SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V11I8P112

Volume 11 Issue 8, 134-144, August 2024

Original Article

Optimal Planning for Deployment of DG and RPC Considering Techno-Economic Aspects with Different Scenarios

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Received: 05 June 2024 Revised: 08 July 2024 Accepted: 06 August 2024 Published: 31 August 2024

Abstract *- The growing demand for electrical energy has made Distributed Energy Resources (DER), including wind and solar photovoltaics, increasingly prominent in distribution networks. Placement of these distributed resources across the distribution network changes the line flows and modifies network performance parameters like network losses and voltage profile predominantly. Distributed Generators and Reactive Power Compensator deployment at load buses inject a partial reactive and active demand, making the distribution system bidirectional and modified line flows need more detailed analysis to improve network performance parameters. The locations and size of these distributed resources have a strong influence on network losses and power quality. The optimal placement problem of DG and RPC simultaneously has been addressed for the IEEE-33 bus network. Minimization type multi-criteria function incorporates four criteria, i.e., loss minimization, investment cost minimization, voltage stability and improvement in network bus voltage. The proposed strategy has been tested for three different scenarios where DGs have been modelled for the PQ bus and PV bus along with RPC. The proposed MOF has been minimized by the GA metaheuristic algorithm to serve all objectives having a conflict of interest. The proposed strategy helps distribution planners maximize the benefits of these distributed resources, considering future load growth.*

Keywords *- Distributed generator, Genetic Algorithm, Multi-objective function, Optimization, Reactive power compensator.*

1. Introduction

Renewable-based Distributed Generators (RDG) are assets that generate power and are connected to distribution networks [1, 2]. The World Energy Council projects that the global output of renewable energy will increase from 23% in 2010 to over 34% in 2030 [3]. Distributed generating generally caters to either a single major customer or a cluster of consumers located nearby. Consequently, it reduces distribution losses, improves system voltage performance, reduces overload of feeders, and prolongs equipment lifespan [4, 5].

The conventional method of producing power through concentrated plants and extensive transmission networks is being replaced by distributed generation. These generators are integrated into electricity systems at the distribution level. To satisfy the increasing expectations of its customers, modern electric power distribution firms are under pressure to increase their networks. Distributed energy sources are necessary to accomplish these goals. Recent technological developments have brought forth several benefits of distributed generation, such as low capital costs, environmental friendliness, ease of installation, modular size, and quick lead times. For a distribution system with dispersed energy resources, probabilistic optimum reactive power planning is presented [6].

This study presents a distribution system that incorporates both on-grid and islanded modes. The stochastic characteristics of the load profile and the sporadic generation of renewable-based Distributed Generators (DGs) have been considered. The suggested strategy has two objectives: annual energy loss reduction and the microgrid success index. Mohmad et al. [7] presented a new strategy for optimal deployment of capacitor placement with distributed generators to bring down the system's active power losses. Loss Sensitivity Analysis was used to determine the suitable spot for the installation of CB and DG.

Additionally, previous research recommends DG locations based on the bus voltage stability study to manage the loadability limit without violating voltage tolerance. A system can sustain voltage so that both power and voltage are under control and that when the system's nominal load increases, so does the active power the system provides to the load. A network is voltage unstable if it cannot sustain power transfer at nominal voltage. The process by which voltage instability results in a considerable amount of the system losing voltage is known as voltage collapse. Voltage instability will occur in a network prior to a voltage collapse.

Various methods have been employed to assess a network's steady-state stability. These methods include the following: sensitivity analysis [20], energy function method [21], artificial neural network [22], model analysis [23], and neuro-fuzzy approach [24]. Gao et al. [25] proposed a model analysis-based method for bus voltage stability.

Table 1. Various aspects of PV type DG's influence on the network's performance

Sr. No.	Type of Impact of DG	Related References
1	Power loss reduction	[8, 9, 10]
2	Peak load reduction	[11, 12]
3	Voltage Profile improvement	[13, 14]
4	Reverse active power flow	[13, 15, 16, 17]
5	Overvoltage	[18, 19]

Lalitha et al. [26] presented a novel methodology in which DG sizing was determined using PSO, and possible CB locations were assessed using a fuzzy approach. By reducing the search space area of the DGs placement problem, the PSO-fuzzy technique increases the probability of finding a solution close to the global optimum. The literature that is currently available addresses the optimal placement challenges for RPC and DGs independently. In addition, a large number of these literature modelled DGs to function at unity PF, giving active support to the network. DGs can, however, function at various power factors and assist the needed reactive power. To find a cost-effective solution, the optimal sizing problem reformulation must consider the reactive power capability of DG with RPC. DGs must be modelled for voltage control buses to enable reactive support at several buses. The Voltage Stability Index is incorporated into the proposed MOF to guarantee network performance that can withstand future load growth.

Many past works of literature addressed the optimal DG placement problem using an analytical approach. However, the analytical approach gives an approximate optimal solution where it may fail to provide a global optimal point around the search space. Further, some literature suggests implementing an AI-based heuristic approach to solve optimization problems. One of the demerits is always there with AI-based techniques to give different solutions in each attempt. Looking at the increased reliability of getting optimal points across search space, a mixture of analytical and heuristic approaches has been presented here to solve the problem of the most effective size for DGs and RPC. Analytical-based sensitivity analysis has been applied to RPC, and a voltage stability-based analytical approach has been used for DG deployment.

