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Article

Optimal Placement and sizing of Multiple DGs for Loss Minimization and Voltage Stability Enhancement using Golden Eagle Optimization Technique

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Abstract: The modern power distribution systems face many challenges due to the increasing electricity demand, urbanization, industrial growth and the incorporating renewable energy sources like wind and solar power. The traditional radial distribution systems suffer from problems like high power losses, poor voltage profile, feeder overloading and reduced voltage stability especially under heavy loading conditions. In order to solve the above problems, Distributed Generation (DG) units are connected near the load centers for good system performance. This project is focused on optimal placement and sizing of DG units in IEEE 33 Bus and IEEE 69 Bus radial distribution systems. Initially the load flow analysis is performed using the Backward-Forward Sweep (BFS) technique to find the bus voltages, branch currents and real power losses for base case conditions. Detection of weak buses is based on voltage deviation and system performance indices. Then, the Golden Eagle Optimization (GEO) algorithm is implemented to determine the optimal locations and capacities of DG units to minimize the power loss and to improve the voltage profile. The simulation is performed in MATLAB and the result is compared before and after DG integration. The achieved results indicate significant reduction in power losses and improvement in voltage stability upon optimal placement of DG.
Keywords: Distributed Generation, Golden Eagle Optimization, IEEE 33-Bus System, Power Loss Reduction, Voltage Stability

1. Introduction

The growing need of efficient distribution network operation and increasing penetration of renewable energy resources have made the optimal placement and sizing of Distributed Generation (DG) units an important research topic. Proper DG integration can significantly reduce active power losses, improve voltage profiles, improve system reliability and defer costly network expansion projects. Therefore, many analytical, heuristic and metaheuristic optimization techniques have been proposed to determine the best DG locations and capacities.

In [1], Teja and Maheswarapu have proposed an Imperialist Competitive Algorithm (ICA) for optimal placement and sizing of Distributed Generators (DGs) in IEEE 33-bus radial distribution system. The candidate buses are identified using loss sensitivity analysis and the optimal DG sizes are identified using ICA based optimization. The objective is to reduce the active power losses and improve the voltage profiles. Results showed that better convergence, enhanced global search ability and better loss reduction than Genetic Algorithms (GA) were obtained.

K.M.Muttaqi et al. [2] have proposed an analytical algebraic method to determine the optimal DG location, size and operating parameters in radial distribution networks. The method used voltage sensitivity analysis and Thevenin equivalent modelling to achieve closed form expressions without iterative optimisation. The simulation results showed that the approach provides significant improvements in the voltage profile and feeder support with low computational complexity, which makes it suitable for distribution planning studies.

A brute-force search technique for reconstructing three-dimensional scenes from two projections was presented by O.Enqvist et al. [3]. The approach used robust goal functions for optimization and conducted a thorough search in a four-dimensional parameter space. When compared to traditional methods, experimental results showed increased robustness and global optimality, demonstrating the efficacy of brute-force search tactics for challenging optimization issues. Kong et al. [4] studied the vulnerability of palm print biometric authentication systems against brute force attacks based on a projected multinomial probability distribution model. The recognition of palm print is based on Competitive Code algorithm, and the simulation results show that the successful brute-force attacks are computationally infeasible in the real-world scenarios. The study gave a quantitative framework for evaluating the security of the biometric system against exhaustive search attacks.

Moradi and Abedini [6] proposed a hybrid technique of Genetic Algorithm–Particle Swarm Optimization (GA–PSO) for simultaneous DG placement and sizing in the IEEE 33-bus distribution system. The optimization objective was to minimize the network power losses and improve the voltage regulation subject to operational constraints. Location selection was carried out using GA and DG sizing was carried out using PSO.

Lalitha et al. [7] proposed SOS algorithm for optimal DG placement with reverse power flow constraints. The proposed methodology simultaneously determined the DG locations and sizes in distribution systems. The results showed better network performances and less power losses than existing optimization techniques. Kanth et al. [8] proposed Backtracking Search Algorithm (BSA) to minimize the active power and energy losses subject to the voltage and thermal constraints. The proposed algorithm showed better optimization performance and faster convergence than traditional Big Bang–Big Crunch algorithms. Li et al. [9] proposed an Improved Beluga Whale Optimization (IBWO) algorithm for optimal distributed generation allocation in distribution systems. The validation results show that the active power loss reductions are 55.49% and 45.39% respectively which show superior performance compared with conventional metaheuristic approaches.

Shawon et al. [10] proposed a methodology for distributed generation placement based on AC optimal power flow and non-linear programming for micro grid planning. The framework accounted for uncertainty in renewable generation, load growth, voltage constraints and branch current limits in the optimization process. The simulation results demonstrated considerable increase in voltage profiles while maintaining the safe operation of the system under various loading conditions. Wichitkrailat et al. [11] studied the optimal location and size of multiple Battery Energy Storage Systems (BESSs) in Distribution Systems with Distributed Generation (DG) based on Crayfish Optimization Algorithm (COA). The results showed improvements in voltage deviation of 43.43% and 42.32%, peak demand reductions of 50.00% and 45.74%, and power loss reductions of 12.21% and 4.69%, respectively.

Ntombela et al. [12] proposed a optimization scheme of Genetic Algorithm (GA) and Improved Particle Swarm Optimization (IPSO) for distributed generation sizing and placement. The results showed improved loss minimization capability and better voltage regulation performance, which demonstrated the effectiveness of hybrid intelligence-based optimization techniques for DG planning applications. Raza et al. [13] suggested a coordinated optimization framework of Distribution Network Reconfiguration (DNR) and DG placement using Ant Colony Optimization Algorithm (ACOA). The approach optimized the power loss, voltage profile, stability and reliability by considering Energy Not Supplied (ENS). The results show better performance than stand-alone DG allocation methods. With the integration of DG has become an efficient solution to improve the efficiency of distribution network.

Huy et al. [14] proposed an Enhanced Search Group Algorithm (ESGA) by integrating Chaotic Local Search (CLS) with traditional Search Group Algorithm to enhance global exploration and convergence properties. The optimization framework minimizes the active power loss, the voltage deviation and maximizes the VSI simultaneously. The results show better performance than existing optimization approaches. Manikanta et al. [15] have used the Symbiotic Organism Search (SOS) algorithm for DG allocation. The study showed that SOS provides better loss minimization and VSI improvement over conventional Genetic Algorithm (GA)-based optimization methods. Magadum and Kulkarni [16] have proposed a fuzzy logic based approach for optimal placement and sizing of multiple DG units in distribution network. The fuzzy input variables were the bus voltage magnitude and line losses to find a DG placement index which can effectively identify the candidate buses for the DG integration within acceptable limits of voltage.

Kumar [17] and Ravi Teja studied DG placement in Unbalanced Mesh Distribution Systems (UMDS). The authors used voltage sensitivity index to find the optimal placement for the installation and the variational method to calculate the DG capacity. The results have shown significant reductions in active and reactive power losses and improvement in voltage under different DG power factor operating conditions. Sheng et al. [18] proposed an Improved Non-dominated Sorting Genetic Algorithm-II (INSGA-II) for multi-objective DG. The proposed approach incorporated differential evolution operators and hierarchical clustering strategies to improve population diversity and global search ability, which yielded high-quality Pareto-optimal solutions. Syechu Dwitya Nugraha et al. [22] present a multi-objective method in distribution systems with a focus on distributed rooftop Photovoltaic (PV) systems in a metropolitan city. The study tackles the pressing requirement for prudent planning in contemporary electric power systems to avert network overload, higher power losses and voltage variations stemming from the integration of EVCS and Distributed Generation (DG).

2. Problem Statement

This project's primary goal is to identify the best locations and sizes for distributed generation units in order to reduce overall power loss and increase the voltage stability index.

Case 1: Objective function

The power losses and voltage stability index are the multi objectives that are considered for optimization.

Case 2: Power loss reduction

The real power loss minimization objective function of the distribution system can be expressed mathematically as:

$$P_{loss} = \sum_{i=1}^{nl} |I_i|^2 R_i \quad (1)$$

The reactive power loss of the system can be expressed as:

$$Q_{loss} = \sum_{i=1}^{nl} |I_i|^2 X_i \quad (2)$$

where:

- Ploss = Total active power loss
- Qloss = Total reactive power loss
- Ii = Current flowing through branch i
- nl = Total number of branches

Case 3: Percentage Loss Reduction

$$\text{Loss Reduction (\%)} = \frac{P_{loss,base} - P_{loss,DG}}{P_{loss,base}} \times 100 \quad (3)$$

Case 4: VSI Improvement

The VSI for a branch connecting bus I (sending end) to bus j (receiving end) can be expressed as:

$$VSI(j) = |V_i|^4 - 4\left[P_jX_{ij} - Q_jR_{ij}\right]^2 - 4[P_jR_{ij} + Q_jX_{ij}]|V_i|^2 \quad (4)$$

where:

- Vi = Voltage magnitude at sending bus i
- Pj = Active power demand at bus j
- Qj = Reactive power demand at bus j

Case 4: System Constraints

A. Voltage Constraints

The magnitude of the bus voltage must stay within the allowable bounds.

$$V_{min} \leq V_i \leq V_{max} \quad (5)$$

i.e $0.95 \leq V_i \leq 1.05$ (6)

B. DG Capacity Constraints

The DG output power ought to stay within the designated bounds.

$$P_{DG}^{min} \leq P_{DG} \leq P_{DG}^{max} \quad (7)$$

where PDGmin and PDGmax indicate the power output limits of DG unit.

