transmission system transfers the power to consumers via distribution transformers. These centralized power plants, like thermal, hydro, and nuclear, produce power ranging from several hundred MWs to a few GWs. A transition has recently taken place in economies of scale, where smaller power plants have become more economical. This led to the construction of small power plants, connected closely to the customers and therefore named "dispersed" or "distributed generation" (DG), which are connected on the distribution side of the network [1]. These are often called "embedded" or 'decentralized' generations. These are propelled by the recent advancements in technologies such as Smart Grids, Micro Grids, and Renewable Energy. In the present period, where sustainable development and environmental issues are becoming especially crucial, renewable sources are humanity's key priority in energy production.

Electrical utilities strive for optimal grid operations in order to increase reliability and efficiency. As smart grid technology advances, a large number of distributed generation (DG) units are integrated into low voltage distribution networks to meet the increasing load demand. Smart grids integrated with DGs are evolving with various objectives such as minimized power loss, minimized economic cost, voltage stability, and voltage profile improvement [2]. Different types of DGs and their sizing allocation are considered as non-convex optimization problem. The main aim of this paper is to present a heuristic method for the optimal placement and sizing of multiple and different types of DG units, including both non-conventional and conventional energy sources. The rational allocation of the DGs capacity at the very initial level of system development will efficiently enhance the usage of natural resources and is of great importance in sustaining the system's stable performance and saving construction capital with regard to the constraints of the area and resource availability [3]. This paper presents an effective method to minimize losses through optimal location and sizing of multiple types of DGs with the objectives of reducing the power losses and improving the voltage of the network. The optimization is performed using the simultaneous Particle Swarm Optimization (PSO) method. Index vector, loss sensitivity factor, and voltage stability margin methods are used for comparison. Four realistic frameworks are tested for effect, i.e., 15, 33, 69, and 85 Bus IEEE RDS.

2 DG Sources Modeling

From traditional established internal combustion engines and gas turbines to more recent forms of renewable sources such as wind farms and photovoltaics, there are numerous types of distributed generation technologies [4]. Recently, commercialization has taken place in new technologies such as batteries, fuel cells, and micro-turbines.

2.1 Photovoltaic (PV) Energy System Modeling

The output power $\mathrm{P_{PV}}$(t) and energy $\mathrm{E_{PV}}$ from a PV array can be obtained as [5, 6]:

$$\mathrm{P_{PV}(t) = N_S \times N_P \times I_S(t) \times V_0(t) \times F_F(t)} \tag{1}$$

$$\mathrm{E_{PV} = G(t) \times A \times P \times \eta_{PV}} \tag{2}$$

where, $\mathrm{N_S}$ is the number of PV modules connected in series, $\mathrm{N_P}$ is the number of PV modules connected in parallel, $\mathrm{V_0}$(t) and $\mathrm{I_S}$(t) are the hourly short-circuit current and open-circuit voltage respectively, $\mathrm{F_F}$(t) is the fill factor, G(t) is the hourly irradiance in kWh/m^2, A is the surface area of the PV modules in m^2, P is the PV array penetration level factor and η_{PV} is the efficiency.

2.2 Wind Turbine (WT) Energy System Modeling

The Power output $\mathrm{P_{WT}}$ of the wind turbine (WT) and $\mathrm{E_{WT}}$ (t) of an electric output of a wind generator is [6]:

$$\mathrm{P_{WT}} = \left\{\frac{1}{2}\right\}\rho \mathrm{A}\nu^3\mathrm{C_P}(\lambda, \beta) \times \eta_{\mathrm{T}} \times \eta_{\mathrm{G}} \tag{3}$$

$$\mathrm{E_{WT}(t) = P_{WT} \times t} \tag{4}$$

where, ρ is the air density, A denotes surface area, ν represents wind speed, η_T and η_G shows wind turbine and generator efficiency, C_P is the performance coefficient of the turbine, λ denotes tip speed ratio, β denotes blade pitch angle, and t represents time in hour.

2.3 Battery Modeling

The Storage capacity ($C_{Battery}$) of battery is defined as in Equation (5). The SOC battery defines processes of charge and discharge by varying between lower and higher limits [6, 7].

$$C_{Battery} = \left[\frac{V_{off} \times N_{Day}}{\eta_{Converter} \times \eta_{Battery} \times DOD}\right] \tag{5}$$

$$SOC_{min} < SOC < SOC_{max} \tag{6}$$

where, V_{off} is offload voltage, N_{Day} is the number of days without charging, $\eta_{Converter}$ is yield of convertor, $\eta_{Battery}$ is yield of battery, SOC is state of charge, and DOD is the depth of discharge.