2. Problem Formulation

To maximize the advantages of deploying these distributed resources, an effort has been made to suggest the best plan for the simultaneous deployment of DG and RPC. An evaluation of the present approach was conducted using the IEEE 33 bus network. Distributed Generators (DGs) are commonly used to supply an adequate amount of P, while Reactive Power Compensation (RPC) is utilized to give Q to the network.

The block diagram presented in Figure 1, which defines the problem's variables, problem objectives, and multiple test scenarios, illustrates the suggested planning technique. The suggested technique provides information on the optimal site and size of these dispersed resources in different test scenarios. A novel CVSI index has been implemented to guarantee the enduring efficiency of the network, considering the projected increase in load. Three test scenarios are included in the suggested approach, each of which is based on a different weighted distributed MOF and type of DG modelling. In each test case, the suggested MOF has been optimized using GA.

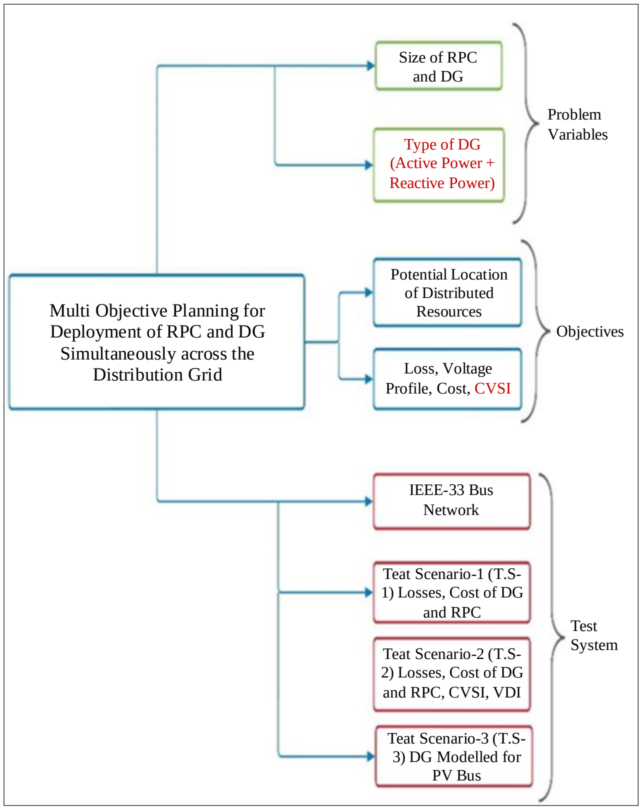

Fig. 1 Block diagram of proposed strategy

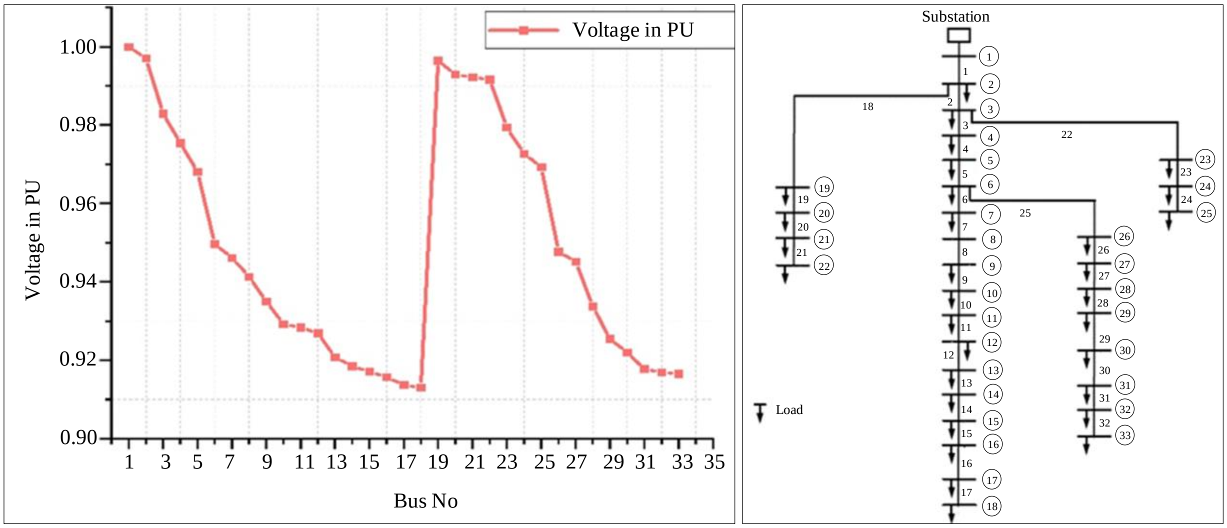

Fig. 2 Voltage profile and network configuration

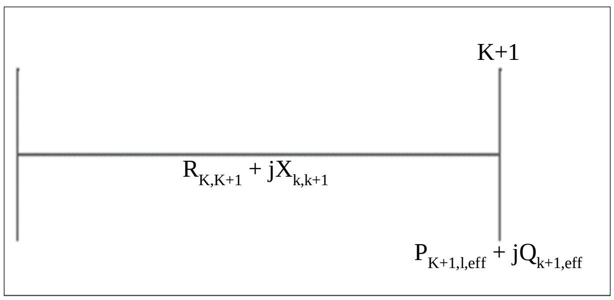

Fig. 3 A two bus system

In Test Scenario 1, Distributed Generation (DG) and Reactive Power Compensation (RPC) are used simultaneously for loss minimization and bus voltage improvement. In addition, the suggested technique also includes certain equality and non-equality constraints to determine a possible optimum solution inside the search space.