3. Golden Eagle Optimization algorithm

Golden Eagle Optimization (GEO) is a nature-inspired optimization algorithm developed from the hunting behavior of golden eagles. In nature, golden eagles are highly intelligent predators that search large areas to locate prey and then attack the most suitable target with speed and accuracy. This natural strategy is mathematically modeled for solving complex optimization problems in engineering and science. The algorithm is based on two main important mechanisms: exploration and exploitation. Exploration is searching new regions of the solution space to find better possibilities and exploitation is improving the best solution found so far. The balance between these two processes enables GEO to avoid local optimum solutions and move towards the global optimum.

GEO is very useful in power system applications for solving nonlinear and constrained optimization problems such as capacitor placement, network reconfiguration and DG allocation. In this work GEO is used to determine the best location and size of DG units in radial distribution systems. The algorithm is composed of a number of eagles. Each eagle represents a candidate solution i.e. placements and sizes of DGs. The fitness function used in this paper is the total active power loss of the system and it is expressed as:

Fitness = Ploss,total = Iij2Rij (8)

A smaller fitness value indicates a better solution. GEO repeatedly updates the candidate solutions until the minimum possible loss is achieved under system

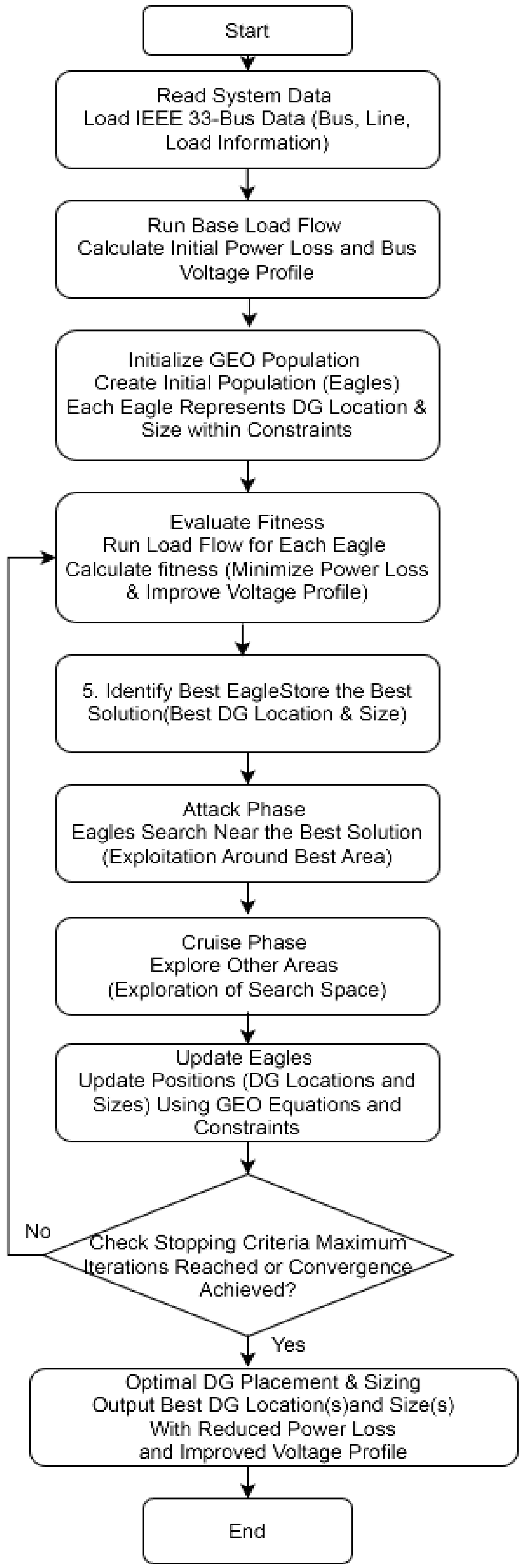

Fig. 1: Flow chart for the proposed system

constraints. The flow chart for the proposed system is shown in fig.1.

Working Steps:

The GEO algorithm begins by generating an initial population of eagles randomly within these arch limits. In this project, each eagle contains DG locations and DG sizes selected within allowable ranges. For example, DG buses are selected between valid bus numbers, while DG capacities are selected between minimum and maximum limits. A sample candidate solution for two DG units can be represented as:

X = [Bus1, Bus2, PDG1, PDG2] (9)

After initialization, each eagle is evaluated using load flow analysis. The Backward–Forward Sweep method is used to calculate bus voltages, branch currents, and total real power loss for every candidate solution. The eagle with the lowest power loss is selected as the current best solution. This best eagle guides the movement of the remaining population.

Each eagle updates its position by moving towards the best solution while continuing with random movement for global exploration. The position update equation is given by:

$$X_{new} = X_{current} + \propto (X_{best} - X_{current}) + \beta(rand - 0.5) \qquad (10)$$

Where

$\propto (X_{best} - X_{current})$ = exploitation factor, $\beta(rand - 0.5)$ = exploration factor

The first term directs the eagle toward the best solution, whereas the second term provides a random component that allows for exploration of new areas. This combination improves the convergence and prevents premature trapping in local minima. If duplicate DG locations or invalid values occur, penalties are applied or corrections are made. The evaluation and updating process continues for several iterations until the stopping condition is reached. Finally, the best eagle provides the optimal DG locations, DG sizes, minimum power loss and improved voltage profile of the distribution system.

4. Results

A. IEEE 33-bus:

The IEEE 33-bus distribution system is a commonly used network for analysis of power system. The system base voltage is 12.66 kV with a base power of 100 MVA [23]**.** The total system demand in this network is approximately 3.7 MW of real power and 2.3 MVAR of reactive power. As seen in Fig 2, there are 33 busses and 32 branches in this test system. The simulations were conducted using MATLAB R2021a.

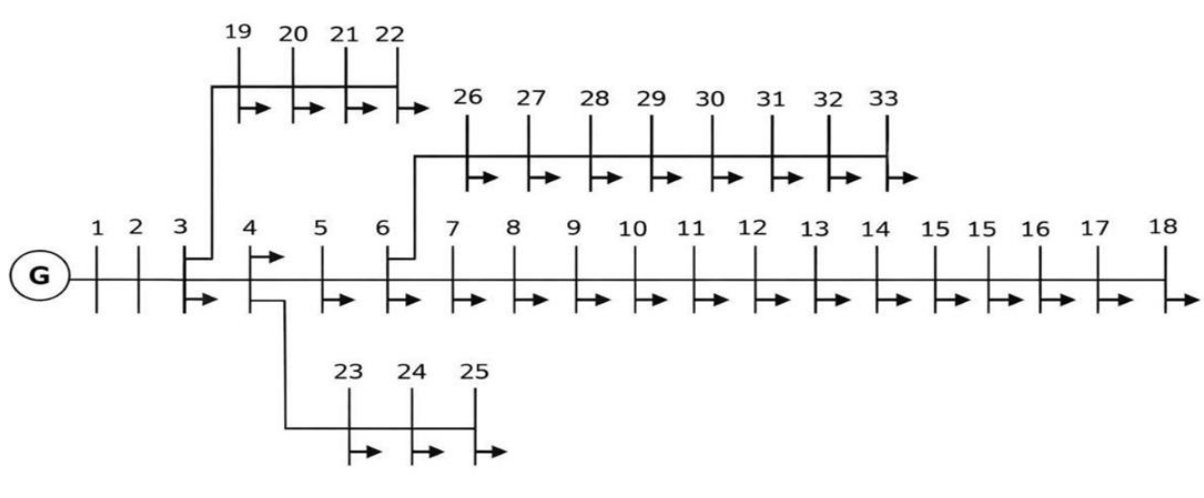

Fig 2: Single line diagram of IEEE 33 Bus distribution system

Table I shows the power losses, percentage loss reduction values, the voltage profile and the VSI values before and after DG placement. The maximum number of DGs connected in this system is three and the size of the DG is taken between 0.1 to 2.5 MW. These three DGs are tested for Type 1, Type 2 and Type 3 systems.

