

Optimal placement and sizing of DG and DSTATCOM in order to mitigate power losses in electrical distribution system

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ABSTRACT

The emphasis is now shifting away from conventional methods of power generation and towards unconventional distributed energy resources (DERs) located at distribution voltage level due to the rapid depletion of fossil fuel supplies and significant environmental pollution. Emphasis on research into the applications of DERs found scope in microgrids and active distribution networks. The placement of DERs close to load centers aids with providing clean, reliable power to additional customers, reduce electricity losses along transmission and distribution lines and in event of faults it allows to operate in islanded mode. This manuscript focuses on power smoothing, which implies reduction of power loss, improved voltage levels, and voltage stability. This study aims to optimize the capacities and placements of distributed generations (DGs) and distribution static compensators (DSTATCOMs) in order to reduce real power loss and improve the voltage profile. The problem of voltage from undistributed energy resources can best be solved by DSTATCOM. The goal function of the direct load flow technique, which also makes use of voltage deviation and the loss sensitivity factor, is used in this study to pinpoint the ideal placement for the DG and DSTATCOM on the MATLAB platform. The method is tested using the 33 and 69 bus routes. When the results are compared to recent methodologies, they show encouraging results.

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1. INTRODUCTION

Climate change, energy security, and the rapid depletion of fossil fuel sources [1] have put the global energy sector in a crisis. This change from centralized power generation to distributed energy resources (DERs) that are strategically placed at distribution voltage levels has been very important [2]. As governments all over the world set strict goals for carbon neutrality and renewable energy, the number of solar systems and wind generators has grown at an unprecedented rate [3]. The way electricity is distributed today is changing a lot. Power can now flow in both directions, which makes managing voltage harder, and the system needs to be more flexible [4]. Electric cars, heat pumps, and other technologies that use electricity have changed the way people use power, making it hard to plan for distribution. New ideas are needed to keep the system reliable and efficient [5].

This changing environment makes it possible for distributed generation (DG) and distribution static compensators (D-STATCOM) to make systems work better and support energy systems that are good for the environment. Wind turbines, small-scale combined heat and power plants, and solar photovoltaic systems are all examples of dispersed generation units. These units [6] are needed to modernize distribution networks.

These systems make electricity close to where it is used, which cuts down on transmission losses and makes the system work better [7]. Putting DG units in the right places helps the environment and makes the grid stronger by letting it run on its own when there are problems with the grid and lowering the need for centralized generation [8].

DG units provide active power, while distribution static compensators (D-STATCOM) help with reactive power and voltage management to keep the power quality of the distribution system high [9]. D-STATCOM devices use voltage source converter technology to manage voltage in real time, fix the power factor, and reduce harmonics [10]. DG and D-STATCOM work together to solve problems with managing active and reactive power in modern distribution networks [11]. Putting DG and D-STATCOM systems together can make many parts of the distribution system work better [12]. Numerous studies have demonstrated that the simultaneous implementation of these technologies diminishes system losses and enhances voltage profiles, power quality, and the hosting capacity for renewable energy sources [13]. Smart grid technologies and better control systems make it easier to coordinate the installation of DG and D-STATCOM [14].

The effectiveness of DG and D-STATCOM integration depends on how well the strategic distribution network is laid out and sized [15]. If these devices are not put in the right place or sized correctly, they could cause more losses, voltage instability, or problems with protection coordination [16]. Finding the best size and location for DG and D-STATCOM units is a multi-dimensional optimization problem that must take into account technological, economic, and operational limits [17]. When placing things, the electrical properties of the distribution network, the patterns of load, the profiles of generation, and the conditions under which the system runs are all taken into account [18]. Loss sensitivity factors and voltage stability indices are necessary for pinpointing areas where the system can be improved [19]. Sizing optimization must find a balance between the costs of investment, the benefits of operation, and the limits of technology, all while staying within voltage limits, temperature ratings, and safety standards [20].

Recent studies have shown that it is better to optimize the positioning and sizing of DG and D-STATCOM at the same time than to do them separately [21]. This integrated approach sees the connections between managing active and reactive power, which helps find solutions that make the system work better [22]. Because of changes in renewable energy production and load demand, better placement and sizing strategies are needed [23]. The best way to connect DG and D-STATCOM in distribution systems cuts down on power loss [24]. Usually, distribution networks lose between 8 and 15% of their energy. This costs the economy and environment a lot, but planned DER use can cut it down [25]. Integrating distributed generation (DG) into the grid lowers power loss by meeting local load demand and lowering the flow of current in distribution lines [26]. There are many ways that coordinating DG and D-STATCOM cuts down on losses [27]. DG units cut down on active power losses by lowering the net power flow at substations. D-STATCOM devices, on the other hand, help reduce losses by supporting reactive power locally. This lowers reactive current on distribution lines [28]. By optimizing both active and reactive power flows at the same time, it is possible to find operational points with the least loss that neither technology could find [29].

Changing the patterns of load and generation is one of the new ways to reduce losses. This lets dynamic optimization methods change to fit the system [30]. To deal with the multi-dimensional, non-linear, and often non-convex nature of concurrent DG and D-STATCOM optimization, we need advanced computational methods [10]. Metaheuristic optimization algorithms that look through huge solution spaces for practical near-optimal solutions have replaced most analytical methods [11]. Genetic algorithms, particle swarm optimization, whale optimization, artificial bee colony, and newer ideas like artificial rabbit and black widow optimization are well-known [12]. Mixed-integer linear programming (MILP) and mixed-integer nonlinear programming (MINLP) formulations are more widely used because they can handle discrete decision factors that have to do with choosing and placing devices while still being mathematically correct [13]. These methods allow for complicated operational limits and goal functions while still ensuring the best possible solution or quality [14]. These methods are more useful in the real world because they measure uncertainty [15]. Multi-objective optimization frameworks have become popular because they can take into account conflicting goals like lowering costs, lowering losses, raising voltage, and protecting the environment all at once [16]. There are many trade-offs in Pareto-optimal solution sets, depending on the needs and limits of the system [17]. Hybrid optimization methods that use the best algorithms for big distribution system optimization problems are promising [18].

This study aims to optimize the capacities and placements of DGs and DSTATCOMs in order to reduce real power loss and improve the voltage profile. The problem of voltage from undistributed energy resources can best be solved by DSTATCOM. The goal function of the direct load flow technique, which also makes use of voltage deviation and the loss sensitivity factor, is used in this study to pinpoint the ideal placement for the DG and DSTATCOM.