In Test Scenario 2, two more performance parameters, CVSI and VSI, were added to the proposed MOF to improve stability and voltage profile and strengthen the network, considering future load growth. Test Scenario 3 involves optimizing the same MOF with DG modelling for the voltage control bus. These DGs can absorb and deliver a certain amount of Q to the distribution network within their Q limit to regulate the voltage.

The IEEE-33 network is used to assess the given technique. The one-line diagram of the IEEE-33 bus network and its voltage profile is depicted in Figure 2. The network parameters are presented in Table 2. The system consists of thirty-two load buses and one slack bus. The NR-based load flow approach was employed to assess branch losses and bus voltages in the network. An analytical-based Loss-Sensitive Factor (LSF) has been employed to narrow down the search area for the optimization method, aiming to identify prospective locations for Reactive Power Compensation (RPC). Additionally, VSI has been utilized to identify potential locations for Distributed Generators (DGs). The proposed technique has been thoroughly analyzed in the subsequent subsections.

Table 2. Network parameters

Network Profile	Value
Active Power (P)	3.72 MW
Reactive Power (Q)	2.30 KVAR
Power Loss (P_l)	0.203 MW
Reactive Loss (Q_l)	0.14 MVAR
Tail End Minimum Voltage	0.917 P.U
Type of Network	Radial Type

2.1. Potential Location for RPC Deployment

LSF has been evaluated to identify effective places for the deployment of the RPC. The first evaluation of these potential buses assists in narrowing down the search boundary of optimization. Figure 3 shows a distribution line segment with an impedance and a load connected between two successive buses. The active-loss occurs across the line can be illustrated by,

$$P_{k+1} = R_{k-k+1} * \frac{P^2{}_{k+1} + Q^2{}_{k+1}}{|V_{k+1}|^2} \qquad (1)$$

Now, the LSFs are obtained using the following equation,

$$\frac{\partial P_{K-K+1}}{\partial Q_{k+1}} = \frac{2 * Q_{k+1} * R_{k-k+1}}{|V_{k+1}|^2} \qquad (2)$$

Table 3. Potential locations for RPC based on LSF

Bus Location for RPC	05	28	23	08
Loss Sensitivity Factor (LSF) $\frac{\left(\partial P_{((Loss,K+1))}\right)}{\left(\partial Q_{((k+1,eff))}\right)}$	0.02200	0.012887	0.006369	0.0060

The LSF for all the buses has been calculated using Equation (2), which involves determining branch losses and bus voltages using load flow analysis. The suggested technique selects the first four buses with greater LSF values and voltage below (0.96 PU) for the deployment of the RPC. These buses have been evaluated for implementation in the IEEE-33 network for placement of RPC. Potential locations for RPC placement based on their LSF values are shown in Table 3.

2.2. *Potential Location for the Deployment of DG*

Voltage regulation is critical in indicating that voltage drop occurs across the line. Although voltage regulation should ideally be zero, there are drops due to a line's resistance and reactance. Resistance is substantially less than the reactance in transmission lines, but reactance is much less than the line's resistance in overhead distribution systems. However, by supporting power demands locally, the voltage-drop across the line can be significantly reduced, resulting in lower line current and power loss and, hence, improved system efficiency.

To strengthen the distribution network, considering future load growth, finding the key busses that cause the system to become unstable when the load goes beyond a certain threshold is essential. Voltage Stability Index (VSI) shows that the weaker sections and subsequent buses are prone to voltage collapse, considering future load growth. Equation (3) shows the VSI of each section of the network. The sections with a higher VSI value are considered for the DG placement. Figure 4 shows the VSI values of different network sections where sections with high VSI values and their subsequent buses are considered for DG deployment. Table 4 shows potential locations for DG deployment based on high SI values.

$$VSI_{ij} = \frac{4r_{ij}(P_l - P_g)}{[|V_i|\, cos(\theta - \delta)]^2} \leq 1 \qquad (3)$$

2.3. Constraints and Variable Bounds for Optimization Problem

In the present analysis, inequality constraint across the power distribution system has been incorporated in terms of voltage limit to avoid any solution considering load bus voltage violation limit as shown in Equation (4).

$$V_{i\,min} \leq V_i \leq V_{i\,max} \qquad (4)$$

DG sizing variable bounds range from zero to 50% penetration level depending upon network total demand. The upper limit for the RPC sizing variable has been set based on the total reactive demand of the network.

3. Proposed MOF for Optimal Sizing of DG (T.S-1)

$$MinF = K_1 * \frac{P_{Loss}}{P_{Loss\,B}} + K_2 * \frac{\sum Cost_{DG}}{Cost_{DG}max} + K_3 * \frac{\sum Cost_{RPC}}{Cost_{RPC}max} \qquad (5)$$

Where,

F = Minimization type multi-objective optimization function.

K1, K2, K3 = Weighting factors.

P_{Loss} = Active loss of the network after deployment of DG and RPC.

$P_{Loss\,B}$ = Network Power loss without DG and RPC.

$\sum Cost_{DG}$ = Investment Cost of DG to be placed across the network.

$Cost_{DG}max$ = Maximum cost of investment for DG with its full capacity.

$\sum Cost_{RPC}$ = Investment cost of RPC to be placed across the network.