Table 1: DGs at 0.9 power factor for IEEE 33 Bus system

0.9 PF	**Optimal DG Bus Number**	**Injected Active power (MW)**	**Injected Reactive Power (MVAr)**	**Active Power loss**	**Reactive Power loss**	**% Loss Reduction**	**Min Voltage, Bus Number**	**Max Voltage, Bus Number**	**VSI**
Base Case				**0.211**	**0.143**		**0.9038, 18**		**0.666763**
				Type 1					
1 DG	7	2.0000	0	0.1152	0.0824	45.40	0.9364, Bus 18	1.0000, Bus 1	0.768668
2 DG	13 30	0.8494 1.1177	0	0.0872	0.0597	58.66	0.9672, Bus 33	1.0000, Bus 1	0.875087
3 DG	3 30 13	1.3287 0.9850 0.7851	0	0.0785	0.0550	62.81	0.9671, Bus 33	1.0000, Bus 1	0.874759
				Type 2					
1 DG	30	0	1.2577	0.1514	0.1038	28.26	0.9165, Bus 18	1.0000, Bus 1	0.705144
2 DG	26 30	0	0.8288 0.8792	0.1454	0.0999	31.07	0.9208, Bus 18	1.0000, Bus 1	0.718540
3 DG	30 13 24	0	1.0328 0.3974 0.5402	0.1383	0.0942	34.47	0.9320, Bus 18	1.0000, Bus 1	0.754269
				Type 3					
1 DG	28	2.0000	0.9686	0.0772	0.0597	63.39	0.9432, Bus 18	1.0000, Bus 1	0.791289
2 DG	13 30	0.8271 1.3678	0.4006 0.6624	0.0353	0.0252	83.29	0.9803, Bus 25	1.0000, Bus 1	0.923056
3 DG	13 30 3	0.8297 1.1729 1.5318	0.4018 0.5681 0.7419	0.0251	0.0196	88.08	0.9865, Bus 25	1.0030, Bus 13	0.946909

The comparison of active power loss in the system under base case, single DG, two DG and three DG operating conditions for three different DGs. The active power loss in the base case is highest at approximately 0.211 MW because the entire load demand is supplied only from the main substation, causing higher feeder current and greater transmission losses. After installing one DG unit, the active power loss decreases for all DG types. Type-1 DG installed at bus 7 reduces the loss to about 0.115 MW by supplying real power locally, while Type-2 DG installed at bus 30 reduces it to around 0.151 MW through reactive power support. Type-3 DG installed at bus 28 provides the best performance in the single DG case, reducing the loss to nearly 0.077 MW. When two DG units are optimally placed, the loss reduces even further. Type-1 DG placed at buses 13 and 30 achieves approximately 0.087 MW, Type-2 DG placed at buses 26 and 30 gives around 0.145 MW and Type-3 DG placed at buses 13 and 30 reaches the minimum value of nearly 0.035 MW. When three DG units are optimally placed, the loss reduces even further. Type-1 DG placed at buses 3, 30 and 13 achieves approximately 0.078 MW, Type-2 DG placed at buses 30, 13 and 24 gives around 0.138 MW, and Type-3 DG placed at buses 13, 30 and 3 reaches the minimum value of nearly 0.025 MW. This significant reduction occurs because multiple DG units share the load demand, reduce feeder current, shorten power flow distance, and improve voltage support. Overall, the Fig clearly shows that increasing the number of DG units improves system efficiency, and the three DG Type-3 configuration gives the best result for active power loss reduction.

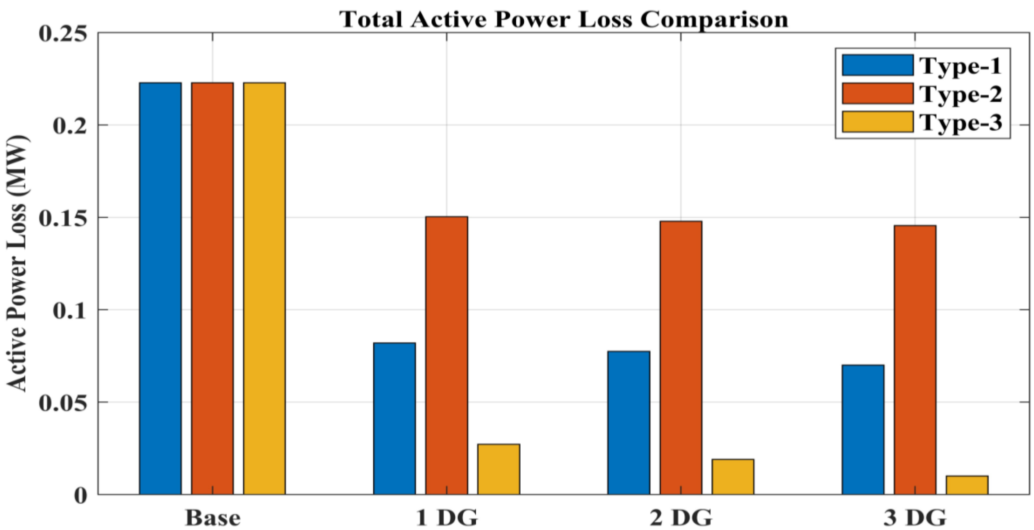

Fig.3. Active Power Loss Comparison

The fig.3 illustrates the comparison of reactive power loss for all the cases. The reactive power loss is highest at around 0.143MVAr without DG installation. After installing one DG, the reactive losses reduced for all DG types. Type-1 lowers the loss to nearly 0.082 MVAr, while Type-2 reduces it to about 0.104 MVAr. Type-3 gives the best result in the single DG case with a loss of approximately 0.059MVAr. When two DG units are placed optimally, the reactive loss decreases further. Type-1 reaches around 0.059MVAr, Type-2 gives nearly 0.099MVAr, and Type-3 achieves the minimum value of about 0.025MVAr. When three DG units are placed optimally, the reactive loss decreases further. Type-1 reaches around 0.055MVAr, Type-2 gives nearly 0.094MVAr, and Type-3 achieves the minimum value of about 0.0196MVAr. This confirms the superiority of multi-DG placement especially Type-3 DG for reactive compensation and system losses minimization.

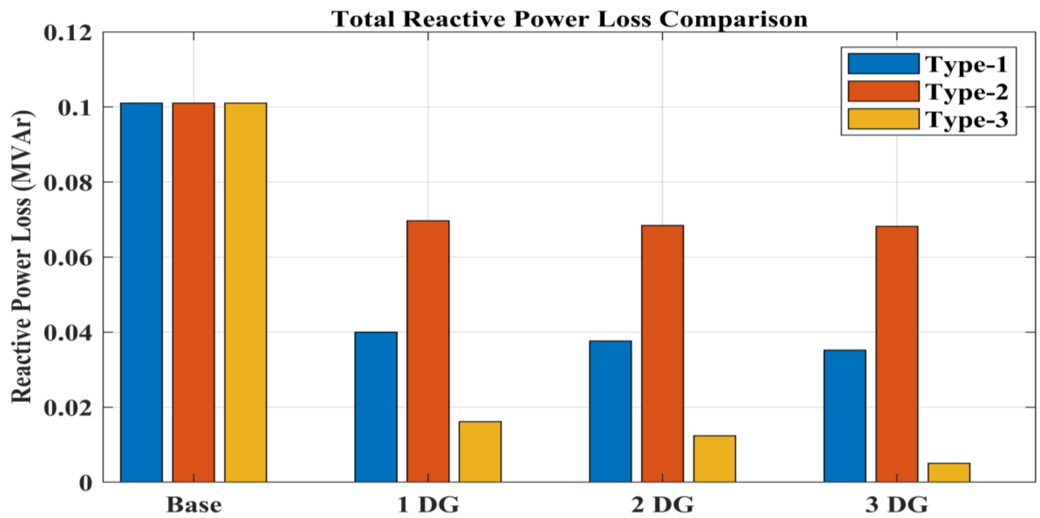

Fig.4. Reactive Power Loss Comparison

Figure 4 presents the percentage reduction of active power loss after installation of DG units with respect to the base case. The base case is the zero reduction, as there is no DG installed. Type-1 gives around 45.4% loss reduction, Type-2 gives around 28.26%, and Type-3 gives nearly 63.39%, which is the maximum among single DG cases, at one DG level. The percentage reduction is further increased when two DG units are installed. Type-1 reaches about 58.66 Type-2 gives nearly 31.07 and Type-3 gives the highest overall reduction of about 83.29. This indicates the addition of DG units increases the system efficiency and Type-3 DG is the best for loss minimization due to simultaneous active and reactive power support.