2. DISTRIBUTION STATIC COMPENSATOR

In high voltage transmission networks, shunt FACTS devices, such as static synchronous compensator (STATCOM), are commonly utilized. When deployed in low-voltage distribution networks, it is referred to as DSTATCOM. This shunt device, DSTATCOM, is capable of injecting and absorbing real or reactive power at the bus, effectively reducing bus voltage sag. Connecting to the distribution network requires a coupling transformer, while a DC energy storage device, specifically a DC link capacitor, is employed to maintain a constant DC-link voltage. Acting as a synchronous voltage source, DSTATCOM is responsible for regulating and correcting the bus voltage and power factor. When faced with high load levels or short circuits, DSTATCOM supplies or injects the necessary current at the connection point to elevate the voltage profile at the connected load bus and ensure regulation to the desired reference value. The simultaneous exchange of reactive and real power is enabled by DSTATCOM. The type and quantity of energy source utilized determine the actual power exchanged. Voltage fluctuations are mitigated by DSTATCOM through a comparison of the line waveform with a reference signal and subsequent adjustments as necessary. Reactive current is injected or absorbed by DSTATCOM to rectify any voltage errors. The main components of DSTATCOM comprise a coupling transformer, PWM, control scheme, DC-link capacitor, inverter modules, and an AC filter. The direction and magnitude of the reactive current depend on the voltage sources employed in DSTATCOM. When the voltage at the connection point exceeds that of the voltage source, DSTATCOM acts as a reactor and absorbs excessive reactive power. Conversely, when the voltage is lower than that of the voltage source, DSTATCOM operates as a variable capacitor and injects the required reactive power.

3. MATHEMATICAL MODELING OF DSTATCOM

Figure 1 shows the installation of DSTATCOM in an IEEE bus system. The line resistance and reactance between interchange nodes are represented by r_p and x_p respectively. The voltage and local loads connected to n and o nodes are denoted by V_n , V_o , $p_n + jq_n$ and $p_o + jq_o$ respectively. The phase angle of V_o is α . The voltage V_o is considered to have magnitude less than 1.0 p.u. such that DSTATCOM can be utilized to improve its voltage profile. DSTATCOM injects reactive power to the system; consequently current injected by the DSTATCOM (I_{dstat}) is in quadrature with voltage of the system. After the application of DSTATCOM, the voltage changes to V_{onew} . In order to make the calculations simpler, the angle of voltage V_n is assumed to be zero.

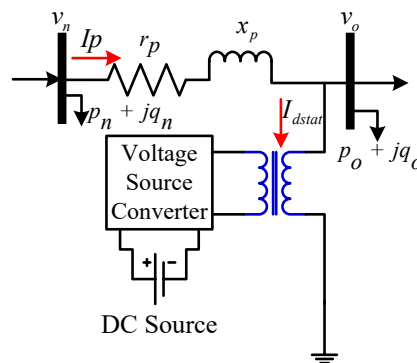


Figure 1. DSTATCOM model

Figure 1 illustrates the schematic representation of a distribution static synchronous compensator (DSTATCOM), which is primarily used for reactive power compensation and voltage regulation at the distribution level. The core component of the DSTATCOM is a voltage source converter (VSC), which is connected to the distribution network through a coupling transformer. The VSC converts DC voltage from a DC source into a controllable AC voltage, allowing it to inject or absorb reactive power depending on the system requirements. The coupling inductor (or interfacing inductor) helps in filtering out high-frequency switching harmonics and regulates the power exchange between the VSC and the grid. The DSTATCOM operates by adjusting the magnitude and phase of the output voltage of the VSC relative to the grid voltage. When the VSC output voltage is higher than the grid voltage, it supplies reactive power (capacitive mode), and when it is lower, it absorbs reactive power (inductive mode). This dynamic control capability enables the DSTATCOM to provide fast voltage support, mitigate voltage sags and swells, and improve power quality in

distribution systems. Its compact design, high reliability, and rapid response make it an effective solution for enhancing the stability and performance of active distribution networks, especially those integrated with distributed energy resources (DERs).

$$v_{new} \angle \alpha_{new} = v_n \angle \delta - (r_p + jx_p) I_p \angle \theta - (r_p + jx_p) I_{dstat} \angle \alpha_{new} + \frac{\pi}{2} \quad (1)$$

The (2) and (3) are obtained by equating real and imaginary parts of (1).

$$v_{new} \cos \alpha_{new} = \operatorname{Re}(v_n \angle \delta) - \operatorname{Re}(r_p I_p \angle \theta) + x_p I_{dstat} \sin \left(\alpha_{new} + \frac{\pi}{2} \right) - r_p I_{dstat} \cos \left(\alpha_{new} + \frac{\pi}{2} \right) \quad (2)$$

$$v_{new} \sin \alpha_{new} = \operatorname{Im}(v_n \angle \delta) - \operatorname{Im}(r_p I_p \angle \theta) - x_p I_{dstat} \cos \left(\alpha_{new} + \frac{\pi}{2} \right) - r_p I_{dstat} \sin \left(\alpha_{new} + \frac{\pi}{2} \right) \quad (3)$$

Simplifying in (2) and (3), $a = \operatorname{Re}(v_n \angle \delta) - \operatorname{Re}(r_p I_p \angle \theta)$, $vb = \operatorname{Im}(v_n \angle \delta) - \operatorname{Im}(r_p I_p \angle \theta)$. $C_1 = -r_p$, $C_2 = -x_p$, $d = v_{new}$, $x_1 = I_{dstat}$, and $x_2 = \alpha_{new}$. The (2) and (3) can be rewritten as in (4) and (5).

$$d \cos x_2 = a - C_1 x_1 \sin x_1 - C_2 x_1 \cos x_2 \quad (4)$$

$$d \sin x_2 = b - C_2 x_1 \sin x_2 + C_1 x_1 \sin C_2 x_2 \quad (5)$$

The values for x_1 and x_2 as obtained from (4) and (5) are expressed in (6).

$$x_1 = \frac{d \cos x_2 - a}{-C_1 \sin x_2 - C_2 \cos x_2}; \quad x_1 = \frac{d \sin x_2 - b}{-C_2 \sin x_2 + C_1 \cos x_2} \quad (6)$$

The (7) is obtained by equating $k_1 = a_1 C_2 - a_2 C_1$, $x = \sin x_2$, $k_2 = a_1 C_1 + a_2 C_2$ and substituting in (6).

$$(k_1^2 + k_2^2)x_2 + (2k_1 d C_1) + (d^2 C_1^2 - k_2^2) = 0 \quad (7)$$

The solution of (7) can be expressed by (8) and (9).

$$x = \frac{2k_1 d C_1 \pm \sqrt{(2k_1 d C_1)^2 - 4(k_1^2 + k_2^2)(d C_1^2 - k_2^2)}}{2(k_1^2 + k_2^2)} \quad (8)$$

$$\alpha_{new} = x_2 = \sin^{-1} x \quad (9)$$

Now the injected reactive power (Q_{dstat}), current and voltage where DSTATCOM is installed is given by (10)-(12).