$Cost_{RPC}max$ = RPC's maximum expenditure on investments while operating at maximum capacity

Table 4. Potential location for DG based on VSI

Potential location for DG placement	08	24	25	31

The prime objectives of the suggested multiobjective function are to bring down the active losses and reduce the cost of resource investment. Equation (5) displays the suggested MOF with multiple objectives included. Based on the relationship importance matrix, weights have been allocated to each objective.

The weights K1, K2, and K3 are allocated to each target according to their importance to one another. Equation (6) displays the relative significance matrix for this MOF. The loss and cost objectives have normalized weighting values of 0.6 and 0.4, respectively. Based on the initial costs for resources of the DG and RPC types, the cost weighting factor is further split into k2 and k3.

$$\begin{matrix} & P_{loss}\,Cost \\ A_1 = \begin{matrix} P_{loss} \\ Cost \end{matrix} & \begin{pmatrix} 1 & \frac{3}{2} \\ \frac{2}{3} & 1 \end{pmatrix} \end{matrix} A_2 = W = \begin{pmatrix} 0.6 \\ 0.4 \end{pmatrix} \qquad (6)$$

Optimal sizing of these resources gives maximum benefits in terms of loss reduction with adequate resource capacity. A genetic algorithm has been used to find a trade-off solution for the proposed MOF satisfying all the constraints.

Figure 5 shows a flow chart of GA used to minimize the proposed MOF and thus finds a trade-off solution. Table 5 shows various algorithm-specific parameters and their values, which have been used for GA to optimise MOF. Figure 6 represents the convergence of MOF.

Where it can be found that MOF has been minimized using GA with each generation increment. Table 6 shows the results of the optimal sizing problem. The optimal size of DG has been shown with each DG location. Table 6 shows various potential locations of RPC devices and their optimal size in terms of KVAR.