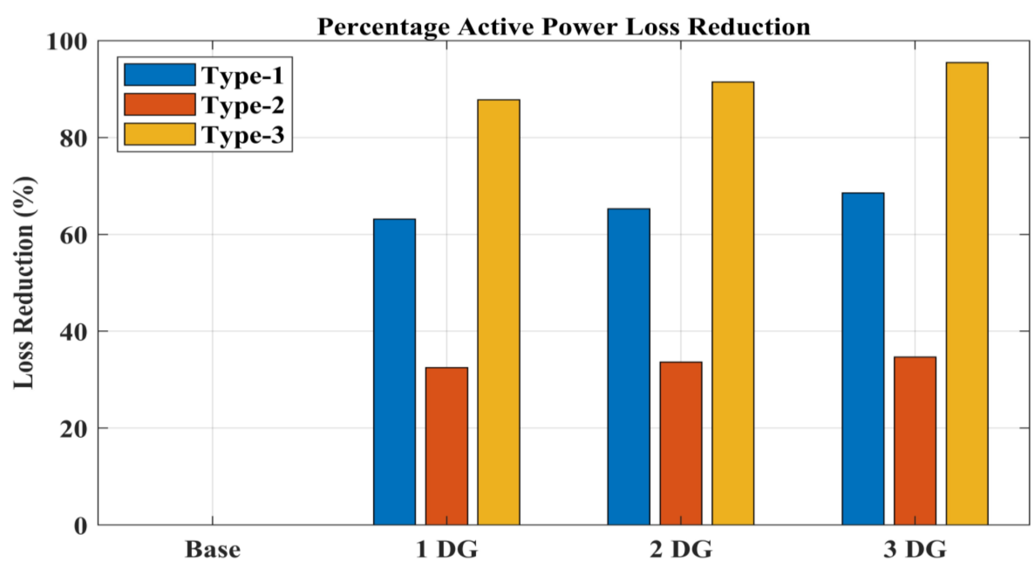

Fig.5: Percentage Loss Reduction

The fig.5 represents the comparison of bus voltage profile of system for base case and one DG placement for all three DG types. In the base case, the voltage gradually decreases with the increase of bus number and the minimum value is at the remote buses because of feeder impedance and heavy load demand. One DG installation improves the voltage profile significantly over the network. Type-1 DG supplies localized injection of real power to improve bus voltages. Type-2 provides moderate level of improvement through reactive compensation. Type-3 provides the best voltage support by maintaining the higher voltage magnitude across almost all buses because it provides active power and reactive power. This indicates that a single DG when placed properly can improve voltage regulation effectively especially when Type-3 DG is used.

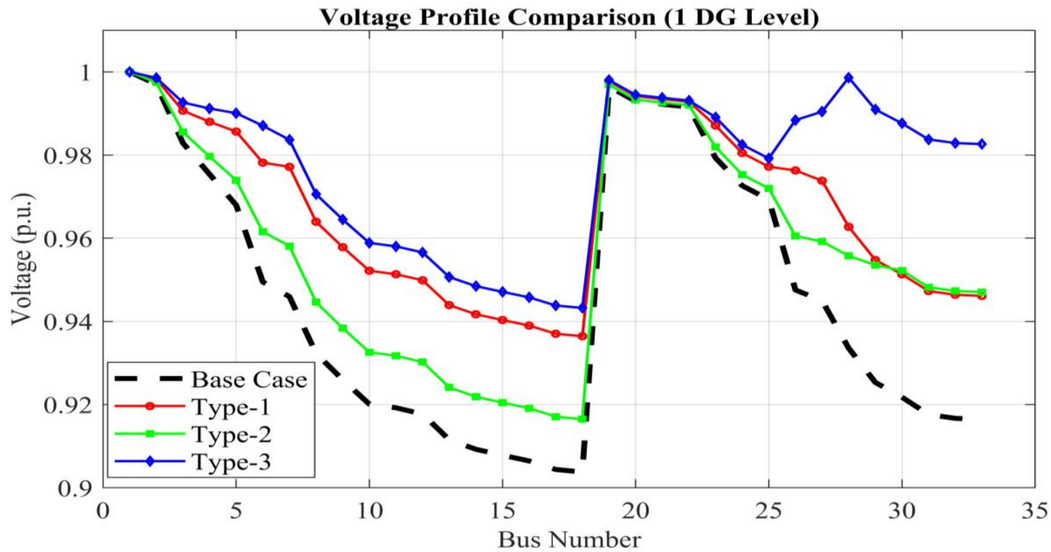

Fig.6.Voltage Profile Comparison for One DG

The voltage profile when the two DG units are optimally placed in the network is shown in Fig.6. The voltage profile is stable and flat in all buses as compared to the one DG case. The base case still shows the lowest voltages, especially at the far buses. Type-1 gives a significant improvement in voltage whereas Type-2 gives a moderate support. The Type-3 offers the highest voltage levels in the system and maintains most of the buses near unity voltage. Since two DG units are installed at different buses, the local power support is more effectively distributed, thus reducing feeder burden and minimizing voltage drop. It reveals that the multi-DG placement provides better voltage improvement than the single DG placement.

Fig.7 illustrates the bus voltage profile of the for the three-DG operating condition for all the cases. The base case shows the lowest voltage magnitude, especially at buses far from

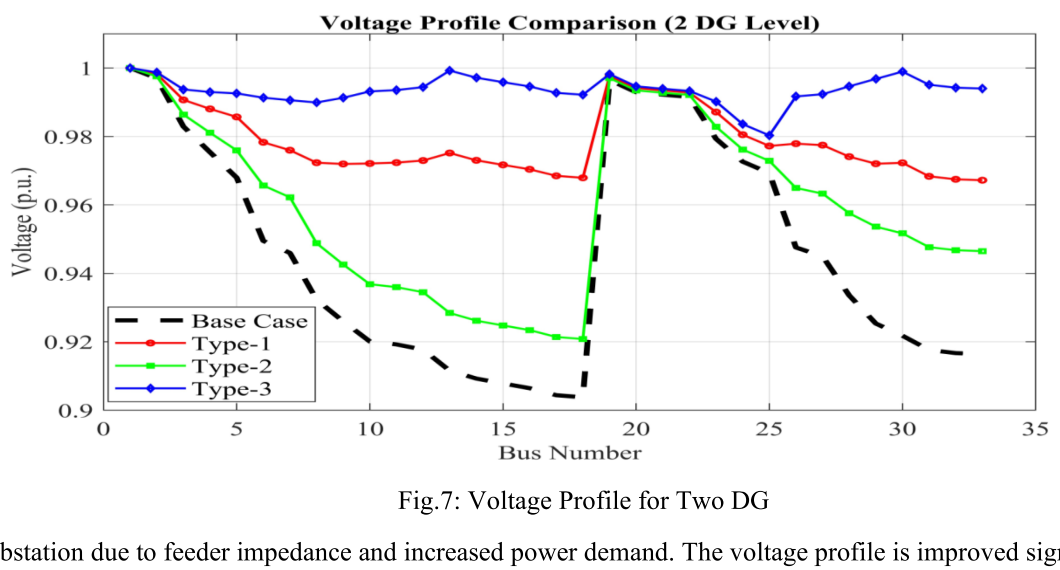

Fig.7: Voltage Profile for Two DG

the substation due to feeder impedance and increased power demand. The voltage profile is improved significantly in all the buses after installing three DG units. Type-1 DG improves voltage level significantly by supplying active power locally, while Type-2 DG improves voltage level moderately by providing reactive compensation. Type-3 DG provides the best overall voltage support and keeps most of bus voltage near unity value. The minimum voltage is improved to 0.9852 p.u. It shows that multiple DG units optimally placed reduce the voltage drop and strengthen the network.

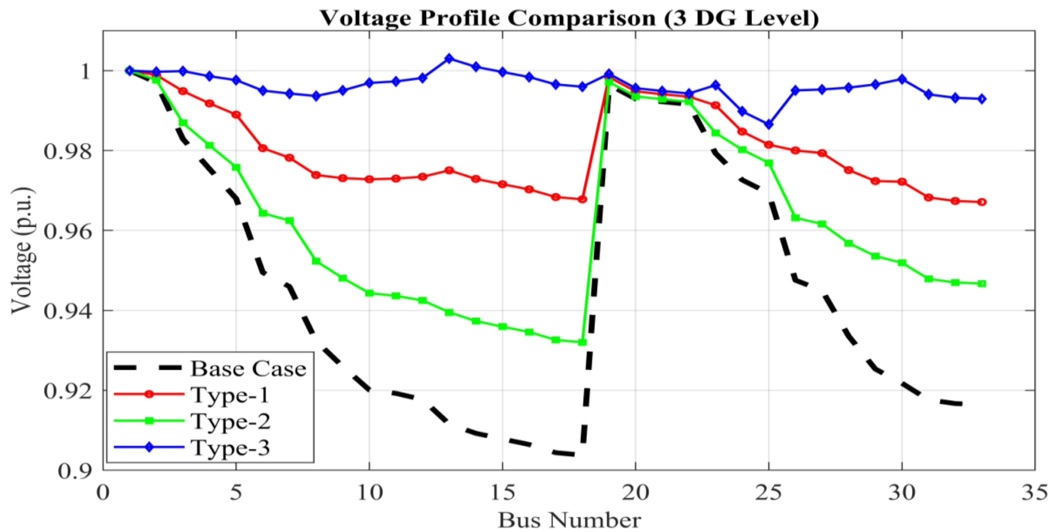

Fig.8.Voltage Profile Comparison (3DG Level)

The Fig.8 shows the graph of VSI for one DG level. It shows the system's capacity to maintain a stable voltage under load conditions. In the base case, VSI values decrease sharply at the weaker buses, which signifies poor stability margin and higher risk of voltage collapse. VSI improves after placement of one DG for all DG types. Type-1 gives good enhancement, Type-2 gives moderate improvement and Type-3 gives highest VSI values at almost all buses. The graph clearly shows that one DG installation significantly improves voltage stability.

