Chapter 3

VOLTAGE STABILITY ENHANCEMENT AND LOSS REDUCTION WITH DG AND RECONFIGURATION

3.1 INTRODUCTION

The continuously increasing demand in transmission as well as distribution networks have rendered many planning and operational challenges such as maintaining voltage stability, network loss reduction and voltage profile improvement. Voltage stability is the ability of system to maintain bus voltages within permissible limits. According to IEEE/CIGRE joint task force, ‘‘Voltage stability is defined as the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition’’ [187]. The increased load of the distribution network and other disturbances creates risk to voltage instability of the network due to deterioration of voltage profile in a significant part of the network. A system with fairly good voltage profile having nearly the same voltage magnitude at all the buses at the base case operating point may also face voltage instability under severe contingencies. Thus, it is important to maintain sufficient voltage stability margin (the distance between the base case operating point and voltage stability limit). A continuously increasing load increases the chance of voltage collapse within the system. When voltage instability occurs, voltages at some buses may progressively fall or rise that may ultimately lead to voltage collapse. The main factor causing this problem is the inability of the power system to meet the reactive power demand as it is difficult to transmit reactive power under heavily loaded conditions. Voltage stability is a key issue in radial distribution networks as increase in demand may deteriorate voltage at remote buses to unacceptable limits leading to partial/complete blackout [112]. Voltage stability can be examined in terms of maximum loadability (λ_{max}) of the system. Several methods have been reported in the literature to evaluate maximum loadability [52], [56]–[58]. Remote end buses of radial distribution networks undergo very low voltage that poses threat of voltage instability as system may reach maximum loadability limit under contingencies [47]. Therefore, proper strategy is required to enhance maximum loadability of these networks in order to improve voltage stability. Optimal network reconfiguration and/ or placement of distributed generations (DGs) seem to be a viable solution for voltage stability enhancement of radial distribution networks.

This chapter proposes a multi-objective fitness function to enhance maximum loadability and reduce network losses by reconfiguration and DG unit allocation in the system. The fitness function has been optimized through the modified Grey Wolf Optimization (GWO) technique proposed in chapter 2. The maximum loadability obtained by the proposed approach has been compared with existing approaches to establish its effectiveness.

3.2 SOLUTION METHOD FOR THE RECONFIGURATION

Distribution network has number of switches, few of which remain normally opened and others remain normally closed. The normally open switches are termed as tie-switches, while those which are normally closed are termed as sectionalizer switches. The loads in the distribution system may be supplied by several ways through different paths depending upon existence of number of substations and feeders. Hence, the topology of distribution system may be altered by changing the status of sectionalizer and tie switches, depending upon the desired task to operate the system. Altering the topology of distribution system by means of opening and closing the tie and sectionalizer switches is known as network reconfiguration. Network reconfiguration has been proved as a viable solution to improve the system performance quite effectively if planned properly. Since, as the network size increases the number of these switches also increases, which makes it quite cumbersome to select the appropriate switches to reconfigure the network, hence proper algorithm must be incorporated to effectively achieve the reconfiguration of distribution system without violating the system constraints.

3.2.1 Reconfiguration using fundamental loops method and its demerits

In a radial distribution system (RDS), there are certain number of initially opened tie-switches and normally closed branches, in general. These normally closed branches are equipped with sectionalizer switches. Closing these tie-switches creates many numbers of loops in the system. To reconfigure the distribution system, associated sectionalizer switches of a set of particular branches in association with the available tie-switches must be opened and closed. Selection of these switches to alter the topology of network is a tedious and cumbersome job as there are huge numbers of possible combinations of switches. Generally, a random selection of these switches is done. To generate the random initial population, meta-heuristic methods have been proposed [188]. Thus, a random selection of these switches in the decision variable population creates large number of network configurations many of which may violate radial topology constraints as well as load bus disconnection while dealing with distribution network reconfiguration problem leading to infeasibility. Fundamental loop (FL) analysis is a viable and suggested solution to reduce this tedious job to a certain extent [189]. Selection of random switches in decision variable is now made only with associated fundamental loop. Fundamental loop analysis using graph theory not only ascertains the reduction in search space of network configuration but also elimination of many infeasible population generations. Total number of fundamental loops (nFL) present in an RDS is obtained using (3.1) given below:

$$nFL = NTie + b - nb + 1 \tag{3.1}$$

Total number of FLs in an RDS is same as the number of available tie-switches, NTie. Each FL has constituent branches and tie-switches associated with it. To determine the constituent/members of FLs, each loop-forming branch has been selected including the tie-switch closed to form the loop.

The incidence matrix 'A', is generated using the graphical method representation of distribution system [190]. The size of matrix 'A' is $b \times nb$. The element A_{ij} in matrix 'A' is obtained using expression (3.2):

$$A_{ij} = \begin{cases} 1, & \text{if branch i is away from } j^{th} \text{ bus} \\ -1, & \text{if branch i is incident to } j^{th} \text{ bus} \\ 0, & \text{otherwise} \end{cases} \tag{3.2}$$

To obtain the first FL, an open branch containing the first tie-switch is inserted into the incidence matrix'A'. The sum of the absolute value of each element in each column of matrix 'A' is evaluated. Buses which have the sum equals to 1 are identified. Branches connected to these buses are removed. The procedure is repeated until the sum result is no longer equal to 1. A vector is formed to store the remaining branches in matrix 'A' representing first FL. The remaining FLs are determined using the same procedure as the first FL [191], [192].

For a system having $NTie$ tie-switches, the required length of the decision vector becomes equal to $NTie$ as each switch is selected from each fundamental loop. Hence, the decision variables DV_R in this system are represented by actual branch/tie number as

$$DV_R = [TS_1, TS_2, \dots TS_i \dots \dots, TS_{NTie}] \tag{3.3}$$

where, TS_i is the branch/tie-switch to be opened in the i^{th} fundamental loop created by closing the tie switch associated with the loop. To illustrate this, Figure A.1 shown in Appendix A is represented as Figure 3.1 with the schematic of the IEEE 33-bus distribution system [126] as shown. In Figure 3.1, the digits 1, 2, 3, etc., represent the bus numbers, while the branches (switches) are numbered as b1, b2, b3,…. etc. Total five number of tie switches represented as b33, b34, b35, b36, and b37, forming five fundamental loops are present in this system. Details of these loops are also presented in Table 3.1.

However, selection of switches from each fundamental loop has its own demerits. Certain combinations of selected switches from each fundamental loop may isolate one or more system buses in radial distribution system. For simple understanding, consider the IEEE 33-bus distribution network shown in Figure 3.1. Let us suppose decision variable [b6 b14 b21 b7 b22] is generated with the selection of one switch from each fundamental loop. If this decision variable is selected, then load bus 7 will be isolated as both b6 and b7 belongs to fundamental loops 1 and 4. Both these branches are common to fundamental loops 1 and 4 and hence participation of such common branches between two loops must be restricted to only one in either loop. There are many more such combinations that exist between any two loops. Let us take another combination of switches [b6 b34 b8 b25 b5] selected from each fundamental loop. Opening of these switches isolate the load bus 6 from the distribution system. This is because of bus 6, which is common to fundamental loops 1, 4 and 5 and branches b6, b25 and b5 common between two loops participating, simultaneously. To overcome these demerits, each combination of decision variable for reconfiguration must adhere to a set of rules designed. And hence, the concept of switch selection from each fundamental loop needs to be modified based on certain rules.

