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A Hybrid Local Search-Genetic Algorithm for Simultaneous Placement of DG Units and Shunt Capacitors in Radial Distribution Systems

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ABSTRACT Controlling active/reactive power in distribution systems has a great impact on its performance. The placement of distributed generators (DGs) and shunt capacitors (SCs) are the most popular mechanisms to improve the distribution system performance. In this line, this paper proposes an enhanced genetic algorithm (EGA) that combines the merits of genetic algorithm and local search to find the optimal placement and capacity of the simultaneous allocation of DGs/SCs in the radial systems. Incorporating local search scheme enhances the search space capability and increases the exploration rate for finding the global solution. The proposed procedure aims at minimizing both total real power losses and the total voltage deviation in order to enhance the distribution system performance. To prove the proposed algorithm ability and scalability, three standard test systems, IEEE 33 bus, 69 bus, and 119-bus test distribution networks, are considered. The simulation results show that the proposed EGA can efficiently search for the optimal solutions of the problem and outperforms the other existing algorithms in the literature. Moreover, an economic based cost analysis is provided for light, shoulder and heavy loading levels. It was proven, the proposed EGA leads to significant improvements in the technical and economic points of view.

INDEX TERMS Distributed generators (DGs), shunt capacitors (SCs), distribution system performance, enhanced genetic algorithm (EGA).

NOMENCLATURE

$R_{i,i+1}$	Resistance of branch between nodes i and i + 1
$X_{i,i+1}$	Reactance of branch between nodes i and i + 1
P_{loss}	Active power loss of line
Q_{loss}	Reactive power loss of line
TP_{loss}	The total active power loss
TQ_{loss}	The total reactive power loss
P_{DGi+1}	Injected distributed generation active power
Q_{DGi+1}	Injected shunt capacitor reactive power
Q_{Li+1}	Reactive power load demand
Vn	Voltage of the bus n.
P_{Li+1}	Real power load demand
Vi	Voltage of the bus i.
$Vref$	Slack voltage of the system equal 1p.u
$Vi\ max$	Maximum value of bus i voltage
$Vi\ min$	Minimum value of bus i voltage
$I_{i,i+1}$	The current the flow between nodes i and i+1
$I_{i,i+1(\max)}$	Maximum value of current the flow between nodes i and i+1
Pdg	The size of DG
Pd	The probability density of normal distribution of load
μ_d	The mean
σ_d	Standard deviation value

I. INTRODUCTION

A. MOTIVATION

A power network consists of generation, transmission lines, and a distribution network, which is connected to different types of residential, commercial, and industrial loads. Owing

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to the increase in power demand, utility companies face many challenges, such as the increased power loss and poor voltage regulation, low power factor, worst power quality, discontinuity, high short-circuit level, and stability. The distribution system has a higher current than power transmission lines and thus has a higher power loss. Power quality problems can be solved by maintaining low voltages in load points, but some solutions, such as increasing the capacity of delivered power to load points, are impractical. Another problem is that transmission lines in a radial system are limited. The highest problem in distribution systems power losses as 13% of generated power is wasted in distribution networks [1]. There are many intelligent computing paradigms were utilized to handle those problems [2], [3]. The need for solving the previous challenges is an open research area with the aim of finding new paradigms. Therefore, this paper contributes to propose a new enhanced genetic algorithm methodology that combines the distributed generation units and shunt capacitors to enhance the overall performance of distribution systems.

B. LITERATURE REVIEW

In the literature, the mentioned issues and challenges of the distribution system can be addressed through several solutions. For example, power compensators can be used to reduce power loss, improve power quilt, and enhance voltage. In terms of environmentally friendliness and economy, using distributed generation (DGs) units and shunt capacitors (SCs) is the most effective solution for the distribution system problem. Owing to the advantages of the DGs and SCs, they are widely used in radial systems. DGs are used as active and reactive power compensators, whereas capacitors are used as reactive power compensators. DGs are typically used in renewable power sources, such as solar thermal systems, photovoltaic (PV) systems, and wind turbines. DGs have three types. The first type can supply active power (P), the second can supply reactive power (Q), and the third can supply both. SCs can provide only Q to the network and work as a compensator for lagging volt-ampere reactive (VAR). Therefore, SCs are less effective than DGs in minimizing real power loss in power networks. When used with DCs, SCs complements DGs in improving power quality, minimizing power loss, improving voltage profile, and enhancing reliability.

Several optimization algorithms for handling optimal siting and sizing problems in DG units and capacitors in radial distribution systems have been proposed. Among the proposed approaches for solving the optimization problem, genetic algorithms, particle swarm optimization, and multi-objective algorithms are the most common approaches used. Genetic algorithms are considered the most powerful methods for solving optimal placement and sizing DG units and capacitors in radial distribution systems. In [4], the authors proposed an improved genetic algorithm called IGA, where system reconfiguration is considered after DG and SC placement. The proposed algorithm is investigated on IEEE 33-bus and 69-bus test distribution networks and showed promising results compared with other methods. In another study [5], the stability of distribution systems was studied by using a simple genetic algorithm with a voltage stability index. In [6], the authors suggest a hybrid optimization technique based on the Imperialist Competitive Algorithm (ICA) and Genetic Algorithm (GA) to solve the problem of optimal placement and size of DG and SC. Minimizing the power loss, increasing the voltage stability index and enhancing the voltage profile are considered objective functions. In [7], a new GA was suggested for solving the problem of optimal sitting and sizing of DG and capacitors by enhancing active power, reactive power, and voltage. In [8], the GA was used to find the optimal siting and capacity of the same problem, and the system reconfiguration was exploited. In [9], anthers proposed hybrid method has been presented based on GA and moth swarm algorithm (MSA) to solve the problem of optimal sitting and sizing of DG and SC for reducing power loss. In [10], the authors developed a new GA and used it to solve the problem in DG and SC placement and sizing. Voltage stability margin, power loss, and the costs of DG units and SC are considered multi-objective functions but merged in a single fitness function.

In [11], multi-objective algorithms, reducing real power loss, balancing current in buses, and enhancing voltage stability, are used to determine the exact positions and capacities of DGs and SCs by utilizing the particle swarm optimization (PSO). In [12], a multi-objective evolutionary algorithm based on decomposition MOEA/D approach was used to solve the optimal placement and sizing of DGs and SCs problem.

Memetic algorithms are also used to solve the problem of optimal siting and sizing of DGs and shunt capacitors. For example, in [13] a memetic algorithm was used to determine the optimal placement and size of DGs and SCs. The authors considered different scenarios to demonstrate the effectiveness of the algorithm and prove the importance of using the voltage stability index in the objective function. Another study [14] combined pattern search and genetic algorithms. PSO has stable convergence and generates high-quality solutions [15] and is thus one of the most widely used methods for solving engineering problems. In [16], a simple PSO algorithm with the Newton-Raphson method was used to solve the problems in the optimal placement and sizing of DGs and SCs. Kanwar and Gupta [4] presented a new algorithm called (IPSO) and compared it with standard PSO. Reza and Seyyed [17], suggested a binary PSO (BPSO) algorithm for solving the problems in DG and SC placement and sizing. The objective function consists of many parameters, namely, voltage profile index, DG's and capacitor's investment cost index, active power loss index, reliability index, and voltage profile index. In [18], authors adopted Discrete Particle Swarm Optimization (DPSO) method to optimize sitting and sizing of DG and SC for the voltage profile enhancement, loss minimize and decrease the total harmonic distortion. In Ref. [19], the Adaptive Particle Swarm Optimization (APSO) was presented for finding optimal sitting and sizing of DG and SCs in the redial distribution network (RDN).

Recently, a hybrid approach called hybrid WIPSO-GSA [20], which consists of weight improved PSO (WIPSO) and gravitational search algorithm (GSA), was proposed. Additionally, a new method using PSO, called the Salp Swarm Algorithm (SSA) [21], was proposed and tested against many other algorithms. Recently, a combined optimization method that developed based on Salp Swarm Algorithm (SSA) and loss sensitivity is proposed to solve the problem of optimal allocation in radial distribution networks [22]. In [23], Sambaiah and Jayabarathi proposed Salp Swarm Algorithm (SSA) for determining DG and SC placement and size in RDN. Khodabakhshian and Andishgar [24] proposed the intersect mutation differential evolution (IMDE) algorithm to find the optimal sites and sizes of DGs and SCs in radial systems. Reducing total power loss was considered an objective function. Khatod and Sharma [25] presented an analytical approach for solving the optimization problem and applied a sensitive analysis and heuristic curve fitting techniques to determine the optimal location and size, respectively. In [26], the water cycle algorithm (WCA) was used to solve the placement problem. Researchers in [27] presented a binary collective animal behavior approach to determine the best placement and size in a radial network. Reducing total power loss and voltage deviation are considered objective functions. The Grey wolf optimizer (GWO) is another technique that is also applied for the allocation problem of PV based DG and DSTATCOM by using IEEE 85 bus distribution system [28]. The Bacterial Foraging Optimization Algorithm [29] was adapted to find the optimal sizes of DGs and SCs. In [30], the teaching-learning-based optimization (TLBO) algorithm has been addressed to find the optimal location and capacity of SC and DG to achieve maximum benefit in regard to cost (BRC). The Grasshopper Optimization Algorithm (GOA) is also used to determine the best locations and sizes of capacitor banks as presented in [31]. In [32], the analytical technique is used to find the exact positions and capacities of DGs and SCs with different load levels (50%, 100%, and 150%). In another article [33], a hybrid approach called Harmony Search Algorithm (HSA) and the Particle Artificial Bee Colony algorithm (PABC) has been used to determine the optimal siting and sizing of DG and SC. In [34], authors consider the uncertainties of the system and proposed lightning attachment procedure optimization (LAPO) for finding the best placement of renewable energy resources (wind and solar PV units) in the radial distribution network (RDN). Authors in [35] developed a new hybrid optimization approach based on Artificial Bee Colony (ABC) and Artificial Immune System (AIS) to find the optimal sitting and sizing of DG and SC. In another similar study, the authors suggested a method based on Backtracking Search Algorithm (BSA) to solve the problem of the optimal location of both DG and static capacitor banks for enhance voltage profile and decrease the power loss of distribution system [36].