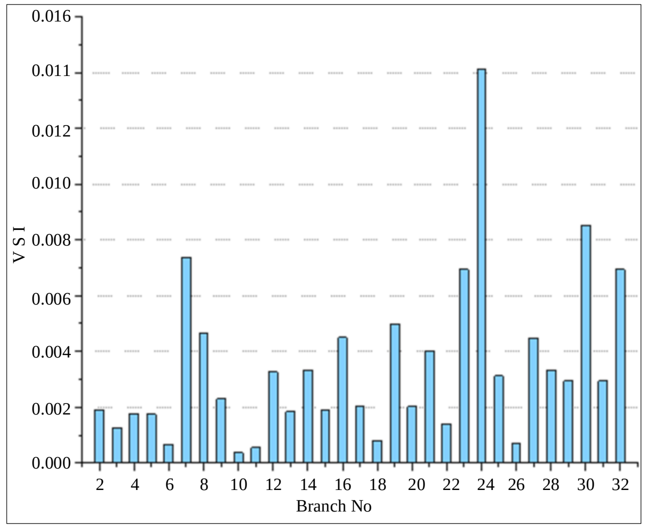

Fig. 4 VSI of different sections of the network

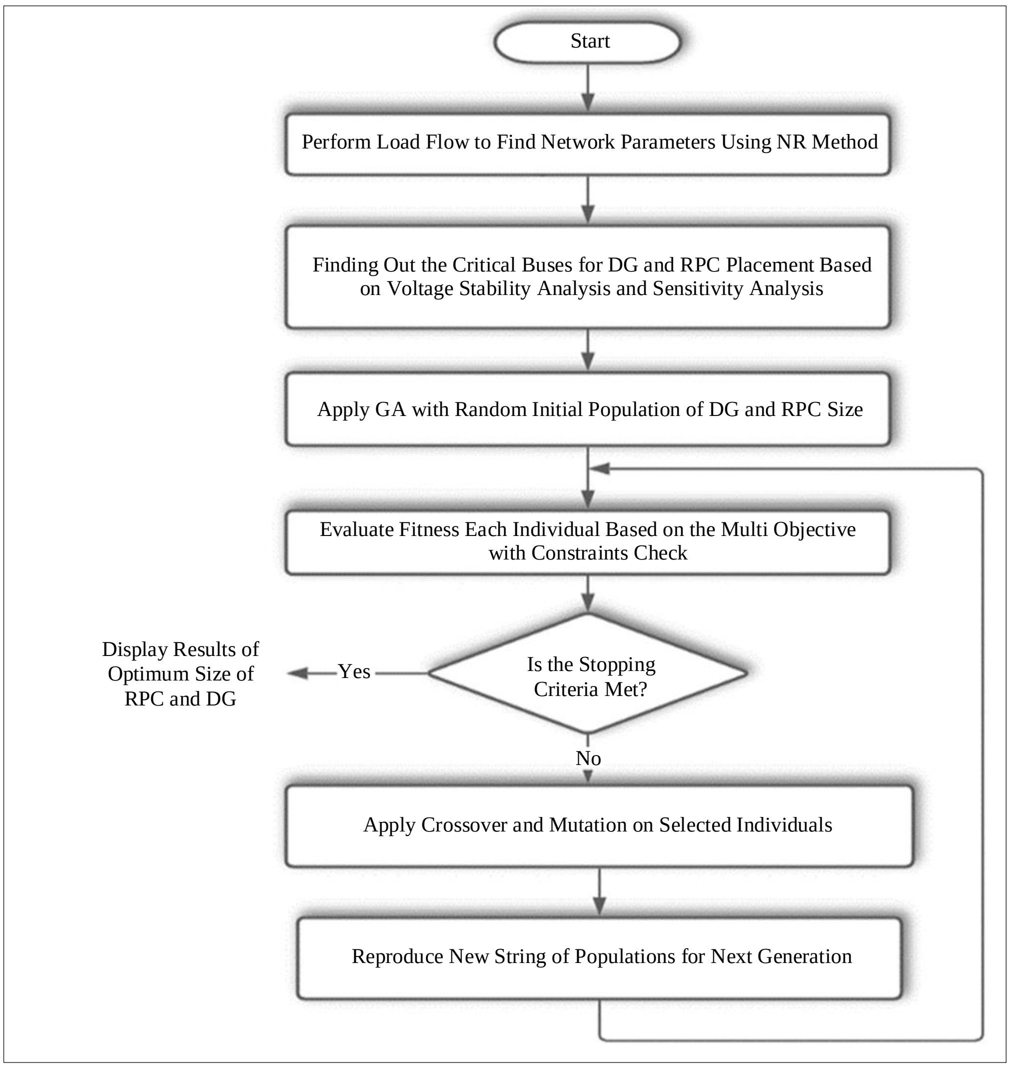

Fig. 5 Operational flow chart of proposed strategy using GA

Table 5. Algorithm specific parameters for GA

Sr. No.	GA Parameters	
1	Mutation operator rate	0.25
2	Crossover operator rate	0.92
3	Total Populations	80
4	Total Nos of Generations	100
5	Termination Method	Max. No. of Generations
6	Type of Fitness Function	Minimization Type

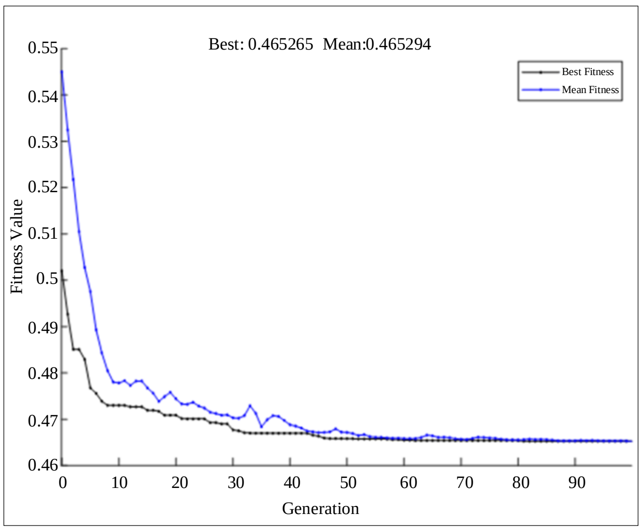

Fig. 6 Convergence graph of MOF using GA

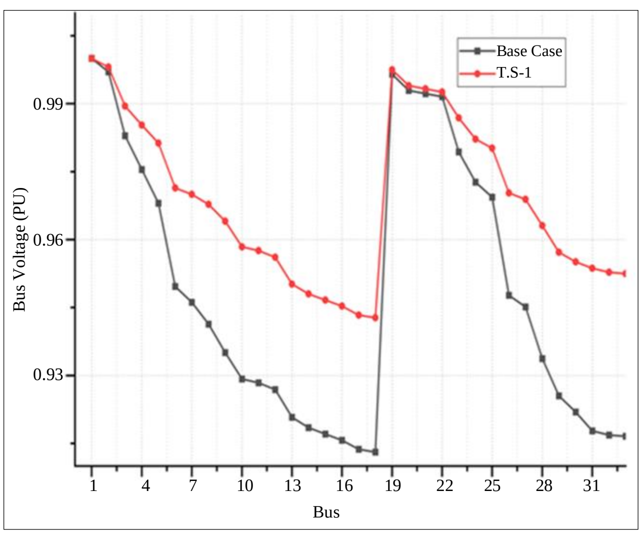

Fig. 7 Comparison of voltage profile with TS-1 and base case

Table 7 compares Test Scenario-1 and Base Case scenarios concerning various network performance parameters. Figure 7 shows a voltage profile comparison chart with TS-1 and base case.

Table 6. Optimal size and locations for RPC and DG

RPC Locations	05	08	23	28
Capacity in Mvar	0	0.4	0	0.4
D.G .locations	8	24	25	31
Capacity in Mw	0.284	0	0.1	0.396

Table 7. Comparison of network performance parameters

Sr. No.	Network Parameter	Base Case	T.S-1
1	Real Loss of Network	0.203	0.095
2	Reactive Loss of Network	0.14	0.06
3	Tail End Voltage (PU)	0.9165	0.9498
4	Voltage Deviation Index	0.0048	0.002

4. Proposed MOF for Optimal Sizing of DG (T.S - 2)

Cumulative Voltage Stability (CVSI) and Voltage Deviation Index (VDI), two more newly introduced network performance indices, have been included in the proposed multi-objective function with test scenario 1. Equation (7) displays the suggested CVSI for strengthening the network given anticipated increases in load.