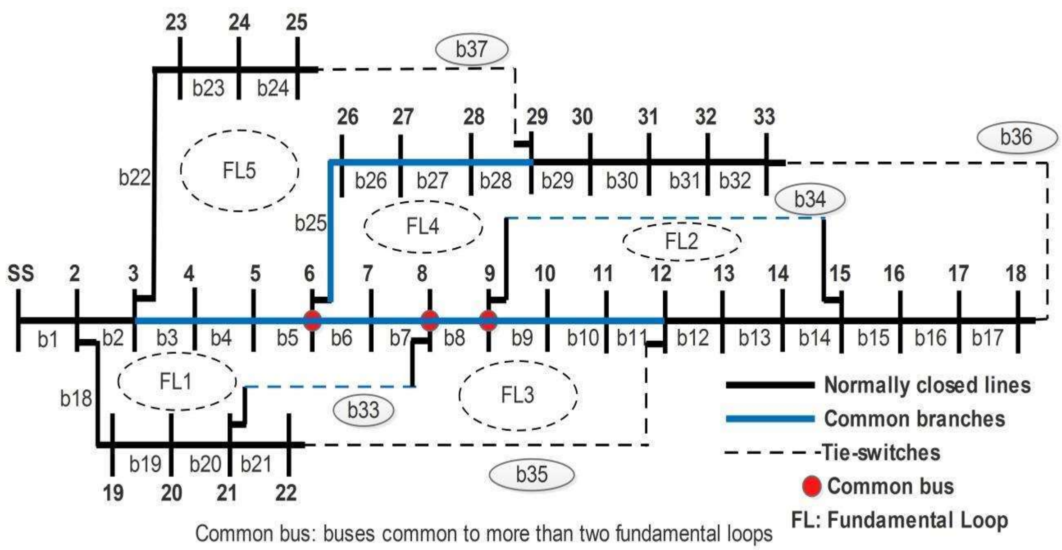

Figure 3.1 Schematic of IEEE 33-bus distribution system

Table 3.1: Fundamental loops for the IEEE 33-bus distribution system.

FL	Switches (Tie/Sectionalizer)	Tie-Switch	Length of FL
1	b2, b3, b4, b5, b6, b7, b18, b19, b20, b33	b33	10
2	b9, b10, b11, b12, b13, b14, b34	b34	7
3	b8, b9, b10, b11, b33, b21, b35	b35	7
4	b25, b26, b27, b28, b29, b30, b31, b32, b15, b16, b17, b34, b6, b7, b8, b36	b36	16
5	b3, b4, b5, b22, b23, b24, b25, b26, b27, b28, b37	b37	11

3.2.2 Rule based decision variables modification

Each decision variable must have $NTie$ number of elements in the decision variable of reconfiguration, representing the number of switches to be opened to operate system in a radial manner. To incorporate the demerits of fundamental loops reported in sub-section 3.2.1 the set of rules defined are as below:

Rule-1: At least one element must be chosen from each fundamental loop. $TS_i \in FL_i$.

Rule-2: If a common branch vector participates while creating a decision variable, it must be ensured that at most a single element is chosen.

Rule-3: While creating a decision variable it must be ensured that all the vectors with common branches of any restricted group must avoid the simultaneous participation.

To form the feasible decision variables, algorithm is explained as below [124]:

Step 1: Create fundamental loop vectors, having the set of switches in each fundamental loop, as shown in Table 3.1.

Step 2: Obtain the decision variable such that TS_i belonging to FL_i following the 1^{st} rule.

Step 3: Obtain vectors of common branches, B_{jk} , having the set of switches common between two loops FL_j and FL_k.

Step 4: Obtain vectors of restricted group RG_i, cluster of common branch vectors incident at the i^{th} common bus(es) of the distribution network.

Step 5: Check and modify the decision variable to satisfy the feasibility based on the 1^{st}, 2^{nd} and 3^{rd} rules designed.

The 1^{st} rule ensures the selection of switches to be opened from each fundamental loop and prevention of any load bus disconnection at the exterior of the network, while 2^{nd} and 3^{rd} rules prevent the disconnection of the load buses at the interior of the network. Hence, these rules ensure the generation of feasible decision variables with radiality of the network as well as prevention of any bus disconnection. In this work, GWO is adapted using basics of graph theory to populate the decision variables. The GWO guided by set of rules defined above modifies the infeasible decision variable into feasible one during the iteration process. This algorithm bypasses the hectic mesh check and overcomes the deficiency of the reconfiguration method by [189], [190], [192] to create feasible decision variables. To understand the algorithm for reconfiguration, let us consider the IEEE 33-bus distribution network, shown in the Figure 3.1.

Table 3.2: Vectors of common branches for the IEEE 33-bus RDS.

Vectors of common branches.	
$CB_{13} = [b33]$	$CB_{24} = [b34]$
$CB_{14} = [b6, b7]$	$CB_{34} = [b8]$
$CB_{15} = [b3, b4, b5]$	$CB_{45} = [b25, b26, b27, b28]$
$CB_{23} = [b9, b10, b11]$	

Table 3.3: Vectors of restricted group for the IEEE 33-bus RDS.

Vectors of restricted group	**Common bus(es) disconnected**
$RG_6 = [CB_{14}\ CB_{15}\ CB_{45}]$	6
$RG_8 = [CB_{13}\ CB_{14}\ CB_{34}]$	8
$RG_9 = [CB_{23}\ CB_{34}\ CB_{24}]$	9
$RG_{68} = [CB_{13}\ CB_{15}\ CB_{34}\ CB_{45}]$	6, 8
$RG_{89} = [CB_{13}\ CB_{14}\ CB_{23}\ CB_{24}]$	8, 9
$RG_{689} = [CB_{13}\ CB_{15}\ CB_{23}\ CB_{24}\ CB_{45}]$	6, 8, 9

The list of vectors of common branches between two fundamental loops, obtained from Figure 3.1, are presented in Table 3.2. The restricted group vectors and the associated common buses that may be disconnected, if all the common branch vector participate in decision variable creation for the system are obtained from Figure 3.1 and shown in Table 3.3. For the distribution system shown in Figure 3.1, the decision variable constitutes total five switches selected from each fundamental loop according to 1^{st} rule. Suppose the decision variable [b20 b13 b35 b26 b25] is populated at any instant of iteration. It can be observed that this decision variable is violating the 2^{nd} rule as both b26 and b25 switches belong to CB_{45}. If this decision variable is selected, then load bus 26 will be isolated. Let us Consider another infeasible decision variable [b7 b34 b8 b25 b4], violating the 3^{rd} Rule, since switches b7, b25, b4 belong to vector of common branches CB_{14}, CB_{45} and CB_{15} respectively, which falls under the vectors of restricted group $RG_6 = [CB_{14}\, CB_{15}\, CB_{45}]$ isolating common bus 6. Selecting switches for reconfiguration creates many more infeasible decision variables which can be converted into feasible ones in accordance with $1^{st}, 2^{nd}$and 3^{rd} rules. To demonstrate the modification of infeasible decision variable into the feasible decision variable under the guidance of vectors of common branches and restricted groups are shown in Figure 3.2 through an example. As shown in Figure 3.2 decision variable [b20 b13 b35 b26 b25] populated at any stage of iteration, violates the 2^{nd} rule. According to 2^{nd} rule switches [b25 b26 vb27 b28], which belong to CB_{45} and hence only one switch has to participate either in 4^{th} or 5^{th} fundamental loop from this vector. Therefore, 4^{th} loop switch is modified under the guidance of $1^{\text{st}}, 2^{\text{nd}}$ and 3^{rd} rules replacing the switch b25 by b29 creating a feasible decision variable [b20 b13 b35 b29 b25].