$$v_{new} = v_{new} \angle \alpha_{new} \quad (10)$$

$$I_{dstat} = I_{dstat} \angle \alpha_{new} + \frac{\pi}{2} \quad (11)$$

$$jQ_{dstat} = v_{new} I_{dstat}^* \quad (12)$$

The formulation of DSTATCOM aims to set the voltage magnitude node at the DSTATCOM's location to a value of 1 per unit (p.u.). The phase angle of the DSTATCOM's node is determined using in (9), while in (11) is employed to calculate the I_{dstat} . Lastly, the amount of reactive power injected by the DSTATCOM is evaluated by implementing in (12). The three primary components of the power system are generation, transmission, and distribution. Power for end users is provided by the distribution system. Distribution system types include radial, ring, and doubly fed configurations for the distribution lines. Because of its durability and affordability, radial distribution systems are one of the most popular configurations. Voltage sag and stability issue cause high losses in the radial distribution network. These distribution losses in India range from 13% to 14% of the nation's total power output. To minimize losses in the distribution network, a strategic approach involves the placement of distributed generation (DG) and

distribution STATCOM (DSTATCOM) at weak buses. Conventional load flow models like Newton-Raphson, Gauss-Seidel, and fast-decoupled methods are considered unsuitable for load flow studies in distribution systems due to their high R/X ratio. These methods do not accurately determine line flows and line voltages within the distribution system. To tackle this issue, advanced numerical algorithms and techniques are employed in this manuscript to analyze the load flow. Specifically, the methodology based on direct load flow (DLF) analysis is utilized in this paper for performing load flow calculations. The complex load (s_o) for o^{th} bus in an IEEE bus system is represented by (13).

$$s_o = p_o + jq_o \quad (13)$$

Where, p_o and q_o represents the real power and reactive power at o^{th} bus. The (14) represents the current injected at the o^{th} bus.

$$I_o = \left(\frac{s_o}{v_o} \right)^* \quad (14)$$

Where, v_o represents the voltage at the o^{th} bus. The relationship matrix is developed by using the 33 bus radial distribution network. The (14) is utilized to calculate the current injection matrix from the power injection values. Kirchhoff's current law is utilized to establish correlation between the branch current and bus current of 33 bus radial distribution network. The (15) represents the correlation between the branch current (B) and bus current injections ($BIBC$) for the 33 bus radial distribution network.

$$B = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} BIBC \quad (15)$$

The (16) represents the correlation between the B and bus voltages (Δv) for the 33 bus radial distribution network.

$$\Delta v = [BCBV]B \quad (16)$$

Where, $BCBV$ is the branch current bus voltage matrix. The relationship between $BCBV$ and $BIBC$ is expressed by (17).

$$BCBV = [BIBC]^T \times Z \quad (17)$$

Where, Z is the diagonal bus impedance matrix. The correlation between Δv and $BIBC$ is established by (18).

$$\Delta v = [BCBV][BIBC] \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (18)$$

The load flow solution in a radial distribution system can be attained by iteratively solving in (19), (20).

$$I_o^c = \left(\frac{s_o}{v_o^c} \right)^* \quad (19)$$

$$\Delta v^{c+1} = [DLF]i^c \quad (20)$$

Where, $[DLF] = [BCBV][BIBC]$, c is current iteration, $i = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$, $\Delta v^{c+1} = [\Delta v_o][\Delta v^{c+1}]$, and v_o is the reference voltage.

This section elaborates on the optimum location and sizing of DGs and STATCOM. One of the factors used to determine where to place DGs in a given distribution network is the loss sensitivity factor (LSF). The choice of LSF is because LSF shrinks the search space, the optimization process can be calculated more quickly. The real ($P_{loss(o)}$) and reactive power loss ($q_{loss(o)}$) for the line is expressed mathematically by (21) and (22).

$$P_{loss(o)} = \frac{((BIBC \times p_{RLPM})^2 + (BIBC \times q_{REPM})^2) \times r_p}{v_o^2} \quad (21)$$

$$q_{loss(o)} = \frac{((BIBC \times p_{RLPM})^2 + (BIBC \times q_{REPM})^2) \times x_p}{v_o^2} \quad (22)$$

Where, p_{RLPM} and q_{REPM} represents the total real and reactive power supplied ahead of node o . The LSF (P_{lsf} and q_{lsf}) is obtained by performing partial fraction of $P_{loss(o)}$ with respect to p_{RLPM} and q_{REPM} respectively. LSF is expressed mathematically by (23) and (24).

$$P_{lsf} = \frac{\partial P_{loss(o)}}{\partial p_{RLPM}} = \frac{(2 \times (BIBC \times p_{RLPM})) \times r_p}{v_o^2} \quad (23)$$

$$q_{lsf} = \frac{\partial P_{loss(o)}}{\partial q_{REPM}} = \frac{(2 \times (BIBC \times q_{REPM})) \times x_p}{v_o^2} \quad (24)$$

The best buses for DG placement are those with the highest LSF values. Here, the voltage deviation from the allowable limit and both the real and reactive power LSFs are used to determine where the DG should be placed. The (25) describes the objective function (F_1) for choosing the best DG location.

$$\max(F_1) = k_1 + P_{lsf} + k_2 \times q_{lsf} - k_3 \times [\sum_{o=1}^{nb} \{(v_o - v_{min})^2 + (v_o - v_{max})^2\}] \quad (25)$$

Where k_1 , k_2 , and k_3 are the weighing factors, nb total number of buses and the values of v_{min} and v_{max} is 0.95 and 1.05 p.u.

4. OPTIMAL PLACEMENT OF DSTATCOM

The reduction of overall network losses and the enhancement of the distribution network's overall voltage profile are goals behind the calculation of DSTATCOM's optimal location. After installing DSTATCOM, all of the buses' voltages should be within the permitted deviation range (0.95 to 1.05 p.u.). The placement of DSTATCOM must take into account and validate all operational and system constraints. The acceptable range of voltage deviation and overall system losses determine the best location for DSTATCOM. Consequently, the objective function (F_2) is being formulated as expressed mathematically by (26).

$$\min(F_2) = \frac{p'_{loss}}{p_{loss}} \times 0.01 \times [\sum_{o=1}^{nb} \{(v_o - v_{min})^2 + (v_o - v_{max})^2\}] \quad (26)$$

Where, p'_{loss} and p_{loss} indicate the loss after and before the installation of DSTATCOM.

The optimal size of DSTATCOM and DG is determined by considering the variables kVAR and kW, respectively. The calculation of the optimal size focuses on enhancing the overall voltage profile, minimizing network losses, and reducing energy costs. The (27) represents the expression used to determine the optimal size of DSTATCOM.

$$jQ_{dstat} = v_{new} I_{dstat}^* \quad (27)$$

The optimum size of DG (P_{DG}) is expressed by (28).

$$F_3 = C_E \times p_{PLR} \times 8760 - C_G \times P_{DG} \times \gamma \quad (28)$$

Where, F_3 , C_E , p_{PLR} , C_G , and γ represents the objective function for DG and DSTATCOM size, cost of the energy (INR/kW h), power loss reduction after the installation of DG, capital cost of the DG (per kW), and annual rate of depreciation and interest charges respectively. The size of the DG will be optimum and maximum when the function F_3 will have the maximum value. The (28) and (25) is used for location

finalization and sizing respectively. Voltage violation serves as the primary criterion for DSTATCOM placement and sizing. As a result, DSTATCOM will be positioned in accordance with (26) and its size will be determined using (27) if there is a voltage violation in the network.