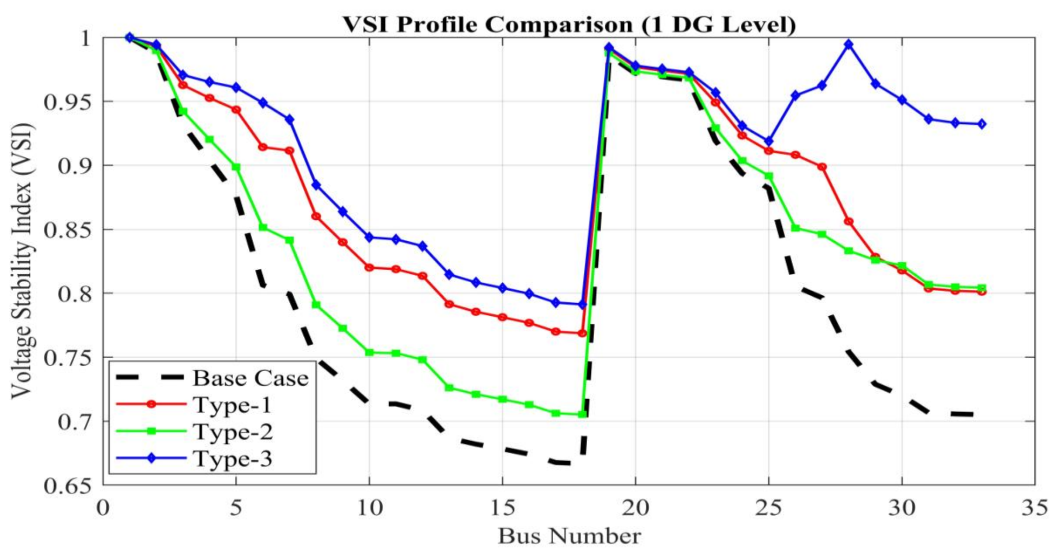

Fig.9: VSI Profile Comparison for One DG

The VSI profile for two DG level case is shown in Fig.9. The VSI values increase further and remain higher in all buses as compared to one DG scenario. The base case still has the weakest stability margin and the Type-1 and Type-2 improve the index moderately. Type-3 is again the best performing type with VSI values close to unity for a large number of buses. The use of two DG units spreads the power support more evenly, which reduces line loading and enhances the voltage security. It shows that multi-DG placement improves the system stability significantly and makes the network more reliable.

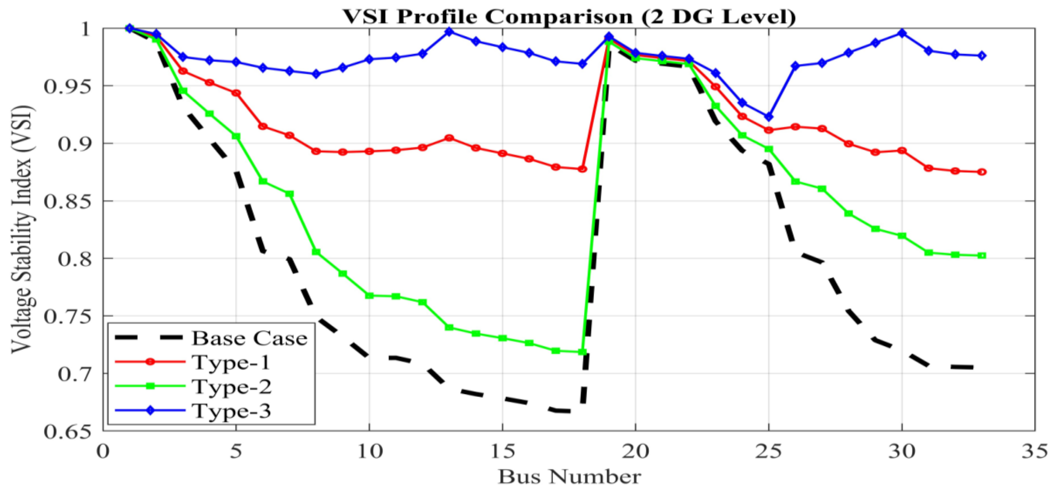

Fig.10: VSI Profile Comparison for Two DG

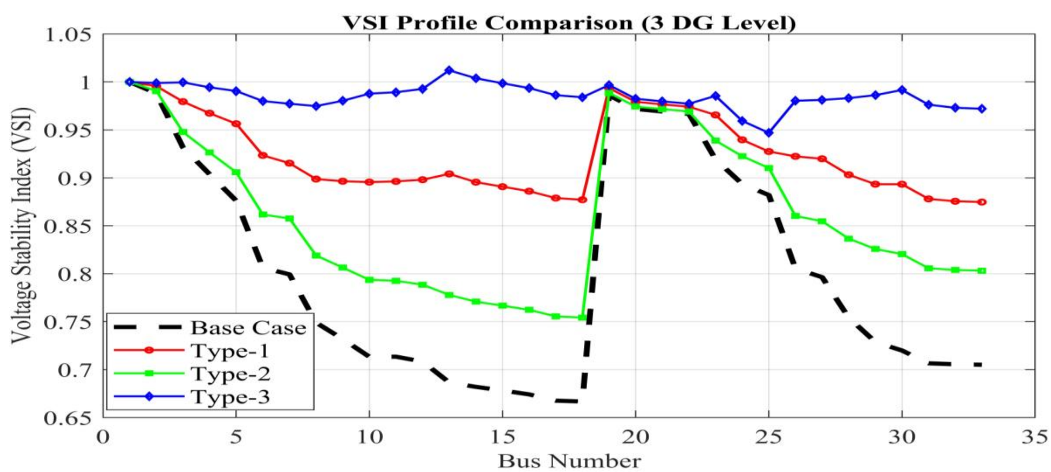

Fig.11: VSI Profile Comparison for Three DG

Fig.11 shows the profile of VSI for three-DG operating condition. In the base case, VSI values decrease considerably at weak buses, which mean a smaller voltage stability margin and a higher risk of voltage collapse. The VSI values are highly increased for all types of DGs after the installation of three DG units. Type-1 DG improves the stability margin while the type-2 gives moderate enhancement. Type- 3 DG has the highest VSI values for most of the buses and has a minimum VSI of 0.941784 which shows the strongest and secure operating condition. These results clearly indicate that the optimal multi-DG placement using the GEO algorithm greatly improves the voltage stability and the overall system reliability.

From the analysis of all the nine result graphs, it can be seen that the integration of Distributed Generation units improves the performance of the IEEE 33-bus radial distribution system. In the base case, the system has poor voltage regulation and voltage stability margins, and higher active and reactive power losses, especially at buses far from the substation. After optimal placement of DG units using Golden Eagle Optimization algorithm, it reduces the feeder current and supplies the power closer to the load centers. Thus the system losses are reduced significantly, bus voltages are improved and the VSI is also improved. The graphical results clearly show that the performance is enhanced continuously with the increase of the DG level from one DG to two DG and further to three DG units.

Type-3 DG always provides the best results among all the tested configurations because it injects both active and reactive power simultaneously. The combined support helps to reduce line losses, improve voltage magnitude along the feeder and strengthen network stability. The three DG Type- 3 case achieves the highest overall performance with 87.82% active power loss reduction, reactive loss reduced to 0.0199 MVAr, minimum bus voltage improved to 0.9852 p.u., and the highest VSI. Therefore, the overall graph analysis confirms that optimal multi-DG placement using the GEO algorithm is a highly effective and reliable solution for modern radial distribution system planning.