2.4 Fuel Cell (FC) Modeling

A fuel cell (FC) is an electro-chemical cell which, through two redox reactions, converts the chemical energies of a fuel (often hydrogen) and an oxidizing agent (usually oxygen) into electricity. Fuel cells can continuously generate electricity for the duration of the supply of fuel and oxygen [8]. The new fuel cells are categorized by the type of electrolyte used in them and the start-up time gap from 1 second to 10 minutes for proton exchange membrane fuel cells (PEM fuel cells, or PEMFC) and solid oxide fuel cells (SOFC) [8]. High performance, adaptive reliability, modularity, and capacity to operate with different kinds of fuel, low noise, and variance are the key advantages of these energy sources. The equation below describes the active power output of FC:

$$P_{FC\_gen} = N_{s\_cell} \times \left(E_v - a \cdot \log\left(\frac{I_{Cell}}{A_{FC}}\right) - R \cdot \frac{I_{Cell}}{A_{FC}} - m \cdot e^{\left[\frac{n \cdot I_{Cell}}{A_{FC}}\right]}\right) \times I_{Cell} \tag{7}$$

The above modelled DG sources and other sources can be grouped into four main categories according to their terminal features:

- DGs of Type-1 inject active power, and they operate at unity pf. These include PV cells, fuel cells, batteries, etc.
- DGs of Type-2 DG that inject reactive power like synchronous compensators, capacitors, etc.
- DGs of Type-3 DG with active and reactive power injection, such as synchronous machine cogeneration, gas turbines, etc.
- DGs of Type-4 consume reactive power and inject active power. These include induction generators in wind farms.

3 Objective Function

This optimization problem aims primarily at reducing line losses, which are estimated as:

$$\mathrm{P_{Loss}} = \sum_{\mathrm{i=1}}^{\mathrm{nb}} \mathrm{I_i^2 R_i} \tag{8}$$

Hence, growing demand for the load of a single bus would lead to net growth in the distribution network's total power losses:

$$\mathrm{Minimization}\{\mathrm{P_{Loss}}\} \tag{9}$$

3.1 DG Constraints

3.1.1 Current limit

$$|\mathrm{I_{ij}}| \leq \mathrm{I_{maximum}} \tag{10}$$

3.1.2 Voltage limit

$$\mathrm{V_{Bus\_min}} \leq \mathrm{V_{Bus}} \leq \mathrm{V_{Bus\_max}} \tag{11}$$

$$0.95\ \mathrm{pu} \leq \mathrm{V_{Bus}} \leq 1.05\ \mathrm{pu} \tag{12}$$

3.1.3 DG limit

$$\mathrm{P_{Grid}} + \sum_{\mathrm{bus=1}}^{\mathrm{N}} \mathrm{P_{DGbus}} = \sum_{\mathrm{bus=1}}^{\mathrm{N}} \mathrm{P_{Dbus}} + \mathrm{P_{Losses}} \tag{13}$$

$$50 \leq \mathrm{P_{DG}} \leq 3500 \tag{14}$$

Multiple types of DGs such as Type-1, Type-2, Type-3, and Type-4 DGs are chosen, whose limits are in kW, kVAr, KVA, and KVA respectively.

4 Optimal Location of DGs Using Sensitivity Based Methods

Potential locations of DGs are obtained directly by using these methods [9].

4.1 Index Vector Method (IV)

Depending on the Index Vector elements, this approach defines a sequence of nodes to be linked to DG. For bus n, Index-Vector is formulated as [10]:

$$\mathrm{IV[n]} = \mathrm{V(n)}^2 + \frac{\mathrm{I_q\ [k]}}{\mathrm{I_p\ [k]}} + \frac{\mathrm{Q_{eff}\ [n]}}{\mathrm{total\ Q}} \tag{15}$$

where, $\mathrm{I_p[k]}$, $\mathrm{I_q[k]}$ are real and imaginary part of current in $\mathrm{k^{th}}$ branch, $\mathrm{Q_{eff}[n]}$ is effective load at $\mathrm{n^{th}}$ bus, V[n] is voltage at $\mathrm{n^{th}}$ bus, and total reactive load is taken as total Q.

4.2 Loss Sensitivity Factor Method (LSF)

For the identification of the candidate nodes for DG installation, active power loss sensitivity factors are determined. Loss Sensitivity Matrix [11]:

$$\mathrm{LSF} = \begin{vmatrix} \frac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{P_i}} & \frac{\partial \mathrm{Q_{Loss}}}{\partial \mathrm{P_i}} \\ \frac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{Q_i}} & \frac{\partial \mathrm{Q_{Loss}}}{\partial \mathrm{Q_i}} \end{vmatrix} \tag{16}$$

4.3 Voltage Stability Margin Method (VSM)

VSM distinguishes nodes that are closer to failure, the low VSM node being the vulnerable node that positions the DG. It is calculated by using the equation [12]:

$$\mathrm{VSM} = |\mathrm{V(s)}|^4 - 4(\mathrm{P(r)X} - \mathrm{Q(r)R})^2 - 4|\mathrm{V(s)}|^2(\mathrm{P(r)R} + \mathrm{Q(r)X}) \tag{17}$$

where, V(s) is sending end node voltage, P(r) is total real power load fed through receiving node, Q(r) is total reactive power load fed through receiving node, R is the resistance of branch, and X is the reactance of branch.