C. CONTRIBUTION AND PAPER ORGANIZATION

The salient contributions and findings of this study can be summarised as follows:

- An efficient optimization approach for solving the problem in the optimal placement and size of SCs and DGs in a radial distribution network (RDN) was developed for the reduction of power loss and reduction voltage deviation.
- A new local search mechanism is incorporated into GA to reduce the searching time and enhance convergence ability and therefore enhance the overall solution quality.
- The proposed approach is tested for different DGs and Capacitors on two IEEE 33-bus, and 69-bus distribution networks. Added to that, the scalability and flexibility of the proposed EGA are proved for IEEE 119-bus distribution network.
- The simulation results prove that the proposed algorithm is reliable, scalable promising results and high solution quality compared with other methods reported in the literature.
- Economical assessment study based on cost analysis is provided at three light, shoulder and heavy loading levels.

This rest parts of this paper is organized as follows: Section 2 describes the mathematical formulation of the considered problem. Section 3 introduces genetic algorithms and our enhanced genetic algorithm and how these algorithms solve the problem in determining the optimal allocations and capacities of DGs and SCs in radial distribution systems. Section 4 provides the first scenario implemented setting of the proposed approach for radial distribution networks RDN (33 bus, 69 bus, and 119 bus) and the second scenario applied different load levels to RDN to investigate the annual cost before and after compensation, and the results and detailed discussion. Finally, Section 5 concludes the paper and proposes some future work.

II. PROBLEM FORMULATION

This paper addresses the problem in the optimal placement and sizing of DGs and SCs in radial systems. The advantages of active and reactive power compensators are necessary for the identification of their best location in the distribution system to minimize the system power losses.

Figure 1 shows a single line diagram of the two nodes of a distribution system. The two branches in Figure 1 (bus_i) is the sending end bus and (bus_{i+1}) is the receiving end bus. Real power (P_{i+1}) and reactive power (Q_{i+1}) can be determined by Eqs (1) and (2), respectively, without compensator sources.

$$P_{i+1} = P_i - P_{lossi,i+1} - P_{Li+1} \tag{1}$$

$$Q_{i+1} = Q_i - Q_{lossi,i+1} - Q_{Li+1} \tag{2}$$

When DG (injected active power to (bus_{i+1}) and SC (injected reactive power to bus_{i+1}) are installed, real power (P_{i+1}) and reactive power loss (Q_{i+1}) can be calculated by

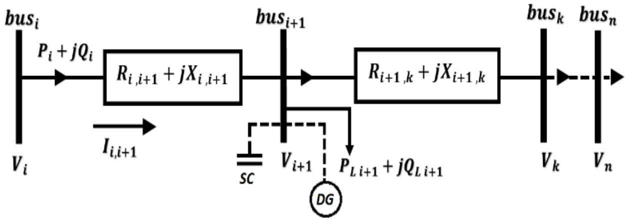

FIGURE 1. **Single line diagram of a radial feeder with SC and DG placement.**

Eqs. (3) and (4).

$$P_{i+1} = P_i - P_{lossi,i+1} - P_{Li+1} + P_{DGi+1} \tag{3}$$

$$Q_{i+1} = Q_i - Q_{lossi,i+1} - Q_{Li+1} + Q_{SCi+1} \tag{4}$$

The real power loss ($P_{lossi,i+1}$) and reactive power ($Q_{lossi,i+1}$) between two nodes can be determined by Eq (5) and Eq (6). $R_{i,i+1}$ represents the resistance of the line between nodes i and $i+1$, and $Q_{i,i+1}$ is the reactance between (bus_i) and (bus_{i+1}).

$$P_{loss(i,i+1)} = I^2_{i,i+1} * R_{i,i+1} = \left(\frac{P_i^2 + jQ_i^2}{|V_i^2|}\right) * R_{i,i+1} \tag{5}$$

$$Q_{loss(i,i+1)} = I^2_{i,i+1} * X_{i,i+1} = \left(\frac{P_i^2 + jQ_i^2}{|V_i^2|}\right) * X_{i,i+1} \tag{6}$$

The total active power loss TP_{loss} and reactive power loss TQ_{loss} of the radial distribution network at any load, levels can be computed by Eq (7) and Eq (8) respectively.

$$TP_{loss} = \sum_{i=0}^{n-1} P_{loss(i,i+1)}. \tag{7}$$

$$TQ_{loss} = \sum_{i=0}^{n-1} Q_{loss(i,i+1)}. \tag{8}$$

Total voltage deviation (TVD) at any load level can be minimized by sitting of DGs and SCs to the network. The TVD can be calculated by Eq (9) as:

$$TVD = \sum_{i=0}^{n-1} |Vref - Vi| \tag{9}$$

The primary objective function in this work aims to minimize the total active power as:

$$F(x) = Minmize(TP_{loss}) \tag{10}$$

- Problem Constraints
  The constraints of the considered problem are described in this subsection. First, the constraints of voltage and current nodes are explained, and then the constraints of DGs and SCs sizing.
- Node Voltage and Current
  The current $I_{i,i+1}$ the flow between nodes i and i+1 must be less than the maximum current capacity of this branch $I_{i,i+1(max)}$, as provided in Eq (11).

$$I_{i,i+1} \leq I_{i,i+1(max)} \tag{11}$$

  The voltage magnitude of a node should lie within voltage and lie between the range from the minimum voltage ($V_{\min}$) to maximum voltage (V_{max}). In this paper, voltage is ±5% of the nominal voltage of the RDN. The voltage V_i should lie within 0.95 per unit (p.u) as V_{min} and 1.05 p.u as V_{max}, as indicated in Eq (12):

$$V_{min} \leq V_{i,i+1} \leq V_{max} \tag{12}$$

- DG and Shunt Capacitor Sizes
  In the placement of DG compensators, the power factor of the DGs is the unity power factor ($p.f = 1$). The total real power $\left(P_{DG,(i)}\right)$ provided by the DG units to be installed should be equal to 50% or less than the total real power loads ($\sum_{i=1}^{n} P_{L(i)}$) of the RDN so that overcompensation can be prevented. The DG size constraint is provided in Eq (13).

$$\sum_{i=1}^{NDG} P_{DG,(i)} \leq 0.5 * \sum_{i=1}^{n} P_{L(i)} \tag{13}$$

- SC compensator placement.
  The total reactive power ($Q_{SC,(i)}$) provided by the SC units to be installed should be less than the total reactive power loads ($\sum_{i=1}^{n} Q_{L(i)}$) of the RDN so that overcompensation can be prevented. SC size constraint is provided in Eq (14).

$$\sum_{i=1}^{NSC} Q_{SC,(i)} \leq 1.0 * \sum_{i=1}^{n} Q_{L(i)} \tag{14}$$

III. PROPOSED SOLUTION METHODOLOGY

In this paper, a new hybrid and improved genetic algorithm for solving the problem of the optimal siting and capacity of DG units and capacitors in the radial distribution system is proposed. The proposed algorithm merges the genetic algorithm with another local search algorithm to exploit their advantages. Merging the local search and genetic algorithms is a common approach in the computer engineering field and it is conducted to solve the difficult and complex optimization problems in several domains. Algorithm 1 shows the steps of the normal genetic algorithm. In the normal genetic algorithm, a number of solutions are selected and then the crossover and mutation operations are applied to them to generate the new set of solutions. After that, a number of old solutions are replaced by the new generated solutions. These steps are repeated until the end condition is satisfied. The main difference between our proposed algorithm and the normal genetic algorithm is inserting a fast and simple local search mechanism in each generation. The new local search mechanism tries to enhance the current solutions by searching around them in the close search regions.

