Optimal Reconfiguration of Distribution Network in Presence of D-STATCOM and Photovoltaic Array using a Metaheuristic Algorithm

Kola Sampangi Sambaiah and T Jayabarathi

Abstract — In this paper, grasshopper optimization algorithm (GOA) a novel meta-heuristic optimization algorithm is used to solve the network reconfiguration problem in presence of distribution static compensator (D-STATCOM) and photovoltaic (PV) arrays in a distribution system. Here, D-STATCOM acts as distribution flexible ac transmission (D-FACT) device and PV arrays as decentralized or distributed generation (DG). The main purpose of the present research includes power loss minimization and voltage profile (VP) enhancement in radial distribution systems under different loading conditions. The proposed GOA is based on swarming behavior of grasshoppers in nature. The proposed GOA is validated using the standard 33, 69 and 118 – bus test systems. The simulation results proved that the optimal network reconfiguration in presence of D-STATCOM units and PV arrays leads to significant reduction in power loss and enhancement in VP. The results obtained by the proposed GOA are compared with base value and found that the optimal network reconfiguration in presence of D-STATCOM and PV arrays is more beneficial than individual objective optimization. Also, the proposed GOA is more accurate, efficient and reliable in finding optimal solution when compared to existing modified flower pollination algorithm (MFPA), firework algorithm (FWA), fuzzy-based ant colony optimization (ACO) and genetic algorithm (GA).

Index Terms— Distribution Systems, D-STATCOM installation, Network Reconfiguration, Power loss Minimization, PV arrays allocation.

I. INTRODUCTION

Nowadays, distribution systems are receiving more attention from distribution network operators (DNO) and researchers due to its technical, economic and environmental benefits. Due to radial structure power losses are more in distribution systems when compared to transmission systems. It is observed that for a fixed network configuration with varying load conditions in a distribution system power loss will not be minimum. Hence, there is a need for timely network reconfiguration to minimize power loss and relieve network overloading. There are two lines present in a primary distribution network namely sectional switches (normal closed condition) and tie switches (normal open condition). The process of altering the topological structure of distribution feeders through varying open/closed

condition of sectional and tie switches is known as network reconfiguration. Reconfiguration is preferred in low voltage distribution networks. The main advantages of reconfiguration are:

- a. power loss minimization
- b. service restoration during feeder faults
- c. relieve network overloading
- d. voltage profile enhancement and
- e. network maintenance through planning outages

Since reconfiguration is a complex combinatorial constrained optimization problem, several researchers have proposed various algorithms in the past. Merlin and Back [1] first proposed the concept of network reconfiguration and they used branch and bound method for optimizing. However, the method has to solve 2^n possible system configurations, where n is the total number of line switches which is a time consuming process. Shirmohammadi and Hong [2] proposed a heuristic algorithm which is based on the method of Merlin and Back [1]. The main drawback of this algorithm is simultaneous switching operation is not considered. Civanlar et al [3] presented a heuristic algorithm based on a simple mathematical formula which determines the change in power loss during the process of branch exchange. However, in this method network reconfiguration is depends on initial switch status and it considers only the sole pair of switching operation. Baran and Wu [4] suggested a simple search method for reconfiguration with load balancing based on branch exchange and two load flow methods for evaluating network power loss.

However, the method has to solve m^2 possible system configurations, where m is the total number of line switches and it has to solve m power flow solutions which are a time-consuming process. In recent years the researchers have proposed numerous methods for distribution system reconfiguration considering reliability enhancement and power loss reduction are available in the literature [5]. Recently, Sarantakos et al [6] suggested cost-based analysis for component condition and substation reliability enhancement through network reconfiguration. However, due to increasing load, the distribution system demand is more than generation capacity which makes it impossible to relieve loads on the feeders. Also, only reconfiguration is not suitable for improving voltage profile to the optimal level. Hence distributed generation (DG) units are integrated into distribution system to meet the increasing load demand, to manage the network performance, operation, and control.

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In many countries across the world deregulation of electricity markets offers new perspective for distributed or decentralized or local generation of electrical energy through renewable energy sources with small capacity. Typically, the capacity of DG units is from 5 kW to 10 MW. Generally, DG units are installed closer to the end-consumer to provide electric power. The DG units may be combustion turbines, micro turbines, wind turbines, fuel cell and solar photovoltaic (PV) etc., so that the total or a part of distribution system load demand can be served. The optimal allocation (location and size) of DG will minimize the power loss, enhances voltage profile (VP), improves power quality and reliability of the system. However, inappropriate allocation of DG units will impact the system performance adversely. Since optimal allocation of DG is also a complex combinatorial constrained optimization problem several methods have been proposed by various researchers in the recent past [7]. These methods are often based on analytical, classical, heuristic or meta-heuristic and artificial intelligence algorithms. Mahmoud et al [8] proposed an efficient analytical method for optimal allocation of different DG units to minimize network power loss. Jeddi et al [9] proposed a robust optimization framework based on harmony search algorithm for planning of dynamic distributed energy resources in distribution systems. Saha et al [10] proposed a chaos embedded symbiotic organisms search algorithm for DG allocation in a radial distribution system for loss minimization and VP enhancement. Sanjay et al [11] proposed a hybrid algorithm which is a combination of grey wolf optimizer and differential evolution operators called hybrid grey wolf optimizer for optimal allocation of different DG types based on nature of power injection for achieving power loss minimization.