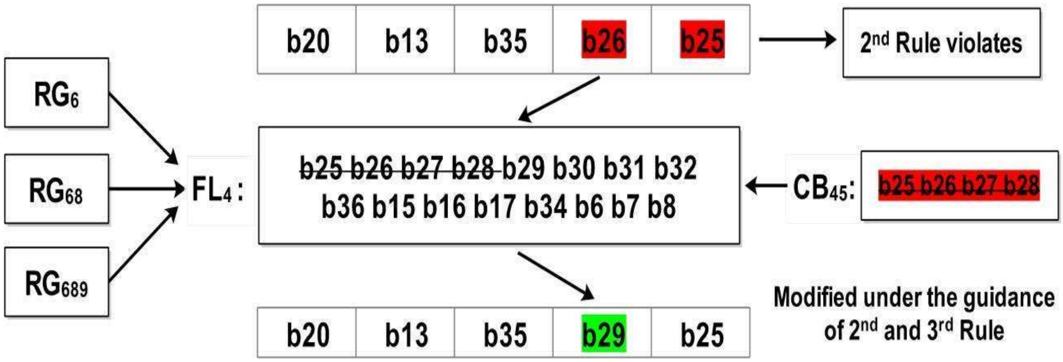

Figure 3.2. Modification of decision variable.

Once the modification of decision variables for reconfiguration under guided rule is performed the radiality is insured by checking the resulting network for radiality. Present work has checked radiality of the network using (3.4) and (3.5), where (3.5) corresponds to commands written in MATLAB to check radiality of the network.

$$nb = b + 1 \tag{3.4}$$

where, nb and b are number of buses and closed branches of the system.

$$graphisspantree(G) = \begin{cases} 1, & \text{radial} \\ 0, & \text{non} - \text{radial} \end{cases} \tag{3.5}$$

where, G is the adjacency matrix of the network under consideration.

To check the radiality of network following steps are performed.

Step 1: Generate the adjacency matrix G $(nb \times nb)$ considering all the tie and sectionalizer switches closed.

Step 2: Update and modify G by replacing the '1's by '0's for the set of open tie and sectionalizer switches obtained by modifying the initially generated combinations of switches as discussed in Section 3.2.2.

Step 3: Test the radiality of network using MATLAB function '$graphisspantree\ (G)$'.

The command '$graphisspantree\ (G)$' is sufficient and enough condition to ensure the radiality of the system generated by modifying the combination of switches availed. It is logical 1 or 0 for verifying the radiality as expressed in (3.5).

3.3 PROBLEM FORMULATION: OBJECTIVE FUNCTION AND CONSTRAINTS

In this work, network reconfiguration and DG allocation have been performed for a certain designed set of objective functions. To achieve the optimum solution space with the optimum objective, the modified Grey Wolf Optimization tool has been implemented. Real power loss minimization is the main factor that distribution companies want to perform since this objective is not only economically favourable to distribution companies worldwide but also it enhances the operational constraints of the distribution system. Apart from this, increasing load demand restricts the distribution system planners to operate it within the stable region, beyond a particular load the network does not remain stable and becomes unstable. To accomplish the increased load demand and stable system operation, voltage stability or loadability limit of the system must be incorporated in the objective problem formulation. Therefore, a multi-objective function has been proposed in this work that considers power loss minimization and voltage stability enhancement under DG placement and reconfiguration. The formulation of proposed multi-objective function is presented below:

3.3.1 Proposed Multi-objective Function

The real power loss P_L under reconfigured network is given by function, f_1, as,

$$f_1 = P_L = \sum_{i=1}^{b} sw_i[I_i^2 R_i] \tag{3.6}$$

where sw_i is the status of i^{th} branch, sw_i=0 if the switch is open and sw_i=1, if it is closed, P_L is total network real power loss i.e. sum of real power losses in all closed branches, I_i is magnitude of current flowing in i^{th} branch and R_i is the resistance of i^{th} branch, and b represents total number of branches.

Voltage stability index is given by objective function, f_2 as per following:

$$f_2 = DVSI_{system} = \sum_{i=1}^{nb} [VSI_i] \tag{3.7}$$

where,

$$VSI_i = |V|_{i-1}^4 - 4(P_{ei}X_i - Q_{ei}R_i)^2 - 4(P_{ei}R_i - Q_{ei}X_i)|V|_{i-1}^2 \quad \forall \text{ i} \in \text{ [2 nb]} \tag{3.8}$$

$DVSI_{system}$ represents voltage stability index of whole distribution system. Determination of VSI_i is explained by means of a simple distribution network shown in Figure 3.3. In Figure 3.3, P_{ei} and Q_{ei} represent effective real and reactive power demand at i^{th} bus in two bus equivalent network [139], X_i represents reactance of i^{th} closed branch and nb represents total number of buses present in the system.

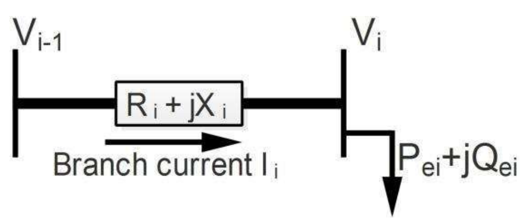

Figure 3.3: Simple distribution network line.

The effective load P_{ei} (Q_{ei}) at i^{th} bus can be evaluated by addition of all real (reactive) demands at i^{th} bus and all other buses beyond i^{th} bus towards remote end and the addition of real (reactive) losses incurred across all the branches beyond i^{th} bus towards remote end.

Minimization of a multi-objective problem formulation has been proposed in this work that considers minimization of network losses and maximization of voltage stability. The proposed multi-objective function is given as:

$$f = w_1 f_1 - w_2 f_2 \tag{3.9}$$

$$\text{subjected to } w_1 + w_2 = 1 \tag{3.10}$$

where, w_1 and w_2 represent weightage assigned to f_1 and f_2, respectively. To convert the maximization optimization formulation into minimization, negative sign has been assigned to the objective function, f_2. The proposed multi-objective function has been minimized under set of equality constraints, presented in Section 2.5.2 (chapter 2) and inequality constraints presented in Section 2.5.3 (chapter 2) and radiality constraint given by (3.4) and (3.5). Present work has considered placement of Type-1 DG, only at a single optimal location. Hence, inequality constraints (2.27), (2.29) and (2.30) have not been considered in this work.

Satisfaction of (3.4) and (3.5) ensures continuation of radiality of the network under reconfiguration.

3.4 PROPOSED MODIFIED GWO BASED ALGORITHM FOR MULTI-OBJECTIVE FUNCTION

The application of the modified GWO algorithm for the reconfiguration of the distribution system by closing/opening of branch/tie switches to evaluate the proposed multi-objective function is presented in this section. In this work, a number of cases that consist of reconfiguration with and without simultaneous allocation of single DG injecting only real power are taken to minimize the objective function using GWO. To reconfigure the distribution system, variables of decision vector, DV_R are same as the total number of loops (represented by a discrete variable) present in the system as given by (3.3).

However, for the application of simultaneous DG allocation and reconfiguration, the length of decision variables in the decision vector DV_{RDG}, are equivalent to the addition of elements in DV_R and double the number of DG, each for DG location (discrete variable DG_l) and DG size (continuous variable DG_s) as represented below:

$$DV_{RDG} = [TS_1, TS_2, \dots \dots, TS_{NTie} \quad DG_l \quad DG_s] \tag{3.11}$$

For better understanding, further, the variables either for switches, location and size will be denoted as U_x (x = 1, 2, 3, . . . , N). This notation will be used for optimal switches, location and size of DG to evaluate the fitness function.