5 Simultaneous Particle Swarm Optimization (PSO) Methodology

Kennedy and Eberhart developed the early PSO technique as a stochastic optimization strategy based on swarming behavior [13]. It offers solutions for complicated numerical maximization or minimization of constrained nonlinear problems. Due to a number of benefits compared to certain other heuristic optimization algorithms, PSO was preferred to mitigate the optimization problem in this article. The adaptive and exhaustive nature of the essence of the objective function coupled with the requirement of low memory size and computation time makes this method more advantageous [14]. A decreased reliance on the set of initial points also ensures that the convergence algorithm will be versatile and vigorous. Particles travel at a certain velocity through the multi-dimensional problem field in this method. Each particle in the swarm is in a position to interact. This helps them to change their moving speed in accordance with their own and other particles' movement patterns. The particle swarm's spontaneous motion keeps the solution from being stuck at a local minimum. Each particle maintains control of its own location in the problem space throughout the PSO iteration. For each iteration, the present position of each particle is evaluated if it can be found to be greater than all the values that have previously been found, and then these coordinates are stored as PBest,i. A variable named GBest,i stores the best value of the function. Every particle makes evolutionary decisions based on its own experience as well as the experiences of its neighbors. The particles' position and velocity are updated with each iteration. If k iterations are performed with i particles, the position (X) and velocity (V) of each particle can be calculated using [15]:

$$\mathrm{X}_{\mathrm{i}}^{\mathrm{k+1}} = \mathrm{X}_{\mathrm{i}}^{\mathrm{k}} + \mathrm{V}_{\mathrm{i}}^{\mathrm{k+1}} \tag{18}$$

$$\begin{aligned}\mathrm{V}_{\mathrm{i}}^{\mathrm{k+1}} &= \omega^{\mathrm{k}} \times \mathrm{V}_{\mathrm{i}}^{\mathrm{k+1}} + \mathrm{C}_1 \times \mathrm{rand}_1 \times (\mathrm{P}_{\mathrm{Best,i}}^{\mathrm{k}} - \mathrm{X}_{\mathrm{i}}^{\mathrm{k}}) \\ &\quad + \mathrm{C}_2 \times \mathrm{rand}_2 \times (\mathrm{G}_{\mathrm{Best,i}}^{\mathrm{k}} - \mathrm{X}_{\mathrm{i}}^{\mathrm{k}})\end{aligned} \tag{19}$$

$$\omega^{\mathrm{k}} = \omega_{\max} - \left(\frac{\omega_{\max} - \omega_{\min}}{\mathrm{k}_{\max}}\right) \times \mathrm{k} \tag{20}$$

where, ω is the inertia weight factor, C_1, C_2 are acceleration coefficients, rand_1 and rand_2 are the random variables with a uniform distribution between 0 and 1, $\mathrm{P}_{\mathrm{Best,i}}$ is the local best of particle i, and $\mathrm{G}_{\mathrm{Best,i}}$ is the global best of the group.

6 Simulation Results

DGs of types 1, 2, 3, and 4 are considered in which Type-3 DGs with power factors of 0.707, 0.9, and unity power factors (pf) are taken as Type-3A, Type-3B, and Type-3C respectively. Table 1 shows the DG types with their notations for easy use in further paper.

6.1 System 1: IEEE 15-Bus System

The first test system, the IEEE 15-Bus radial distribution system, is taken. Using load flow, the active and reactive power losses obtained are 61.7944 kW and 57.2977 kVAr, respectively, with a minimum voltage of 0.9445p.u when no DG installation is considered. The voltage profile of the system is plotted using the PSO method and it is inferred that voltage values are improved more when Type-3A DG is used as in Figure 1. Table 2 shows the location of multiple DGs along with DG sizes using sensitivity methods and simultaneous PSO.

Table 3 shows the active and reactive power loss reduction percentages. PLR and QLR indicate the active and reactive power loss reduction,

Table 1 DG locations and their total sizing for 15-Bus system

DG Type	Notation
Type-1(Kw)	A
Type-2 (kVAR)	B
Type-3(A) 0.707 lag pf (kVA)	C
Type-3(B) 0.9 lag pf (kVA)	D
Type-3(C) unity pf (kVA)	E
Type-4 (kVA)	F

Table 2 DG locations and their total sizing for 15-Bus system

		A	B	C	D	E	F
Method	Locations of DG	Total DG Size					
IV	15 4 11 (Type-1 to 4)	949.71	965.21	1339.5	1264.5	949.71	528.28
LSF	3 4 2 (Type-1 to 4)	1278.9	1298.3	1777.4	1683	1278.9	1000.9
VSM	13 12 15 (Type-1 to 4)	806.05	816.8	1145.3	1080.1	806.05	554.56
PSO	4 6 11 (Type-1 to 3) 13 6 3 (Type-4)	1177.1	1196.4	1645.6	1556.1	1177.1	931.44

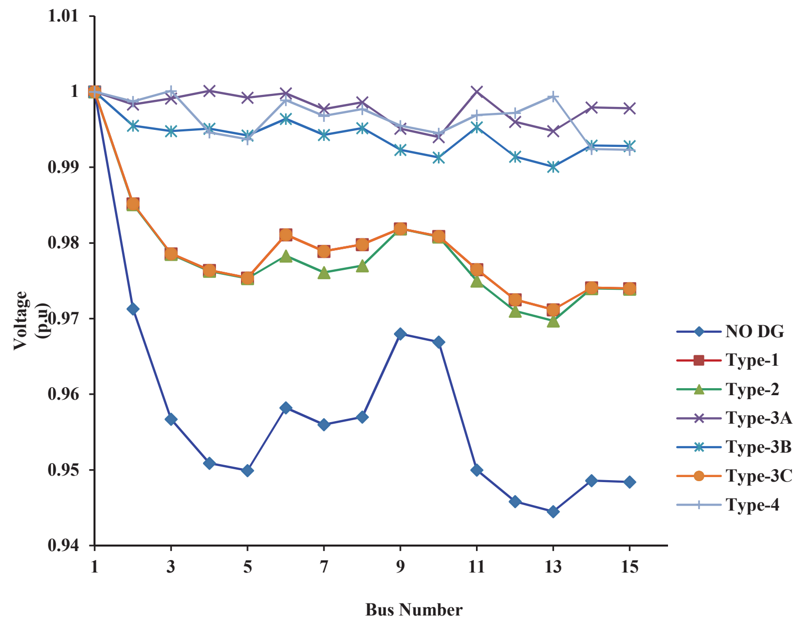

Figure 1 Voltage profile for 15-Bus system.