Rao et al [12] proposed a meta-heuristic technique called harmony search algorithm to analysis the performance of simultaneous reconfiguration and DG allocation for power loss minimization and VP enhancement. Esmailian et al [13] proposed the concept of integrating genetic algorithm and improved switch exchange method for achieving network minimum loss configuration in the presence of DG units. Esmail et al [14] proposed an enhanced gravitational search algorithm for simultaneous reconfiguration and DG allocation with the objectives of enhancing transient stability, minimizing operational cost and power loss in the distribution system. Moreover, various techniques used for reconfiguration in the presence of DG units in distribution systems for loss minimization and VP enhancement are discussed in [15]–[19].

Distribution flexible ac transmission system (D-FACT) devices are considered as imperative equipment in distribution systems with several application and controlling techniques for enhancing the power quality indices. Distribution static compensator (D-STATCOM), dynamic voltage restorer (DVR), unified power flow controller (UPFC) are widely used D-FACT devices. These devices play a vital role in overcoming distribution problem through a substantial reduction in power loss, VP enhancement and power factor correction in distribution systems. The optimal allocation of D-STATCOM will provide reactive power support to the distribution system. Since the optimal allocation of D-STATCOM is also a complex combinatorial constrained optimization problem several researchers have

proposed various techniques. Farhoodnea et al [20] proposed a firefly algorithm for optimal allocation of D-STATCOM in distribution system for power quality improvement. Taher and Afsari [21] presented an immune algorithm for power loss minimization and enhancement of VP and current profile in distribution network. Yuvaraj et al [22] presented a harmony search algorithm for optimal allocation of D-STATCOM with total network loss minimization as objective. Devi and Geethanjali [23] presented the particle swarm optimization algorithm for power loss minimization through simultaneous allocation of DG and D-STATCOM in distribution systems. Devabalaji and Ravi [24] presented a bacterial foraging optimization algorithm for simultaneous allocation of DG and D-STATCOM in radial distribution systems with different load models. El-Ela et al [25] proposed water cycle algorithm for optimal allocation of DG and D-STATCOM in radial distribution systems for achieving techno-economic and environmental benefits.

In addition, several techniques have been proposed for loss minimization and VP enhancement among these techniques' simultaneous reconfiguration and optimal DG allocation or D-STATCOM allocation are most commonly used in the literature. However, only few researchers have focused on network reconfiguration in presence of both DG and D-STATCOM.

In this paper, the grasshopper optimization algorithm (GOA) has been used for solving optimal network reconfiguration problem in presence of D-STATCOM and PV arrays in radial distribution systems. The main objective of the present work includes loss minimization and enhancement of VP in the network under different loading conditions. The present algorithm has been tested on standard 33, 69 and 118 – bus test systems. The simulated results obtained by the proposed GOA are compared with base case and other existing methods available in the literature.

II. PROBLEM FORMULATION

A. Power Flow Equations

In this paper, for evaluating the system power flow the direct approach method is used [26]. The power flow calculation is constructed from the bus injection to branch current (BIBC) matrix and branch current to bus voltage matrix and their multiplication matrix. The direct approach for power flow is based on the equivalent current injection (ECI). The set of basic recursive equations are derived from the single line diagram shown in Fig. 1 for calculating distribution system power flow. From Fig. 1, the ECI at node i is calculated as

$$I_i = \left(\frac{P_{Li} + jQ_{Li}}{V_i} \right)^* \quad (1)$$

By Kirchhoff's current law, the branch current in the line section i is evaluated as

$$J_i = I_{i+1} + I_{i+2} \quad (2)$$

Fig. 1. Sample distribution feeder.

The equation (2) is generalized in a matrix form by using BIBC. Now at each line section the branch current branch can be evaluated in a matrix form as follows:

$$[J] = [BIBC] * [I] \quad (3)$$

By Kirchhoff's voltage law, the voltage at the bus $i + 1$ can be evaluated as

$$V_{i+1} = V_i - J_i * (R_i + jX_i) \quad (4)$$

The power loss in the line section i connecting between buses i and $i + 1$ is evaluated as:

$$P_{loss}(i, i + 1) = |J_i|^2 * R_i = \left(\frac{P_i^2 + Q_i^2}{V_i^2} \right) * R_i \quad (5)$$

The system overall power loss is evaluated by the summation of line losses in all line sections, which is given as:

$$P_{T,loss} = \sum_{i=1}^n P_{loss}(i, i + 1) \quad (6)$$

B. Network Reconfiguration

For reconfiguration problem, the radial structure of the network is considered as an imperative constraint. Hence, during reconfiguration to maintain the radial structure of the network, it is necessary to order distribution system nodes optimally in order to generate parent node-child node path as given in [27]. This path generation will retain the radial structure of the network, also avoids the formation of mesh loops and the creation of unconnected branches or nodes. Therefore, at each level of network reconfiguration, the power flow is evaluated only after the generation of appropriate parent node-child node path of the network. The generation of parent node-child node path for the sample distribution system shown in Fig. 2 is present in Table I.

Fig. 2. Sample distribution system.

TABLE I: REPRESENTATION OF PARENT NODE-CHILD NODE PATH
GENERATION

Parent node	1	2	2	2	5	5	4	4	9	9
Child node	2	3	4	5	6	7	8	9	10	11

In a distribution system, the network reconfiguration problem is solved to identify the optimal structure of the network that gives minimum power loss by satisfying imposed system operating conditions of system voltage profile, feeder current carrying capacity and radial structure of the distribution system. The power loss in the line section i connecting between buses i and $i + 1$ after system reconfiguration is evaluated as

$$P'_{loss}(i, i + 1) = |J'_i|^2 * R_i = \left(\frac{P_i'^2 + Q_i'^2}{|V'_i|^2} \right) * R_i \quad (7)$$

The reconfigured system overall power loss is evaluated by the summation of line losses in all line sections, which is given as

$$P'_{T,loss} = \sum_{i=1}^n P'_{loss}(i, i + 1) \quad (8)$$

The system net power loss ΔP_{loss}^R , is the difference of the power loss obtained before and after system reconfiguration, i.e., eq (6)-eq (8) and can be given as

$$\Delta P_{loss}^R = \sum_{i=1}^n P_{loss}(i, i + 1) - \sum_{i=1}^n P'_{loss}(i, i + 1) \quad (9)$$

In order to enhance the voltage profile of the system, the voltage deviation must be minimized. This index maintains the configuration which gives the lower voltage deviation [28]. The voltage deviation index ΔV_D can be represented as

$$\Delta V_D = \min \left(\frac{V_1 - V_i}{V_1} \right) \forall i = 1, 2, \dots, n \quad (10)$$

The proposed algorithm will try to maintain the value of ΔV_D closer to zero and thereby enhances the system voltage stability without violating the voltage limits.