In the start, GWO optimization parameters are assigned and a Decision Vector Population Matrix (DVPM) is created. Every row of DVPM is denoted by a decision vector. The elements of the $DV_R(U_x)$ are generated using (3.12) as shown below:

$$U_x^k = U_{min,x} + rand(U_{min,x} - U_{max,x}) \tag{3.12}$$

where, $rand$ represents generation of random variables in the range $(U_{min,x} - U_{max,x})$. The population matrix of decision vectors DVPM is generated using (3.13) as shown below:

$$DVPM = \begin{bmatrix} U_1^1 & U_2^1 & U_3^1 & \cdots & U_{N-1}^1 & U_N^1 \\ U_1^2 & U_2^2 & U_3^2 & \cdots & U_{N-1}^2 & U_N^2 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ U_1^{P-1} & U_2^{P-1} & U_3^{P-1} & \cdots & U_{N-1}^{P-1} & U_N^{P-1} \\ U_1^P & U_2^P & U_3^P & \cdots & U_{N-1}^P & U_N^P \end{bmatrix} \tag{3.13}$$

In GWO the decision vector represents the grey wolf. Corresponding to grey wolf evaluated fitness function given by (3.9) represents the position of prey.

The flowchart for proposed modified GWO based voltage stability enhancement and loss reduction approach under optimal DG placement and network reconfiguration is shown in Figure 3.4. As per this flowchart maximum loadability of the system is computed under optimal fitness function and decision variables, where decision variables may consist of open status of tie-switches, DG location and size.

The following three cases have been studied to examine impact of network reconfiguration alone as well as simultaneously with DG unit for loss reduction and voltage stability margin (maximum loadability) enhancement.

Case 1: It is a case study of base-case i.e. without reconfiguration or DG placement.

Case 2: It is an application of only network reconfiguration.

Case 3: It is the case study for simultaneous reconfiguration and DG allocation.

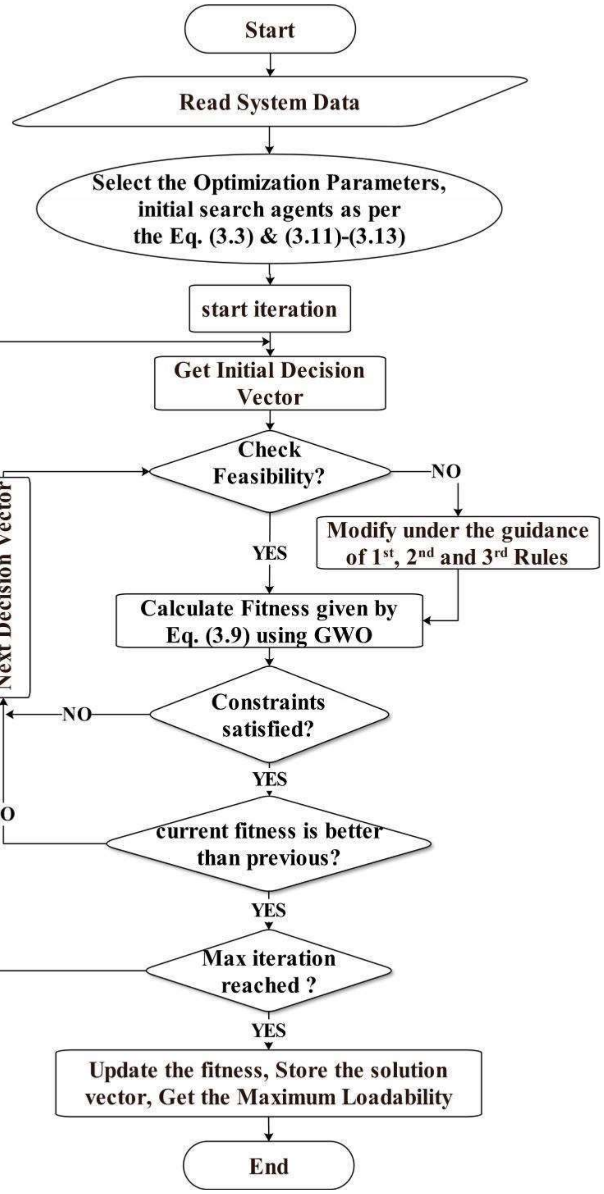

Figure 3.4: Flowchart for minimization of multi-objective function using modified GWO algorithm

3.5 MAXIMUM LOADABILITY CALCULATION

In voltage stability analysis, one of the most significant part is the determination of maximum system loadability. Considering a load case, a successive load flow utilizes the network solution to evaluate the minimum voltage magnitude till the collapse point (i.e., where the load flow solution diverges) to evaluate the voltage stability margin [58] and to draw the loadability curve. The voltage stability margin is calculated in terms of maximum loadability. The voltage stability margin is termed as the extent from an operating point to a voltage collapse point until the load increment can be served without fail. In the successive procedure, the active and reactive load power at each bus in the system is increased repeatedly by a loading factor λ given by:

$$P_{new} = P_0(1 + \lambda) \tag{3.14}$$

$$Q_{new} = Q_0(1 + \lambda) \tag{3.15}$$

where, P_0 and Q_0 are the active and reactive power loads at initial operating point, and P_{new} and Q_{new} are new active and reactive power demand at loading factor λ which has been increased at a rate of 1% in this work.

Voltage stability margin has been defined as the distance between initial operating point (loading factor $\lambda = 0$) to maximum loadability point having loading factor as λ_{max}. Maximum loadability point has been obtained based on the divergence of load flow. Voltage stability margin has been shown in Figure 3.5 representing loading factor, λ vs. voltage magnitude curve for the system. The flowchart in Figure 3.6 presents the algorithm to calculate the maximum loadability. The flowchart in Figure 3.6 is based on divergence of load flow solution at the nose point beyond which voltage magnitude at the bus no more decreases.