Table 3 Loss reduction percentage for 15-Bus system

	A		B		C		D		E		F	
Method	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%
IV	41.83	43.37	43.23	44.83	81.99	85.03	73.29	76.01	41.83	43.37	66.53	69.25
LSF	43.32	45.50	44.72	46.97	84.38	88.63	75.54	79.35	43.32	45.5	80.37	84.40
VSM	37.87	40.12	39.10	41.41	74.77	79.16	66.76	70.69	37.87	40.12	67.65	72.43
PSO	49.25	49.77	50.91	51.45	95.83	96.83	85.78	86.68	49.25	49.77	87.99	89.14

respectively. From Table 3, it is identified that the maximum amount of loss reduction can be obtained by using simultaneous placement of multiple DGs using PSO compared to the other 3 sensitivity methods for all types of DGs.

Table 4 represents the location, sizing and loss reduction percentage values obtained by proposed simultaneous PSO method in comparison with other methods.

6.2 System 2: IEEE 33-bus System

The second test system considered is the IEEE 33-Bus radial distribution system. Using load flow, the active and reactive power losses are 210.9983 kW and 142.5335 kVAr, respectively, with a minimum voltage of 0.9038 p.u

Table 4 Loss reduction comparison with proposed and other methods – 15 Bus system

Single DG	Type-1 (kW) Reddy et al. [16]	Type-1 (kW) Proposed Method	Type-2 (kVAR) Reddy et al. [16]	Type-2 (kVAR) Proposed Method	Type-3 (kVA) Reddy et al. [16] at 0.9 lag pf	Type-3 (kVA) Proposed Method at 0.9 lag pf	Type-3 (kVA) Proposed Method at 0.707 lag pf
Location	6	3	6	3	6	3	3
DG Size	675.25	1024.10	682.34	1040.50	907.79	1363.00	1443.70
TLP (kW)	45.80	37.86	45.32	37.09	33.39	19.78	14.78
TLQ (kVAR)	41.88	33.99	41.43	33.23	29.89	16.37	11.50
Loss reduction (%)	25.88	38.73	26.66	39.98	45.97	67.99	76.08

Table 5 DG locations and their total sizing for 33-Bus system

		A	B	C	D	E	F
Method	Locations of DG	Total DG Size					
IV	30 14 11 (Type-1 to 4)	2082.80	1537.00	2513.60	2506.30	2082.80	1096.80
LSF	6 26 7 (Type-1 to 4)	2583.90	1801.60	3044.80	3061.20	2583.90	2010.60
VSM	18 17 16 (Type-1 to 4)	998.43	570.02	1152.10	1183.30	998.43	737.93
PSO	13 30 24 (Type-1 to 3) 29 15 3 (Type-4)	2946.70	1969.20	3399.40	3443.10	2946.70	2646.80

Table 6 Loss reduction percentage for 33-Bus system

	A		B		C		D		E		F	
	Loss Reduction (%)											
Method	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$
IV	60.16	59.87	33.15	32.77	85.17	84.53	84.89	84.32	60.16	59.87	64.44	63.76
LSF	48.82	46.69	24.14	22.49	67.76	64.33	68.36	65.11	48.82	46.69	65.93	62.35
VSM	35.30	35.20	12.11	11.28	44.07	43.07	46.68	45.99	35.30	35.20	41.38	39.98
PSO	65.50	64.46	34.47	33.89	90.89	89.48	91.27	89.85	65.50	64.46	85.34	83.73

when no DG installation is considered. The voltage profile of the system is plotted using the PSO method, and it is inferred that voltage values are improved more when Type-3A DG is used as in Figure 2. Tables 5 and 6 show the location of multiple DGs and percentage of loss reduction compared to the system with no DGs, along with DG sizes.

From Table 6, it is identified that the maximum amount of loss reduction can be obtained by using simultaneous placement of DGs using PSO compared to the other three methods for all types of DGs.