The CVSI serves as a loadability indicator for the whole network. An enhancement in CVSI guarantees steady and sustainable network performance, considering future load growth and further boosting network loadability without exceeding the voltage limit. The voltage deviation index is displayed in Equation (7), demonstrating a quantifiable improvement in the network voltage profile. These two indices provide more resource capacity, which enhances network performance.

$$CVSI = \sqrt{\frac{\sum_{i=1}^{n}(VSI_i - VSI_0)^2}{n}} \quad Vdi = \sqrt{\frac{\sum_{i=1}^{n}(V_i - V_0)^2}{n}} \qquad (7)$$

$$MinF = K_1 * \frac{P_{Loss}}{P_{LossB}} + K_2 * \frac{\sum Cost_{DG}}{Cost_{DG}max} + K_3 * \frac{\sum Cost_{RPC}}{Cost_{RPC}max} + K_4 * \frac{CVSI}{CVSI_B} + K_5 \frac{Vdi}{Vdi_B} \qquad (8)$$

Equation (8) displays the proposed multi-objective fitness function, including the weighting factors for each objective. Weighting considerations are crucial in demonstrating how each target affects the MOF throughout the optimization process. The current study determines the weighting factor for each of the five objectives k_1, k_2, k_3, k_4, and k_5 using the AHP approach. The relative importance matrix A1 has been created, as Equation (9) indicates. A1 shows how important each attribute is to the others. A normalized weighting factor matrix can be given by Equation (9).

$$A_1 = \begin{array}{c} \\ P_{loss} \\ Cost \\ VDI \\ VSI \end{array} \begin{array}{c} \begin{array}{cccc} P_{loss} & Cost & VDI & VSI \end{array} \\ \begin{bmatrix} 1 & 2 & 5 & 4 \\ 1/2 & 1 & 3 & 2 \\ 1/5 & 1/3 & 1 & 9/10 \\ 1/4 & 1/2 & 10/9 & 1 \end{bmatrix} \end{array} \quad A_2 = W = \begin{pmatrix} 0.50946 \\ 0.266609 \\ 0.100261 \\ 0.123669 \end{pmatrix} \tag{9}$$

The Random Index for four attributes is 0.86, considering that the Consistency ratio for the present relative importance matrix is 0.004494, which is within the permissible limit (CR<0.1); furthermore, it implies that normalized weighting factors are appropriate based on the relative importance matrix. The Proposed Multi-Objective Fitness function has been optimized by GA to find the effective size of DG and RPC.

Table 8. Optimal size of DG and RPC with TS-1 and TS-2

DG Locations	08	24	25	31
Capacity in MW (T.S-2)	0.4	0.101	0.235	0.38
Capacity in MW (T.S-1)	0.284	0	0.1	0.396
RPC Locations	05	08	23	28
Capacity in MVAR (T.S-2)	0.166	0.4	0	0.4
Capacity in MVAR (T.S-1)	0	0.4	0	0.4

Table 9. Comparison of network performance parameters

Sr. No.	Network Parameters	Base Case	T.S-1	T.S-2
1	Real Loss of Network (MW)	0.203	0.095	0.080
2	Reactive Loss of Network (MVAR)	0.14	0.06	0.05
3	Tail End Voltage (PU)	0.9165	0.9498	0.9524
4	Voltage Deviation Index	0.0048	0.002	0.0018

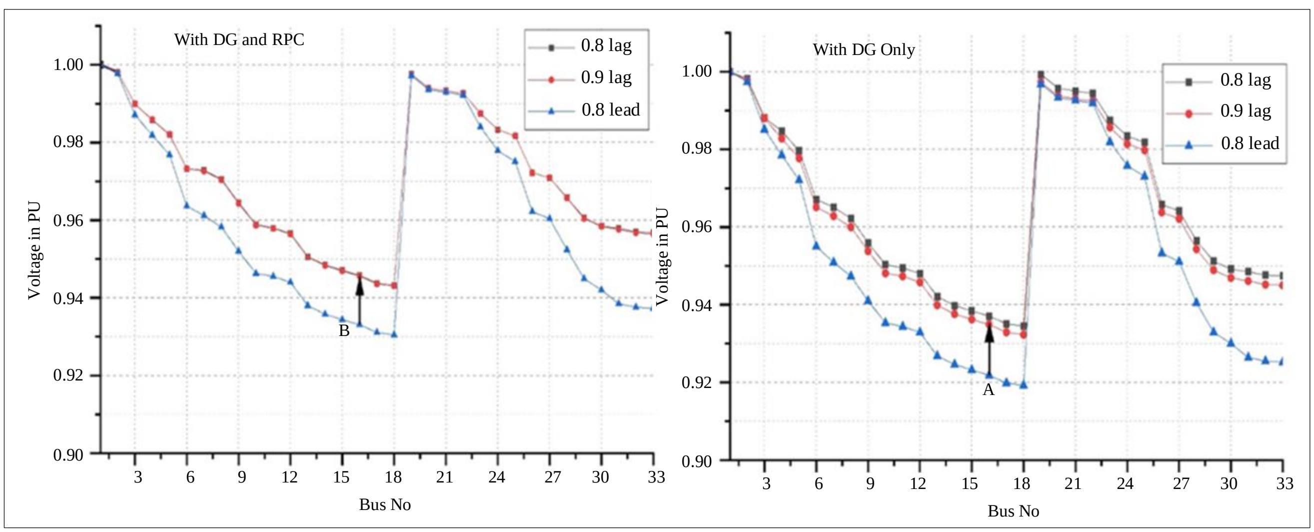

Fig. 8 Voltage profile comparison with DGs operating at various PF

Results of the Placement Problem with T.S.-2 are shown in Table 8. The figure shows a convergence graph of fitness value VS generations. Table 9 compares various network performance parameters with all previous scenarios. Figure 8 shows the network voltage profile comparison chart with TS-1 and TS-2.

