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An efficient allocation of D-STATCOM and DG with network reconfiguration in distribution networks

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Abstract
This work solves the optimal allocation problem of distribution static compensator (D-STATCOM) and distributed generation (DG) simultaneously. The network reconfiguration (NR) is also applied in this work for better utilization of the existing distribution network infrastructure. This work proposes a robust and efficient NR algorithm to address the NR problem, including DG and D-STATCOM allocation by considering techno-economic objectives. Power loss minimization is selected as an objective and a gravitational search algorithm (GSA) is used to solve this efficient allocation problem. This approach has been executed on IEEE 33 bus radial distribution system (RDS). The results demonstrate that the application of simultaneous NR, D-STATCOM, and DG allocation has resulted in a reduction in network losses as well as enhancement in the voltage profile of entire RDS. By this simultaneous approach, the power loss has reduced by 77.5% and minimum voltage in the RDS has increased from 0.9131 p.u. to 0.9735 p.u.

Keywords
Distribution system, Distributed generation, Reconfiguration, Gravitational search algorithm, D-STATCOM, Renewable energy.

1.Introduction
Nowadays the major concern of global warming leads to the transition from fossil fuels to green energy for the generation of electricity. On the distribution level and customer side, microgrids (MGs) are the important subsets of the smart grid (SG). The heart of MGs has distributed generations. The roots of the power system issues found in the electrical distribution system. The distributed generation (DG) applies small-scale technology to generate electricity near to the consumers and it is capable of lowering costs, improving reliability, reducing emission, and expanding energy options [1, 2]. The work presented in this paper is concentrated on the optimal bus and capacity of distribution static compensator (D-STATCOM) and DG as well as network reconfiguration (NR) of radial distribution system (RDS). While deciding the position of DG unit, care has to be taken to maximize the benefits. Optimal sizing and siting of D-STATCOM and DG units in the presence of deregulated power industry is very important for the efficient enhancement of the RDSs.

The work presented in this paper describes the technique to identify the best suitable locations of D-STATCOM and DG. The transmission of electrical energy is done at an extra-high voltage and the distribution is done at a low voltage level. The traditional centralized power system operation has many drawbacks. In the traditional system, such a long-distance transmission result in electrical power loss and much electromagnetic radio interference. This system has a very high operating cost and it mainly depends upon fossil fuels [3, 4]. Therefore, it has a severe environmental impact. In addition to this, fossil fuel cost is increasing and hunger for energy also results in the depletion of conventional energy resources. It is noticeable that global worldwide demand for energy has been increasing speedily. Therefore the increase in electrical power generation is essential. But the traditional power plants require very high investment costs. It is necessary to shift from a traditional power system to a smart deregulated power system. On the distribution level and customer side, MGs are the subsets of the SG [5].

The rest of the work is arranged as follows. Section 2 reviews the literature and motivation of this work.

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Section 3 introduces the description of the load flow analysis of RDS, the importance of DG, and also the description of the proposed problem formulation and the related constraints. Simulation results on IEEE 33 RDS by considering various scenarios are demonstrated in section 4. Section 5 presents the discussion on the obtained results as well as the limitations of this work. The paper finishes with the conclusion and scope of future work in section 6.

2.Literature review

The distribution system plays a key role in the power network and it widely operates under heavy loading conditions. For achieving actively satisfactory power demand reliably, the distribution losses are needed to be taken care of and they must be minimized as much as possible. Several methodologies are adopted in the literature to overcome this power loss issue. Recently, allocation of D-STATCOMs and DGs is getting the most attention for increasing corporation of integrated small generations to it. It has been reported that with the usage of D-STATCOMs and DGs, the reliability of the distribution system has been improved which leads to the minimization of power line losses in entire RDS. To meet active and reactive power demands of customers, D-STATCOMs and DGs are installed. The impacts of the D-STATCOMs and DGs in the distribution system are vast and can be classified in terms of environmental, economic and technical impacts. Several researchers have implemented various optimization techniques to inspect and find the optimal allocation of DGs in solving the complexities. The earnings of power companies in addition to this the power transfer prices are very much affected by the real power losses. A methodology to find the allocation of D-STATCOMs and DGs in RDS is proposed in [6]. A methodology using cuckoo search-based algorithm for the allocation of D-STATCOM is demonstrated in [7].