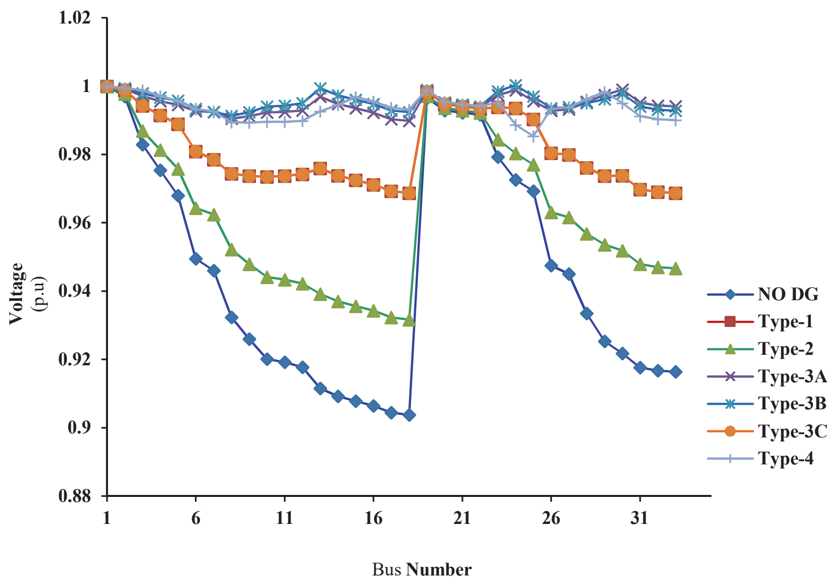

Figure 2 Voltage profile for 33-Bus system.

Tables 7 and 8 show the location, sizing, and loss reduction values obtained by the proposed simultaneous PSO method in comparison with other methods using single DG and multiple DG simultaneously.

6.3 System 3: IEEE 69 Bus System

The third test system, the IEEE 69-Bus radial distribution system, is chosen. Using load flow, the active and reactive power losses are 224.9846 kW and 102.1937 kVAr, respectively, with a minimum voltage of 0.9092 p.u when no DG installation is considered. The voltage profile of the system is plotted using the PSO method and it is inferred that voltage values are improved more when Type-3A DG is used as in Figure 3. Tables 9 and 10 show the location of multiple DGs and percentage of loss reduction compared to the system with no DGs, along with DG sizes. From Table 10, it is identified that the maximum amount of loss reduction can be obtained by using simultaneous placement of DGs using PSO compared to the other 3 methods for all types of DGs.

Tables 11 and 12 represent the location, sizing, and loss reduction values obtained by the proposed simultaneous PSO method in comparison with other methods using single DG and multiple DG simultaneously.

Table 7 Loss reduction comparison with proposed and other methods – 33 Bus system with Single DG

Single DG		Location	DG Size	TLP (kW)	TLQ (kVAR)	Loss Reduction (%)
Type-1 (kW)	Reddy et al. [16]	15	1061.00	133.50	90.74	36.73
	Ankit Uniyal [17]	7	1900.00	116.77	82.72	44.66
	S. Kansal et al. [18]	6	3150.00	115.29	**	45.36
	Proposed Method	6	2590.20	111.02	81.68	47.38
Type-2 (kVAR)	Reddy et al. [16]	15	612.04	183.93	125.62	12.83
	S. Kansal et al. [18]	30	1230.00	151.41	**	28.24
	Proposed Method	30	1258.00	151.37	103.81	28.26
Type-3 (kVA)	Reddy et al. [16]	15	1255.89	108.41	74.77	48.62
at 0.9	V.V.S.N. Murthy [20]	30	1950.00	78.42	59.00	62.83
p.f lag	Ankit Uniyal [17]	8	2100.00	120.60	87.04	42.84
	Proposed Method	6	3073.50	70.86	56.77	66.42
Type-4 (kVA)	Wichit Krueasuk [19]	12	2.56	163.85	115.57	22.35
	Proposed Method	6	2142.20	72.62	57.64	65.58

Table 8 Loss reduction comparison with proposed and other methods – 33 Bus system with Multiple DG

	Type-1 (kW)		Type-2 (kVAR)		Type-4 (kVA)	
Multiple DG	Wichit Krueasuk [19]	Proposed Method	Wichit Krueasuk [19]	Proposed Method	Wichit Krueasuk [19]	Proposed Method
Location	10 29 22	13 24 30	27 22 10	13 30 24	3 12 2	29 15 3
DG Size	2857.60	2946.70	1860.70	1969.20	4221.60	2646.80
TLP (kW)	76.17	72.79	144.91	138.26	166.83	30.92
TLQ (kVAR)	52.97	50.65	98.75	94.22	117.10	23.18
Loss reduction (%)	63.90	65.50	31.32	34.47	20.93	85.35

Table 9 DG locations and their total sizing for 69-Bus system

		A	B	C	D	E	F
Method	Locations of DG	Total DG Size					
IV	61 64 65 (Type-1 to 4)	1871.60	1329.60	2213.00	2215.60	1871.60	555.85
LSF	62 63 60 (Type-1 to 4)	1906.60	1354.70	2249.50	2252.40	1906.60	1567.98
VSM	61 64 65 (Type-1 to 4)	1871.60	1329.60	2213.00	2215.60	1871.60	555.85
PSO	61 18 11 (Type-1 to 3) 62 19 66 (Type-4)	2626.10	1875.80	3081.30	3084.80	2626.10	2099.90