5. RESULT ANALYSIS

The effectiveness of the proposed allocating DGs and DSTATCOMs technique is evaluated by conducting tests on two commonly used distribution systems: a 33-bus system and a 69-bus system. To validate the method's efficacy, three distinct scenarios are examined. In the first scenario, only one DGs and D-STATCOMs is installed. In the second and third scenarios, two and three DGs and D-STATCOMs are respectively considered. The best outcome from ten separate algorithm runs is reported for each scenario. The proposed algorithm is executed on an AMD Ryzen 9 7950X CPU operating at 5.70 GHz with 32 GB of RAM using the MATLAB environment.

5.1. 33 bus system

The IEEE 33 bus test system has a combined load of $3715 + j 2300$ kVA. The IEEE-33 bus system is subjected to load flow analysis with and without the presence of DSTATCOM. The results of which are presented in Tables 1 and 2. As shown in Table 1, the system exhibits poor performance with a single DG allocation in 9th node, characterized by a real power loss of 117.64 kW, reactive power loss 79.5749 kVAR, stability index of 0.778 p.u. with a low voltage magnitude of 0.9391 p.u. for constant power load model. There is an improvement in the power loss as well as voltage profile when two and three numbers of DGs are placed, in all types of load models.

Table 1. Effect of DG allocation on 33 bus system

DGs	Type of load	Location	Size in kW	Ploss in kW	Qloss in kVar	SI p.u.	Min (abs(V)) p.u.
1	CP	9	1500	117.64	79.5749	0.778	0.9391
2	CP	13, 30	904.7037, 1348.1	87.525	60.2068	0.905	0.9753
3	CP	30, 24, 13	1227.9, 984.34, 883.72	73.238	50.6817	0.904	0.975
1	CC	9	1500	107.53	72.7027	0.789	0.9425
2	CC	30, 13	1289.2, 887.7787	83.099	56.991	0.9	0.9739
3	CC	25, 13, 30	804.0159, 837.5683, 1266.1	70.877	49.0014	0.905	0.9755
1	CI	8	1500	97.143	65.5841	0.799	0.9455
2	CI	13, 30	1289.2, 887.7787	78.990	54.0273	0.896	0.9729
3	CI	30, 24, 14	804.0159, 837.5683, 1266.1	65.944	45.6696	0.891	0.9716

Table 2. Effect of DG and DSTATCOM allocation on 33 bus system

DGs	STATCOM	Type of load	Location		Size in kW		Ploss in kW	Qloss in kVar	SI p.u.	min(abs(V)) p.u.
			DGs	STATCOM	DGs	STATCOM				
1	1	CP	12	30	766.5581	1000	84.3915	56.221	0.8242	0.9528
2	2	CP	13, 30	12, 30	1252.8, 1046	720.4521, 926.8181	36.8783	26.2313	0.9291	0.9818
3	3	CP	30, 24, 14	24, 30, 8	920.3924, 1045.4, 976.9502	801.7348, 894.3995, 690.2476	16.4085	13.0937	0.9767	0.9941
1	1	CC	12	30	1450	998.279	66.9244	45.105	0.8625	0.9637
2	2	CC	11, 31	30, 11	1196.3, 1033	984.5369, 696.1826	32.1737	23.3261	0.9296	0.982
3	3	CC	32, 13, 28	10, 30, 24	1191, 954.7022, 1391.1	581.7748, 777.4626, 601.7183	74.5671	57.5312	0.9641	0.9909
1	1	CI	12	30	1348	1000	63.3668	42.5778	0.8624	0.9637
2	2	CI	31, 13	8, 30	1091.1, 1296	784.3324, 945.5014	39.9447	29.3436	0.9331	0.9829
3	3	CI	25, 29, 14	30, 7, 24	889.8907, 1294.6, 1083.4	675.4819, 888.4512, 646.4502	24.5258	19.6241	0.9775	0.9943

Table 2 shows, with the inclusion of D-STATCOM(s), there is a significant improvement in the real power loss of the system. With one D-STATCOM, the real power loss is 84.3915 kW and reactive power loss is 56.221 kVAR, with two D-STATCOMs it is 36.1737 kW and 26.2313 kVAR, and with three D-STATCOMs it is reduced to 16.4085 kW and 13.0937kVAR for CP load model. Based on the results, it can

be said that by using three DGs and DSTATCOMs simultaneously, the system performs better than using one or two. To further support this conclusion, Figures 2(a)-2(c), Figures 3(a)-3(c), and Figures 4(a)-4(c) display the voltage profile, branch current profile, and a multi objective function-based power loss profile for a varying number of DGs allocations, for constant power, constant current, and constant impedance load types respectively. Figures 5(a)-5(c), Figures 6(a)-6(c), and Figures 7(a)-7(c) display the voltage profile, branch current profile, and a multi-objective function-based power loss profile for all the above types of load models for simultaneous DGs and DSTATCOMs placement.

Figure 2 presents the performance of the IEEE-33 bus system with constant power (CP) load type under different distributed generation (DG) scenarios. Figure 2(a) shows the voltage profile across the buses, where the optimal DG placement scenario significantly improves voltage stability by maintaining bus voltages closer to the nominal 1 p.u. Figure 2(b) displays the branch current profiles, highlighting a reduction in current magnitudes when DG is appropriately integrated, which helps in relieving stress on distribution lines. Figure 2(c) illustrates the minimization of multi-objective function (MoF) under the optimal DG configuration. These results demonstrate that under CP load conditions, proper DG placement effectively enhances voltage regulation, reduces branch current loading, and minimizes real power losses, contributing to a more efficient and reliable operation of the distribution network.

Figure 3 shows what happened when the IEEE-33 bus system ran with a constant current (CC) load type and different distributed generation (DG) scenarios. Figure 3(a) shows the voltage profile across the buses. The best DG placement scenario gets better voltage levels, keeping values closer to 1 p.u. than other setups, which makes voltage stability better. Figure 3(b) shows the branch current profiles, which show that the best way to integrate DG leads to a big drop in current magnitudes across several branches. This helps with better load distribution and less line loading. When DG is put in the best place, Figure 3(c) shows how to minimize the multi-objective function (MoF). These results all show that strategically placing DG under CC load conditions greatly improves voltage regulation, lowers current flow in the network, and makes the whole system more efficient.