4.1. DG's Operation at Various Power Factors with T.S-2

DGs are often utilized to add active power to the local grid at a UPF. Recent advancements in power electronics devices have made it feasible for DG to operate at different PFs. DG may function at a lead or lag type PF to control bus voltages. Reactive power may also be supplied or absorbed by it for the local distribution network.

Additionally, it may impact the profit margin of DG's owner, which would significantly limit its ability with DG's operation at lower PF. DG may offer reactive-power assistance to the local network to enhance network performance and partially regulate bus voltages as part of the ancillary service. For the analysis in TS-1 and TS-2, the functioning of DGs at the unity power factor has been considered. According to TS-2, each of the four DGs operates at a different power factor; the current subsection examined how this affects network performance.

Three distinct power factors, 0.9-lagging, 0.8-lagging, and 0.9-leading, have been considered for DG operation. The network-voltage profile, considering the operation of DG at different power factors without RPC support, is displayed in Figure 9. It also shows the network voltage profile with RPC support. Line A is more significant than line B, illustrating voltage improvement at bus nos. 16 with and without RPC assistance.

In the case of DG alone, the rate of bus voltage improvement is more significant than DG with RPC support. An active/reactive loss comparison for DG running at different power factors is presented in Figure 10, which considers two scenarios: DG only and DG with RPC support. The findings demonstrate that in case-1 (only DG), operating the DG from 0.9 lag pf to 0.8 lag pf reduces the network's active power loss from 0.104MW to 0.102MW by giving the system more reactive power to mitigate losses. However, in case-2 (DG with RPC), operating the same DG from 0.9 lag pf to 0.8 lag pf causes an overcompensation issue, increasing the network's active power loss from 0.074MW to 0.077MW. Considering DG modelling for the voltage control bus, the optimal size of the DG and RPC problem was further changed. GA must be applied to minimize the proposed MOF by considering modified DG modelling for the IEEE-33 network, which is covered in the following subsection.

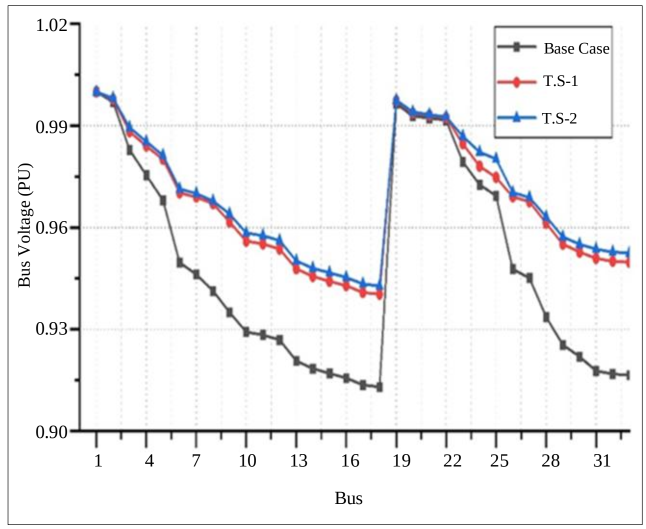

Fig. 9 Voltage profile comparison with different test case

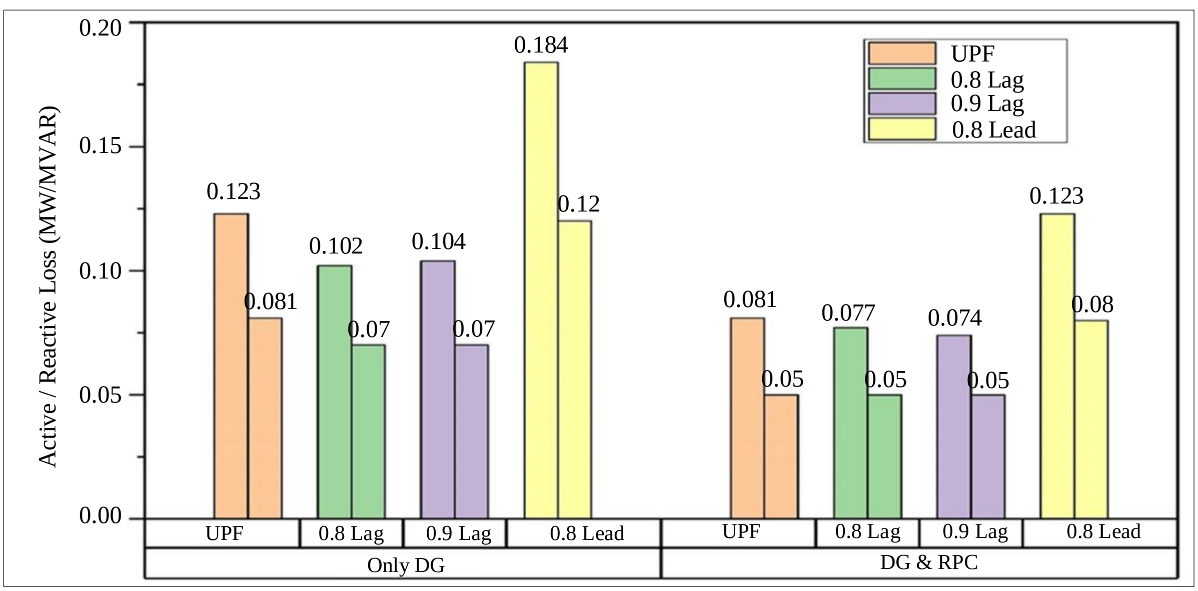

Fig. 10 Comparison of performance parameters with DG modelled for PV bus

5. Problem Formulation for Optimal Sizing of DG and RPC (T.S-3)

As DGs supply active power to the network in TS-1 and TS2, DGs are modelled for the PQ bus; therefore, they operate at a unity power factor. Since DGs in TS-3 have been modelled for PV buses, they can either provide or absorb a portion of the reactive demand needed to control the bus voltage. To satisfy the network's reactive power needs, DGs have been modelled to function at either a lead type or lag type power factor in accordance with the Q-limit. The suggested