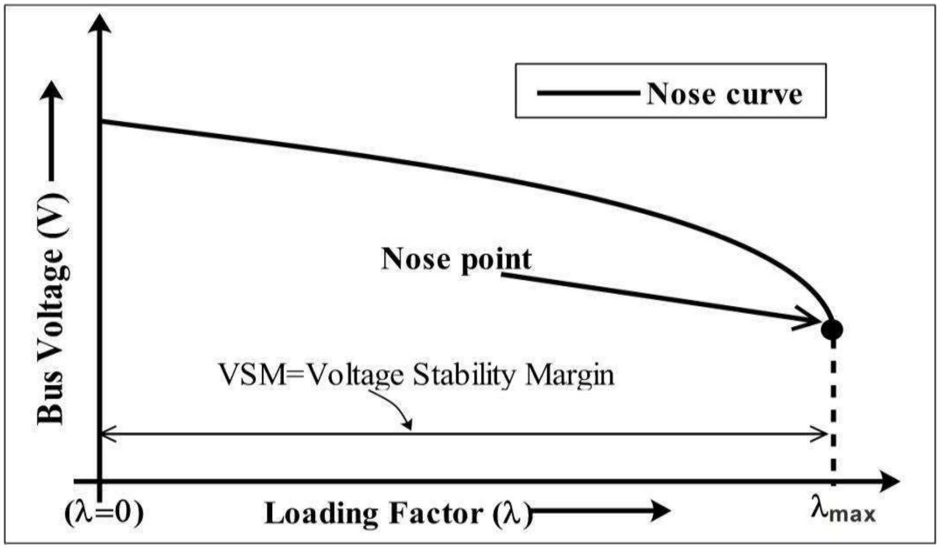

Figure 3.5: Maximum loadability calculation by nose curve

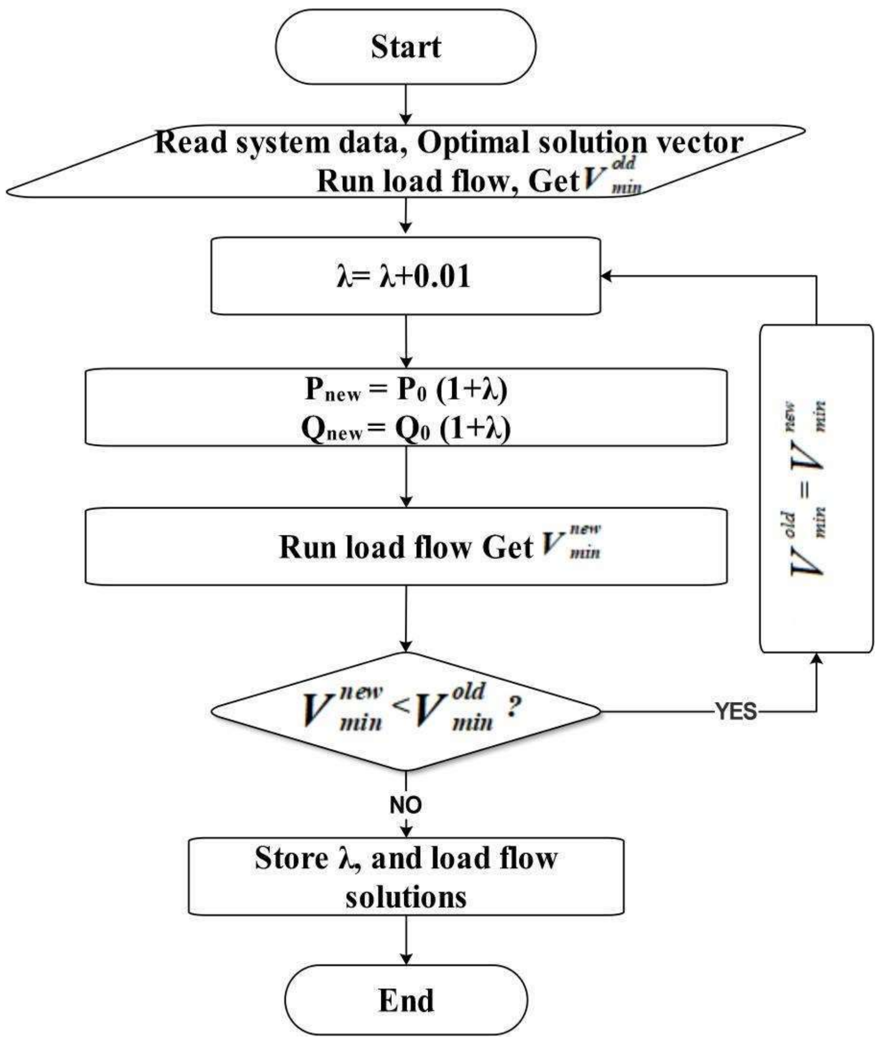

Figure 3.6: Flow chart for determination of maximum loadability

3.6 INDICES TO EXAMINE SYSTEM PERFORMANCE

To analyse the effects of reconfiguration and/or DG placement, different performance indices [113] have been evaluated. These indices are defined as below:

3.6.1 Number of voltage limit violating buses (NVVB)

$NVVB$ signifies the number of buses violating the permissible voltage limits in the system considered.

3.6.2 Voltage deviation index (VDI)

In order to specify the measure of violation of limits imposed on voltage magnitudes at buses in an nb bus system, the voltage deviation index (VDI) is defined as:

$$VDI = \sqrt{\frac{\sum_{i\in[NVVB]}(V_i - V_{limit})^2}{nb}} \tag{3.16}$$

where, i belong to set of buses $[NVVB]$ violating upper or lower voltage limit.

V_i = voltage magnitude at bus-i.

V_{limit} = upper or lower voltage limit.

During reconfiguration and DG placement, VDI signifies the amount of voltage fluctuation at buses violating voltage limits. It is desired to have zero voltage deviation index (VDI), i.e. voltage at all buses should be within permissible limits.

3.6.3 Voltage profile improvement index (VPI)

The voltage profile improvement index (VPI) is given as,

$$VPI = \sqrt{\sum_{i=1}^{nb}\left(V_i^{base} - V_i^{REC/DG}\right)^2} \tag{3.17}$$

where,

V_i^{base} = voltage magnitude at bus-i at the base case operating point.

$V_i^{RDG/DG}$ = voltage magnitude at bus-i after reconfiguration and /or DG placement.

In a radial distribution system at base load condition, the voltage at remote buses fall much below the desired 1 pu value, due to voltage drop in lines. With the incorporation of distributed generation and/ or tie-switch allocation the voltage at each bus changes to different operating value. Incorporation of these devices in system leads to further rise or drop in voltages leading to improvement or deterioration in voltages at a specific or set of buses in the network. Hence, voltage profile improvement index (VPI) signifies the appropriate selection of these devices/strategies (Reconfiguration and DG placement considered in this chapter) for enhancement of the voltage profile of the network.

3.6.4 Qualified load index (QLI)

Qualified load index is defined as:

$$QLI = \sum_{i=1}^{nb} V_i \, . P_{L,i}^{base} \quad (3.18)$$

where, $P_{L,i}^{base}$ = real power drawn by load at bus-i at the base case operating point.

A higher value of QLI represents higher distance of base case operating point from the maximum loadability point as bus voltages are high in magnitude, and therefore, minimum acceptable voltage may occur at higher loading condition. Thus, QLI is an index helpful in assessing voltage stability margin (The distance between the base case operating point and maximum loadability point). QLI may be enhanced by optimal DG placement/network reconfiguration. Modified QLI after DG placement/network reconfiguration is given by:

$$QLI^m = \sum_{i=1}^{nb} V_i^{\mathrm{REC/DG}} . P_{L,i}^{base} \tag{3.19}$$

where, QLI^m represents modified value of QLI after network reconfiguration/DG placement.

It is apparent that by improving QLI by network reconfiguration and DG placement, voltage stability of radial distribution system may be enhanced.

3.6.5 Active power loss reduction (%APLR)

$APLR$ represents percent reduction in active power loss and is given by:

$$\%APLR = \frac{APL_{old} - APL_{new}}{APL_{old}} \times 100 \tag{3.20}$$

where,

APL_{old} = active power loss in the radial distribution system without DG and/ or reconfiguration.

$AP\ _{new}$ = active power loss in the radial distribution system with DG and/ or reconfiguration.

3.6.6 Reactive power loss reduction (%QPLR)

$QPLR$ represents percent reduction in reactive power loss and is given by:

$$\%QPLR = \frac{QPL_{old} - QPL_{new}}{QPL_{old}} \times 100 \tag{3.21}$$

where,

QPL_{old}= reactive power loss in the radial distribution system without DG and/ or reconfiguration

QPL_{new} = reactive power loss in the radial distribution system with DG and/ or reconfiguration

All the indices defined in this section have been summarized in Table 3.4.

Table 3.4: Performance indices [113] used in this work

$\%APLR = \frac{APL_{old} - APL_{new}}{APL_{old}} \times 100$
$\%QPLR = \frac{QPL_{old} - QPL_{new}}{QPL_{old}} \times 100$
$NVVB = length(V_i^{REC/DG} < V_{L,min} \; and \; V_I^{REC/DG} > V_{L,max})$
$VDI = \sqrt{\frac{\sum_i^{NVVB}(V_i - V_{limit})^2}{nb}}$
$VPI = \sqrt{\sum_i^{nb}\left(V_i^{base} - V_i^{REC/DG}\right)^2}$
$QLI == \sum_{i=1}^{nb} V_i^{REC/DG} . P_{L,i}^{base}$
$QLI^m = \sum_{i=1}^{nb} V_i^{REC/DG} . P_{L,i}^{base}$ pu

3.7 RESULTS AND DISCUSSION

3.7.1 Test system 1 (33-bus RDS)

Numerical simulation is accomplished on IEEE 33-bus, 37 branch distribution system [126]. It has 33 buses, 32 generally closed branches and 5 tie switches generally kept open with 4 feeders. The total load demand on substation bus of this RDS constitutes 3.715 MW of real power load and 2.3 MVAr of reactive power load, respectively. The details of the system configuration and related data are given in Appendix A. The simulation study is performed using code developed on MATLAB on a system having Intel(R) Core(TM) i7-8700 CPU @ 3.20 GHz processor.