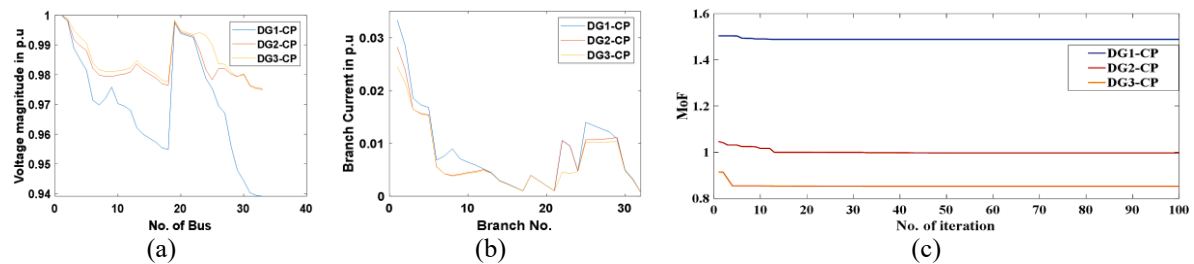


Figure 2. Results for the IEEE-33 bus system with CP load type under varying DG scenarios:
(a) voltage profile, (b) branch current profile, and (c) power loss plot

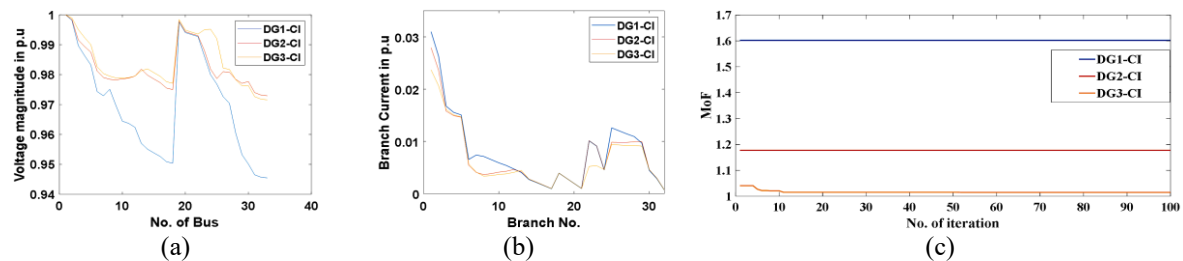


Figure 3. Results for the IEEE-33 bus system with CC load type under varying DG scenarios:
(a) voltage profile, (b) branch current profile, and (c) power loss plot

Figure 4 shows the simulation results for the IEEE-33 bus system with a constant impedance (CI) load type in different distributed generation (DG) scenarios. Figure 4(a) shows the voltage profiles. The integration of DG units, especially when they are placed in the best way, raises voltage levels across the buses significantly, keeping them closer to the nominal 1 p.u. Figure 4(b) shows the branch current profiles, which show that adding DG lowers the current in several branches. This lowers the stress on the network and improves the flow of current. Figure 4(c) shows how the multi-objective function (MoF) is minimized, which

shows how well DG works to make the system more efficient. Overall, the results show that putting DG in the right place under CI load conditions improves voltage regulation, lowers branch currents, and cuts down on power losses in the distribution network.

Figure 5 shows the results for the IEEE-33 bus system with a constant power (CP) load type in different DG-STATCOM situations. Figure 5(a) shows the voltage levels across the buses. It shows that the DGStat3-CP setup gives the highest and most stable voltage levels, keeping them close to the nominal 1 p.u. level compared to DGStat1-CP and DGStat2-CP. Figure 5(b) shows the branch current profiles. Under the DGStat3-CP scenario, the current magnitudes drop significantly, which means that the load is better distributed and the lines are less crowded. Figure 5(c) shows how to make the multi-objective function (MoF) as small as possible. These results show that the best way to coordinate DG and STATCOM under CP load conditions greatly improves voltage stability, reduces current flow, and lowers overall system losses. This makes the distribution network work more efficiently.

Figure 6 shows the results of the simulation for the IEEE-33 bus system with a constant current (CC) load type in different scenarios for deploying DG-STATCOM. Figure 6(a) shows the voltage profile across the buses. The DGStat3-CC configuration does the best job of keeping voltages close to 1 p.u., while the DGStat1-CC and DGStat2-CC configurations do not. Figure 6(b) shows the branch current profiles, which show that the DGStat3-CC scenario causes the current to be lower in several branches. This means that load balancing is better and line congestion is lower. Figure 6(c) shows how to minimize the multi-objective function (MoF), which shows the advantages of placing DG and STATCOM in the best places. Overall, the results show that putting DG and STATCOM in the right places together greatly improves voltage stability, lowers branch current, and cuts down on power losses in the distribution system when there is a CC load.

Figure 7 displays the performance results of the IEEE-33 bus system with a constant impedance (CI) load type under various DG-STATCOM scenarios. Figure 7(a) shows the voltage profile across the buses, where the DGStat3-CI configuration provides the most improved and stable voltage levels, indicating effective voltage regulation due to optimal coordination of DG and STATCOM. Figure 7(b) presents the branch current profiles, demonstrating that the DGStat3-CI scenario leads to a noticeable reduction in current magnitudes across several branches, which helps reduce network congestion and improves overall load distribution. Figure 7(c) illustrates the minimization of multi-objective function (MoF). Overall, the results validate that the strategic placement of DG along with STATCOM under CI load conditions significantly enhances voltage stability, reduces current loading, and minimizes power losses in the distribution network.

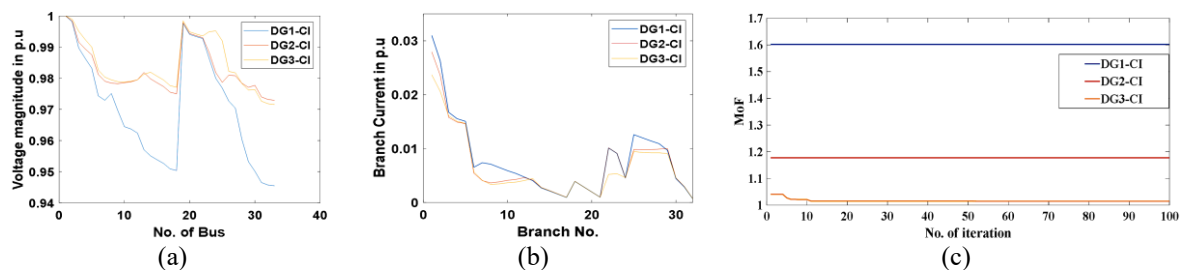


Figure 4. Results for the IEEE-33 bus system with CI load type under varying DG scenarios: (a) voltage profile, (b) branch current profile, and (c) power loss plot

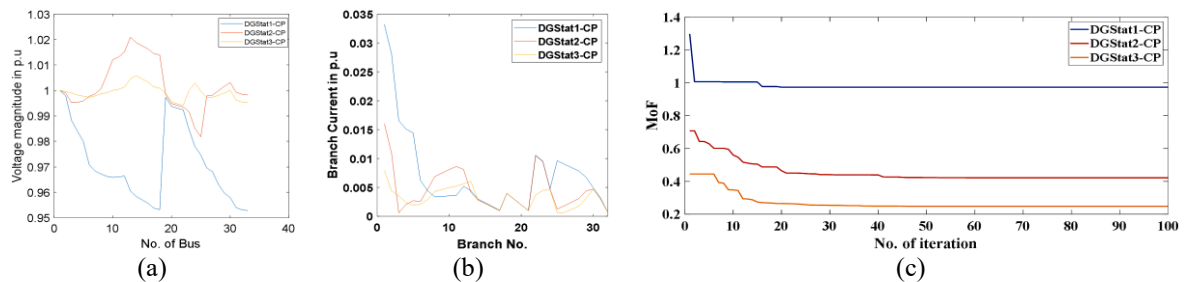


Figure 5. Results for the IEEE-33 bus system with CP load type under varying DG-STATCOM scenarios: (a) voltage profile, (b) branch current profile, and (c) power loss plot