Two different mechanisms are applied, the first one for enhancing the locations of capacitors and DGs, and the second one for enhancing the capacities of them. Moreover, the proposed enhanced genetic algorithm uses a hybrid replacing mechanism instead of the normal replacing mechanism used in the normal genetic algorithm. The hybrid mechanism works by replacing some of the existing solutions randomly and some of them by removing the worst solutions. By using this hybrid replacing mechanism, the algorithm is able to both reserves the good solutions and gives more opportunities to bad solutions in order to enhance themselves in the

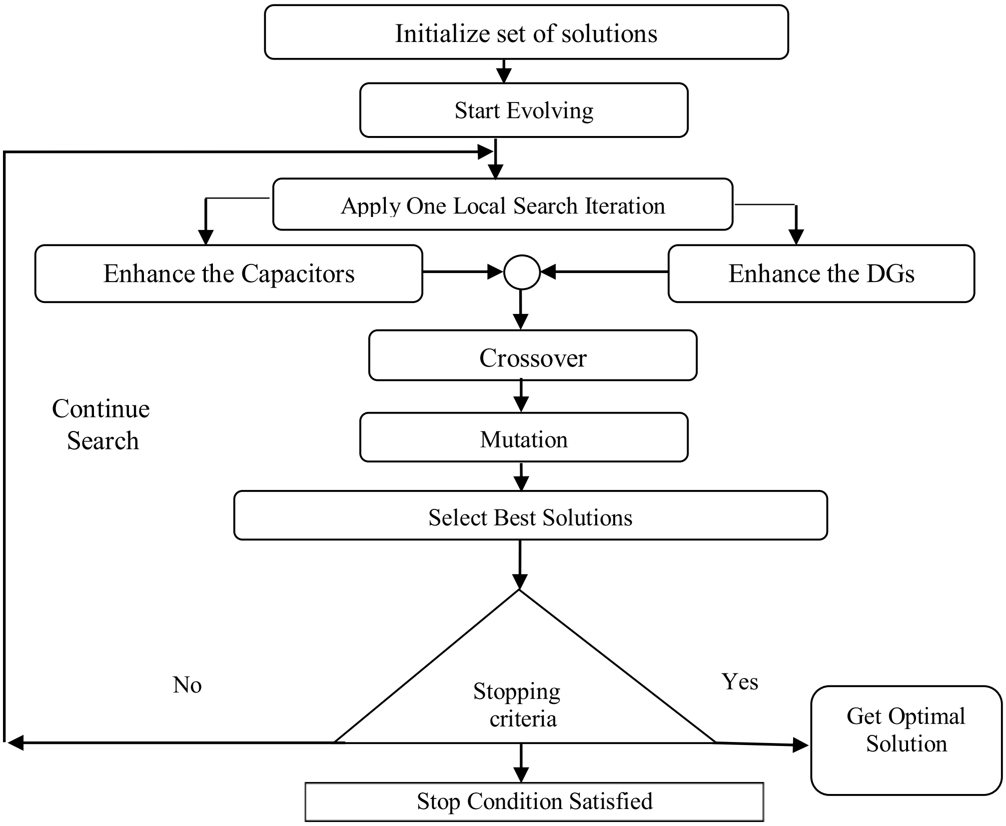

FIGURE 2. **Main steps of the proposed algorithm.**

next generations. The steps detail of our enhanced algorithm is given in the next paragraphs. Algorithm 1 shows the main steps of the genetic algorithm before the enhancement.

Figure 2 shows the main parts of the proposed framework. First, a set of solutions is initialized for the generation of the population of the genetic algorithm. Second, the iterations of the algorithm start by applying the local search algorithm. Third, a generation from the genetic algorithm is executed to enhance and guide the search process. The algorithm then decides if the search mechanism will continue or will be stopped according to the stop condition before the algorithm starts, many parameters related to the genetic algorithm, such as the number of variables in the population, should be initialized and selected, and the number of generations is executed. Some parameters are related to the definition of the problem, such as the maximum number of capacitorsand the minimum and maximum locations that can be used in the replacement process. These parameters are discussed in detail in the experimental results section. Subsequently, the population of the genetic algorithm is initialized randomly based on the conditions of the problem, such as the minimum and maximum values of the capacity of capacitors.

In the EGA, the presentation of each solution is divided into two parts, as shown in Figure 3. The first part in 2* N places represents the locations of the N capacitors and N DGs of the problem, whereas the other 2* N places represent the capacities of the placed N capacitors and N DGs. To take decisions based on these solutions, we should evaluate the values by using a suitable fitness function. In this study, Eq (10) (described in the problem definition) is utilized to compute the fitness function. Algorithm 2 shows the steps of the proposed algorithm. After the evaluation process, a fast-local search algorithm is applied to enhance the solutions before the first iteration of the genetic algorithm. The main task of the local search is to fasten the process of searching for optimal solutions by guiding the solutions of the population to the correct directions. Therefore, the solutions quickly catch the directions that make them more close to optimal solutions.

Algorithm 1 Main Steps of the Normal Genetic Algorithm

```
Begin
Generate random population of n solutions/chromosomes.
While stop condition is not satisfied
Evaluate the fitness of each solution/chromosome in the population.
Select some solutions to create new better solutions for next generation.
    Perform the crossover mutation operation.
        Place new generated solutions in the new population.
End
Return the best solution in current population.
```

Capacitor (C1) Location	Capacitor (C2) Location	.....	Capacitor (CN) Location	Capacitor (C1) Capacity	Capacitor (C2) Capacity	.....	Capacitor (CN) Capacity
DG (DG1) Location	DG (DG2) Location	.....	DG (DG_N) Location	DG (DG1) Capacity	DG (DG2) Capacity	.....	DG (DGN) Capacity

FIGURE 3. The presentation of each solution in the proposed EGA.

Algorithm 2 The main steps of the enhanced genetic algorithm

```
Begin
Initialize the constants and input parameters;
Initialize the population solutions randomly;
Check the validity of initialized solutions based on constraints explained in Section 2, and corrects the solutions that violate the constraints;
while Stop condition is not satisfied do
        /* use the equations and formulas in the previous section*/
        Evaluate the solutions of the population using the power loss objective function;
        /* apply the local search algorithm*/
        Enhance the solutions by searching for better solutions around each solution;
        /* to generate new good solutions from them */
        Select the besttwo solutions from the population;
        /* perform genetic algorithms operators*/
        Apply the crossover operator;
        Test the validity of the new generated solutions after crossover;
        Apply the mutation operator;
        Test the validity of the new generated solutions after mutation;
        /* insert the new solutions*/
        Replace the new generated solutions with randomly selected solutions;
end
```

Algorithm 3 The steps of the enhanced local search algorithm used in the proposed framework

```
Begin
for all solutions in the population
for all variables in the solution
    if the variable presents the location
        f = fitness value of the solution without any change.
            f1 = re-evaluate the solution after randomly select another location close to the current one (higher location value than the current location).
            f2 = re-evaluate the solution after randomly select another location close to the current one (lower location value than the current location).
            Select the best value of this variable by
        comparing f1, f2, and f.
    end
    if the variable presents a capacity
  f = fitness value of the solution without any change.
    f1 = re-evaluate the solution by decreasing the variable with small random value c.
    f2 = re-evaluate the solution by increasing the variable with small random value c.
 Select the best value of this variable by comparing f1, f2, and f.
    end
end for
end for
end
```

The pseudo-code of the local search mechanism is described in Algorithm 3. After a local search is conducted on all solutions, the algorithm selects two solutions to be used as the fathers of newly generated solutions. The proposed algorithm uses the common method of selecting the best two solutions. The two new solutions are derived from the selected two solutions by applying crossover and mutation operators. The crossover operator is used as a one-point crossover that substitutes two parts of the parents based on a randomly selected point. For the application of the mutation, a small value is added or subtracted from each chromosome in the considered solution. We use different values for the locations and capacities of the DGs and capacitors because the range of changing the DGs and capacitors capacities are larger than the range of the DGs and capacitor places. The validity of the new solutions or children is ensured by applying a check and handling process on each solution. This approach prevents any solution from exceeding the specified limits of each variable and ensures that the new solutions do not violate the constraints of the problem. Finally, the two generated solutions are inserted into the population by removing the worst two solutions from the population. The algorithm repeats these steps until the stopping condition is satisfied. By evolving the solutions with these procedures, the solutions are enhanced gradually until an optimal or near-optimal solution is obtained.

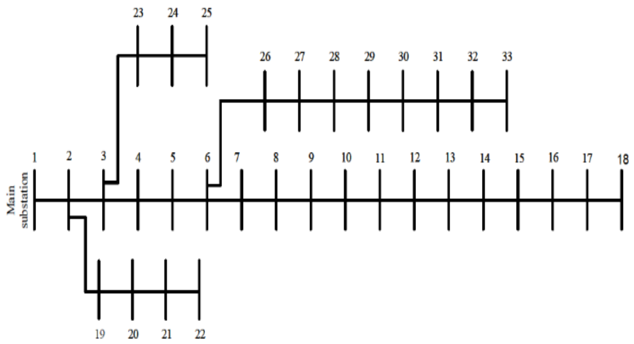

FIGURE 4. IEEE 33-bus distribution system.

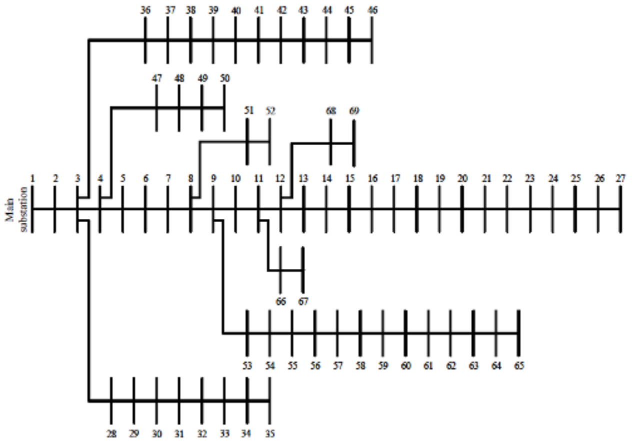

FIGURE 5. IEEE 69-bus distribution system.

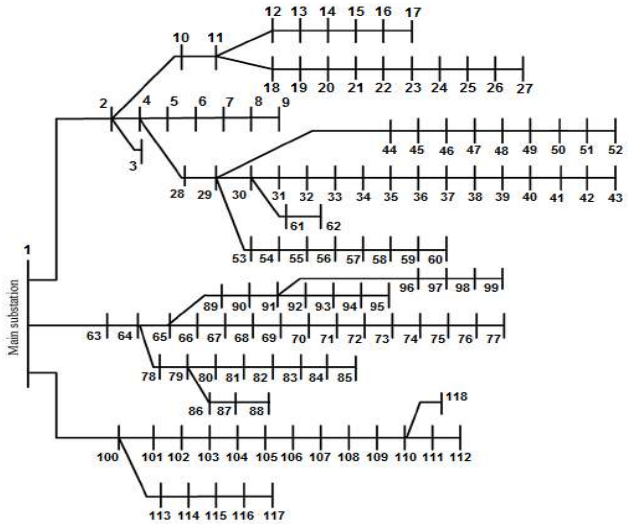

FIGURE 6. IEEE 119-bus distribution system.