C. PV Array Allocation

Optimal allocation of PV arrays in the distribution network will minimize power losses, enhances voltage profile, avoids feeder overloading and have minimum impact on environment. A sample PV array is connected to AC mains supply through an inverter, main fuse box, and meter as shown in Fig. 3. After allocation of PV array, the active and reactive powers of the system can be calculated by following equations [29]:

$$P^{PV} = \left[\frac{V_L^2}{R_i} P_{loss}^{PV} - (P_i^2 + Q_i^2) - (Q_{PV}^2 - 2P_i P_{PV} - 2Q_i Q_{PV}) \left(\frac{G}{L} \right)^{1/2} \right] \quad (11)$$

$$Q^{PV} = \left[\frac{V_L^2}{R_i} P_{loss}^{PV} - (P_i^2 + Q_i^2) - (P_{PV}^2 - 2P_i P_{PV} - 2Q_i Q_{PV}) \left(\frac{G}{L} \right)^{1/2} \right] \quad (12)$$

Fig. 3. Sample PV array connected to AC main supply.

D. D-STATCOM Installation

The D-STATCOM is a D-FACT device which consists of a DC capacitor, a GTO/IGBT voltage source converter (VSC), and a coupling transformer with a leakage reactance [30]. Fig. 4 illustrates D-STATCOM installed at bus $i + 1$ of a distribution feeder. The reactive power flow in the distribution transformer windings can be minimized by the D-STATCOM capacity. The active power is set to zero and reactive power of the system after D-STATCOM allocation can be calculated by following equation [30]:

$$Q^{D-STATCOM} = \left(\frac{V_i^2}{X_L} \right) - \left(\frac{V_i V_M}{X_L} \right) \cos \delta \quad (13)$$

Fig. 4. D-STATCOM installed at bus $i + 1$.

E. Objective Function

The main objective of the proposed method is to identify an optimal configuration for the distribution network, D-STATCOM and PV array allocation for minimization of loss and enhancement of VP. The objective function used to minimize the power loss in the distribution system is given as

$$\text{Minimize } F = \min(\Delta P_{loss}^R + \Delta P_{loss}^{D-STATCOM} + \Delta P_{loss}^{PV}) \quad (14)$$

Subjected to following constraints:

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (15)$$

$$\sum_{i=1}^n P_i^{PV} \leq \sum_{i=1}^n (P_i + P_{i,loss}) \quad (16)$$

$$\sum_{i=1}^n Q_i^{D-STATCOM} \leq \sum_{i=1}^n (Q_i + Q_{i,loss}) \quad (17)$$

$$0_{kW} \leq P_{kW}^{PV} \leq 2000_{kW} \quad (18)$$

$$0_{kVar} \leq Q_{kVar}^{D-STATCOM} \leq 1900_{kVar} \quad (19)$$

$$\left. \begin{aligned} \det(A) &= 1 \text{ or } -1 \text{ (radial network)} \\ \det(A) &= 0 \text{ (not radial)} \end{aligned} \right\} \quad (20)$$

The above constraint will check the radial structure of the network by energizing all the nodes [30].

III. OVERVIEW OF GRASSHOPPER OPTIMIZATION ALGORITHM

Grasshopper optimization algorithm was proposed by Saremi et al [31] in 2017. Grasshoppers are insects which cause damage to crop production and cultivation. Fig. 5 shows the life of grasshoppers. The optimization algorithm is based on the swarming behavior of grasshoppers in nature.

Fig. 5. (a) Grasshopper (b) Life cycle of grasshoppers.

The mathematical model for solving optimization problems based on swarming behavior of grasshoppers is represented as follows

$$X_j^D = c \left[\sum_{k=1, k \neq j}^N c \left(\frac{UB_D - LB_D}{2} \right) s(|x_k^D - x_j^D|) \frac{x_k - x_j}{D_{jk}} \right] + \hat{T}_D \quad (21)$$

where UB_D and LB_D are the upper and lower bound in the D^{th} dimension, respectively. x_k and x_j are k^{th} and j^{th} position of grasshoppers, x_k^D and x_j^D are the positions of k^{th} and j^{th} grasshoppers in the D^{th} dimension, respectively. N is the population size of the grasshoppers, $\hat{T}_D$ is the target value in the D^{th} dimension.

The adaptive component c first (outside bracket) present in the equation (21) is used to stabilize the exploration and exploitation of the whole swarm towards the target or best value. In addition, the component c (inside bracket) is decreasing coefficient for reducing attraction zone, repulsion zone and comfort zone between the grasshoppers.

For stabilizing the exploration and exploitation the component c has to be reduced linearly along with iterations. This process helps in exploitation as the iteration increases. The relation between component c and number of iterations is given by:

$$c = (c_{max} - m) \left(\frac{c_{max} - c_{min}}{iter_{max}} \right) \quad (22)$$

where c_{max} and c_{min} is the maximum and minimum value of component c , respectively. m indicates current iteration and

$iter_{max}$ is the maximum number of iterations. Fig. 6 shows the pseudo-code of the GOA.