Table 3.5, displays the optimal load flow outcome of IEEE 33-bus distribution system for the different cases under study. It can be realized that 202.68 kW of real power loss is incurred in the system at base case. The maximum loadability of the base case system without reconfiguration is found to be 2.63. The farthest bus 18 possesses the lowest voltage of 0.9131 pu in the system. Table 3.5 also presents the outcome of reconfiguration with and without DG allocation in IEEE 33-bus RDS. It is observed from Table 3.5 that simultaneous reconfiguration and DG placement (Case 3) results in maximum reduction in power loss, and maximum voltage stability enhancement. Simultaneous reconfiguration and DG placement results in best other performance indices too, for IEEE 33-bus radial distribution system. Figure 3.7 shows comparison of voltage vs. loading factor curves obtained by proposed approach and existing approaches. Figure 3.8 shows comparison of voltage profile obtained by proposed approach and existing approaches. It is observed from Figure 3.7 and Figure 3.8 that simultaneous reconfiguration and DG placement by proposed approach results in best enhancement in maximum loadability and voltage profile compared to existing approaches.

Table 3.5: Results for cases under study for IEEE 33-bus RDS

Items/Cases	**Proposed Approach**		
	Case 1	**Case 2**	**Case 3**
Open switches	33, 34, 35, 36, 37	7, 10, 24, 28, 32	14, 20, 32, 35, 37
DG MW @ bus	NA	NA	3.6397 @ 6
APL (kW)	202.68	140.7058	**114.72**
QPL (kVAr)	135.14	105.4183	**83.799**
λ_{max}	2.63	4.26	**5.29**
NVVB	21	8	**0**
VDI	0.020197	0.002524	**0**
VPI	0	0.023689	**0.057445**
QLI/QLI$_m$	3.53112	3.579628	**3.6527**
APLR%	NA	30.5764	**43.395**
QPLR%	NA	21.994	**37.991**
V_{min} @ bus	0.9131 @ 18	0.9413 @ 32	**0.96887 @ 32**
V_{max} @ bus	**1 @ 1**	**1 @ 1**	**1 @ 1**

NA- Not applicable

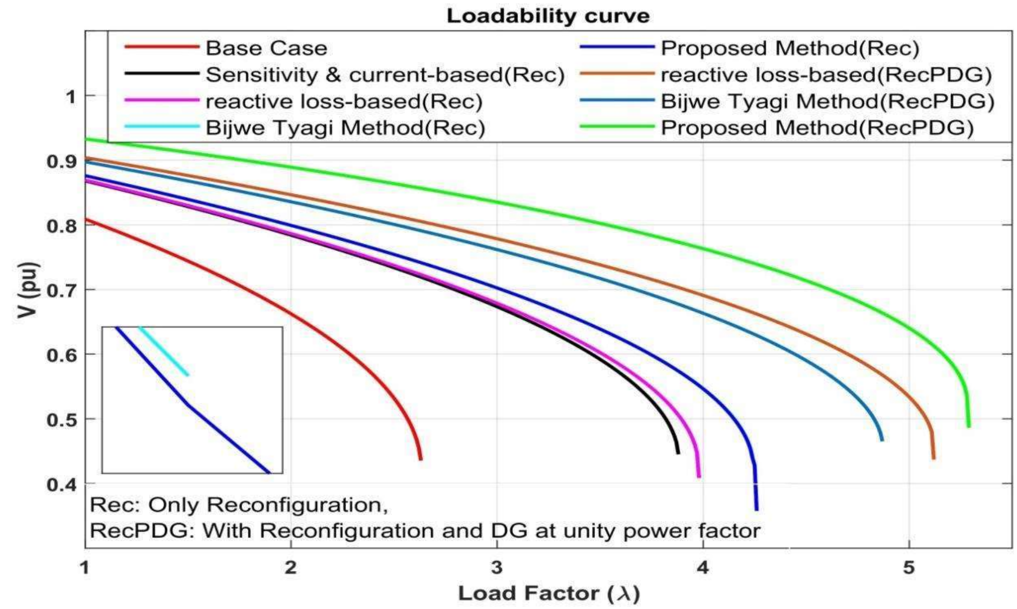

Figure 3.7: loadability curve for different cases for 33-bus RDS

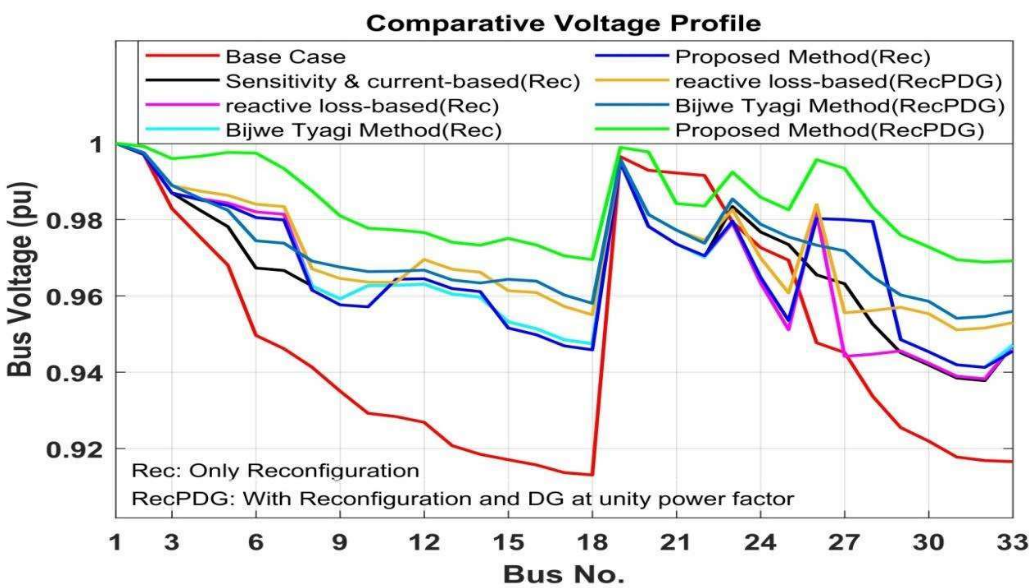

Figure 3.8: Voltage profile for different cases for 33-bus RDS

The work reveals the efficacy of the proposed method to enhance/improve the maximum loadability by simultaneously allocating the DG and reconfiguring the RDS. The system performance enhancements are realized based on the performance indices defined in Table 3.4 and have been presented in Table 3.5. The different results and their comparison with the work in existing literature are accessible in Table 3.6 and Table 3.7. The consequences of results are analysed as below:

i. From Table 3.5, it is perceived that with decrease in APL and QPL enhancement in λ_{max} is observed with reconfiguration and simultaneous application of reconfiguration and DG allocation. The extreme improvement in λ_{max} is witnessed as 101.14% for Case 3. The Reductions of 30.58% and 21.99% in APL and QPL are noticed, w.r.t. base case. While improvement in the lowest system voltage is achieved to 0.96887 pu with this case.