B. IEEE 69 BUS:

A standard IEEE 69 distribution system [24] is used in this section. The comparison of active power loss in the IEEE 69 bus radial distribution system under base case, single DG, two DG and three DG operating conditions for three different DG types is shown in the table 2. Without DG the active power loss is highest at approximately 0.2228 MW because the entire load demand is supplied only from the main substation, causing higher feeder current and greater transmission losses. After installing one DG unit, the active power loss decreases for all DG types. Type-1 DG placed at bus 61 reduces the loss to about 0.0821 MW by supplying real power locally,

Table 2: DGs at 0.9 power factor for IEEE 69 Bus system

0.9 PF	**Optimal DG Bus Number**	**Injected Active power (MW)**	**Injected Reactive Power (MVAr)**	**Active Power loss**	**Reactive Power loss**	**% Loss Reduction**	**Min Voltage, Bus Number**	**Max Voltage, Bus Number**	**VSI**
Base Case				**0.2228**	**0.101**		**0.9095, 65**		**0.666763**
				Type 1					
1 DG	61	1.8652	0	0.0821	0.04	63.16	0.9693, 27	1.0000, 1	0.882871, 27
2 DG	61 69	1.7685 0.6268	0	0.0737	0.0364	66.91	0.9793, 65	1.0000, 1	0.919862, 65
3 DG	53 47 61	0.5379 1.8312 1.7935	0	0.0782	0.0380	64.91	0.9721, 27	1.0000, 1	0.893085
				Type 2					
1 DG	61	0	1.3268	0.1504	0.0696	32.51	0.9310, 65	1.0000,1	0.751333, 65
2 DG	61 28	0, 0	1.2912, 1.9027	0.1505	0.0699	32.45	0.9305, 65	1.0001, 28	0.749721, 65
3 DG	67 51 61		0.5121, 0.3928, 1.1645	0.146	0.0677	34.47	0.9315, 65	1.0000, 1	0.752943, 65
				Type 3					
1 DG	61	1.9867	0.9622	0.0272	0.0161	87.78	0.9734, 27	1.0005, 61	0.897768, 27
2 DG	69, 61	0.6518, 1.8451	0.3157, 0.8936	0.0160	0.0114	92.81	0.9855, 27	1.0000, 1	0.943241, 27

3 DG	66, 61, 16	0.6568, 1.7979, 0.4508	0.3181, 0.8707, 0.2183	0.0105	0.0093	95.28	0.9943, 50	1.0036, 16	0.977241, 50

while Type-2 DG placed at bus 61 reduces it to around 0.1504 MW through reactive power support. Type-3 DG placed at bus 61 provides the best performance in the single DG case, reducing the loss to nearly 0.0272 MW because it supplies both real and reactive power simultaneously. When two DG units are optimally placed, the loss reduces even further. Type-1 DG placed at buses 61 and 69 achieves approximately 0.0737 MW, Type-2 DG placed at buses 61 and 28 gives around 0.150 MW, and Type-3 DG placed at buses 69 and 61 reaches the minimum value of nearly 0.016 MW. When three DG units are optimally placed, the loss reduces even further. Type-1 DG placed at buses 53, 47 and 61 achieves approximately 0.0782 MW, Type-2 DG placed at buses 67, 51 and 61 gives around 0.146 MW, and Type-3 DG placed at buses 66, 61 and 16 reaches the minimum value of nearly 0.0105 MW. This significant reduction occurs because multiple DG units share the load demand, reduce feeder current, shorten power flow distance and improve voltage support. Overall, the Fig.12 clearly shows that increasing the number of DG units improves system efficiency and the three DG Type-3 configuration gives the best result for active power loss reduction.

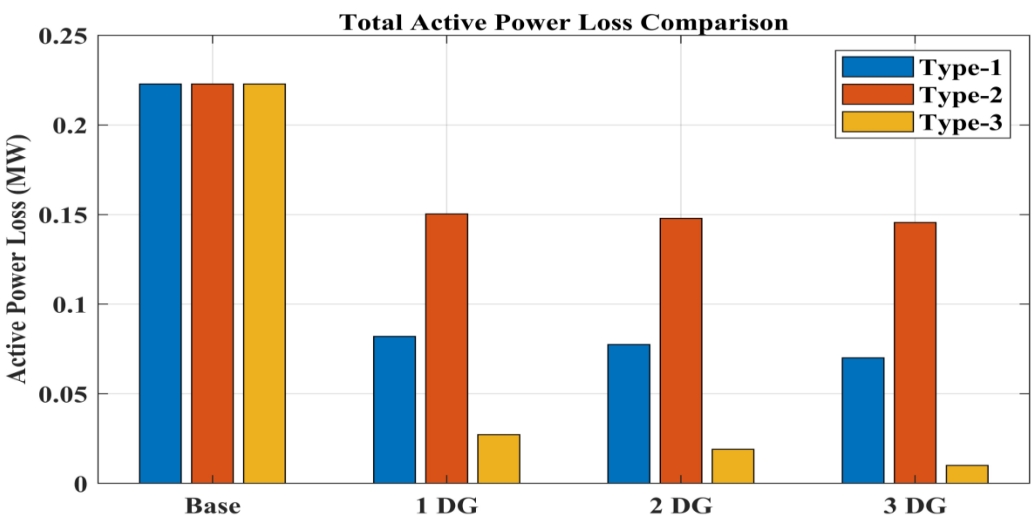

Fig.12. Active Power Loss Comparison

The Fig.13 illustrates the comparison of reactive power loss for the base case, one DG, two DG and three DG levels under three different DG types. In the base case, the reactive power loss is highest at around 0.101 MVAr because the complete reactive power demand is supplied from the main substation, resulting in higher line current and larger losses. After installing one DG, the reactive losses reduce for all DG types. Type-1 DG lowers the loss to nearly 0.04 MVAr, while Type-2 reduces it to about 0.0696 MVAr. Type-3 gives the best result in the single DG case with a loss of approximately 0.0161MVAr because it supplies both real and reactive power simultaneously. When two DG units are placed optimally, the reactive loss decreases further. Type-1 reaches around 0.0364 MVAr, Type-2 gives nearly 0.0699 MVAr and Type-3 achieves the minimum value of about 0.0114MVAr. When three DG units are placed optimally, the reactive loss decreases further. Type-1 reaches around 0.0782 MVAr, Type-2 gives nearly 0.0677 MVAr, and Type-3 achieves the minimum value of about 0.0093MVAr. This confirms that multi-DG placement, especially Type-3 DG, provides superior reactive compensation and minimizes system losses effectively.

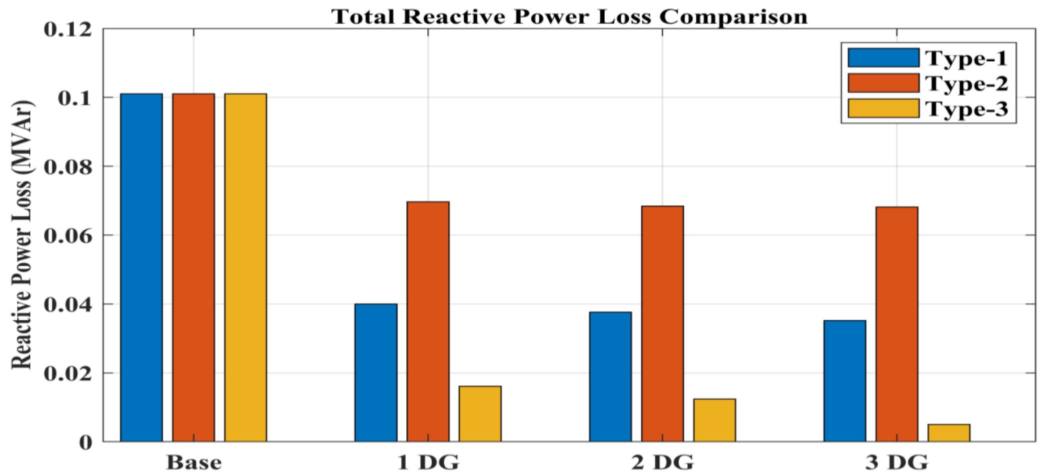

Fig.13.Reactive Power Loss Comparison

The fig.14 shows the percentage reduction in active power loss after the installation of DG units in comparison with the base case. The base case has zero reduction as there is no installed DG. Type-1 reduces loss by about 63.16 at the one DG level. Type-2 and Type-3 provide approximately 32.51 and about 87.78 respectively which is the best among single DG cases. When two DG units are installed the percentage reduction is even more. Type-1 is approximately 66.91, Type-2 is approximately 32.45 and Type-3 is the highest total reduction of approximately 92.81. With the installation of three DG units the percentage reduction further increases. Type-1 achieves around 64.91, Type-2 achieves around 34.47 and Type-3 achieves the highest overall reduction of around 95.28%. This clearly indicates that the system efficiency increases with increase in the number of DG units and Type-3 DG provides most effective loss minimization due to combined active and reactive power support.

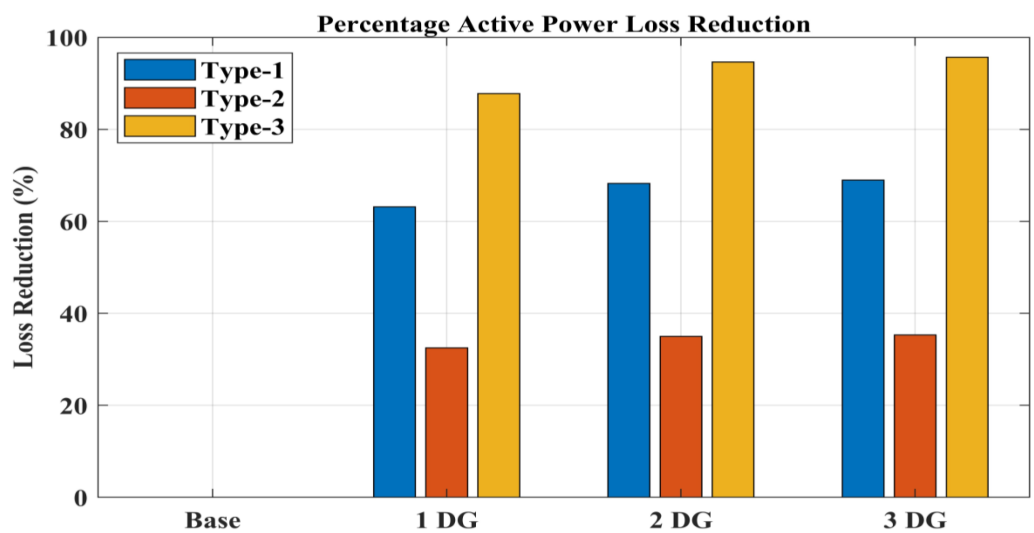

Fig.14: Percentage Loss Reduction

Fig.15 shows the bus voltage profile of the IEEE 69-bus system in base case and one DG placement for all the three types of DG. In the base case, the voltage gradually decreases with increase in bus number and reaches minimum value at the remote buses due to feeder impedance and heavy load demand. After the installation of one DG, the voltage profile is improved significantly on the network. Type-1 DG delivers real power locally to increase bus voltages whereas Type-2 offers moderate improvement through reactive compensation. Type-3 is the best because of the active and reactive powers supply that support voltage, thus higher voltage magnitude in almost all buses is maintained. This shows that a single DG when placed properly can greatly improve the voltage regulation especially for the case of Type-3 DG.