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Initialize the swarm  $X_j$  ( $j=1,2,\dots,n$ )
Initialize maximum number of iterations ( $iter_{max}$ ),  $c_{max}$  and  $c_{min}$ 
Calculate the fitness of all search agents
 $T$ =the best search agent
while ( $t < iter_{max}$ )
    Update  $c$  using Eq. (22)
    for every search agent
        Normalize the grasshopper distances in  $[1,4]$ 
        Update the current search agent position by the Eq. (21)
        Guide the current search agent towards the target if it goes outside the boundaries
    end for
    Update  $T$  if there is a better solution
     $m=m+1$ 
end while
Return  $T$ 

```

Fig. 6. Pseudocode of the GOA.

It is observed that GOA has the ability to explore the promising regions of the search space and cluster around the global optima eventually. These make the GOA suitable for solving complex combinatorial constrained optimization problems with increased accuracy and convergence. Sultana *et al* [32] recently used GOA for solving distribution system optimization problem of identifying the optimal location and sizing of multiple DG and battery swapping stations

IV. IMPLEMENTATION OF GOA FOR NETWORK RECONFIGURATION IN THE PRESENCE OF D-STATCOM AND PV ARRAYS

The sequence of steps involved in distribution network optimization using GOA is presented as follows:

Step 0: Initialization of the GOA parameters;

$iter_{max}$: maximum number of iterations;

D : dimensions of search space i.e. number of tie lines or open switches, number of D-STATCOM units and PV arrays to be installed.

Generate the initial swarm of size equal to search space dimensions which satisfies all the constraints listed in section 2.4.

$$X = \begin{bmatrix} \text{tie switches} & \text{PV array} & \text{D-STATCOM} \\ SW_1^1 SW_2^1 SW_3^1 SW_4^1 SW_5^1 & S_{PV_1}^1 L_{PV_1}^1 & S_{D-STATCOM_1}^1 L_{D-STATCOM_1}^1 \\ SW_1^2 SW_2^2 SW_3^2 SW_4^2 SW_5^2 & S_{PV_1}^2 L_{PV_1}^2 & S_{D-STATCOM_1}^2 L_{D-STATCOM_1}^2 \\ SW_1^3 SW_2^3 SW_3^3 SW_4^3 SW_5^3 & S_{PV_1}^3 L_{PV_1}^3 & S_{D-STATCOM_1}^3 L_{D-STATCOM_1}^3 \\ SW_1^4 SW_2^4 SW_3^4 SW_4^4 SW_5^4 & S_{PV_1}^4 L_{PV_1}^4 & S_{D-STATCOM_1}^4 L_{D-STATCOM_1}^4 \\ \vdots & \vdots & \vdots \\ SW_1^N SW_2^N SW_3^N SW_4^N SW_5^N & S_{PV_1}^N L_{PV_1}^N & S_{D-STATCOM_1}^N L_{D-STATCOM_1}^N \end{bmatrix} \quad (23)$$

wherein the above Eq. (24) the first portion (SW_1, SW_2, SW_3, SW_4 and SW_5) of the solution, vector represents the tie switches or open switches, second portion (S_{PV_1} and L_{PV_1}) represents the size and location of PV array and the third portion ($S_{D-STATCOM_1}$ and $L_{D-STATCOM_1}$) represents the size and location of the D-STATCOM unit. However, for the 118 – bus distribution system the number of tie switches are 15, number of locations considered for PV arrays and D-STATCOM units for integration is six.

Step 1: Provide the required input data for load flow program which are base MVA, line voltage, line and bus data.

Step 2: Evaluate the value of the component c using the Eq. (22) for each and every iteration.

Step 3: Update the current search agent position by the Eq. (21) for guiding the grasshopper towards the fitness (target) value.

Step 4: Evaluate the objective function F using the Eq. (14) through load flow without violating the operational constraints.

Step 5: Adjust the position of search agents and update the fitness (target) value if the current solution is better than the solution obtained so far.

Step 6: Check for the stopping criterion. If the current iteration number is equal to maximum iterations then display the fitness (target) value and corresponding tie switches, location and size of and D-STATCOM and PV array. Otherwise, repeat the steps 2 to 5.

The sequence of steps employed for solving network reconfiguration problem in presence of D-STATCOM and PV array using GOA is clearly illustrated in Fig. 7.

Fig. 7. Flow chart of the GOA.

V. SIMULATION AND NUMERICAL RESULTS

In order to demonstrate and validate the effectiveness of the present method (network reconfiguration in presence of D-STATCOM and PV array) using GOA, it is applied to

three test systems consisting of 33, 69 and 118 – buses. In this paper, six different cases are considered to analyze the superiority of the proposed method.

Case 1: The system with standard configuration without D-STATCOM and PV array installation (base case)

Case 2: The system is reconfigured by the available tie and sectional switches.

Case 3: After system reconfiguration (i.e. case 2) D-STATCOM are installed.

Case 4: After system reconfiguration (i.e. case 2) PV array is installed.