The optimal network reconfiguration (ONR) approach is a complex decision making process even though it has several advantages. An approach for simultaneous ONR and DG allocation with the aim of loss reduction, balancing the feeder load balancing, and voltage profile improvement is proposed in [8]. An optimal approach for the RDS voltage profile improvement objective for various loading conditions and is solved by using a grasshopper optimization algorithm is proposed in [9, 10]. A copula theory for modelling the nonlinear correlation of uncertainties for dynamic NR is proposed in [11]. An improved heap-based optimizer is used in [12] to solve the combinatorial optimization problem of NR with DG allocation. The simultaneous NR and allocation of DG problem with the aim of power loss minimization in RDS using the chaotic search group technique are proposed in [13]. A methodology for multi-period NR planning of RDSs with the automated switches is proposed in [14]. A parallel slime mould algorithm for solving the NR problem with the allocation of DG is proposed in [15]. The problem of ONR is solved in [16] with various objectives such as minimization of voltage deviation, power losses, and load balance as a multi-objective problem of the RDS by satisfying various network constraints. An approach for the mitigation of voltage volatility in the RDS of using the ONR has been proposed in [17]. The proposed approach presents new insights into the voltage regulation problem with large scale penetration of renewable energy sources. A multi-objective based ONR problem by considering the DG units and electric vehicles by handling the uncertainties related to them has been proposed in [18].

After the literature review of NR approaches, it has been concluded that this problem has been solved by using various conventional and evolutionary based algorithms. Several established techniques that are developed in the literature does not solve the problem simultaneously by considering the NR and optimal allocation of DGs, D-STATCOMs. It necessitates the development of an efficient NR approach and optimal allocation with consideration of techno-economic objectives. To solve this optimization problem, an evolutionary based gravitational search algorithm (GSA) is used.

3.Methods

3.1Distribution system load flow (DSLF)

In general, the distribution networks in the power system are radial, and *Figure 1* describes the feeder structure of RDS. It has a very high R/X ratio. For solving the power flow problem of RDS, there is only an evaluation of a simple algebraic expression receiving end voltages. Loads will be treated as a constant power type load. In this paper, a direct method-based load flow analysis method is used to solve the DSLF. Here, the distribution load flow developed in [19] is used. In this load flow, the matrix transformation is integrated with the forward-backward sweep (FBS) based technique. This approach can be used in both current flow and power flow-based load flow methods. These two load flow techniques are described next:

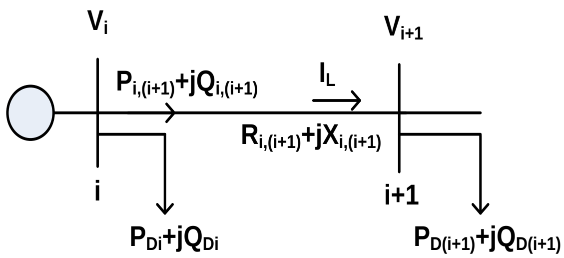

Figure 1 Feeder structure of RDS

In the current flow based FBS approach, during the backward sweep, the load current matrix (LCM) is created by storing the load current ($I_{Load,j}$) at each node j at a location $LCM(i,j)$. Where i is the upstream node just previous to the j[th] node. In LCM, a non-zero row is selected starting from the bottom to the top row of the matrix [20, 21]. Then all the elements of the row are added and it is stored in a temporary variable (TV_j) and it is represented by using Equation 1.

$$TV_j = \sum_{k=1}^{N_B} LCM(j,k) \quad (1)$$

Here N_B is number of buses. Then, elements of the LCM [19] are updated by using Equation 2.

$$LCM'(i,j) = LCM(i,j) + TV_j \quad (2)$$

Where j=N_B, (N_B-1),…,2; and i=k. In the forward sweep approach, node voltages are updated by using Equation 3.

$$V_{k+1} = V_k - LCM'(k,k+1)Z_k \quad (3)$$

Where Z_k is the impedance. In the power flow based FBS approach, the temporary variable (TV_j) is defined by using Equation 4.

$$TV_j = \sum_{k=1}^{N_B} PFM(j,k) \quad (4)$$

During the backward sweep, the power flow matrix (PFM), which is used to find the power fed through each node, is updated by using Equations 5 and 6.

$$PFM'(i,j) = PFM(i,j) + TV_j \quad (5)$$

$$PFM(i,j) = P_{D,j} + P_{loss,j} \quad (6)$$

Where $P_{D,j}$ is load demand at j[th] node/bus. $P_{loss,j}$ is power loss in j[th] line. Now the voltage at each bus/node is updated by using the forward sweep [22], and it is represented by using Equation 7.

$$|V_{k+1}^2| = \left[\left(P_kR_k + Q_kX_k - \frac{|V_k^2|}{2}\right)^2 - (R_k^2 + X_k^2)(P_k^2 + Q_k^2)\right]^{0.5} - \left(P_kR_k + Q_kX_k - \frac{|V_k^2|}{2}\right)^2 \quad (7)$$

3.2Distributed generation (DG)