TABLE 1. Parameters and inputs of our proposed EGA.

Parameter	Value/criteria	Parameter	Value/ criteria
Population size	75	Crossover Operator	0.7
Number of variables	Shunt Capacitors/ DGs) * 2	Mutation Operator	0.1
Crossover Type	One point crossover	Replacement Method	Randomly
Mutation	Bit-flip mutation	Selection	Best Solutions

IV. APPLICATIONS

A. TEST SYSTEMS

Three test systems are considered in this paper to prove the capability of the proposed method for allocating the DGs and SCs. The typical radial distribution systems are shown in Figs. 4-6. The first test 12.66kV, 33-bus system is connected by 32 branches. The total load of the 33-bus RDN is P=3.72MW and Q=2.3 MVAr. The Line and load data are provided in [40]. The base system power and voltage are 10 MVA and 12.66 kV respectively [41]. Fig. 5 shows the second distribution system is 12.66kV, 69-bus system contract of branches. The total load of the 69-bus RDN is P=3.8MW and Q=2.69 MVAr. The base voltage and power are12.66 kV and 10 MVA. The Line and load data are provided in [42]. The standard 11kV 119-bus radial distribution system with 118 branches is shown in Fig.6. The total load of the system is 22.71 MW and 17.04 MVAr. The line and load data are given in [35]. The base power and voltage of the system is 100 MVA and 11 kV, respectively [43].

The cost of power losses, capacitor and DG units are calculated based on the following mathematical model as in [38] for capacitors and in [39] for DGs as: The calculated energy cost and purchase cost of the capacitor are Energy cost = US \$0.06/kWhr. Purchase cost of capacitor = US \$3.0/kVAr. The cost of the DG active power is: $DGC = a.Pdg^2 + b.Pdg + c\$/Mwh$, where the cost coefficients are taken as: a = 0, b = 20, c = 0.25.

B. STUDIED SCENARIOS

In this section, three scenarios applied to prove the capability of the proposed EGA are defined as follows:

- The first scenario investigates the proposed EGA on three radial distribution networks, IEEE 33-, 69- and 119-bus test systems with different combinations between DGs and SCs.
- In the 2nd scenario, the proposed EGA is investigated on three different load levels for computing the optimal placement and capacity of DGs and SCs. About the minimum and maximum limits of DG and SCs size in the second scenario, it is based on the size of the DGs and SCs obtained in the first scenario and changes by the amount of low (50%), nominal (100%), peak (160%) loading levels and the load duration time of 2000, 5260 and 2000 hours, respectively. The cost of power loss, cost of DGs and SCs are calculated to investigate the annual saving at every load level.
- The 3rd scenario is investigated in this study to find the optimal placement and capacity of 2DG and 2SC in the three test systems under uncertainty of load condition according to the load uncertainty considering normal probability density function (PDF) as given [34] in represented in Eq (15).

$$\Delta d\left(P_d\right) = \frac{1}{\sigma_d\sqrt{2\pi}} \exp\left[-\frac{\left(P_d-\mu_d\right)^2}{2\sigma_d^2}\right] \qquad (15)$$

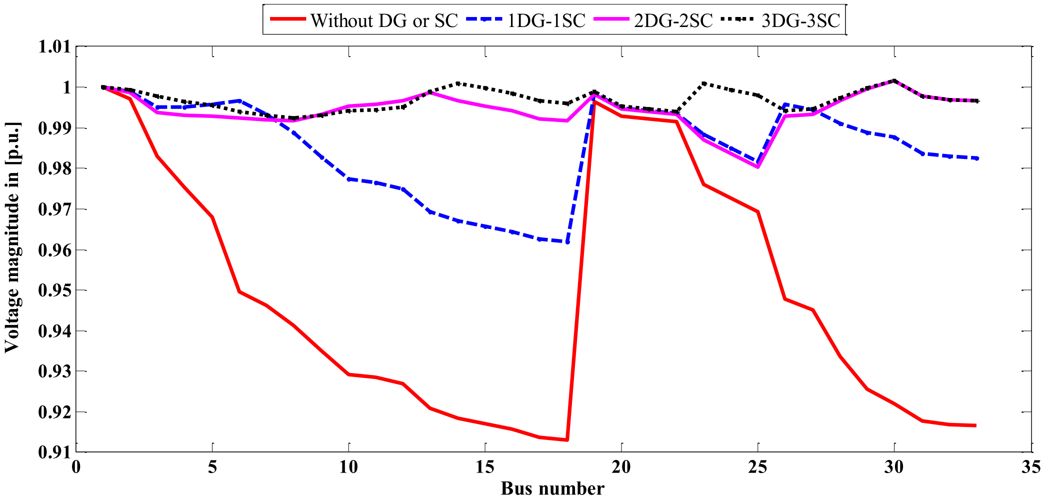

FIGURE 7. 33-bus network voltage profile in different cases.

TABLE 2. Performance of the proposed EGA of different combinations of DGs and SCs for IEEE 33-bus RDN (Scenario1).

Algorithm (Particulars)	SCs Optimal size (kVAr) / Candidate buses	DGs optimal size (kW) / Candidate buses	Total real power loss (kW)	TVD in (p.u.)	% Total real power loss reduction	Min voltage in (p.u.) (bus no).
Base case	-	-	202.69	1.7047	-	0.9130 (18)
GA (1DG+1SC)	1248.40 (30)	1905.74 (7)	52.73	0.5333	73.98%	0.9616 (18)
PSO [15] 1DG+1SC)	1457.0 (30)	2511.0 (6)	59.7	-	-	0.955 (18)
EGA (1DG+1SC)	1253.2 (30)	2499.9 (6)	51.80	0.4907	74.44%	0.9619(18)
GA (2DG+2SC)	947.95 (30) 578.18 (26)	930.83 (30) 1007.9 (12)	31.39	0.3090	84.51 %	0.9802(24)
Analytical [25] (2DG+2SC)	400.0 (33) 500.0 (32)	447.00 (18) 559.00 (17)	84.28	-	-	0.9610 (30)
IMDE [24] (2DG+2SC)	254.8 0(16) 932.30 (30)	1080 (10) 896.4 (31)	32.08	-	-	0.9790 (25)
EGA (2DG+2SC)	438.57 (13) 1047.4 (30)	835.66 (13) 1161.70(30)	28.50	0.192	85.94%	0.9804 (25)
GA (3DG+3SC)	516.04 (10) 468.27 (24) 811.45 (30)	902.17 (24) 1729.90 (6) 645.42 (14)	19.88	0.1387	90.19 %	0.9803 (33)
WCA [26] (3DG+3SC)	465.00 (23) 565.00 (30) 535.00(14)	973.00 (25) 1040.0 (29) 536.00 (11)	24.68	-	87.81%	0.9800 (33)
BFOA [29] (3DG+3SC)	163.00 (18) 338.00 (33) 541.00 (30)	542.00 (17) 160.00 (18) 895.00 (33)	41.41	-	-	0.9780 Not reported
EGA (3DG+3SC)	388.75(25) 334.77 (14) 1189.91 (30)	1094.96 (24) 767.74 (14) 964.2 2(30)	12.70	0.1109	93.73%	0.9924 (8)

For the studied cases, the power flow computations are performed using the Forward-Backwards Sweep Algorithm (FBSA) [37]. For the simulations' experiments, the distributed generation is operated with a unity power factor and supplied active power only such as Photovoltaic. It supplies active power while the SC supplies reactive power. The parameters and inputs of our proposed EGA are given in Table 1. Individual or combined DGs and SCs units are allocated in this study. It can be assigned to any minimum and maximum values within the defined corresponding range. The minimum limits of DGs and SCs are set as 200 kW and 200 kVAr and the maximum respectively based on the research work presented in [12]. Furthermore, the maximum limits of cumulative DG and SC ratings are selected according to Eqs. (13) and (14) respectively. The line data and load profile data used to support the findings of this study have been explained in References [40]–[43].

1) SIMULATION RESULTS OF IEEE-33 BUS RDN

Table 2 reports the simulation results obtained by the proposed EGA of the first IEEE 33-distribution system for the optimal placement and capacity of variant combinations of DGs and SCs. In the case of the first combination with (1DG + 1SC), the proposed EGA leads to the total power loss of 51.80 kW with a reduction of 74.44 % compared with 52.73 kW by using GA with a reduction of 73.98 %, and

TABLE 3. Performance of EGA compared with different load levels on an IEEE 33 bus RDN for Scenario 2.