Case 5: The system with a standard configuration with D-STATCOM and PV array installation.

Case 6: The optimal network reconfiguration in presence of D-STATCOM and PV array (optimum case).

All cases are programed in MATLAB® and simulations are performed in a computer with core i3, 2.9 GHz, 4 GB RAM. To assess the proposed method performance the system is simulated at three different loading conditions: light (0.5), nominal (1.0) and heavy (1.6).

A. Test System 1

The proposed method is initially applied on 33 – bus system having 5 tie switches (open switches) and 32 sectional switches (closed switches). The system total active and reactive power demands are 3.7 MW and 2.3 MVAR, respectively. The power flow analysis is evaluated based on $S_{base} = 100 \text{ MVA}$ and $V_{base} = 12.66 \text{ kV}$. The system line and load data are taken from [33]. In this paper, D-STATCOM acts as a reactive power source and PV array as DG. The limits of D-STATCOM and PV array sizes chosen for installation at candidate bus locations were 0 – 1900 kVAr and 0 – 2 MW, respectively. The numerical results obtained for 33 – bus test system using GOA for six tested cases under three different loading conditions are presented in Table II. It is observed that the base case power loss (in kW) of the system at light load is 47.07 which is reduced to 33.27, 24.56, 23.71, 12.64 and 10.64 using case 2 to 6, respectively. The percentage loss reduction obtained for case 2 to 6 is 29.31, 47.82, 49.62, 73.14 and 77.39, respectively.

Similarly, the percentage power loss reduction obtained for case 2 to 6 at nominal and heavy load conditions are 31.14, 49.76, 51.59, 72.51 and 82.72; 33.47, 52.57, 54.40, 69.98 and 77.70, respectively. It can be noticed that the power loss reduction using case 6 for all three load level, is highest, this elicits the proposed GOA is superior to other existing methods.

From Table II, it can be observed that the base case minimum bus voltage is 0.9131 p.u at bus 18 and voltage deviation index value of 0.0831 p.u. The improvement in minimum bus voltage (p.u) and reduction in voltage deviation index (p.u) at nominal load conditions for case 2 to 6 are 0.9378, 0.9475, 0.9479, 0.9549 and 0.9669; 0.0621, 0.0376, 0.0277, 0.0217 and 0.0038, respectively. From this, it is noticed that improvement in minimum bus voltage and reduction in voltage deviation index are highest in case 6. The optimal configuration of the distribution system for case 6 is shown in Fig. 8. Power loss convergence characteristic of the proposed GOA for 33 – bus system at nominal load is illustrated in Fig. 9. The voltage profile characteristics of case 1 (base case) and case 6 (optimum case) at nominal load level

are illustrated in Fig. 10. The line loss reduction for case 1 to 6 is illustrated in Fig. 11. It can be noticed that the line losses reducing drastically for case 1 to 6 at nominal load level.

The simulated results obtained using the proposed GOA at nominal load level are presented in Table III and the same is compared with other methods existing in the literature. From Table III, it can be observed that the proposed GOA is performing better than the other existing methods in terms of power loss minimization and VP enhancement for all cases.

Fig. 8. Optimal configuration of 33 – bus test system.

Fig. 9. Convergence characteristics of GOA for 33 – bus test system at nominal load condition for five independent runs.

Fig. 10. Voltage profile of 33 – bus test system at nominal load condition.

Fig. 11. Line losses of 33 – bus test system for different cases at nominal load condition.

TABLE II: OBTAINED RESULTS OF 33 – BUS TEST SYSTEM

Case	Parameter	Light (0.5)	Nominal (1.0)	Heavy (1.6)
Case 1	Open switches	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
	P_{Tloss} (kW)	47.07	202.68	575.36
	ΔV_d (p.u)	0.0399	0.0831	0.1406
	V_{min} (p.u)	0.9583 (18)	0.9131 (18)	0.8528 (18)
	CPU time (s)	0.26	0.27	0.28
Case 2	Open switches	7, 14, 9, 32, 37	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	P_{Tloss} (kW)	33.27	139.55	380.45
	% loss reduced	29.31	31.14	33.47
	ΔV_d (p.u)	0.0302	0.0621	0.1033
	V_{min} (p.u)	0.9698 (32)	0.9378 (32)	0.8967 (32)
Case 3	Open switches	7, 14, 9, 32, 37	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	D-STATCOM (kVAr)	511 (31)	1029 (30)	1658 (31)
	P_{Tloss} (kW)	24.56	101.82	272.84
	% loss reduced	47.82	49.76	52.57
	ΔV_d (p.u)	0.0154	0.0376	0.0517
Case 4	Open switches	7, 14, 9, 32, 37	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	SPV (kW)	569 (30)	1153 (29)	1877.1 (29)
	P_{Tloss} (kW)	23.71	98.10	262.31
	% loss reduced	49.62	51.59	54.40
	ΔV_d (p.u)	0.0119	0.0277	0.0449