The ever-increasing demand for electricity leads to the problems of fossil fuel in the direction of climate change, pollution global warming, etc. Due to which researches are accelerating towards the development to improve the entrance of renewable resources of energy that can displace fossil fuel. Now renewable energy technologies develop big belief in industries and academics to find the solution for energy that is cheap and eco-friendly, reliable, and self-sustaining [23, 24]. DG improves the reliability of the power supply to customers and reduces transmission and distribution losses. If suitable DG is installed in a suitable place, then it reduces the power generation costs. Based on replenishing ability, the DGs are categorized into 2 types: renewable DGs and non-renewable DGs. Renewable DGs are replenished naturally and over relatively short periods. The renewable DGs include solar photovoltaic (PV), wind, geothermal, and ocean. Non-renewable DGs are not able to replenish once exhausted. It takes a very long time in replenishing [25]. The non-renewable DGs include gas turbines, IC engines, and fuel cells. DGs have become the driving factor of MG operation. These days renewable-based DGs attract the interest of researchers. The main reason behind it is that renewable sources of energy are eco-friendly.

Solar PV cell works on the principle of the PV effect when photons containing solar energy fall upon semiconductor material, atoms absorb this sunlight of a certain wavelength. For extracting solar energy, PV panels are used. The output of the PV panel each hour of the day can be calculated by various analytical methods. Wind energy is the energy from wind in which wind power system device changes kinetic energy of blowing wind into electricity. In the wind energy system, the wind is struck to turbine blades and rotates the turbine whose shaft is connected to the gearbox to control the speed, and this whole connected to generator prime mover to generate the electricity [26, 27]. Solar thermal energy is completely different from the solar PV panel process [28]. In a solar thermal system, the sunlight is used to increase the temperature of the fluid to generate steam. This steam at high pressure passes through the turbine to run the turbine. The shaft of the turbine is connected to the prime mover of the generator to generate electrical energy.

Based on the terminal characteristics of DGs, they are classified into four parts: type 1 DGs, type 2 DGs, type 3 DGs and type 4 DGs. The type 1 DGs are the

DGs that can provide only real power to the grid. These DGs are represented by the unity power factor DG. Solar PV systems and fuel cells are an example of type one DG [29, 30]. Type 1 DG is P-type DG. It delivers only active power to the system. The solar PV energy system is an example of type 1 DG. Type 2 DGs can provide both real and reactive powers to the utility grid. These DGs are shown as a non-unity lagging power factor. Microturbines, gas turbines, and biomass plants are examples of type 2 DGs. Type 3 DGs have a leading power factor. Type 4 DGs can provide only reactive power to the grid. These DGs are represented by zero power factor DG. Examples are synchronous generators and synchronous compensators. The disadvantages of DGs mainly depend on environmental and economic conditions [31, 32]. The plant area requirement of the wind and solar PV is higher than the traditional power plant of the same capacity. Since the speed of wind and intensity of light varies over time, the output is very difficult to predict. Wave, small hydro, and tidal power plants may affect the ecosystem and fishery. The improper combustion of biomass may produce obnoxious emissions.

3.3Problem formulation

Optimization is generally referred to as finding the best solution to an optimization problem. Along with time, there is an evolution in optimization techniques to reduce the computational effort. Various optimization algorithms are developed and many more types of research are going in this direction [33, 34]. From an electrical power system point of view, few optimal studies in the active distribution network are the optimal allocation of DGs for the enhancement of voltages and reduction of losses, capacitor banks for loss reduction, and up-gradation of voltages, and optimal reconfiguration of active distribution network. In the present work, the loss sensitivity factor (LSF) approach is used for finding candidate nodes for the instalment of D-STATCOMs and DGs in RDS [35]. Real and reactive power losses between buses j and (j+1) are expressed by using Equations 8 and 9 [36].

$$P_{(j,j+1)}^{loss} = R_{(j,j+1)}\left(\frac{P_{(j,j+1)}^2+Q_{(j,j+1)}^2}{|V_j|^2}\right) \quad (8)$$

$$Q_{(j,j+1)}^{loss} = X_{(j,j+1)}\left(\frac{P_{(j,j+1)}^2+Q_{(j,j+1)}^2}{|V_j|^2}\right) \quad (9)$$

The LSF is obtained by partially differentiating the above two equations [37, 38], i.e., Equations 8 and 9, and they are represented in Equations 10 and 11.

$$\frac{\partial P_{(j,j+1)}^{loss}}{\partial Q_{j+1}} = \frac{R_{(j,j+1)}2Q_{j+1}}{|V_j|^2} \quad (10)$$

$$\frac{\partial Q_{(j,j+1)}^{loss}}{\partial Q_{j+1}} = \frac{X_{(j,j+1)}2Q_{j+1}}{|V_j|^2} \quad (11)$$