ii. The QLI of Case 3 is found to be maximum. With respect to Case 2 the enhancement in QLI for Case 3 is found to be 2.041%.

iii. A noteworthy enhancement in the maximum loadability corresponding to Case 3 has been observed with $\lambda_{max} = 5.29$.

iv. The simultaneous application of optimal DG allocation and reconfiguration enhances the maximum loadability of the RDS without violating the bus voltage limits.

v. From Table 3.6, It can be noticed that proposed algorithms give the marginally better result than [143] and much better result than [193] and [194] in terms of enhancing the maximum system loadability for Case 2 considering reconfiguration only.

vi. From Table 3.5 it is noticed that there are 21 and 8 buses in the RDS which violate the permissible voltage limits for Case 1 and Case 2, respectively. Nevertheless, Case 3, implies a significant enhancement in the RDS voltage magnitude with all the bus voltages lying within the permissible voltage limit.

vii. With the application of reconfiguration and DG injection it is found that Case 3 gives much better results than [143] in terms of maximum loadability as shown in Table 3.7. For Case 3, voltages at all the buses lie within the permissible limits. Minimum voltage also gets enhanced, however power loss increases compared to existing approaches.

Table 3.6: Comparison of results for reconfiguration (Case 2) for IEEE 33-bus RDS

Method	λ_{max}	V_{min}	**APL (kW)**	**Open Switches**
Without Reconfiguration	2.63	0.9131	202.67	33, 34, 35, 36, 37
Sensitivity Approach [193]	3.87	0.9378	**139.55**	7, 9, 14, 32, 37
Current-based approach [194]	3.87	0.9378	**139.55**	7, 9, 14, 32, 37
Reactive loss approach [143]	3.96	0.9383	147.25	7, 9, 14, 26, 32
Bijwe, Tyagi method [143]	4.23	**0.9413**	139.98	7, 9, 14, 28, 32
Proposed approach	**4.26**	**0.9413**	140.75	7, 10, 14, 28, 32

Table 3.7: Comparison of results for reconfiguration and DG (Case 3) for IEEE 33-bus RDS

Method	λ_{max}	V_{min}	APL (kW)	Open Switches	DG size @ bus
Reactive loss approach [143]	4.86	0.9511	99.77	7, 11, 14, 26, 30	0.25 @ 16, 0.25 @ 17 0.25 @ 18
Bijwe, Tyagi method [143]	5.11	0.9541	92.91	7, 9, 14, 30, 37	0.25 @ 16, 0.25 @ 17 0.25 @ 18
Proposed approach	5.29	0.96887	114.72	14, 20, 32, 35, 37	3.6397 @ 6

Consequently, Case 3 awards a considerable enhancement in the performance indices and harvests best maximum loadability. The proposed multi-objective algorithm for enhancement of maximum system loadability increases the network loadability with considerable reduction in active power loss, with all buses within the specified voltage limits.

3.7.2 Test system 2 (69-bus RDS)

To validate the study further, numerical simulation is accomplished on IEEE 69-bus, 73 branch distribution system [58]. It has 69 buses, 68 generally closed branches and 5 tie switches generally kept open with 7 laterals. The total load demand on substation bus of this RDS constitutes 3.802 MW of real power load and 2.694 MVAr of reactive power load, respectively. The details of the system configuration and related data are given in Appendix B.

Table 3.8, displays the optimal load flow outcome of IEEE 69-bus distribution system for the different cases under study. It can be realized that 224.95 kW of real power loss incurred in the system at base case. The maximum loadability of the base case system without reconfiguration is found to be 2.22. The farthest bus-65 possesses the lowest voltage of 0.9092 pu in the system. Table 3.8, also presents the outcome of reconfiguration with and without DG allocation of the IEEE 69-bus RDS. It is observed from Table 3.8 that simultaneous reconfiguration and DG placement (Case 3) results in maximum reduction in power losses and maximum voltage stability enhancement. Simultaneous reconfiguration and DG placement results in best other performance indices too, for IEEE 69-bus radial distribution system.

Table 3.8: Results for cases under study for IEEE 69-bus RDS

Items/Cases	**Proposed Approach**		
	Case 1	**Case 2**	**Case 3**
Open switches	69, 70, 71, 72, 73	14, 58, 61, 69, 70	23, 57, 69, 70, 71
DG MW @ bus	NA	NA	2.34639 @ 62
APL (kW)	224.95	98.59	**65.43**
QPL (kVAr)	102.14	92.03	**48.88**
λ_{max}	2.22	4.51	**8.77**
NVVB	9	0	**0**
VDI	0.01185	0	**0**
VPI	0	0.19241	**0.23598**

QLI/QLI$_m$	3.6189	3.6972	**3.7559**
APLR%	NA	56.17	**70.92**
QPLR%	NA	9.89	**52.14**
V_{min} @ bus	0.9092 @ 65	0.95 @ 61	**0.9750 @ 22**
V_{max} @ bus	1 @ 1	1 @ 1	1 @ 1

NA- Not applicable

Loadability curves (voltage vs. loading factor curves), bus voltage profile, real and reactive power losses have been shown in figure 3.9, Figure 3.10, and figure 3.11, respectively, for base case, Case 1 with proposed approach and Case 2 with proposed approach. It is observed from Figure 3.9, Figure 3.10 and Figure 3.11 that Case 3 (simultaneous network reconfiguration and DG placement) results in best enhancement in maximum loadability (voltage stability margin) and voltage profile, and highest reduction in real and reactive power losses compared to other two cases.

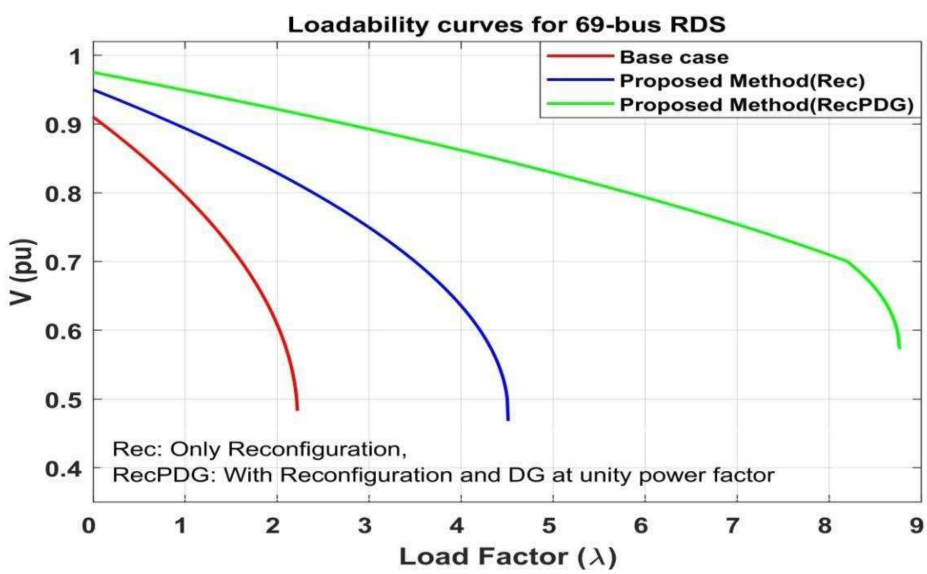

Figure 3.9: loadability curve for different cases for 69-bus RDS.