Case 5	Open switches	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
	D-STATCOM (kVAr)	1238.8 (6)	2000 (25)	2200 (29)
	SPV array (kW)	619.47 (29)	1250.2 (29)	2031.8 (29)
	P_{Tloss} (kW)	12.64	55.71	172.67
	% loss reduced	73.14	72.51	69.98
Case 6	Open switches	33, 13, 9, 16, 26	33, 12, 10, 15, 26	33, 12, 9, 36, 25
	D-STATCOM (kVAr)	963 (29)	1983 (29)	2200 (29)
	SPV array (kW)	541 (32)	1379 (31)	2195 (30)
	P_{Tloss} (kW)	10.64	35.02	128.27
	% loss reduced	77.39	82.72	77.70

TABLE III: COMPARATIVE STUDY OF GOA FOR 33 – BUS TEST SYSTEM

Case	Parameter	FWA [35]	Analytical [34]	MO-MFPA [29]	GOA
Case 2	Open switches	7, 14, 9, 32, 28	7, 9, 14, 28, 31	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	P_{Tloss} (kW)	139.98	121.28	138.55	139.55
	% loss reduced	30.93	42.31	31.88	31.14
	V_{min} (p. u)	0.9413	0.9434 (32)	0.9417 (30)	0.9378 (32)
	Parameter	Fuzzy – GA [36]	Analytical [34]	MO-MFPA [29]	GOA
Case 3	Open switches	9, 14, 27, 33, 36	7, 9, 14, 28, 31	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	D-STATCOM (kVAr)	752	1125 (30)	1174.9 (24)	1029 (30)
	P_{Tloss} (kW)	132.87	92.77	94.37 (131.93 ^a)	101.82
	% loss reduced	34.2	56.08	53.2	49.76
	V_{min} (p. u)	0.9727	0.9438 (32)	0.9704 (33)	0.9475 (33)
	Parameter	FWA [35]	Analytical [34]	MO-MFPA [29]	GOA
Case 4	Open switches	7, 14, 9, 32, 28	7, 9, 14, 28, 31	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	SPV (kW)	1072.7	1425 (29)	1056.2 (20)	1153 (29)
	P_{Tloss} (kW)	83.91	82.76	78.9 (118.56 ^a)	98.10
	% loss reduced	58.59	60.81	60.9	51.59
	V_{min} (p. u)	0.9612	0.9443 (32)	0.9620 (33)	0.9479 (33)
	Parameter	BFOA [24]	Analytical [34]	MO-MFPA [29]	GOA
Case 5	Open switches	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
	D-STATCOM (kVAr)	1094.6 (30)	1250 (30)	1481 (31)	2000 (25)
	SPV array (kW)	1239.8 (10)	2601 (6)	1323.6 (33)	1250.2 (29)
	P_{Tloss} (kW)	70.87	58.55	65.7	55.71
	% loss reduced	65.00	72.28	67.4	72.51
	V_{min} (p. u)	0.9615	0.9545 (18)	0.9612 (29)	0.9549 (17)
Case 6	Parameter	Fuzzy – ACO [30]	Analytical [34]	MO-MFPA [29]	GOA
	Open switches	9, 14, 27, 33, 36	7, 9, 14, 28, 31	7, 11, 14, 28, 32	33, 12, 10, 15, 26
	D-STATCOM (kVAr)	1316 (9)	1125 (30)	1088.7 (23)	1983 (29)
	SPV array (kW)	740 (10)	1425 (29)	1266.8 (21)	1379 (31)
	P_{Tloss} (kW)	48.73	55.53	39.14	35.02
	% loss reduced	75.95	73.71	80.6	82.72
	V_{min} (p. u)	-	0.9447 (32)	0.9753 (22)	0.9669 (13)

a – calculated value of power loss (in kW).

B. Test System 2

The second test system is a 69 – bus distribution system having 5 tie switches (open switches) and 68 sectional switches (closed switches). The system total active and reactive power demands are 3.8 MW and 2.7 MVAR, respectively. The power flow analysis is evaluated based on $S_{base} = 100$ MVA and $V_{base} = 12.66$ kV. The system line and load data are taken from [37]. Similar to test system 1, this 69 – bus system also simulated for six cases under three different loading conditions. The D-STATCOM and PV array limits are the same as the previous test system.

The numerical results obtained for 69 – bus distribution system using GOA for six tested cases under three different loading conditions are presented in Table IV. It is observed that the base case power loss (in kW) of the system at the light, nominal and heavy load conditions are 51.60, 225.06, and 652.96, respectively. From Table IV, it is observed that case 6 is more effective in power loss reduction and VP enhancement compared to other cases. For case 6, the optimal configuration is obtained after opening the switches 69, 14, 17, 21 and 55; and allocation of D-STATCOM and PV array at bus 61 with 1813 kVAr and 1294 kW, respectively is illustrated in Fig. 12.

The voltage profile characteristics of case 1 (base case) and case 6 (optimum case) at nominal load level are illustrated in Fig. 13. The line loss reduction for case 1 to 6 is illustrated in Fig. 14. It can be noticed that the line losses reducing drastically for case 1 to 6 at nominal load level. The simulated results obtained using the proposed GOA at nominal load level are presented in Table V and the same is compared with other methods existing in the literature. From Table V, it can be observed that the proposed GOA is performing better than the other existing methods in terms of power loss minimization and VP enhancement for all cases.

Fig. 12. Optimal configuration of 69 – bus test system.

Fig. 13. Voltage profile of 69 – bus test system at nominal load condition.

Fig. 14. Line losses of 69 – bus test system for different cases at nominal load condition.

TABLE IV: OBTAINED RESULTS OF 69 – BUS TEST SYSTEM

Case	Parameter	Light (0.5)	Nominal (1.0)	Heavy (1.6)