The total power loss in the RDS [39] is represented by using Equation 12.

$$P_T^{loss} = \sum_{j=1}^{N_{Bus}}\left(\frac{P_{(j,j+1)}^2+Q_{(j,j+1)}^2}{|V_j|^2}\right)R_{(j,j+1)} \quad (12)$$

N_{Bus} represents the number of buses in RDS. The objective is expressed by using Equation 13.

$$minimize \quad P_T^{loss} \quad (13)$$

3.3.1Equality constraints

Power flow constraints are expressed by using Equations 14 and 15 [40, 41].

$$P_{j+1} = P_j - P_{D,j+1} - R_{(j,j+1)}\left(\frac{P_{(j,j+1)}^2+Q_{(j,j+1)}^2}{|V_j|^2}\right) + P_{DG} \quad (14)$$

$$Q_{j+1} = Q_j - Q_{D,j+1} - X_{(j,j+1)}\left(\frac{P_{(j,j+1)}^2+Q_{(j,j+1)}^2}{|V_j|^2}\right) + Q_{D-STATCOM} \quad (15)$$

The reactive power output from D-STATCOM can be represented by using Equation 16.

$$Q_{D-STATCOM} = \left(\frac{V_j^2}{X_{(j,j+1)}}\right) - \left(\frac{V_jV_{j+1}}{X_{(j,j+1)}}\right)cos\delta \quad (16)$$

3.3.2Inequality constraints

Constraints on bus voltages

These voltages are limited by using Equation 17 [42].

$$V_i^{min} \le V_i \le V_i^{max} \qquad i = 1,2,\dots,N_{Bus} \quad (17)$$

Line current constraints

The line current is restricted by using Equation 18.

$$I_i \le I_i^{max} \qquad i = 1,2,\dots,N_{Line} \quad (18)$$

DG constraints

The amount of power output from DG can be expressed by using Equations 19 and 20 [43, 44].

$$\sum_{i=1}^{N_{Bus}} P_{DG,i} \le \sum_{i=1}^{N_{Bus}}(P_{D,i} + P_{loss,i}) \quad (19)$$

$$P_{DG}^{min} \le P_{DG} \le P_{DG}^{max} \quad (20)$$

D-STATCOM power constraints

The amount of power output from D-STATCOM units can be expressed by using Equations 21 and 22 [45].

$$\sum_{i=1}^{N_{Bus}} Q_{DG,i} \le \sum_{i=1}^{N_{Bus}}(Q_{D,i} + Q_{loss,i}) \quad (21)$$

$$Q_{D-STATCOM}^{min} \le Q_{D-STATCOM} \le Q_{D-STATCOM}^{max} \quad (22)$$

Radiality constraint

The radiality constraint of the distribution system can be expressed by using Equation 23 [46].

$$N_{Line} = N_{Bus} - 1 \quad (23)$$

Where N_{Line} is the number of lines in the RDS.

3.4Solution methodology

The proposed problem of RDS is implemented by using the GSA. The reader may refer to [47−49] for the complete description of GSA. Here, the GSA is implemented for solving the optimal NR problem with D-STATCOMs and DGs allocation. The detailed steps employed for solving the power loss minimization objective function by using the GSA have been presented in *Figure 2*. Initially read the data related to the lines and buses of RDSs. Initialize the population and identify the search space. Run the DSLF and determine the power loss for each object, and then evaluate the fitness of each object. By using this fitness value, update the best and worst values for all the masses. Then calculate total force in various directions. Update position of each object, after determining the velocity and acceleration. Check for the stopping criterion. If not, repeat this process till reaching the stopping criterion. If yes, display the optimum power loss value and the corresponding NR topology, i.e., open switches, D-STATCOM and DG location and sizes.