Load level	0.5			1			1.6		
Particulars	1DG+1SC	2DG+2SC	3DG+3SC	1DG+1SC	2DG+2SC	3DG+3SC	1DG+1SC	2DG+2SC	3DG+3SC
Annual power loss without compensator (kW)	94140			1066202			863175		
Optimal SCs size kVAr) / Candidate buses	607.92 (30)	404.82 (30) 487.31 (7)	378.14 (30) 208.17 (13) 263.64 (24)	1253.2 (30)	438.57 (13) 1047.4 (30)	388.75 (25) 334.77 (14) 1189.91 (30)	2038.8 (30)	1553.9 (30) 986.68 (9)	1547.6 (30) 763.86 (12) 891.96 (24)
DGs optimal size (kW) / Candidate buses	1222.80 (6)	499.98 (30) 414.61 (13)	505.16 (30) 404.32 (14) 574.52 (24)	2499.9 (6)	835.66 (13) 1161.7 (30)	1094.96 24) 964.22 (30) 767.74 (14)	3997.3 (6)	1278.9 (13) 1978.2 (30)	1850.9 (10) 1847.2 (24) 1144.7 (31)
Annual power loss with compensator (kW)	25302	15000	6808	272468	149910	37872	350274	113805	56599
Annual reduction of power loss %	73.12%	84.06%	92.76%	74.44%	85.93%	96.44%	59.42%	86.81%	93.44%

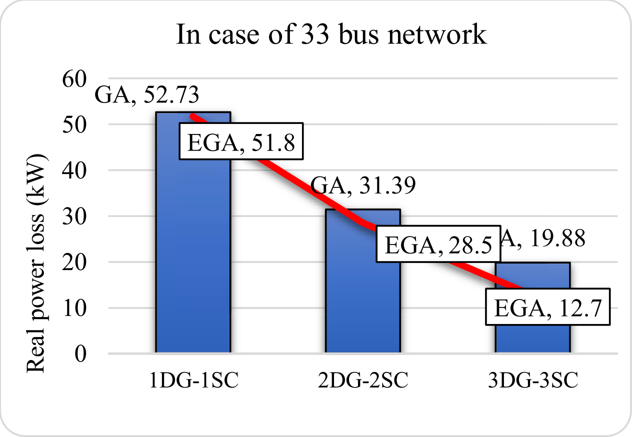

FIGURE 8. Comparison of power losses for different optimization approaches.

59.7 kW by using PSO [15]. For the second combination with (2DGs + 2SCs), the EGA has the best performance compared with IMDE [24], Analytic [25] and GA. In terms of the power losses, the proposed EGA leads to the lowest power loess (28.0 kW) compared with 84.32 kW by the analytical in [25], 31.39 kW by GA, 32.08 kW by IMDE. In the last combination (3DGs + 3SCs), the proposed algorithm outperforms the other algorithms. The real power loss of the EGA algorithm is 12.70 kW with a minimum voltage of 0.9924 p.u. The power loss of GA is only 19.88 kW, and the power loss of WCA [26] is 24.68 kW. Real power loss is 41.41 kW by using BFOA [29]. The minimum voltage is 0.913 p.u in the base case, where the EGA achieved better results by placing 3 DGs and 3 SCs which obtains a minimum voltage level equals to 0.9924 p.u. The lowest power losses in the third combination equal to 12.7 kW. For all studied combinations, the proposed EGA leads to the best voltage profile as the minimum voltage levels for all combinations have the highest levels. Added to that the increased combination of DGs and SCs improves the overall system performance that a high reduction in power losses and improvement in voltage profile as shown in Fig. 7.

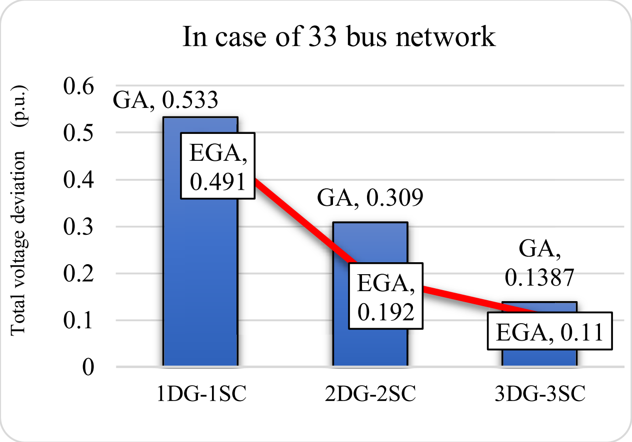

FIGURE 9. Total voltage deviation for different optimization approaches.

TABLE 4. Cost of energy loss and minimum system voltage for 33 IEEE bus RDN for Scenario 2 without SCs/DGs.

Load level	0.50 (light)	1.0 (nominal)	1.60 (peak)
Power loss (kW)	47.07	202.7	575.45
Energy loss cost ($)	5648.4	63972.12	51790.5
Minimum system Voltage (p.u.)	0.9583	0.9131	0.8528
Maximum voltage =1.0 p.u.	Total energy loss cost = 121411 $		

Figures 8 and 9 show a comparison between the total power loss and the total voltage deviation obtained with the proposed EGA compared with other competitive algorithms for the placement combinations. The overall reduction in power loss when the proposed EGA algorithm is used is much better than that when the GA is used in all the tested cases. In the case of 1DG+1SC, the TVD is 0.533 p.u. by GA method and reduced to 0.490 p.u. by EGA. In the 2DG+2SC case, a significant reduction is observed. TVD becomes 0.192 p.u. for the EGA and 0.301 p.u. for the GA. In the case of 2DG+3SC, the TVD is 0.1109 p.u. using the proposed algorithm and 0.1387 p.u. by GA. The obtained results prove that the high capability of the proposed EGA compared with other competitive methods. Figure 10 shows

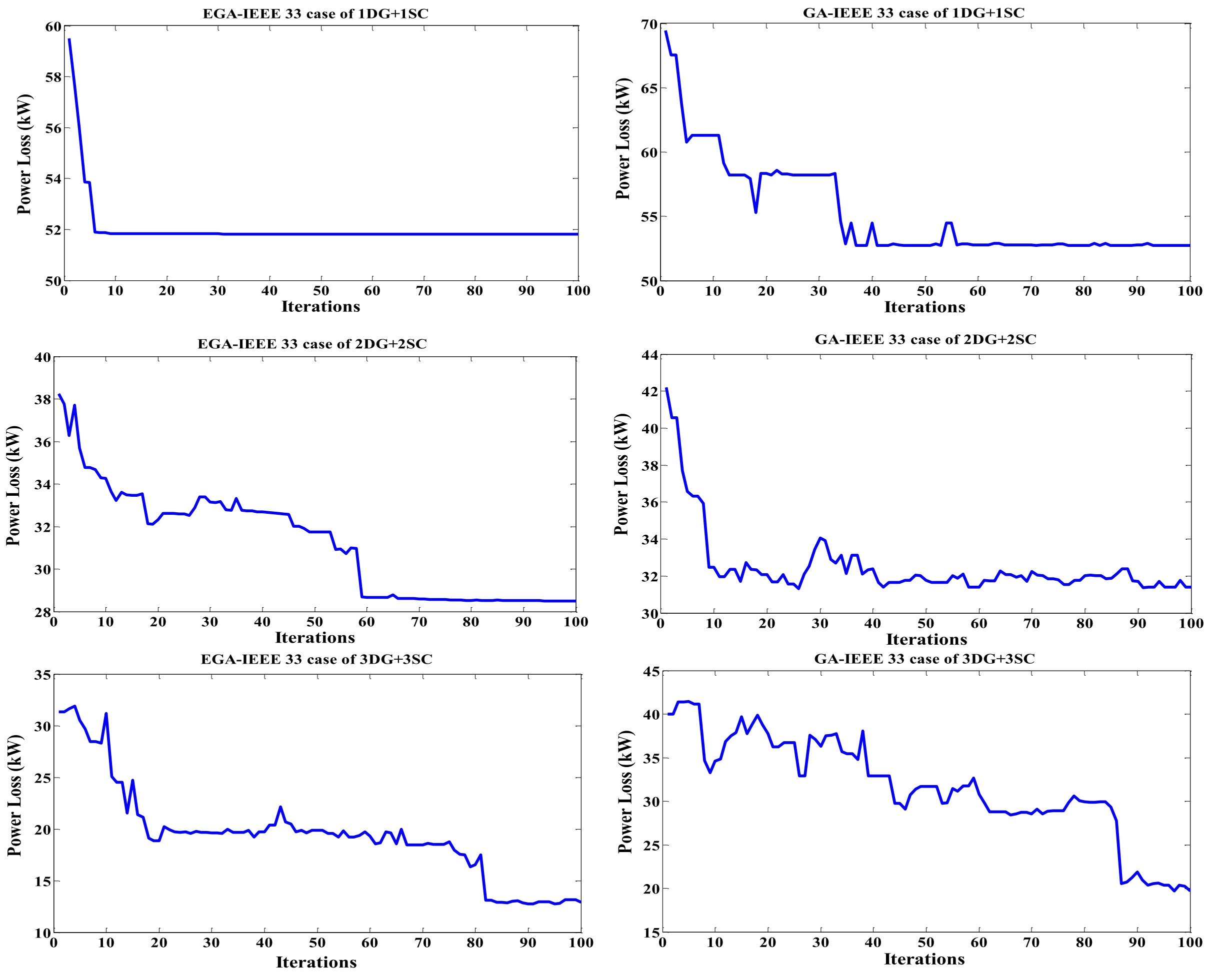

FIGURE 10. Convergence curves of the IEEE 33-bus test system for the three combinations.

TABLE 5. Comparison of results with and without losses on 33 IEEE bus RDN.

Load level	0.5			1			1.6		
Particulars	1DG+1 SC	2DG+2S C	3DG+3S C	1DG+1S C	2DG+2S C	3DG+3S C	1DG+1S C	2DG+2S C	3DG+3S C
Energy loss cost without compensator ($)	5648.4			63972			51790		
Total losses cost with compensator ($)	1518.1	900	408.48	16348.	8994.6	2272.3	21016.	6828.3	3395.9
Total capacitor cost ($)	1823.7	2676.3	2549.8	3759.6	4457.9	5740.3	6116.4	7621.8	9610.2
Total DG cost ($)	24.70	18.54	29.93	50.24	40.197	56.788	80.196	65.392	97.106
Total annual savings ($)	2281	2053	2660	43814	50479	55902	24577	37274	38686

the convergence levels for EGA and GA for finding the best solutions across 100 iterations. Clearly, the proposed algorithm (EGA) can achieve the best solution faster than the genetic algorithm in all cases.