Case 1	Open switches	69, 70, 71, 72, 73	69, 70, 71, 72, 73	69, 70, 71, 72, 73
	P_{Tloss} (kW)	51.60	225.06	652.96
	ΔV_d (p.u)	0.0434	0.0910	0.1559
	V_{min} (p.u)	0.9565 (66)	0.9089 (66)	0.8441 (66)
	CPU time (s)	0.16	0.16	0.17
Case 2	Open switches	69, 14, 71, 61, 58	69, 14, 71, 61, 58	69, 14, 71, 61, 58
	P_{Tloss} (kW)	23.61	98.63	267.26
	% loss reduced	54.24	56.17	59.07
	ΔV_d (p.u)	0.0247	0.0502	0.0838
	V_{min} (p.u)	0.9752 (62)	0.9492 (62)	0.9161 (62)
	CPU time (s)	2.24	2.24	2.22
Case 3	Open switches	69, 14, 71, 61, 58	69, 14, 71, 61, 58	69, 14, 71, 61, 58
	D-STATCOM (kVAr)	512.4 (61)	1038.6 (62)	1690 (62)
	P_{Tloss} (kW)	17.82	73.45	195.37
	% loss reduced	65.46	67.36	70.07
	ΔV_d (p.u)	0.0172	0.0506	0.0837
	V_{min} (p.u)	0.9827 (63)	0.9496 (62)	0.9162 (62)
Case 4	CPU time (s)	2.27	2.15	2.18
	Open switches	69, 14, 71, 61, 58	69, 14, 71, 61, 58	69, 14, 71, 61, 58
	SPV (kW)	713.37 (61)	1434.96 (62)	2312.53 (61)
	P_{Tloss} (kW)	12.44	50.92	134.19
	% loss reduced	75.89	77.37	79.44
	ΔV_d (p.u)	0.0051	0.0103	0.0166
Case 5	V_{min} (p.u)	0.9839 (65)	0.9674 (65)	0.9469 (65)
	CPU time (s)	2.17	2.16	2.19
	Open switches	69, 70, 71, 72, 73	69, 70, 71, 72, 73	69, 70, 71, 72, 73
	D-STATCOM (kVAr)	912.3 (61)	1828.16 (60)	2400 (61)
	SPV array (kW)	648.76 (60)	1301.28 (60)	2078.9 (60)
	P_{Tloss} (kW)	5.68	23.14	70.55
Case 6	% loss reduced	89	89.71	89.19
	ΔV_d (p.u)	0.0080	0.0162	0.0294
	V_{min} (p.u)	0.9864 (26)	0.9725 (26)	0.9521 (21)
	CPU time (s)	0.20	0.37	0.20
	Open switches	69, 14, 71, 25, 53	69, 14, 17, 21, 55	69, 14, 17, 21, 55
	D-STATCOM (kVAr)	909 (62)	1813 (61)	2400 (62)
	SPV array (kW)	642 (60)	1294 (61)	2019 (62)
	P_{Tloss} (kW)	4.43	15.42	48.31
	% loss reduced	91.41	93.14	92.60
	ΔV_d (p.u)	0.0049	0.0139	0.0225
	V_{min} (p.u)	0.9942 (25)	0.9835 (19)	0.9734 (19)
	CPU time (s)	2.24	2.26	2.26

C. Test System 3

The third test system is a 118 – bus distribution system having 15 tie switches (open switches) and 117 sectional switches (closed switches). The system total active and reactive power demands are 22.7 MW and 17 MVAR, respectively. The power flow analysis is evaluated based on $S_{base} = 100$ MVA and $V_{base} = 11$ kV. The system line and load data are taken from [38]. This test system is simulated for six cases under only nominal loading condition. The D-STATCOM and PV array limits are the same as previous test system however, the number of candidate bus locations for placement are six (i.e. three locations for D-STATCOM and three locations for PV array). The numerical results obtained for 118 – bus distribution system using GOA are compared for six tested cases are presented in Table VI. It is observed that the base case power loss (in kW) of the system 1291.01

with minimum bus voltage of 0.8687 p.u at bus 77 and voltage deviation index of 0.092 p.u.

For case 6, the switches 16, 21, 39, 43, 32, 58, 124, 125, 71, 97, 128, 85, 130, 108 and 132 are opened for optimal system configuration and optimal location for D-STATCOM units are 50, 75, 111 and optimal location for PV arrays are 51, 92, 109. It is noticed that the percentage of power loss reduction achieved is slightly lower for case 2 to 4 when compared to MO-MFPA. However, for case 5 and 6 the proposed GOA is achieving a significant reduction in power loss. The optimal configuration of the distribution system for case 6 is shown in Fig. 15. The line loss reduction for case 1 to 6 is illustrated in Fig. 16. It can be noticed that the line losses reducing drastically for case 1 to 6. However, the percentage loss reduction for case 5 is slightly higher than case 6. This is because the system configuration (case 1) is unaltered. The performance analysis of the proposed GOA in terms of percentage power loss reduction and minimum bus

voltage enhancement for all test systems at nominal load conditions are illustrated in Fig. 17 and Fig. 18. The algorithm parameter values for all test systems with six operating cases

under three different load conditions are presented in Table VII.

TABLE V: COMPARATIVE STUDY OF GOA FOR 69 – BUS TEST SYSTEM

Case	Parameter	FWA [35]	MO-MFPA [29]	GOA
Case 2	Open switches	69, 70, 14, 56, 61	69, 18, 15, 54, 61	69, 14, 71, 61, 58
	P_{Tloss} (kW)	98.59	97.95	98.63
	% loss reduced	56.17	56.4	56.17
	V_{min} (p. u)	0.9495	0.9579 (61)	0.9492 (62)
Case 3	Parameter	-	MO-MFPA [29]	GOA
	Open switches	-	69, 18, 15, 54, 61	69, 14, 71, 61, 58
	D-STATCOM (kVAr)	-	1445.2 (46)	1038.6 (62)
	P_{Tloss} (kW)	-	75.7	73.45
	% loss reduced	-	66.3	67.36
	V_{min} (p. u)	-	0.9775 (59)	0.9496 (62)
Case 4	Parameter	FWA [35]	MO-MFPA [29]	GOA
	Open switches	69, 70, 14, 56, 61	69, 18, 15, 54, 61	69, 14, 71, 61, 58