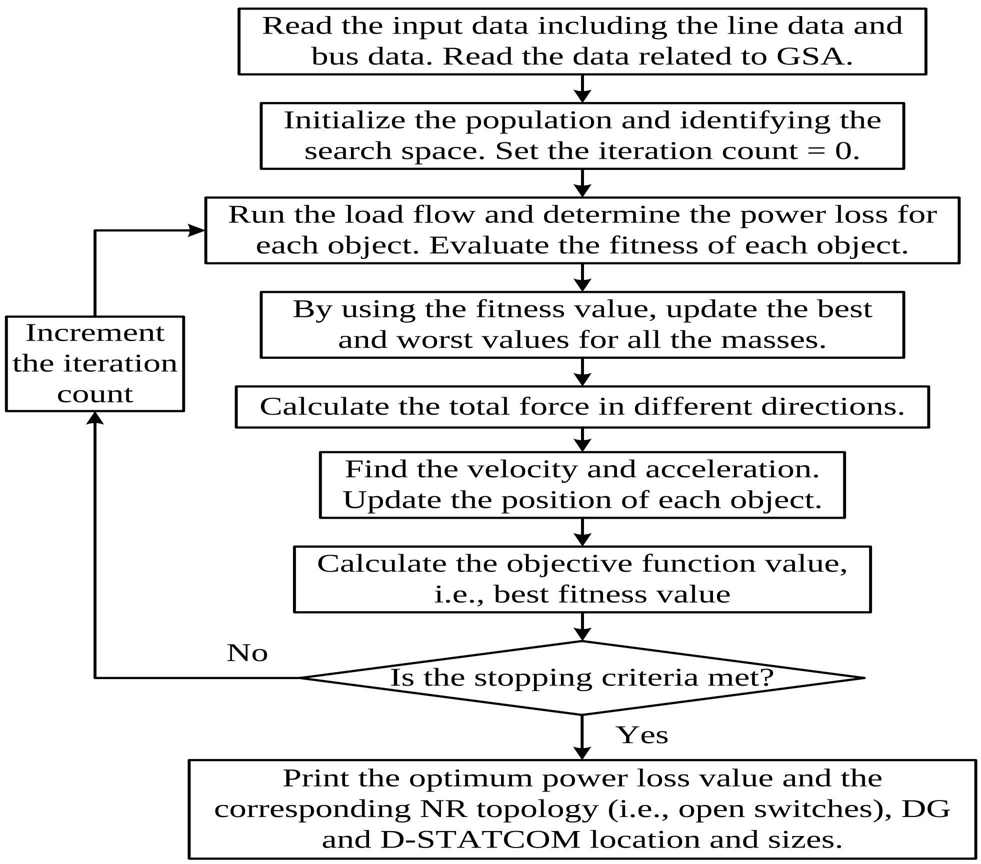

Figure 2 Power loss minimization using GSA

4.Results

The IEEE 33 bus system is used to implement the proposed optimization problem of RDS. The system line data and load data are taken from [50]. Single line diagram (SLD) of test network is depicted in *Figure 3*. This system has a base megavolt ampere (MVA) of 100 and a voltage of 12.66 kV. This test system consists of 32 lines, i.e., sectional switches which are generally closed, and 5 tie switches (generally opened). The reactive and active power demands of this RDS are 2.3 MVAr and 3.7 MW. Here, various case studies are simulated by optimizing the NR, D-STATCOM, and DG allocations. In this work, the sizes of D-STATCOM and DG are considered as 1900 kVAr and 2000 kW, respectively. Here, 7 case studies are simulated, and they are:

- Case 1: Operation of RDS without NR, DG, and D-STATCOM
- Case 2: With only NR
- Case 3: With only optimal allocation of DG units
- Case 4: With NR and DG allocation
- Case 5: With NR and D-STATCOM allocation
- Case 6: With D-STATCOM and DG allocation
- Case 7: With simultaneous NR, DG, and D-STATCOM allocation

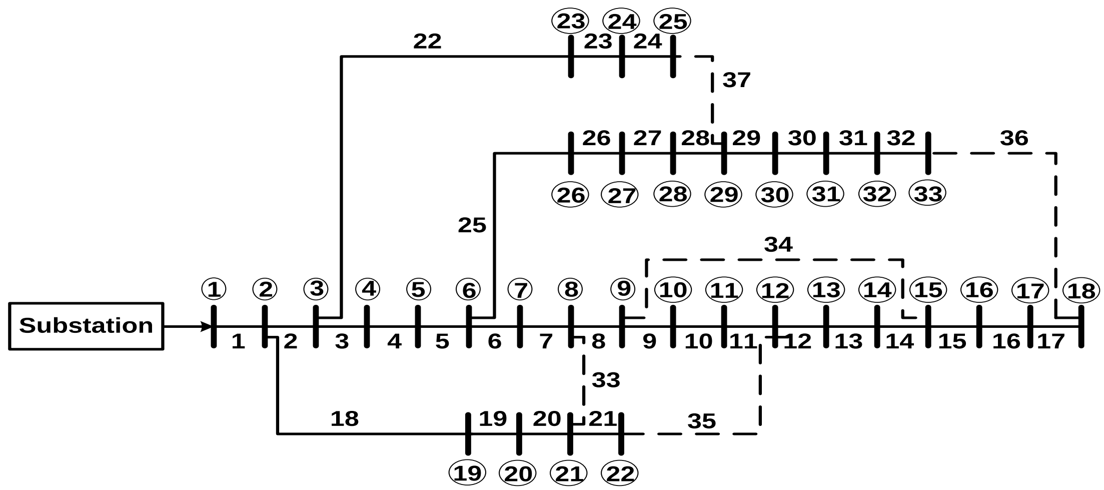

Figure 3 SLD of IEEE 33 bus RDS

4.1 Case 1: Operation of RDS without D-STATCOM, NR, and DG

Here, the program is executed without considering the D-STATCOM, NR and DG, and this is termed as the base case. Here, all tie-line switches (33 to 37) are opened. Here the minimum voltage occurred is 0.9131 p.u. and it is obtained at bus 18. The obtained power loss is 202.68 kW. These results are presented in *Table 1*.