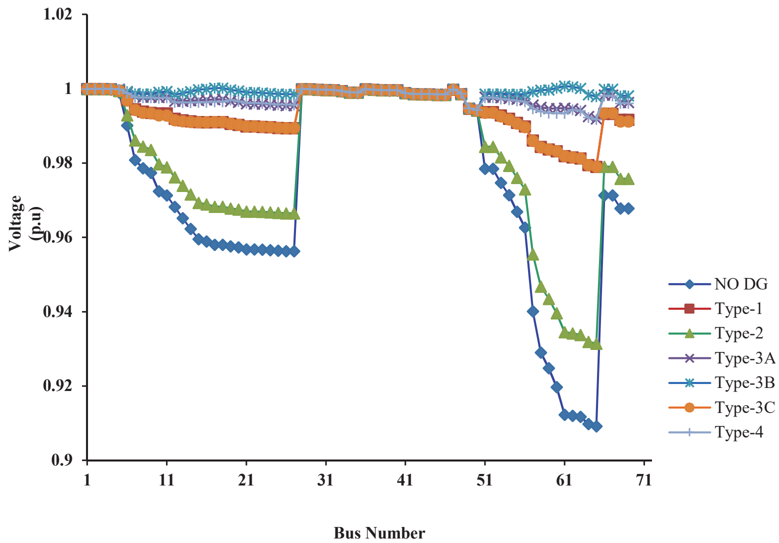

Figure 3 Voltage profile for 69-Bus system.

Table 10 Loss reduction percentage for 69-Bus system

	A		B		C		D		E		F	
Method	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%	P_{LR}%	Q_{LR}%
IV	63.26	60.58	32.58	31.14	87.90	84.21	87.91	84.24	63.26	60.58	30.33	31.34
LSF	62.85	60.17	32.31	30.88	87.28	83.57	87.31	83.62	62.85	60.17	86.88	83.20
VSM	63.26	60.58	32.58	31.14	87.90	84.21	87.91	84.24	63.26	60.58	30.33	31.34
PSO	69.14	65.78	35.42	33.70	95.57	91.00	95.67	91.08	69.14	65.78	94.40	89.76

Table 11 Loss reduction comparison with proposed and other methods -69 Bus system with Single DG

Single DG		Location	DG Size	TLP (kW)	TLQ (kVAR)	Loss Reduction (%)
Type-1 (kW)	Reddy et al. [16]	61	1872.82	83.23	40.54	63.01
	S. Kansal et al. [18]	61	1807.80	83.37	**	62.94
	Proposed Method	61	1872.70	83.20	40.56	63.02
Type-2 (kVAR)	Reddy et al. [16]	61	1329.99	152.06	70.51	32.41
	S. Kansal et al. [18]	61	1290.00	152.10	**	32.40
	Proposed Method	61	1329.90	152.03	70.53	32.43
Type-3	Reddy et al. [16]	61	2217.39	27.96	16.46	87.57
0.9 lag	V.V.S.N. Murthy [20]	61	2200.00	27.91	16.46	87.60
pf (kVA)	Proposed Method	61	2217.30	27.95	16.49	87.58
Type-4 (kVA)	Wichit Krueasuk [19]	56	1888.00	161.71	73.94	28.13
	Proposed Method	62	1522.80	30.83	17.95	86.30

Table 12 Loss reduction comparison with proposed and other methods -69 Bus system with Multiple DG

Multiple DG	Type-1 (kW) Wichit Krueasuk [19]	Type-1 (kW) Proposed Method	Type-2 (kVAR) Wichit Krueasuk [19]	Type-2 (kVAR) Proposed Method	Type-4 (kVA) Wichit Krueasuk [19]	Type-4 (kVA) Proposed Method
Location	56 55 33	61 11 18	56 61 33	61 18 11	56 3 2	62 19 66
DG Size	2551.00	2626.10	1806.40	1875.50	4410.60	2099.90
TLP (kW)	70.88	69.41	148.31	145.13	161.69	12.60
TLQ (kVAR)	35.69	34.97	69.12	67.69	73.97	10.46
Loss reduction (%)	68.50	69.15	34.08	35.49	28.13	94.40

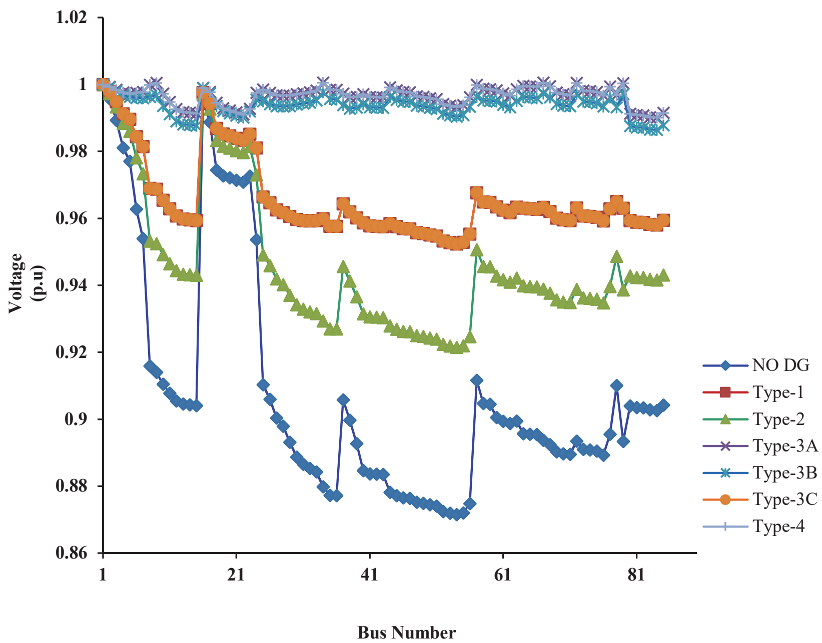

Figure 4 Voltage profile for 85-Bus system.