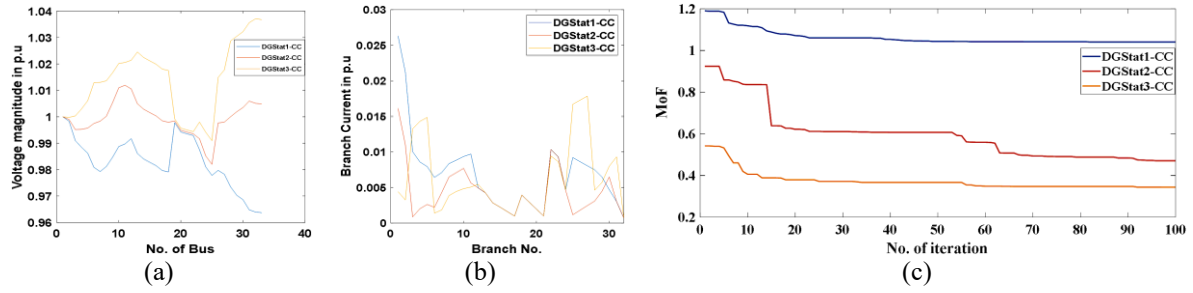


Figure 6. Results for the IEEE-33 bus system with CC load type under varying DG-STATCOM scenarios: (a) voltage profile, (b) branch current profile, and (c) power loss plot

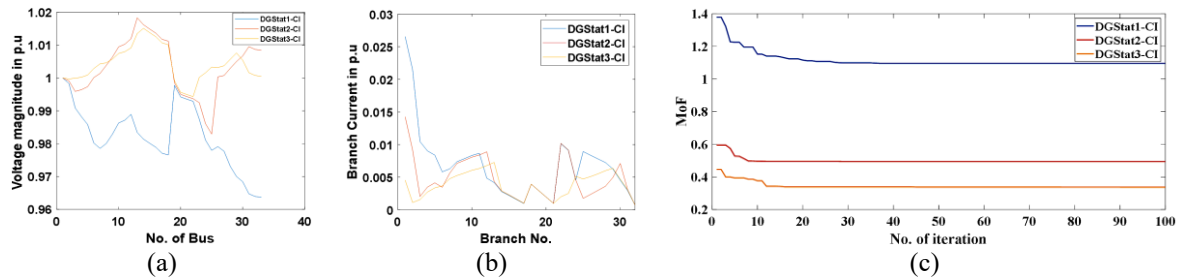


Figure 7. Results for the IEEE-33 bus system with CI load type under varying DG-STATCOM scenarios: (a) voltage profile, (b) branch current profile, and (c) power loss plot

5.2. 69 bus system

The IEEE 69 bus test system has a combined load of $3791.9 + j 2694$ kVA. The IEEE-69 bus system is subjected to load flow analysis with and without the presence of DSTATCOM(s). The results of which are presented in Tables 3 and 4.

The outcomes in Table 3 evidently specify that the system exhibits inadequate performance in the absence of D-STATCOM. With one DG placed in 61st node, in constant power load model results a real power loss of 88.1599 kW, reactive power loss of 43.1434 kVAR, stability index of 0.8704 p.u. and a low magnitude of voltage is 0.9659 p.u. There is an improvement in the power loss as well as voltage profile for all types of load models, when two and three numbers of DGs are placed.

Table 3. Effect of DG allocation on 69 bus system

DGs	Type of load	Location	Size in kW	Ploss in kW	Qloss in kVar	SI p.u.	min(abs(V)) p.u.
1	CP	61	1500	88.1599	43.1434	0.8704	0.9659
2	CP	15, 61, 63	789.7819, 1320.6, 697.3356	76.5353	37.4888	0.9589	0.9896
3	CP	62, 61, 13	839.026, 1170, 889.1996	76.4244	37.458	0.9578	0.9893
1	CC	61	1462.8	83.9633	41.3271	0.8696	0.9657
2	CC	61, 11	1461.7, 1356.2	73.8839	36.1706	0.8976	0.9734
3	CC	59, 61, 13	905.7184, 1182.3, 870.773776	75.8046	37.1052	0.9473	0.9866
1	CI	61	1500	78.6473	38.9537	0.8775	0.9679
2	CI	15, 61	646.2781, 1492	68.1465	34.2966	0.8892	0.9711
3	CI	17, 60, 61	674.0863, 704.2579, 1235.2	70.0613	34.8203	0.9357	0.9835

In Table 4, we can see that, with the inclusion of D-STATCOM(s), again there is a significant improvement in the system parameters. For constant power load model, with one D-STATCOM, the real power loss is 30.8152 kW and reactive power loss is 18.4219 kVAR, with two D-STATCOMs the real and reactive power losses are 30.3037 kW and 16.8051 kVAR, and with three D-STATCOMs it is 56.88 kW and 27.0467kVAR, respectively. Based on the results shown, it can be said that by allocating two DGs and two DSTATCOMs simultaneously, the system performs better than using one or three. Figures 8(a)-8(c), Figures 9(a)-9(c), and Figures 10(a)-10(c) display the voltage profile, branch current profile, and a multi-objective function-based power loss profile for varying numbers of DGs allocations for constant power,

constant current, and constant impedance load types respectively. Figures 11(a)-11(c), Figures 12(a)-12(c), and Figures 13(a)-13(c) display the voltage profile, branch current profile, and a multi-objective function-based power loss profile for constant power, constant current, and constant impedance load types, respectively, for simultaneous DGs and DSTATCOMs placement.

Table 4. Effect of DG and DSTATCOM allocation on 69 bus system

DGs	STATCOM	Type of load	Location		Size in kW		Ploss in kW	Qloss in kVar	SI p.u.	min(abs(V)) p.u.
			DG	STATCOM	DG	STATCOM				
1	1	CP	62	61	1500	1000	30.8152	18.4219	0.8839	0.9696
2	2	CP	62, 63	61, 55	1230.7, 954.9207	880.091, 694.8588	30.3037	16.8051	0.9052	0.9754
3	3	CP	61, 64, 22	61, 51, 13	1031.2, 1340.4, 1186	755.928, 736.825, 436.8241	56.88	27.0467	0.9773	0.9943
1	1	CC	62	61	1038.1	1000	46.2681	25.3544	0.8729	0.9666
2	2	CC	62, 61	61, 62	1156.7, 807.0161	831.081, 695.4821	25.294	14.8336	0.9022	0.9746
3	3	CC	62, 25, 61	61, 36, 11	1270.8, 828.094, 1057.4	941.500, 677.745, 555.7608	35.8031	18.4679	0.9774	0.9943
1	1	CI	62	61	1026.4	1000	44.4738	24.5205	0.875	0.9672
2	2	CI	61, 63	12, 63	1402.6, 810.5623	878.732, 862.4592	28.3785	15.7177	0.9227	0.9801
3	3	CI	60, 17, 61	36, 51, 63	983.553, 1485.3, 1196.6	813.364, 559.630, 968.1988	64.7281	28.5983	0.9776	0.9943

Figure 8 shows the results of the simulation for the IEEE-33 bus system with a constant power (CP) load type in different scenarios for distributed generation (DG). Figure 8(a) shows the voltage profile. Adding DG units greatly improves the voltage levels across the buses, and the best placement of DG units gets voltages closest to the nominal 1 p.u., which means better voltage regulation. Figure 8(b) shows the branch current profile, which shows that integrating DG lowers the current flow through multiple branches. This lowers line loading and makes the system more reliable. Figure 8(c) shows how optimal DG placement reduces the multi-objective function (MoF) compared to other situations. These results show that putting DG units in the right places under CP load conditions improves the performance of the distribution network by making the voltage more stable, lowering network stress, and cutting down on power losses.