4.2 Case 2: With only NR

Here, only NR is implemented. In this case, obtained simulation results give the optimum power loss of 138.62 kW, and opened tie-line switches are 7, 9, 14, 28, and 37. The network topology after the NR is shown in *Figure 4*. *Table 1* also depicts the results for case 2. The obtained loss is 31.61% less when compared to the base case. The minimum voltage reported is 0.9412 p.u., and it is better when compared to case 1's minimum voltage of 0.9131 p.u

Table 1 Results for cases 1 to 4

	Case 1	**Case 2**	**Case 3**	**Case 4**
Opened tie switches	33, 34, 35, 36, 37	7, 9, 14, 28, 37	33, 34, 35, 36, 37	7, 14, 10, 32, 34
DG size (DG bus location)	---	---	782.3 kW (13) 1096.5 kW (23) 1100.6 kW (29)	930.5 kW (18) 1105.2 kW (24) 1016.1 kW (31)
Total capacity of DGs	---	---	2979.4 kW	3051.8 kW
Size and location of D-STATCOM	---	---	---	---
Minimum bus voltage (bus location)	0.9131 p.u. (18)	0.9412 p.u. (32)	0.9653 p.u. (33)	0.9692 p.u. (32)
Total loss (in kW)	202.68	138.62	78.16	62.93
Percentage loss reduction	---	31.61%	61.44%	68.95%

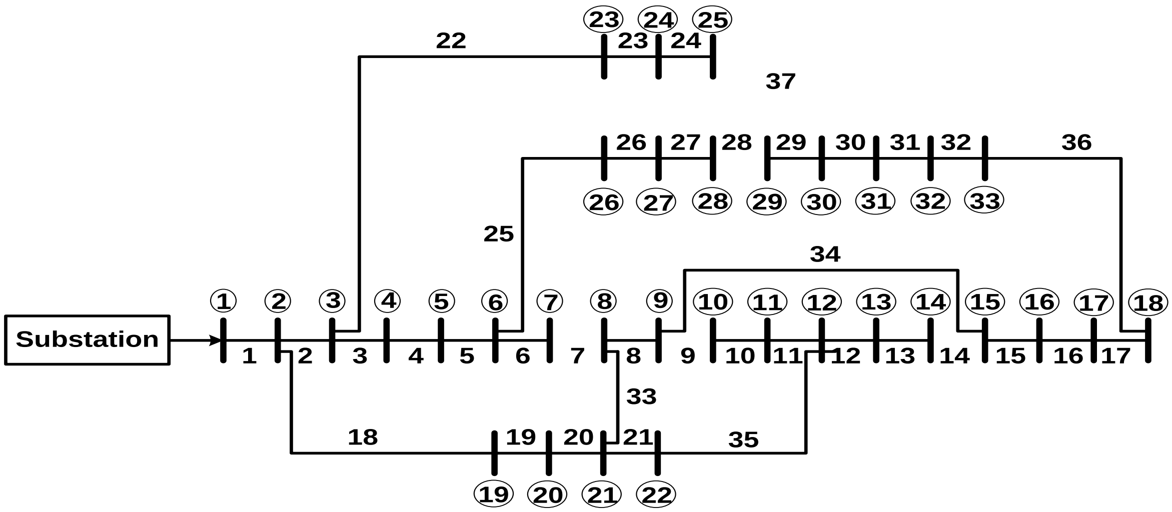

Figure 4 Network topology after the ONR (Case 2)

4.3Case 3: With DG unit allocation

The obtained results in this case are presented in Table 1. 3 DGs are installed on buses 13, 23, and 29 with the sizes of 782.3 kW, 1096.5 kW, and 1100.6 kW. The total installed capacity of DG units is 2979.4 kW. The resulted minimum voltage is 0.9653 p.u. at bus 33, and it is better when compared to case 1's voltage of 0.9131 p.u. The minimum loss occurred is 78.16 kW, and it is 68.95% less than the losses obtained in Case 1.

4.4Case 4: With NR and DG allocation

Here, both the NR and DGs are considered. NR obtained is 7, 14, 10, 32, and 34. The DGs are located on buses 18, 24, and 31 and their sizes are 930.5 kW, 1105.2 kW, and 1016.1 kW. Minimum loss occurred is 62.93 kW, and it is 68.95% less than case 1. The minimum voltage reported in this case is 0.9692 p.u., and it is better when compared to case 1's voltage of 0.9131 p.u.