6.4 System 4: IEEE 85 Bus System

The fourth test system is the IEEE 85-Bus radial distribution system. Using load flow, the active and reactive power losses are 314.6786 kW and 198.2695 kVAr, respectively, with a minimum voltage of 0.8715 p.u when no DG installation is considered. The Voltage profile of the system is plotted using the PSO method and it is inferred that voltage values are improved more when Type-3A DG is used as in Figure 4. Tables 13 and 14 show the location of multiple DGs and percentage of loss reduction compared to the system

Table 13 DG locations and their total sizing for 85-Bus system

		A	B	C	D	E	F
Method	Locations of DG	Total DG Size					
IV	54 55 51 (Type-1 to 4)	1069.40	1000.80	1513.00	1442.40	1069.40	895.57
LSF	9 8 25 (Type-1 to 4)	2360.00	2323.90	3177.00	3027.40	2360.00	2174.40
VSM	54 55 53 (Type-1 to 4)	974.03	903.09	1387.50	1323.40	974.03	828.01
PSO	34 9 67 (Type-1 to 4)	2291.50	2272.40	3066.10	2922.50	2291.50	2167.80

Table 14 Loss reduction percentage for 85-Bus system

	A		B		C		D		E		F	
Method	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$	$P_{LR}\%$	$Q_{LR}\%$
IV	32.54	34.65	31.14	32.93	61.50	65.54	55.65	59.36	32.54	34.66	59.79	64.14
LSF	46.24	48.80	44.76	47.48	83.31	88.21	75.79	80.17	46.25	48.81	83.23	88.13
VSM	29.97	32.12	28.47	30.27	57.06	61.21	51.63	55.44	29.98	32.13	55.54	59.97
PSO	53.04	53.37	52.41	52.80	95.36	96.11	86.58	87.23	53.05	53.37	95.35	96.10

Table 15 Loss reduction comparison with proposed and other methods -85 Bus system

	Type-1 (kW)		Type-2 (kVAR)		Type-3 (kVA)		
Single DG	Reddy et al. [16]	Proposed Method	Reddy et al. [16]	Proposed Method	Reddy et al. [16] at 0.9 pf lag	Proposed Method at 0.9 pf lag	Proposed Method at 0.707 pf lag
Location	55	8	55	8	55	8	8
DG Size	946.35	2371.40	873.85	2330.80	1289.00	3047.90	3198.80
TLP (kW)	224.05	174.47	229.02	179.50	157.49	84.56	61.79
TLQ (kVAR)	136.30	104.09	140.14	106.96	90.98	43.32	27.81
Loss reduction (%)	28.80	44.56	27.22	42.96	49.95	73.13	80.36

with no DGs, along with DG sizes. From Table 14, it is identified that the maximum amount of loss reduction can be obtained by using simultaneous placement of DGs using PSO compared to the other 3 methods for all types of DGs.

Table 15 represents the location, sizing and loss reduction values obtained by proposed simultaneous PSO method in comparison with other methods.

6.5 Comparing P_{loss} and Q_{loss} Values

Table 16 shows the active and reactive power loss values in kW and kVAR obtained before and after the installation of different types of DGs by using

Table 16 Active and Reactive power losses of all bus systems before and after placement of different types of DGs

Bus	NO DG		A		B		C		D		E		F	
System	P_{Loss}	Q_{Loss}	P_{Loss}	Q_{Loss}	P_{Loss}	Q_{Loss}	P_{Loss}	Q_{Loss}	P_{Loss}	Q_{Loss}	P_{Loss}	Q_{Loss}	P_{Loss}	Q_{Loss}
15	61.79	57.30	31.36	28.78	30.33	27.81	2.57	1.81	8.78	7.63	31.36	28.78	7.42	6.22
33	211.00	142.53	72.79	50.65	138.26	94.22	19.22	14.98	18.41	14.46	72.79	50.65	30.92	23.18
69	224.98	102.19	69.41	34.97	145.13	67.69	9.61	9.07	9.41	8.99	69.41	34.97	12.60	10.46
85	314.68	198.27	147.75	92.45	149.75	93.58	14.60	7.72	42.23	25.32	147.75	92.45	14.60	7.72

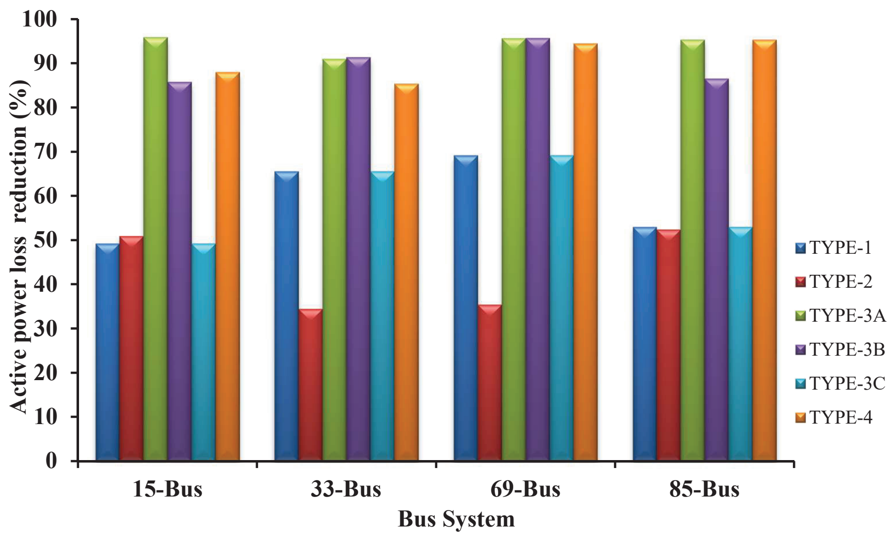

Figure 5 Active power loss reduction (%) of all bus systems.

the simultaneous PSO method of all the bus systems considered earlier. When compared to other DG types, the Type-3A DG operating at 0.707 p.f can reduce the amount of losses more.