For the 2nd scenario, Table 4 shows the results of optimal placement and size of DGs and SCs at three load levels (light, nominal and peak) considered using the proposed algorithm EGA for performance testing. Table 3 presents the technical and economical assessment of the proposed EGA at different loading conditions for the second scenario at low (50%), nominal (100%), peak (160%) loading levels and the load duration time of 2000, 5260 and 2000 hours, respectively. The total energy loss costs equal 121411 $ without any DGs or SCs. Table 5 shows a comparison of cost energy loss for different combinations of DGs/SCs for IEEE 33 bus RDN by using the proposed EGA. The energy cost loss has been reduced in all combinations of DGs/SCs at different load levels. At light load level 0.5, the total annual savings of the three combinations, 1DG+1SC, 2DG+2SC and 3DGs+SCs, are 2281 $, 2053 $ and 2660 $, respectively. Whereat

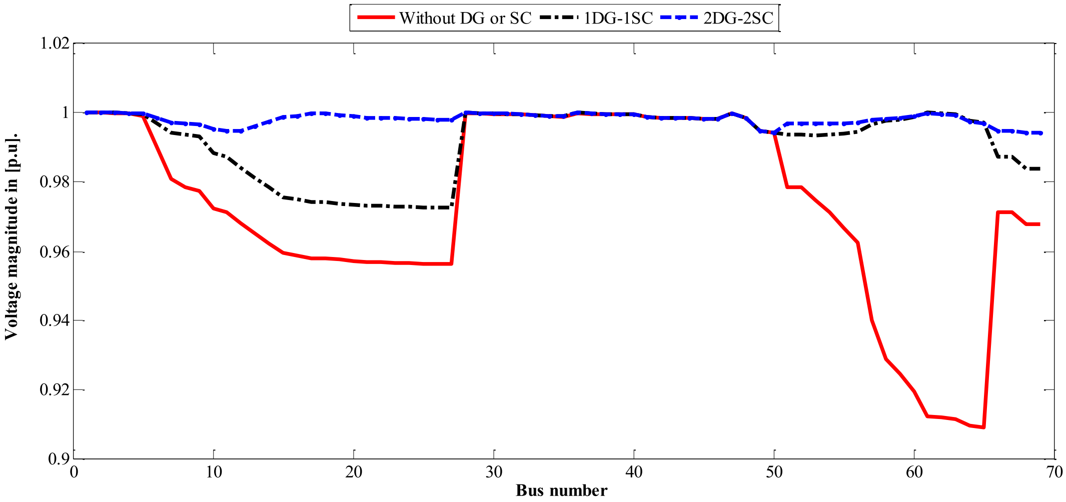

FIGURE 11. Comparison of voltage profile for different cases in the 69-bus network.

TABLE 6. Optimal placement and sizing of (2DGs+2SCs) under PDF uncertainty (third scenario) for 33-bus system.

% Loading Pd	SC1 size kVAr (place)	SC2 size kVAr (place)	DG1 size kW/(place)	DG2 Size kW /(place)	TPL (kW)
70	653.76 (30)	423.96 (9)	795.56 (30)	586.69 (13)	14.07
80	853.05 (30)	443.06 (10)	678.74 (13)	883.57 (30)	18.39
90	914.72 (30)	458.83 (11)	908.66 (30)	1026.40 (10)	23.68
100	438.57 (13)	1047.4 (30)	835.66 (13)	1161.70 (30)	28.50
110	1096.69 (30)	618.96 (10)	1287.04 (30)	983.98 (13)	35.08
120	1351.30 (30)	377.10 (14)	1047.50 (13)	1503.30 (29)	42.33

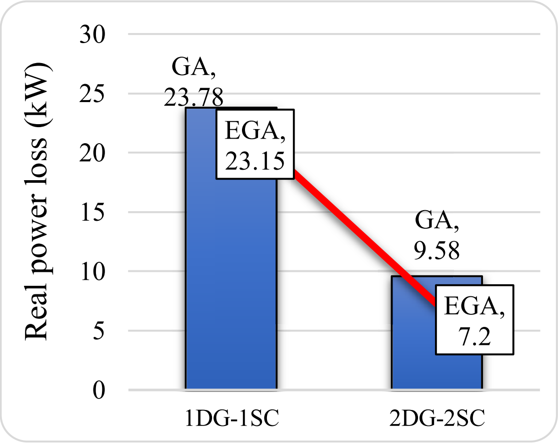

FIGURE 12. Comparison of power losses for EGA and GA.

normal load level 1 the total annual saving is 43814 $, 50479 $ and 55902 of 1DG+1SC, 2DG+2SC and 3DG+ SC, respectively. At a heavy load level, the annual saving in the case of 3DG+3SC is 38686 $. The simulation results show the capability of the proposed algorithm. Considering the third scenario, Table 6 represents the results of placement of 2DG and 2SC under load uncertainty dependent on Eq. (15) at different loading conditions in the range from 70%-120% considering the second combination, which combines two DGs and two SCs. σ_d and μ_d are 112.8 kW and 90 kW, respectively.

2) SIMULATION RESULTS OF IEEE-69 BUS RDN

Similar to the second test system, IEEE-69 bus radial distribution network. Table 7 presents the simulation results obtained by the proposed EGA for the optimal placement and capacity of variant combinations of DGs and SCs. In the case of the first combination with (1DG + 1SC), the proposed EGA leads to the total power loss of 23.15 kW with reduction 89.71 % compared with 23.79 kW by using GA with reduction of 89.42 %, and 25.9 kW by using PSO [15] and 23.17 kW by using MOEA/D [12]. For the second combination with (2DGs + 2SCs), the EGA has the best performance compared with IMDE [24], Analytic [25] and GA. In terms of the power losses, the proposed EGA leads to the lowest power loess (7.20 kW) compared with 84.32 kW by the analytical in [25], 9.58 kW by GA, 7.20 kW by using MOEA/D [12], 13.83 kW by IMDE. The minimum voltage is 0.9092 p.u at bus 65 in the base case, where the EGA achieved better results by placing 2DGs and 2SCs which obtains a minimum voltage level equals to 0.9943 p.u. at bus 68.

For the two combinations, the proposed EGA leads to the best voltage profile as the minimum voltage levels for all combinations have the highest levels. Added to that the increased combination of DGs and SCs improves the overall system performance that a high reduction in power losses and improvement in voltage profile as shown in Fig. 11. Figures 12 and 13 show a comparison between the total power loss and the total voltage deviation obtained with the pro-

TABLE 7. Performance of EGA compared with other methods applied for IEEE 69-bus RDN for the first Scenario.

Algorithm (Particulars)	Total real power loss (kW)	% Total real power loss reduction	SC optimal size (kVAr) / Candidate buses	DGs optimal size (kW)/ Candidate buses	TVD in (p.u.)	Min voltage in (p.u.) (bus no).
(Base case)	224.95	-	-	-	1.8369	0.9092 (65)
GA (1DG+1SC)	23.79	89.42%	1268.80 (61)	1694.51 (61)	0.6569	0.9716 (26)
EGA (1DG+1SC)	23.15	89.71%	1306.26– (61)	1838.71– (61)	0.5810	0.9726 (27)
PSO [15] (1DG+1SC)	25.90	-	1401.3 – (61)	1566.0 – (61)	-	0.9700 (27)
MOEA/D [12] (1DG+1SC)	23.17	-	1301.0– (61)	1829.0– (61)	-	0.9731 (27)
GA (2DG+2SC)	9.58	95.74%	437.28– (15) 1116.21– (61)	532.37– (18) 1507.24– (61)	0.2369	0.9877 (65)
MOEA/D [12] (2DG+2SC)	7.20	-	353.00 – (17) 1239.0 – (61)	1731.0 – (61) 520.00 – (17)	-	0.9943 (69)
IMDE [24] (2DG+2SC)	13.83	-	109.00 – (63) 1192.0 – (61)	1738.0 – (62) 479.00 – (24)	-	0.9915 (68)
EGA (2DG+2SC)	7.20	96.80 %	1243.66 – (61) 355.08 – (17)	522.85 – (18) 1734.10 –(61)	0.1278	0.9943 (68)

TABLE 8. Performance of EGA compared with different load levels on an IEEE 69-bus RDN for the 2nd Scenario.

Load level	**0.5**		**1**		**1.6**	
Particulars	1DG+1SC	2DG+2SC	1DG+1SC	2DG+2SC	1DG+1SC	2DG+2SC
Annual power without compensator (kW)	103190		1183252		978580	
Optimal size of SCs (kVAr) /Candidate buses	649.3 (61)	245.21 (12) 641.20 (61)	1306.26(61)	1243.66(61) 255.08 (17)	2107.7 (61)	2025.8 (61) 386.25 (18)
DGs optimal size (kW) / Candidate buses	911.71 (61)	818.74 (61) 310.72 (16)	1838.71(61)	522.85 (18) 1734.10 (61)	2941.8 (61)	873.53 (18) 3036.4 (61)
Annual power with compensator loss (kW)	11360	4094	121769	37872	90990	33270
Annual reduction of power loss %	88.99%	96.03%	89.71%	96.80%	90.70%	96.62%

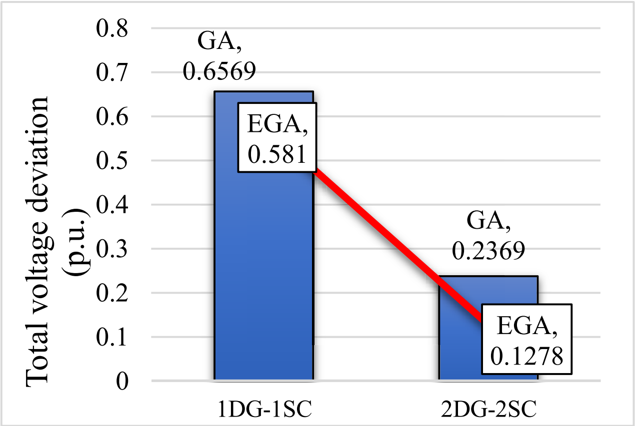

FIGURE 13. Total voltage deviation for EGA and GA.