4.5Case 5: With NR and D-STATCOM allocation

The results in this case are depicted in *Table 2*. Here, the RDS is optimized by considering both NR and D-STATCOM allocation. Opened tie-line switches, in this case, are 9, 14, 28, 33, and 36. D-STATCOM is placed at bus 29 with the size of 1156. kVAr. The minimum loss occurred is 78.32 kW, and it is 61.36% less than case 1. The minimum voltage reported is 0.9610 p.u., and it is better when compared to case 1's minimum voltage of 0.9131 p.u.

Table 2 Results for Cases 5, 6, and 7

	Case 5	Case 6	Case 7
Opened tie-line switches	9, 14, 28, 33, 36	33, 34, 35, 36, 37	7, 11, 26, 32, 33
DG size (location)	---	865.3 kW (13) 1100.0 kW (23) 1075.4 kW (29)	910.4 kW (13) 1096.2 kW (23) 1101.8 kW (29)
Total capacity of DGs	---	3040.7 kW	3108.4 kW
Size and location of D-STATCOM	1156.9 kVAr (29)	1125.8 kVAr (30)	1182.6 kVAr (23)
Minimum bus voltage (location)	0.9610 p.u. (18)	0.9649 p.u. (18)	0.9735 p.u. (18)
Total power loss (in kW)	78.32	63.96	45.61
Percentage loss reduction	61.36%	68.44%	77.50%

4.6Case 6: With DG and D-STATCOM allocation

D-STATCOM and DG are allocated without considering the NR. In this case, DGs are installed on buses 13, 23, and 19 with the sizes of 865.3 kW, 1100.0 kW, and 1075.4 kW. The total installed size of DG units is 3040.7 kW. D-STATCOM is installed bus 30 with the capacity of 1125.8 kVAr. The minimum power loss occurred is 63.96 kW, which is 68.44% less than the base case (Case 1) power loss. Minimum voltage reported is 0.9649 p.u. at bus 18, and it better when compared to case 1's voltage of 0.9131 p.u., and it is presented in *Table 2.*

4.7 Case 7: With the allocation of NR, D-STATCOM, and DG

As mentioned earlier, here, all three approaches are allocated simultaneously. The simulation results report that the tie-lines 7, 11, 26, 32, and 33 are opened, which gives optimal NR of the IEEE 33 bus RDS. In this case, DGs are allocated at buses 13, 23, and 29 with the sizes of 910.4 kW, 1096.2 kW, and 1101.8 kW. The total capacity of DG units is 3108.4 kW. Here, one D-STATCOM is installed with the capacity of 1182.6 kVAr at bus number 23. The minimum loss occurred is 45.61 kW and it is 77.5% less than case 1. Minimum voltage resulted is 0.9735 p.u. at bus 18, and it is better when compared to case 1's voltage of 0.9131 p.u., and it is presented in *Table 2*. The network topology after the ONR, DGs, and D-STATCOM is depicted in *Figure 5*. From obtained results, it is clear that network loss has decreased drastically and voltage profile improved from the base case.

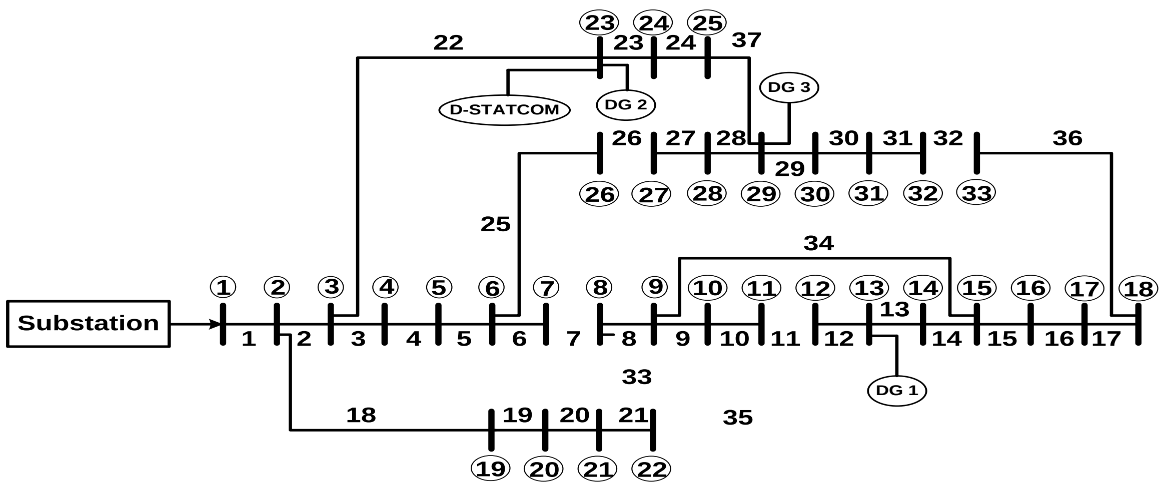

Figure 5 Network topology after the ONR, DG units, and D-STATCOM allocation (Case 7)