The Fig.16 shows the voltage profile with two DG units placed at optimal locations in the network. The voltage profile is more stable and flat at all buses compared with the one DG case. The base case still exhibits the lowest voltages, in particular at remote buses. Type-1 gives a significant voltage boost, and Type-2 offers moderate support. Type-3 has the highest voltage levels in the system and maintains many buses near unity voltage. The feeder burden is reduced and voltage drop is minimized due to more efficient distribution of local power support by the installation of two DG units at different buses. This confirms that multi-DG installation is more effective than single DG installation in voltage enhancement

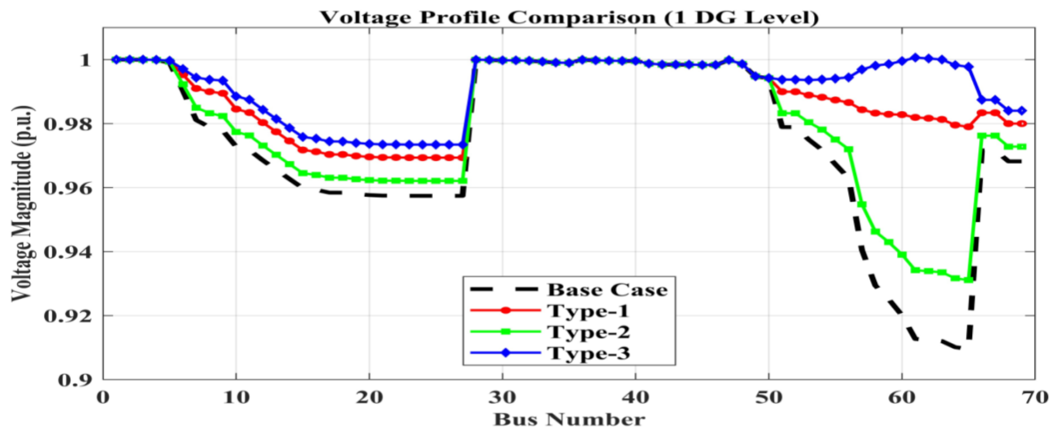

Fig.15: Voltage Profile Comparison for One DG.

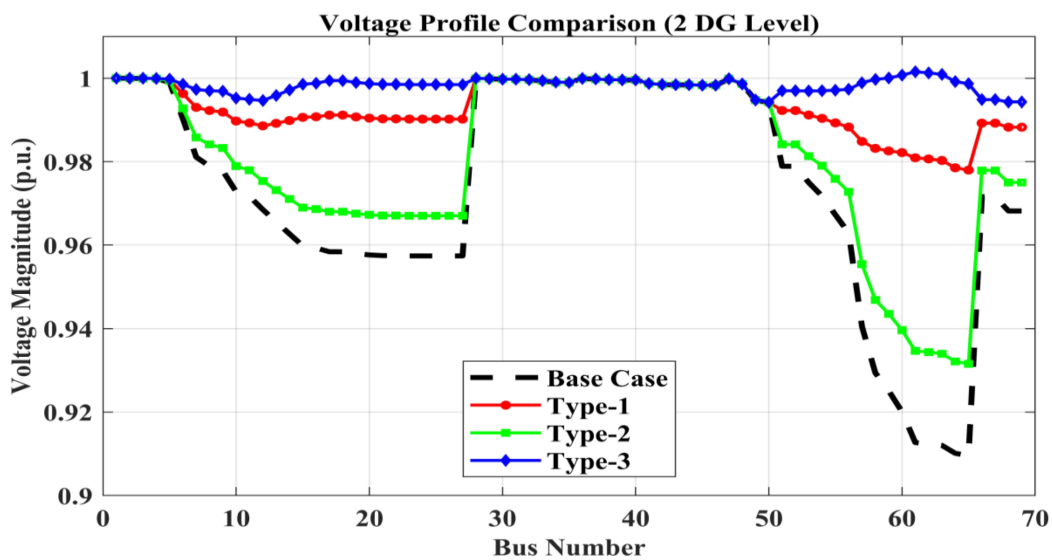

Fig.16: Voltage Profile Comparison for Two DG

The bus voltage profile of the system in three DG operating condition for all DG models is shown in Fig.17. The base case has the lowest voltage magnitude especially at buses far from the substation because of the feeder impedance and increased power demand. The voltage profile at all the buses improves significantly after installing the three DG units. Type-1 DG gives significant voltage improvement through injection of active power at local level while Type-2 DG provides reasonable improvement with reactive compensation. The DG of type-3 provides the best overall voltage support and keeps most of the bus voltages close to the unity value. The minimum voltage is improved to 0.9852 p.u. which confirms that optimally placed multiple DG units can effectively reduce voltage drop and strengthen the network.

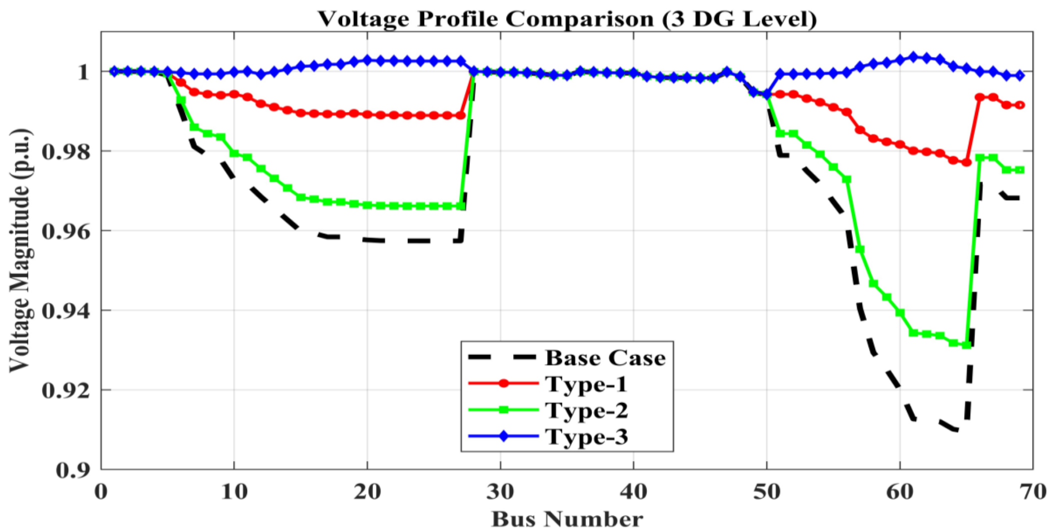

Fig.17: Voltage Profile Comparison for Three DG

The graph of VSI is shown for one DG level in fig.18. In the base case, the VSI values drop drastically at weaker buses implying poor stability margin and higher propensity to voltage collapse. After placing one DG for all DG types, VSI improves. Type-1 offers good enhancement, Type-2 moderate improvement and Type-3 yields the highest VSI values for almost all buses. This is because Type-3 provides both real and reactive support, reducing the load on the feeder and thus increasing the robustness of the system. The graph evidently shows that the installation of one DG enhances the voltage stability considerably.