From Figures 5 and 6, it is observed that in comparison with other types of DG, the percentage of loss reduction and minimum voltage level are greater with increased DG sizing in Type-3A DG, which operates at a power factor of 0.707. This is because of the locally available reactive power for the loads, thus reducing the available reactive power from the substation [16]. The minimum voltage values are plotted for three bus systems using all types of DGs as in Figure 7. When sensitivity methods with DGs are compared to PSO, it can be seen that the V_{min} values are better with PSO.

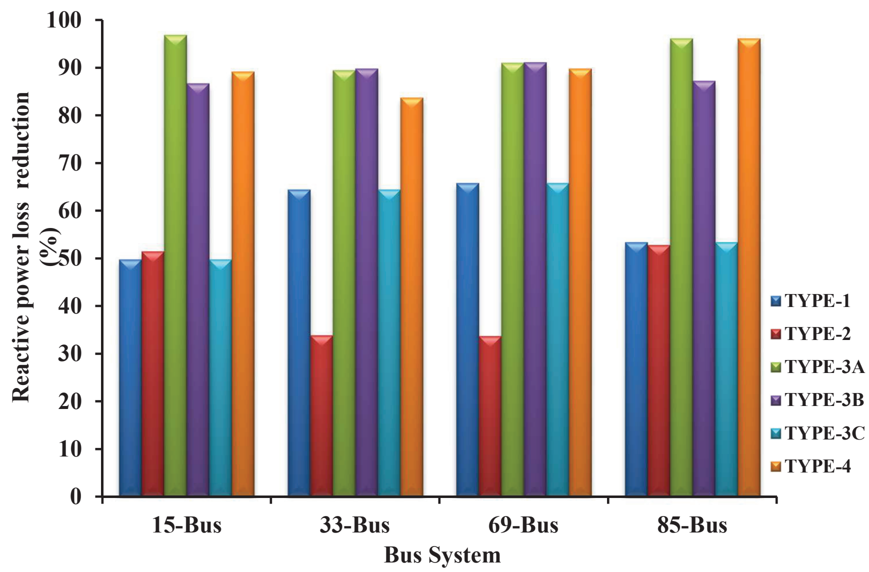

Figure 6 Reactive power loss reduction (%) of all bus systems.

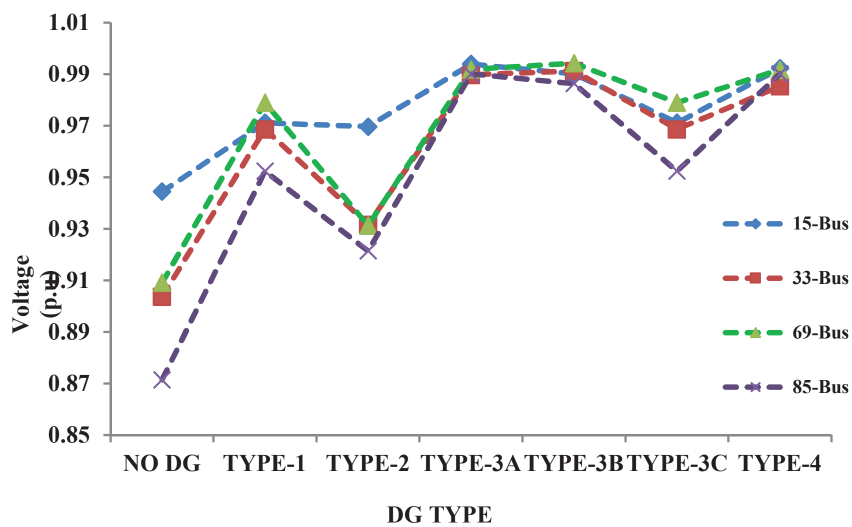

Figure 7 V_{min} for all bus systems with all types of DGs and without DG.

7 Conclusions

In the present study, in order to mitigate losses, the nature-inspired Particle Swarm Optimization Algorithm was used for the optimal allocation of different DG types. IEEE 15, 33, 69, and 85-bus typical radial types of distribution systems with multiple numbers and various DG types were used in comparison with other sensitivity-based approaches along with the proposed method. The Simultaneous PSO placement methodology has provided better results. From the results obtained, it is concluded that a Type-3A DG operating at a 0.707 power factor reduces losses effectively compared to all other DGs with various power factors since both real power and reactive power are generated.

Declarations

Availability of data and materials Not applicable.

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Author's Contributions Prof. M. Damodar Reddy designed the research work. Devisree Chippada carried out the research work. Both authors analyzed the data. Devisree Chippada has written the paper. Prof.M.Damodar Reddy edited the paper. Both authors had approved the final version of the paper.

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