TABLE 9. Cost of energy loss and minimum system voltage without adding DGs/SCs for IEEE 69-bus RDN.

Load level	0.50 (light)	1.0 (nominal)	1.60 (peak)
Power loss (kW)	51.5954	224.9529	652.3868
Energy loss cost ($)	6190.8	70994.22	58714.74
Minimum system Voltage (p.u.)	0.9567	0.9092	0.8445
Maximum voltage =1.0 p.u		Total energy loss cost = 135899.8 $	

posed EGA compared with other competitive algorithms for the placement combinations. The overall reduction in power loss when the proposed EGA algorithm is used is much better than that when the GA is used in all the tested cases. In the case of 1DG+1SC, the TVD is 0.533 p.u. by GA method and reduced to 0.490 p.u. by EGA. In the 2DG+2SC case, a significant reduction is observed. TVD becomes 0.192 p.u. obtained by EGA and 0.301 p.u. by GA. The obtained results prove that the high capability of the proposed EGA compared with other competitive methods. Figure 8 shows the convergence levels for EGA and GA for finding the best solutions across 100 iterations. Clearly, the proposed algorithm (EGA) can achieve the best solution faster than the genetic algorithm in all cases.

For the 2nd scenario, Tables 8-10 show the results of optimal placement and size of DGs and SCs at three load levels (light, nominal and peak) considered using the proposed algorithm EGA for performance testing. Table 8 presents the technical and economical assessment of the proposed EGA at different loading conditions for the second scenario at low (50%), nominal (100%), peak (160%) loading levels and the load duration time of 2000, 5260 and 2000 hours, respectively. The Total energy loss costs equal 121411 $ without any DGs or SCs.

Table 9 shows a comparison of cost energy loss for different combinations of DGs/SCs for the IEEE 69 bus RDN by using the proposed EGA. The energy cost loss equals 6190.8 $, 70994.22 $ and 58714.74 $ for light, nominal and peak loading conditions, respectively without the existence of either DGs or SCs. The combinations of DGs/SCs at

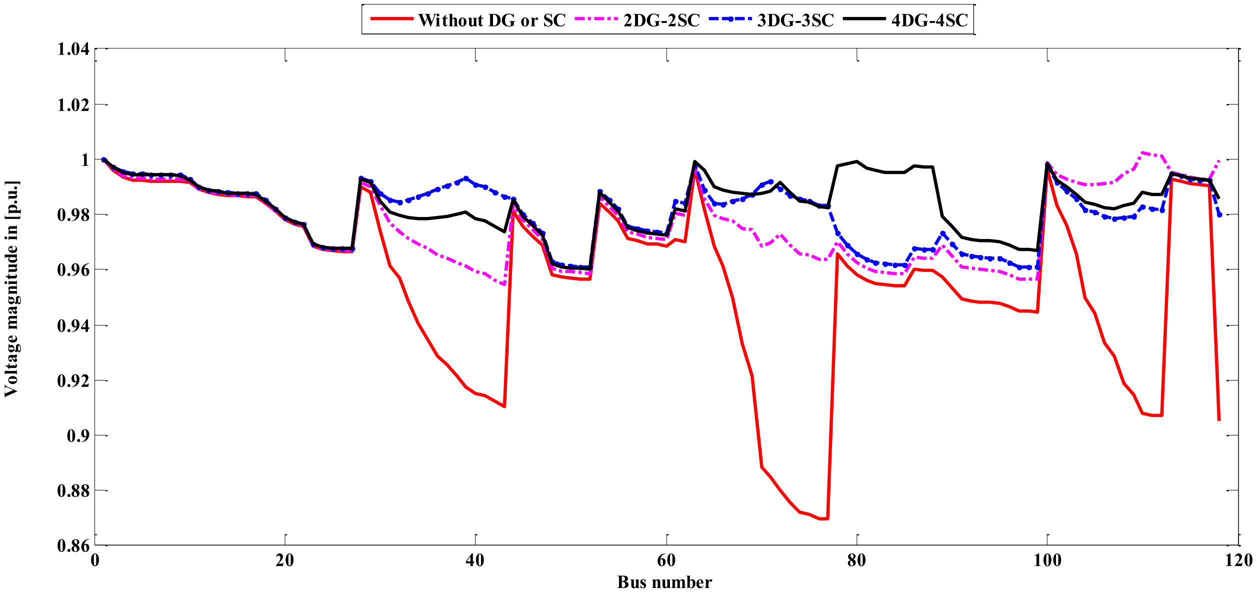

FIGURE 14. Comparison of voltage profile for different case studies in the 119-bus network.

TABLE 10. Comparison of results with and without losses on an IEEE 69-bus RDN for 2nd scenario.

Load level	**0.5**		**1**		**1.6**	
Particulars	1DG+1SC	2DG+2SC	1DG+1SC	2DG+2SC	1DG+1SC	2DG+2SC
Energy loss cost without compensator ($)	6191.4		70995.12		58714.8	
Total losses cost with compensator ($)	681.6	245.64	7306.14	2474.3	5459.4	1996.2
Total capacitor cost ($)	1947.9	2659.2	3918.78	4496.2	6323.1	7236.1
Total DG cost ($)	18.484	22.839	37.0242	45.389	59.086	78.448
Total annual savings ($)	3543	3263	59733	63979	46873	49404

TABLE 11. Optimal placmnet and sizing of (2DGs+2SCs) under PDF uncertainty (third scenario) for 69-bus RDN.

% Loading Pd	SC1 size kVAr (place)	SC2 size kVAr (place)	DG1 size kW (place)	DG2 Size kW (place)	TPL (kW)
70	778.69 (61)	504.00 (66)	317.78 (18)	1068.90 (61)	5.21
80	1055.84 (61)	346.03 (15)	1321.94 (61)	566.31 (14)	5.63
90	308.55 (17)	1138.23 (61)	1505.90 (61)	321.88 (19)	6.91
100	1243.66 (61)	355.08 (17)	522.85 (18)	1734.10 (61)	7.20
110	1210.92 (61)	412.81 (17)	1801.30 (61)	649.19 (17)	10.00
120	1601.20 (61)	544.53 (16)	1900.00 (61)	524.77 (18)	13.26

different load levels are presented in Table 10 for the second scenario. At light load level 0.5, the total annual savings of the two combinations, 1DG+1SC, and 2DGs+2SCs are 3543 $, 3263 $ respectively. Whereat normal load level 1 the total annual savings are 59733 $ and 63979 $ of 1DG+1SC, and 2DG+2SC, respectively. The simulation results show the capability of the proposed algorithm. Considering the 3rd scenario, Table 11 represents the results of placement of 2DG and 2SC under load uncertainty dependent on Eq. (15) at different loading conditions in the range from 70%-120% considering the second combination, which combines two DGs and two SCs.

3) APPLICATION TO LARGE SCALE DISTRIBUTION SYSTEM

Table 12 shows the results of the 119-bus case for the first scenario. The optimal placement and capacity of three combinations of DGs and SCs are considered for displaying the high capability of the proposed EGA for large scale RDN compared with GA. for the first combination (2DGs + 2SCs), EGA reduces the real power loss to 56.20% and the minimum voltage to 0.9545 p.u. for the second combination, three DGs and SCs are connected together, the proposed EGA significantly reduces the total real power loss to 363.42 kW, around 72.02% compared with the base case. In the third combination that merged four DGs and four SCs at the same

TABLE 12. Performance of EGA compared with those of the standard case GA on an IEEE 119-bus RDN.