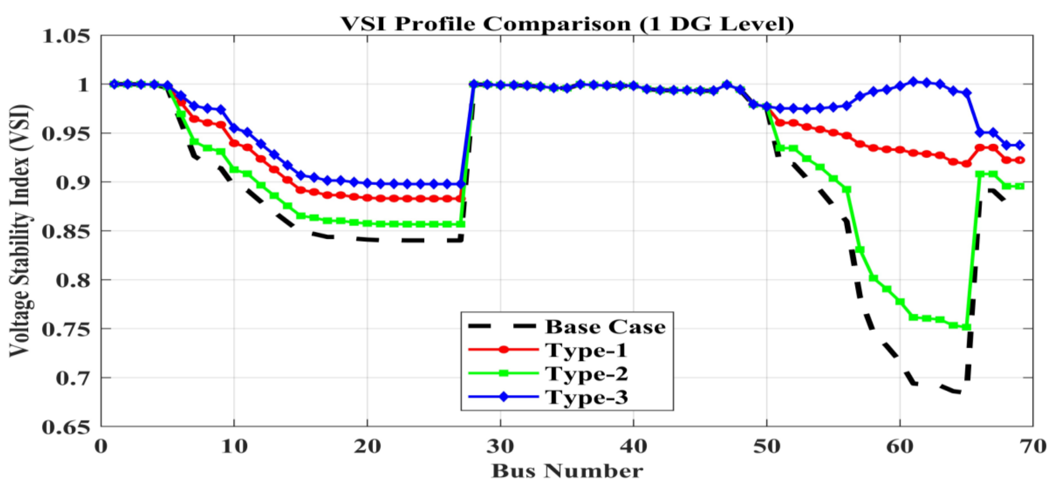

Fig.18: VSI Profile Comparison for One DG

Fig.19 depicts the VSI profile for two DG level case. VSI values are further increased and are higher compared to the one DG scenario for all buses. The base case still shows the lowest stability margin, whereas the Type-1 and Type-2 improve the index moderately. Again, Type-3 shows the best performance with the VSI values close to 1 for many buses. Power support is more evenly distributed with the use of two DG units, the line loading is reduced and voltage security is improved. This indicates that multi-DG placement can enhance the system stability substantially and make the network reliable.

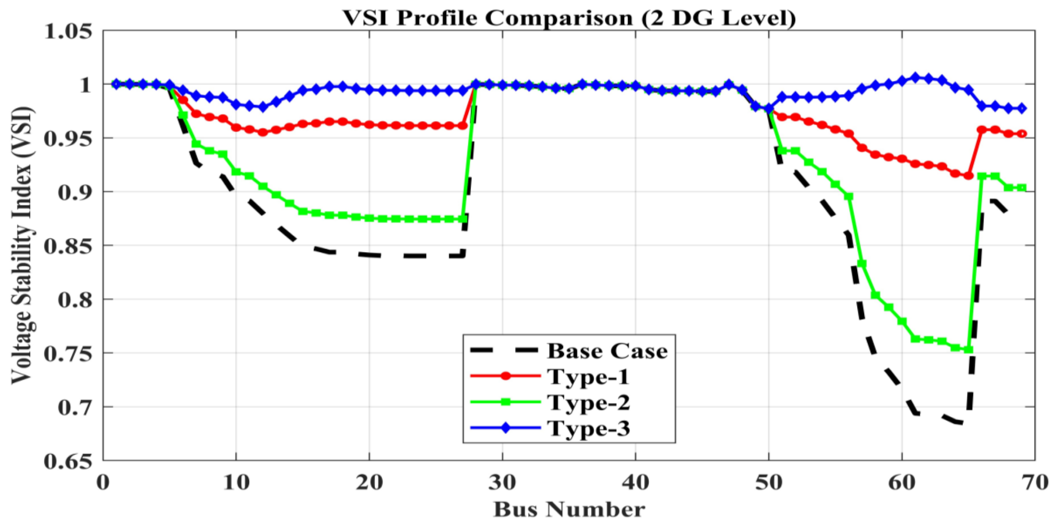

Fig.19. VSI Profile Comparison for Two DG

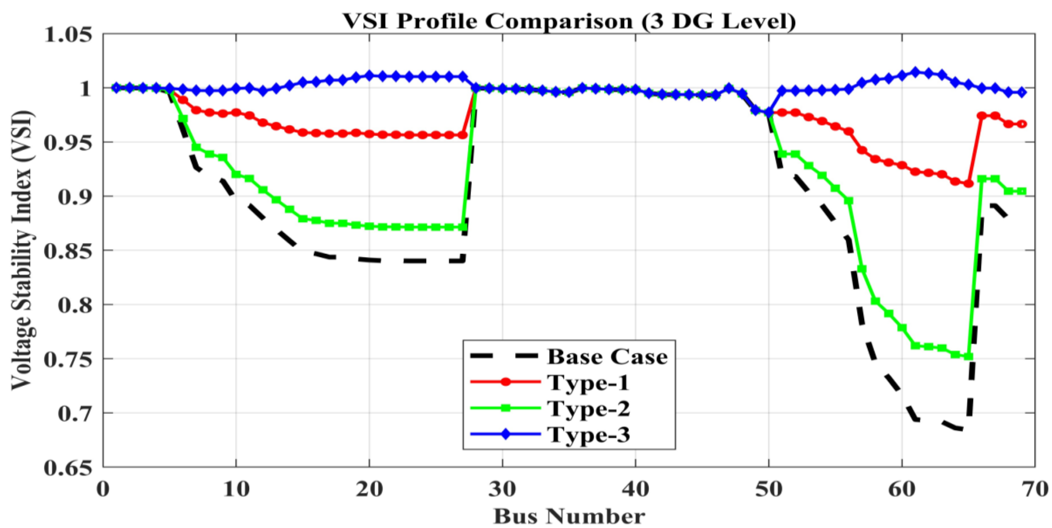

Fig.20: VSI Profile Comparison (3DG Level)

The VSI profile for the three-DG operating condition is shown in Fig.20. In base case, VSI values are considerably reduced in weak buses, indicating reduced voltage stability margin and increased risk of voltage collapse. VSI values are considerably increased for all types of DG after installation of three DG units. Type-1 DG increases the stability margin and Type-2 provides a moderate increase. Type- 3 DG has the highest VSI values for most of the buses and has a minimum VSI of 0.977241 which shows the strongest and most secure operating condition. The results show that the optimal placement of multiple DGs using the GEO algorithm significantly improves the voltage stability and the overall reliability of the system.

From the analysis of all nine result graphs, it is clearly observed that the inclusion of Distributed Generation units enhances the technical performance of the IEEE 69-bus radial distribution system. In the base case, the system experiences higher active and reactive power losses, poor voltage regulation, and lower voltage stability margins, particularly at buses located far from the substation. Once DG units are optimally placed using the Golden Eagle Optimization algorithm, feeder current is reduced and power is supplied closer to the load centers. As a result, system losses decrease significantly, bus voltages improve, and the Voltage Stability Index increases. The graphical results clearly show that the performance continuously improves as the DG level increases from one DG to two DG and then to three DG units.

C. Comparison with Existing Methods:

In Table 3 the suggested algorithm is also compared with other techniques like SIMBO-Q, QOSIMBO-Q, ACOA and AHA. The comparison shows that the proposed method achieves superior loss reduction and improved system performance.

Table 3: Comparison table

Case	Method	Bus Number	Active Power (MW)	Reactive Power (MVAr)	Active Power Loss	Reactive Power Loss	% Loss Reduction
1 DG	Proposed Method	61	1.9867	0.9622	0.0272	0.0161	87.78
2 DG	Proposed Method	69, 61	0.6518, 1.8451	0.3157, 0.8936	0.0160	0.0114	92.81
	Main 6	14, 63	0.9937, 1.9984		0.0187		
3 DG	Proposed Method	66, 61, 16	0.6568, 1.7979, 0.4508	0.3181, 0.8707, 0.2183	0.0105	0.0093	95.28
	ACOA [19]	64, 61, 65	0.5013, 0.9556, 0.5000	0.5, 0.5, 0.5	0.04489		80.25
	AHA [20]	18, 63, 58	0.6726, 1.4962, 0.8242		0.0118		94.75
	SIMBO-Q [21]	18, 64, 61	0.5863 0.5378 1.4321	0.1927 0.1768 0.4707	0.0231		89.73
	QSIMBO-Q [21]	17 64 61	0.5838 0.4148 1.5	0.1919 0.1363 0.4930	0.0229		89.82
	WHO	61 18 11	1.719 0.380 0.527				69.15

5. Conclusion

Golden Eagle Optimization successfully identified optimal DG locations and sizes in the IEEE 33 bus and 69 bus radial distribution systems. Among all tested configurations, the 3 DG Type-3 case achieved the best performance with 88.28% in IEEE 33 bus system and 95.28% in IEEE 69 bus system in the percentage loss reduction. The results clearly prove that multi DG placement is more effective than single DG placement, as it distributes power support more uniformly across the feeder and reduces branch current more efficiently. The study also shows the effectiveness of the Golden Eagle Optimization algorithm to solve complex non-linear optimization problems in the power system planning. GEO provided accurate results with good exploration and exploitation ability, making it suitable for practical engineering applications.

Finally, the proposed GEO-based DG placement technique is a reliable and efficient solution for improvement of the performance of the modern radial distribution systems. It can help utilities to reduce technical losses, improve the quality of the voltage, increase the reliability of the system and support the development of the future smart grid. The proposed model can be extended for future works to include renewable based DG sources such as solar PV and wind systems, uncertainty analysis, economic cost optimization, real time operation and network reconfiguration studies for more advanced distribution planning.

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