	SPV (kW)	1358.4	1274.7 (9)	1434.96 (62)
	P_{Tloss} (kW)	43.88	42.91	50.92
	% loss reduced	80.49	80.92	77.37
	V_{min} (p. u)	0.9720	0.9732 (59)	0.9674 (65)
Case 5	Parameter	WCA [25]	MO-MFPA [29]	GOA
	Open switches	69, 70, 71, 72, 73	69, 70, 71, 72, 73	69, 70, 71, 72, 73
	D-STATCOM (kVAr)	2694.9	1505.3 (64)	1828.16 (60)
	SPV array (kW)	3700	1092.3 (65)	1301.28 (60)
	P_{Tloss} (kW)	33.34	82.9	23.14
	% loss reduced	85.18	63.1	89.71
	V_{min} (p. u)	0.9950 (15)	0.9685 (65)	0.9725 (26)
Case 6	Parameter	-	MO-MFPA [29]	GOA
	Open switches	-	10, 16, 44, 55, 64	69, 14, 17, 21, 55
	D-STATCOM (kVAr)	-	1025.3 (65)	1813 (61)
	SPV array (kW)	-	1396.9 (41)	1294 (61)
	P_{Tloss} (kW)	-	41.73	15.42
	% loss reduced	-	81.5	93.14
	V_{min} (p. u)	-	0.9804 (64)	0.9835 (19)

Fig. 15. Optimal configuration of 118 – bus test system.

Fig. 16. Line losses of 118 – bus test system for different cases.

Fig. 17. Percentage of power loss reduction obtained using GOA for all test systems.

Fig. 18. Minimum bus voltage obtained using GOA for all test systems with six test cases.

TABLE VI: COMPARATIVE STUDY OF GOA FOR 118 – BUS TEST SYSTEM

Case	Parameter	MO-MFPA [29]	GOA
Case 2	Open switches	42, 25, 22, 121, 50, 58, 39, 95, 71, 74, 97, 129, 130, 109, 34	25, 23, 39, 43, 34, 58, 124, 95, 71, 97, 74, 129, 130, 109, 51
	P_{Tloss} (kW)	854	878.57
	% loss reduced	32.90	31.94
	V_{min} (p.u)	0.9310	0.9394 (74)
Case 3	Parameter	MO-MFPA [29]	GOA
	Open switches	45, 25, 19, 121, 122, 58, 39, 125, 70, 127, 128, 81, 130, 131, 132	25, 23, 39, 43, 34, 58, 124, 95, 71, 97, 74, 129, 130, 109, 51
	D-STATCOM (kVAr)	1840 (89)	1857.74 (51) 1900 (80) 1874.49 (108)
	P_{Tloss} (kW)	636	737.30
	% loss reduced	50	42.88
	V_{min} (p.u)	0.9480	0.9436 (74)
Case 4	Parameter	MO-MFPA [29]	GOA
	Open switches	42, 25, 22, 121, 50, 58, 39, 95, 71, 74, 97, 129, 130, 109, 34	25, 23, 39, 43, 34, 58, 124, 95, 71, 97, 74, 129, 130, 109, 51
	SPV (kW)	179 (111)	2000 (50) 1999.5 (80) 2000 (109)
	P_{Tloss} (kW)	589	664.42
	% loss reduced	53.7	48.53
	V_{min} (p.u)	0.958	0.9422 (74)
Case 5	Parameter	MO-MFPA [29]	GOA
	Open switches	118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 13, 131, 132	118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 13, 131, 132
	D-STATCOM (kVAr)	1612 (96)	1900 (49) 1868.5 (71) 1899.6 (110)
	SPV array (kW)	1517 (77)	2000 (49) 2000 (74) 2000 (110)
	P_{Tloss} (kW)	623	404.85
	% loss reduced	51	68.64
	V_{min} (p.u)	0.9520	0.9569 (98)
Case 6	Parameter	MO-MFPA [29]	GOA
	Open switches	42, 25, 21, 121, 48, 60, 39, 125, 126, 68, 76, 129, 130, 109, 33	16, 21, 39, 43, 32, 58, 124, 125, 71, 97, 128, 85, 130, 108, 132
	D-STATCOM (kVAr)	1568 (97)	1868.7 (50) 1269.47 (75) 1104.7 (111)
	SPV array (kW)	1656 (109)	1743.96 (51) 1989.9 (92) 1919.6 (109)
	P_{Tloss} (kW)	544	435.39
	% loss reduced	57.2	66.27
	V_{min} (p.u)	0.9654	0.9459 (71)

TABLE VII: GOA PARAMETERS FOR TEST SYSTEMS

Entity	33 – bus system	69 – bus system	118 – bus system
Population size, N	50	50	50
Maximum number of iterations, $iter_{max}$	200	200	200
c_{max}	1.0	1.0	1.0
c_{min}	0.00004	0.00004	0.00004

VI. CONCLUSIONS

In this paper, a new GOA has been presented for solving network reconfiguration problem in presence of D-STATCOM units and PV arrays. The proposed algorithm is employed for loss minimization and VP enhancement. The

GOA has been successfully tested on 33, 69 and 118 – bus distribution systems with six different test cases under three different loading conditions with the objective of power loss minimization and VP enhancement. The six different test cases are base case, only reconfiguration, D-STATCOM allocation after reconfiguration, PV array allocation after reconfiguration, allocation of D-STATCOM and PV array on

the system with standard configuration, network reconfiguration in presence of D-STATCOM and PV array. Among the six test cases, network reconfiguration in presence of D-STATCOM and PV array is found to be better when compared to other test cases. For 33 – bus system, the percentage power loss reduction obtained is 82.72 with a minimum voltage deviation of 0.0038 *p.u* at nominal load condition. Similarly, for 69 and 118 – bus systems the percentage power loss reduction is 93.14 and 66.27 with minimum voltage deviation of 0.0139 *p.u* and 0.0140 *p.u*, respectively. It is also noticed that the minimum bus voltage (*p.u*) is improved from case 2 to case 6 for 69 – bus system is 0.9492, 0.9496, 0.9672, 0.9725 and 0.9835, respectively. Simulated results obtained are compared with other existing methods in the literature shows the superiority of the proposed GOA.

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