Figure 9 shows how the IEEE-33 bus system works when there is a constant current (CC) load and different types of distributed generation (DG). In Figure 9(a), the voltage profile across the buses shows a clear improvement when DG is added. The best DG scenario keeps voltage levels closer to the nominal value, which makes voltage stability better. Figure 9(b) shows the branch current profiles. The presence of DG causes the current magnitudes in some branches to be lower, which means that the load is shared better and the network is less stressed. Figure 9(c) shows how to minimize the multi-objective function (MoF) with the best DG setup. Overall, the results show that putting DG units in the right places under CC load conditions improves voltage regulation, lowers branch current, and cuts power losses, which makes the distribution system work more efficiently.

Figure 10 shows how the IEEE-33 bus system works with a constant impedance (CI) load type in different distributed generation (DG) situations. Figure 10(a) shows the voltage levels across the buses. The addition of DG units greatly raises the voltage levels, especially when the DG units are placed in the best way, keeping them closer to the nominal 1 p.u. Figure 10(b) shows the branch current profiles, which show that putting DG in the right place lowers the current flow through several branches, which makes the network less stressed. Figure 10(c) shows how to minimize the multi-objective function (MoF) when DG is best integrated into the system. These results show that using DG strategically in CI load conditions makes the distribution network more efficient and reliable by improving voltage stability, lowering branch current levels, and reducing power losses.

Figure 11 shows the results of the simulation for the IEEE-69 bus system with a constant power (CP) load type in different scenarios for deploying DG-STATCOM. Figure 11(a) shows the voltage profiles. The DGStat3-CP configuration shows the best voltage support across the buses, with values close to 1 p.u. This means that the voltage is more stable than with DGStat1-CP and DGStat2-CP. Figure 11(b) displays the branch current profiles, indicating that DGStat3-CP probably results in lower current magnitudes, which

implies a more balanced load flow and less network congestion. Figure 11(c) shows how to minimize the multi-objective function (MoF). In general, the results show that the best placement and coordination of DG and STATCOM under CP load conditions greatly improve voltage regulation, lower branch current, and lower power losses, making the distribution system more efficient and reliable.

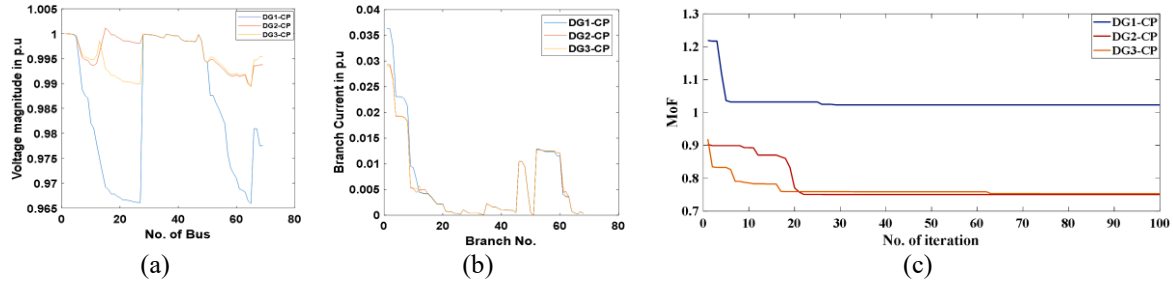


Figure 8. Results for the IEEE-69 bus system with CP load type under varying DG scenarios:
(a) voltage profile, (b) branch current profile, and (c) power loss plot

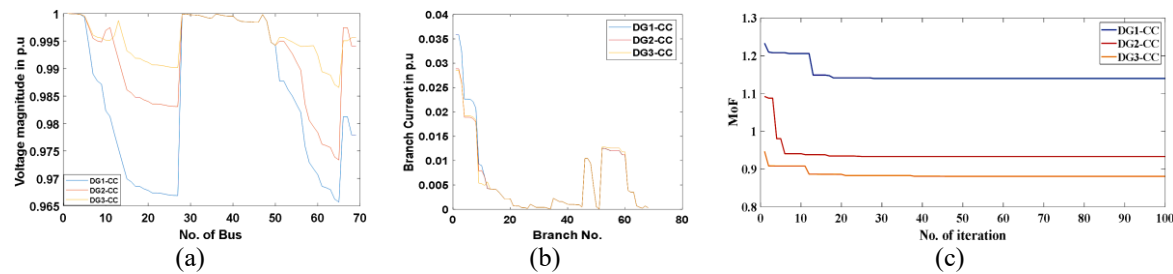


Figure 9. Results for the IEEE-69 bus system with CC load type under varying DG scenarios:
(a) voltage profile, (b) branch current profile, and (c) power loss plot

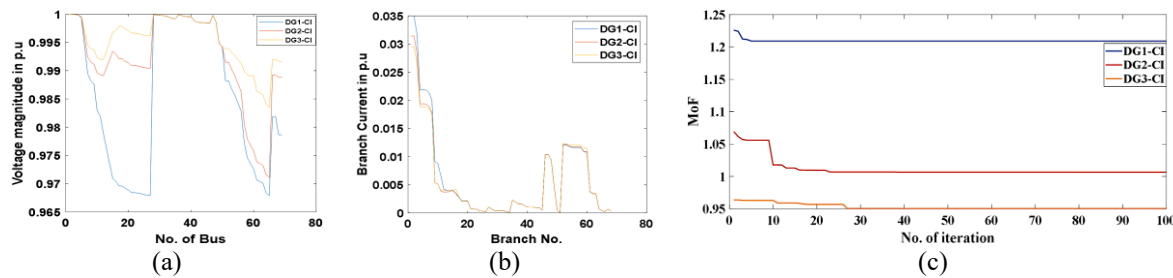


Figure 10. Results for the IEEE-69 bus system with CI load type under varying DG scenarios:
(a) voltage profile, (b) branch current profile, and (c) power loss plot