MOF (TS-2) found in Equation (8) has been re-optimized to address the resource sizing problem with changed DGs modelling.

5.1. Results of the Optimal Placement Problem with TS-3

Table 10 shows the suitable size of DG based on MOF and their corresponding location. Furthermore, it also includes the optimal size of P and Q power supplied to the network. Table 11 shows the optimal size of the RPC and their corresponding location to assist for reactive power to the network.

6. Comparative Results with Different Test Scenarios

The voltage profile comparative chart with all three test scenarios, i.e., Test Scenarios 1, 2 and 3, is demonstrated in Figure 11. Table 12 shows the network parameters comparative chart with all test scenarios. It can be seen that in test scenario 3, as DGS operated with a lagging PF to provide Q to the network, the improvement in network performance parameters was further extended. However, it also results in lower optimal sizing of RPC devices, reducing the cost burden in terms of RPC investment cost. Thus, in test scenario 3, better network performance parameters were achieved with the reduced cost burden of RPC. DGs have been modelled to operate lagging type PF as per the associated Q-limit to provide Q to the network along with the RPC. These DGs operate with UPF and provide P to the network if the network reactive3 demand has been taken care of with RPC only.

Table 10. P and Q supplied by DGs (for PV bus)

D.G locations	8	24	25	31
Capacity in MVA	0.4	0.1	0.352	0.4
P Supplied By DG (MW)	0.32	0.08	0.2816	0.32
Q Supplied By DG (MVAR)	0.24	0.06	0.2112	0.24

Table 11. Optimal size of DGs with TS-2 and TS-3

RPC Locations	05	08	23	28
Capacity in Mvar (T.S-3)	0	0.4	0	0.4
Capacity in Mvar (T.S-2)	0.166	0.4	0	0.4

Table 12. Network parameters comparison with all test scenarios

Sr. No.	Network Parameter	Base Load	T.S-1	T.S-2	T.S-3
1	Real Loss of Network (MW)	0.203	0.095	0.080	0.07
2	Reactive Loss of Network (MVAR)	0.14	0.06	0.05	0.05
3	Tail End Voltage (PU)	0.9165	0.9498	0.9584	0.957
4	Voltage Deviation Index	0.0048	0.002	0.0018	0.0016

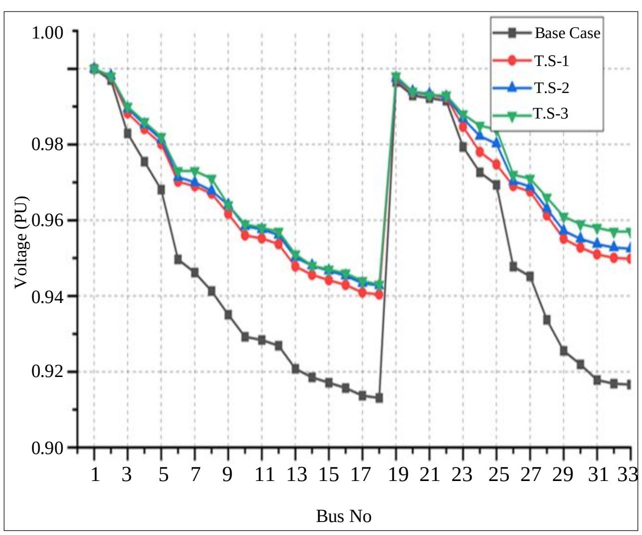

Fig. 11 Voltage profile comparison chart

7. Conclusion

To provide the distribution grid with active and reactive power, this paper presents the best allocation technique for various distributed resource types. Three distinct scenarios have been used to address the suggested approach: DG just, G and RPC, and DG and RPC, whereby DG has been modelled for a voltage control bus. The results of scenario 2 (DG with RPC) indicate that when DG and the RPC have been operating at a power factor that is different from unity, the DG additionally injects proportionate reactive power into the grid, which exacerbates system losses and deteriorates the voltage profile because of an overcompensation issue. In scenario three, the ideal distribution of DG and RPC throughout the distribution grid is discussed. DG is modelled for the voltage control bus while considering Qlim restrictions.

The proposed MOF includes two new indices, the VDI and CVSI, to enhance the distribution grid's loadability and performance. The suggested MOF considers performance and economic objectives and minimizes them using a heuristic algorithm. GA is a competitive and robust optimization technique to tackle this nonlinear, restricted optimization issue. Each of the three cases has been used to identify economically viable trade-off alternatives. The outcomes of every scenario show promise, with notable advancements in voltage profile enhancement, loss reduction, and stability improvement at the lowest possible specific investment cost for both DG and RPC. The network operator has found the suggested approach helpful in determining whether these DG technologies are economically viable to integrate with the distribution grid.

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