Algorithm (Particulars)	SCs Optimal size (kVAr) / Candidate buses	DGs/optimal size (kW)/ Candidate buses	Total real power loss(kW)	% Loss reduction	TVD (p.u.)	Min voltage in (p.u.) - (bus no).
Base case	--	--	1298.9	--	5.1734	0.8697 – (77)
GA (2DG+2SC)	1707.44 – (108) 2371.31 – (37)	3190.10– (71) 2962.92 – (110)	594.64	54.22%	2.9427	0.9431– (43)
EGA (2DG+2SC)	2398.04 – (110) 2858.41 – (39)	2956.47– (110) 2994.69 – (72)	568.87	56.20%	2.779	0.9545– (43)
GA (3DG+3SC)	2074.50 – (110) 2177.28 – (71) 912.08 – (41)	2384.16 – (110) 2126.01 – (39) 1279.70 – (74)	458.70	64.68%	2.9088	0.9555– (78)
EGA (3DG+3SC)	1461.58– (74) 2741.73 – (39) 1496.20 – (110)	2245.25 – (39) 2934.28 – (71) 2460.89 – (110)	363.42	72.02 %	2.2696	0.9608– (77)
GA (4DG+4SC)	2269.67– (71) 2319.37– (38) 1857.66 – (11) 2168.77 – (110)	2082.66– (46) 2028.54– (73) 2493.71– (39) 2357.58– (110)	321.40	75.25%	2.0654	0.9600 – (99)
EGA (4DG+4SC)	1788.64 - (72) 1887.35 - (39) 1866.47 - (110) 2222.03 – (79)	2453.18 - (80) 2221.20– (39) 2306.43 – (72) 2500.00 – (110)	291.59	77.55%	1.9147	0.9603 – (52)

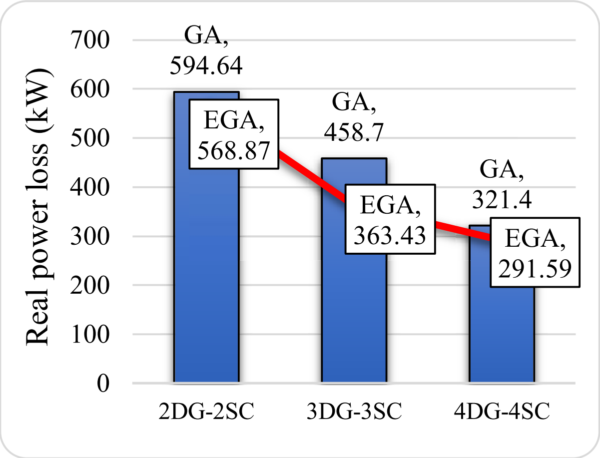

FIGURE 15. Comparison of power losses for GA and EGA.

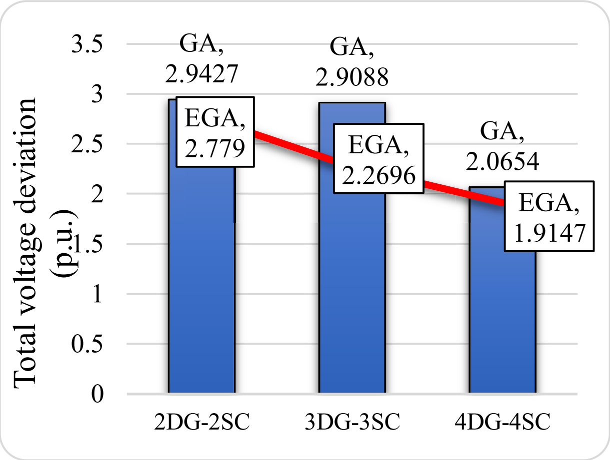

FIGURE 16. Total voltage deviation for EGA and GA.

time. The reduction achieved by EGA is lower than of GA by 2.3%. In all cases, the EGA algorithm obtains better results than the GA.

Figure 14 shows the comparison among the voltage profiles of different cases of optimal placement and capacity of DGs and SCs by using the EGA approach. Voltage greatly improves in all the cases. The minimum voltage in the case of (4DG + 4SC) is 0.9603 p.u.

Figure 15 shows the power loss reduction of the proposed algorithm EGA compared with that obtained by GA. The EGA obtains better results especially in the case of (4DGs+4 SCs), in which 291.59 kW is obtained by EGA and 321.40 kW is obtained by GA. Figure 16 shows a comparison of the total voltage deviation between the EGA algorithm and the GA in three cases. In the case of 2DG+2SCs, the TVD is 2.9427 p.u. by GA method and reduced to 2.7790 p.u. by EGA. In the 3DG+3SC case, a significant reduction is observed. TVD becomes 2.9088 p.u. for the EGA and 2.2696 p.u. for the GA. The TVD in the based case is 5.1734 p.u. and in the case of 4SC+4DG, the TVD reduced to 1.9147 p.u. by the proposed algorithm.

Table 13 shows the results of optimal placement and size of different combinations of DGs and SCs at three load levels (light, nominal and peak) considered using the proposed algorithm EGA for performance testing without adding DGs/SCs for the second scenario. Also, Table 13 shows a comparison of cost energy loss for different combinations of DGs and SCs for IEEE 119 bus RDN by using the proposed approach. By using EGA economic profit achieved after siting the compensators to the RDN. Before power compensators, the energy cost loss was 35701 $ at 0.5 load level then it reduced to 16372 $, 10694 $ and 8467 $ by the placement of (2DG+2SC), (3DG+3SC) and (4DG+4SC), respectively. The total annual saving at a normal load level is 228701 $, 277985 $ and 294424 $ for cases (2DG+2SC), (3DG+3SC) and (4DG+4SC), respectively. Whereat heavy

TABLE 13. Performance of EGA compared with different load levels on an IEEE 119-bus RDN for the 2nd scenario.

Load level	Light (50% loading condition)			Light (100% loading condition)			Light (160% loading condition)		
Particulars	2DG+2SC	3DG+3SC	4DG+4SC	2DG+2SC	3DG+3SC	4DG+4SC	2DG+2SC	3DG+3SC	4DG+4SC
Annual power loss without DG/SC	595020			6832214			5696250		
SCs Optimal size (kVAr) / Candidate buses	1309.56 (39) 1058.34 (110)	1070.76 (71) 1686.69 (109) 1600.92 (39)	1135.17 (110) 1864.88 (36) 787.69 (74) 883.51 (80)	2398.04 (110) 2858.41 (39)	1461.58 (74) 2741.73 (39) 1496.20 (110)	1788.64 (72) 1887.35 (39) 1866.47 (110) 2222.03 (79)	3890.08 (110) 5291.20 (39)	4908.77 (109) 4109.97 (39) 4303.96 (70)	5645.20 (38) 1995.13 (73) 3409.51 (110) 2653.08 (80)
DGs optimal size (kW) / Candidate buses	1583.77 (109) 1445.81 (71)	1515.44(109) 1479.16(39) 1215.96(73)	1472.27 (39) 719.92 (96) 1128.78(110) 1225.91(72)	2956.47 (110) 2994.69 (72)	2245.25 (39) 2934.28 (71) 2460.89 (110)	2453.18 (80) 2221.20 (39) 2306.43 (72) 2500.00 (110)	3197.84 (74) 4320.40 (110)	4669.33 (110) 2547.85 (74) 4766.38 (39)	4667.19 (110) 2512.45 (81) 3987.37 (73) 2033.32 (42)
Annual power loss with compensator (kW)	272880	178240	141120	2992256	1911589	1533763	2394900	1585650	1318050
Annual reduction of power loss %	54.14%	70.04%	76.28%	56.20%	72.02%	77.55%	57.95%	72.16%	77.02%
Total losses cost with compensator ($)	16372	10694	8467	179535	114695	92025	143694	95139	79083
Total capacitor cost ($)	7103.7	13075	14013	1576	17098	23293	27543	39968	41108
Total DG cost ($)	60.84	84.46	91.18	119.27	153.05	189.86	150.61	239.92	264.25
Total annual savings ($)	12164	11847	13129	228701	277985	294424	170387	206428	221319

TABLE 14. Optimal placmnet and sizing of (2DGs+2SCs) under PDF uncertainty (third scenario) for 119-bus RDN.

% Loading Pd	SC1 size kVAr (place)	SC2 size kVAr (place)	DG1 size kW/(place)	DG2 Size kW/(place)	TPL (kW)
70	1682.14 (39)	1868.84 (109)	2306.68 (109)	2434.95 (71)	276.93
80	2069.46 (110)	2323.92 (39)	3002.23 (109)	1726.25 (74)	370.98
90	2087.41 (110)	3789.90 (34)	2662.21 (71)	2732.57 (109)	474.04
100	2398.04 (110)	2858.41 (39)	2956.47 (110)	2994.69 (72)	568.87
110	3302.40 (39)	3546.47 (109)	3221.90 (71)	2856.31 (110)	708.19
120	3548.04 (109)	2813.37 (39)	3945.21 (109)	3658.72 (71)	846.80

load level energy losses cost is 341775 $ in the base case after finding the best place and size the cost reduced to 79083 $ in case of (4DG+4SC). In addition, the annual saving is 221319 $ after subtracting the cost of compensators unites. Overall, the economic study of energy cost before and after installation of DGs and SCs in 119 bus RDN shows the profit obtained by using the proposed algorithm. Table 14 represents the results of placement of 2DG and 2SC under load uncertainty dependent on Eq. (15) at different loading conditions in the range from 70%-120% considering the second combination with two DGs and SCs, that are combined together.

V. CONCLUSION

In this study, an enhanced genetic algorithm has been proposed for solving the optimal placement and capacity of multi distributed generations and shunt capacitors in radial systems. The proposed algorithm combines a local search scheme with the genetic algorithm to take the advantage of both local search scheme and genetic algorithm to reduce the search time required for determining the optimal placement and size of DGs and SCs. Using the proposed EGA algorithm, the voltage improvement and power loss reduction have been achieved by sitting multi distributed generations and shunt capacitors in the radial system. Minimizing total real power loss (P_{loss}) is taken as the main objective function in this study. To explore the performance of EGA, the proposed EGA algorithm is applied to the IEEE 33 bus and 69 bus test networks. The scalability of the proposed method has been validated on IEEE 119 bus test system. The results approved that the proposed EGA reduces significantly the total real power loss and enhances the voltage profile at different loading scenarios. Overall the EGA can efficiently search for the optimal solutions of the problem sitting and capacity of DGs and SCs and outperforms the other existing algorithms from the literature. As future work, we are planning to enhance the proposed genetic algorithm by adding an adaptive archive and testing it under more environments and parameters. It was proven, the proposed EGA leads to significant improvements in the technical and economic points of view. In future work, the load growth of ten years will consider also its economic assessment of three different test systems.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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