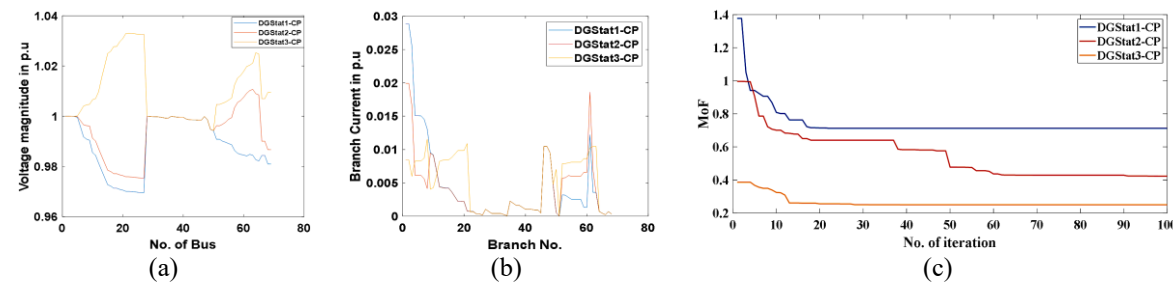


Figure 11. Results for the IEEE-69 bus system with CP load type under varying DG-STATCOM scenarios:
(a) voltage profile, (b) branch current profile, and (c) power loss plot

Figure 12 shows how the IEEE-69 bus system works when there is a constant current (CC) load and different DG-STATCOM integration scenarios. In Figure 12(a), the voltage profile across the buses shows that the DGStat3-CC configuration does a better job of keeping the voltage levels close to the nominal value than the DGStat1-CC and DGStat2-CC configurations. Figure 12(b) shows the branch current profiles. For DGStat3-CC, we expect to see a big drop in current magnitudes, which means better current distribution and system balance. Figure 12(c) shows how to minimize the multi-objective function (MoF), which shows how well optimal DG-STATCOM coordination works. All of these results show that strategically placing DG units along with STATCOM under CC load conditions greatly improves voltage stability, lowers branch currents, and cuts down on overall power losses in the distribution network.

Figure 13 shows the results of a simulation of the IEEE-69 bus system with a constant impedance (CI) load type in three different DG-STATCOM placement scenarios. Figure 13(a) shows the voltage profile across the buses. The DGStat3-CI configuration has the most stable and high voltage levels, which means it provides good voltage support. Figure 13(b) shows the branch current profile. It probably shows that the current magnitudes for DGStat3-CI are lower, which means that the load is better distributed and the network is less stressed. Figure 13(c) shows how to minimize the multi-objective function (MoF). In general, the results show that putting DG and STATCOM in the right places and coordinating them well greatly improves voltage regulation, cuts down on power losses, and makes the distribution system work more efficiently.

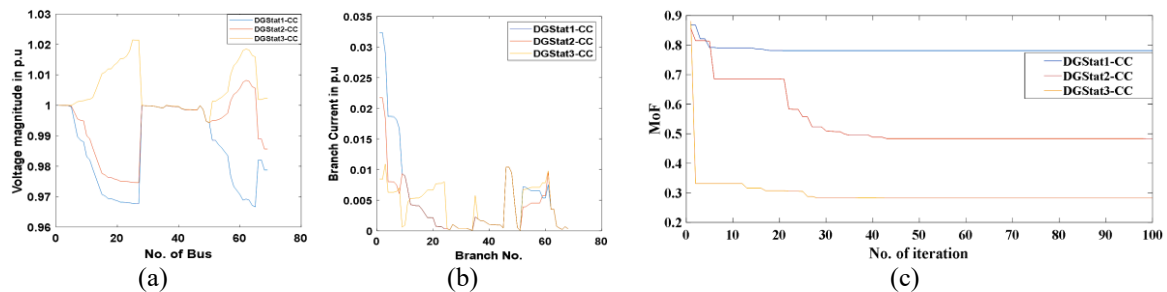


Figure 12. Results for the IEEE-69 bus system with CC load type under varying DG-STATCOM scenarios:

(a) voltage profile, (b) branch current profile, and (c) power loss plot

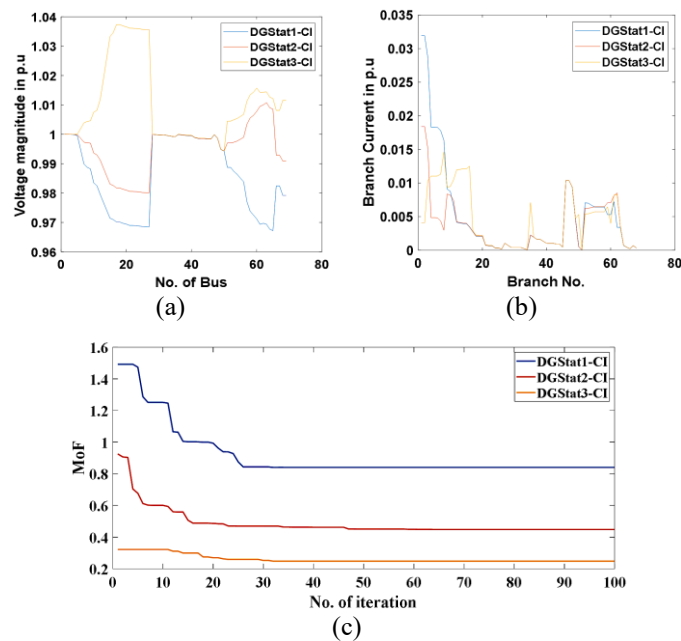


Figure 13. Results for the IEEE-69 bus system with CI load type under varying DG-STATCOM scenarios:

(a) voltage profile, (b) branch current profile, and (c) power loss plot

6. CONCLUSION

Microgrids and active distribution networks are currently a significant area of research due to their ability to provide self-sufficiency to existing networks and extend electricity access to remote areas with limited or no power availability. Reducing losses in active distribution networks is crucial, especially given the limited energy supply. Any losses would worsen the decrease in supply. This study aims to address this problem by examining the best locations for distributed generation (DG) and distribution static synchronous compensator (DSTATCOM). The main goal is to effectively minimize both real and reactive power losses and improve voltage profiles in the distribution network. The study suggests that placing both DG and DSTATCOM simultaneously at proper bus location yields the most favourable results, characterized by minimal losses and reduced capacity requirements. The combined placement of DG and DSTATCOM not only leads to a significant reduction in losses but also improves the voltage profile across the network. The research findings shed light on the distinct impacts of DG and DSTATCOM placement within the distribution network. When solely employing DSTATCOM, a noticeable enhancement in the voltage profile is observed; however, the reduction in losses remains minimal, offering limited improvement in overall system performance. Conversely, the exclusive placement of DG results in a substantial reduction in losses but offers minimal improvement in the voltage profile. Based on the obtained results, it is recommended that placing both DG and DSTATCOM at optimal bus location ensures the most favourable outcomes in terms of enhancing the overall network profile, minimizing real and reactive power losses, and optimizing the performance of the active distribution network.

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This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

The author declares that there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. All simulation results were generated using standard IEEE test systems and can be reproduced with the described methodology.

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