5. Discussion

The overall goal of this paper is the optimal allocation of DGs and D-STATCOMs in an RDS using the GSA for enhancing the system voltage and minimizing the power losses. The approach is also extended to solving the NR problem along with the allocation of DGs and D-STATCOM with loss minimization as an objective considering various operational constraints. The proposed approach is implemented and tested on standard 33 bus RDS to study the sustainability of the proposed approach. In this work, 7 cases are simulated.

In case 1 (which is referred to as base case), the power loss minimization objective is optimized without considering the NR and allocation of D-STATCOM and DG. Minimum loss reported is 202.68 kW and the minimum bus voltage reported is 0.9131 p.u. at bus 18. In case 2, only NR is considered without the allocation of D-STATCOM and DG, and the power loss reported is 138.6 kW, and it is 31.61% less when compared to the base case. Minimum voltage is also improved from 0.9131 p.u. to 0.9412 p.u.

In case 3, the optimization is simulated by the optimal allocation of DGs and optimal power loss obtained has the loss of 78.16 kW and it is 61.44% less compared to the base case. In case 4, optimization is performed by considering both NR and DG allocation simultaneously, and the obtained optimum power loss obtained has the power loss of 62.93 MW, and it is 68.95% less when compared to the case 1. The minimum voltage in the system also increased and it is 0.9692 p.u.

In case 5, optimization is performed by allocating D-STATCOM and NR. The obtained power loss is 78.32 kW and it is 61.36% less compared to the base case. In case 6, the optimization is executed by simultaneous allocation of D-STATCOM and DGs. The obtained power loss is 63.96 kW, and it's 68.44% less compared to the base case. In case 7, the optimization is executed by simultaneous D-STATCOM and DGs allocation along with the NR. Minimum loss incurred is 45.61 kW, and it is 77.50% less compared to the base case. The voltage profile of the entire RDS also increased and the minimum voltage obtained is 0.9735 p.u. At bus number 18.

5.1Limitations

In this paper, the NR is performed along with the optimal allocation of D-STATCOM and DGs on balanced IEEE 33 bus RDS, however, one of the limitations is its execution on a practical RDS by considering its unbalanced nature. This work also does not consider the specific type of renewable-based DG units and their uncertainty modelling. The optimal allocation problem of RDS can also be implemented by evaluating the system reliability indices. Another limitation of this work could be the modelling and allocation of DGs in the practical RDSs by considering the exact geographical location of the network. Electric vehicles and electric vehicle aggregators can also be integrated into the RDS for the improvement of voltage profile and power loss minimization.

A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

An efficient approach for an optimal allocation of D-STATCOM, DGs as well as ONR in RDSs. Minimization of network losses in the RDS is considered as an objective. Optimization techniques play an important role in getting optimal results in a distribution system. In that, recently developed metaheuristic optimization techniques reduce the search space and determine the optimal solution with less computational burden. In this paper, a GSA is used to optimize the real power loss of RDS. Various case studies are performed by considering different scenarios in IEEE 33 bus RDS. From the obtained simulation results, it is clear that the network loss has reduced drastically and the voltage profile of the system is enhanced. By this simultaneous approach, the power loss has reduced by 77.5% when compared to base case topology, and also minimum voltage in RDS has been increased from 0.9131 p.u. to 0.9735 p.u. The ONR of the radial distribution network by installing the electric vehicle aggregators is considered as a scope for future work.

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Conflicts of interest

The author has no conflicts of interest to declare.

Author's contribution statement

Surender Reddy Salkuti: Study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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Appendix I

S. No.	Abbreviation	Description
1	DG	Distributed Generation
2	D-STATCOM	Distribution Static Compensator
3	DSLF	Distribution System Load Flow
4	FBS	Forward-Backward Sweep
5	GSA	Gravitational Search Algorithm
6	LCM	Load Current Matrix
7	LSF	Loss Sensitivity Factor
8	MG	Microgrid
9	MVA	Megavolt Ampere
10	NR	Network Reconfiguration
11	ONR	Optimal Network Reconfiguration
12	PFM	Power Flow Matrix
13	PV	Photovoltaic
14	RDS	Radial Distribution System
15	SG	Smart Grid
16	SLD	Single Line Diagram
17	TV	Temporary Variable