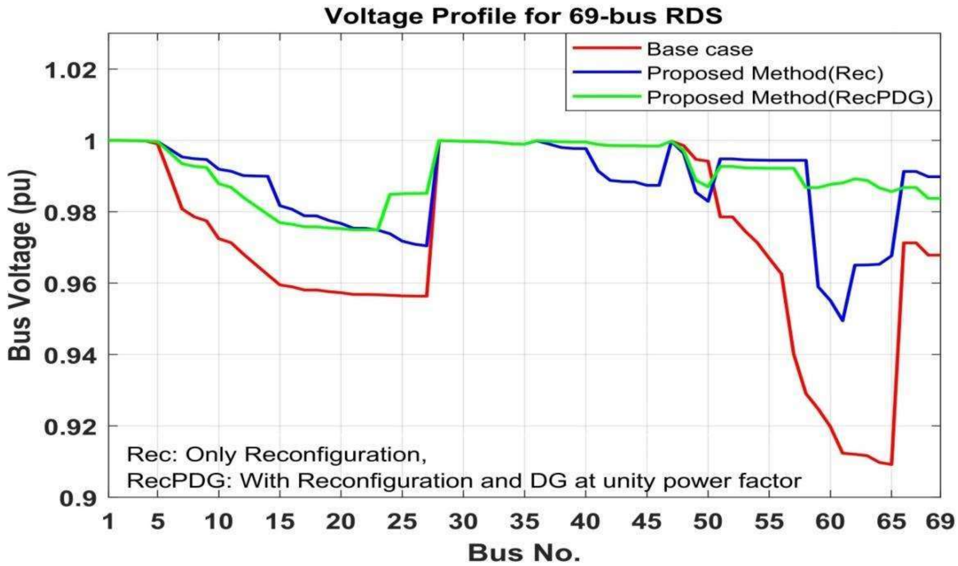

Figure 3.10: Voltage profile for different cases for 69-bus RDS

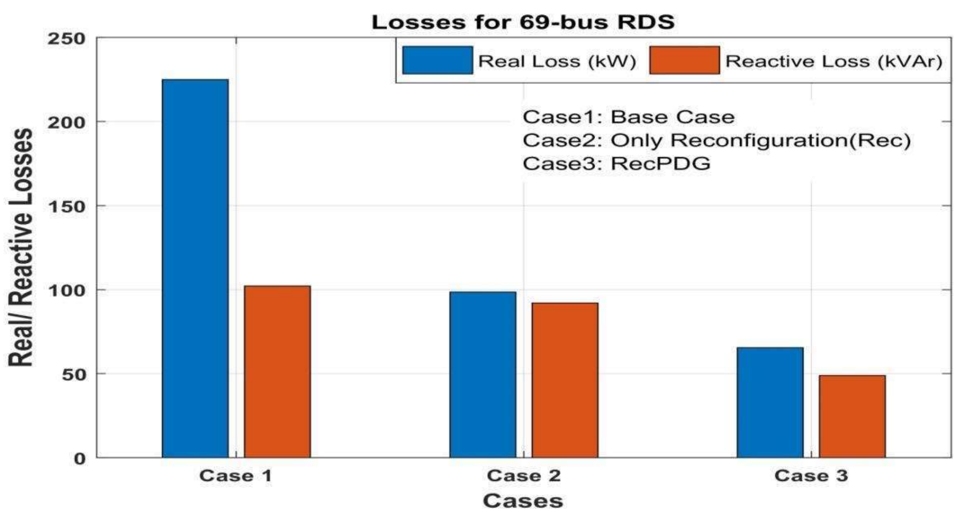

Figure 3.11: Losses with different cases for 69-bus RDS

The work reveals the efficacy of the proposed method to improve the maximum loadability by simultaneously allocating the DG and reconfiguring the RDS. The system performance enhancements are realized based on the performance indices defined in Table 3.4 and have been presented in Table 3.8. The different results and their comparison with the work in existing literature are accessible in Table 3.9 for Case 2. The consequences of results are analysed as below:

i. From Table 3.8, it is perceived that with decrease in APL and QPL, enhancement in λ_{max} is observed with reconfiguration and simultaneous application of reconfiguration and DG allocation. The extreme improvement in λ_{max} is witnessed as 295.05% for Case 3. The Reductions of 70.92% and 52.14% in APL and QPL are noticed w.r.t. base case. While improvement in the lowest system voltage is achieved to 0.9750 pu with this case.

ii. The QLI of Case 3 is found to be maximum. With respect to Case 1 the enhancement in QLI for Case 2 and Case 3 are found to be 2.16% and 3.79%, respectively.

iii. A noteworthy enhancement in the maximum loadability corresponding to Case 3 has been observed with λ_{max} = 8.77, while the same has been observed as 4.51 for Case 2.

iv. The simultaneous application of optimal DG allocation and reconfiguration enhances the maximum loadability of the RDS without violating the bus voltage limits.

v. From Table 3.9, It can be noticed that proposed algorithms give the marginally better result than [136], [142] and much better result than [195] in terms of enhancing the maximum system loadability for Case 2 considering reconfiguration only.

vi. From Table 3.8 it is noticed that there are 9 buses in the RDS which violates the permissible voltage limits for Case 1 i.e. base case configuration. Nevertheless, Case 2 and Case 3 imply a significant enhancement in the RDS voltage magnitude with all the bus voltages lying within the permissible voltage limit.

vii. With the application of reconfiguration and DG injection it is found that Case 3 gives much better results in terms of maximum loadability, and reduction in power losses along with other performance indices as shown in Table 3.8. Voltage at all the buses lie within the permissible limits with the higher minimum bus voltage.

viii. The index for voltage profile improvement shows that the Case 3 attains highest improvement followed by Case 2.

ix. The Voltage deviation has reduced to zero for both Case 2 and Case 3, as compared to voltage deviation present in Case 1. This implies that all the voltages are found to be within the permissible voltage limit constraint for Case 2 as well as Case 3.

Table 3.9: Comparison of results for reconfiguration (Case 2) for IEEE 69-bus RDS

Method	λ_{max}	V_{min}	**APL (kW)**	**Open Switches**
Without Reconfiguration	2.22	0.9092	224.95	69, 70, 71, 72, 73
HS [195]	4.45	0.9483	99.61	14, 58, 63, 69, 70
DABC [142]	4.49	NR	98.6	14, 57, 61, 69, 70
CPF [136]	4.5	0.9495	98.61	14, 55, 61, 69, 70
Proposed approach	**4.51**	**0.95**	**98.59**	14, 58, 61, 69, 70

Consequently, Case 3 awards a considerable enhancement in the performance indices and harvests best maximum loadability. The proposed multi-objective algorithm for enhancement of maximum system loadability increases the network loadability with considerable reduction in power losses, with all buses within the specified voltage limits.

3.8 SUMMARY

This work proposes the computational challenges of network reconfiguration problem for enhancement of loadability in distribution system with the simultaneous Distributed generation allocation. Multi-objective meta-heuristic method is used to simultaneously obtain the objectives of loss minimization and voltage stability enhancement in terms of maximum loadability. The method uses modified GWO optimization algorithm to attain the aforesaid objective for loadability enhancement of the system and active power loss reduction. Case studies performed on IEEE 33-bus and IEEE 69-bus radial distribution systems show that simultaneous reconfiguration and DG placement by proposed approach results in significant enhancement in voltage stability margin and voltage profile, and reduction in power loss. Comparison of results with existing approaches show that proposed approach is best in voltage stability margin enhancement for the two systems considered. Most of the performance indices are better for the proposed approach compared to existing approaches.

Reconfiguration of the distribution system that involves frequent opening and closing of switches may lead to several transient issues such as voltage fluctuations, transient overvoltages, power swings, frequency deviations, transient fault currents, loss of supply and electromagnetic interference. Further effort is required to address such transient issues while performing network reconfiguration.