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Optimal Planning of Conductors and Capacitors in a Distribution Network Using a Hybrid Evolutionary Algorithm

Leila Mohammadian
[*]Department of Electrical Engineering, Shabestar Branch, Islamic Azad University, Shabestar, Iran
Email: Lemohammadian@iau.ir

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Abstract

The optimum planning of power distribution networks is one of the most important research fields for electrical engineers. Normally in a distribution system, operational costs are high because of their losses. In this paper, the practical planning of the distribution system includes the selection of optimal conductor size and capacitor placement in the radial distribution network considering the increasing rate of loads. Technical operational constraints are available conductors and capacitors, voltage limit, maximum permissible carrying current of conductors, and maximum reactive power that could be injected, without overvoltage. The objective function includes the cost of power losses, capacitors, and conductors, also the above constraints are added as penalty functions to the objective function. In this paper, the minimization problem is solved using an effective hybrid method of GA and PSO, which is called HGAPSO. By applying the proposed method, the final cost of network planning, losses, and their cost are considerably reduced and the voltage profile of the network has improved to a semi-flat shape. In the minimization process, an efficient algorithm is used to solve the radial distribution power flow problem in complex mode, which makes it easier to get system data iteratively. Simulation results are investigated on a sample radial distribution network. Finally, the effectiveness of the proposed hybrid method is proved by comparing the results with the results obtained from PSO.

Keywords: distribution system, conductor size, capacitor placement, hybrid evolutionary algorithm, loss reduction, optimization.

1. Introduction

Power distribution systems constitute the largest segment of power systems, delivering electrical energy to end-users via substations, distribution feeders, transformers, secondary conductors, and service mains. Typically designed in a radial configuration, these systems operate at lower voltage levels than transmission systems. Common challenges include technical losses and inadequate voltage regulation, which are addressed through planning techniques such as network reconfiguration, conductor selection, capacitor placement, and the inclusion of distributed generation. Many of these systems were established decades ago and have not been updated, resulting in undersized conductors that increase power losses and lead to significant voltage drops, especially at nodes far from the substation. Additionally, expanding the network can be costly due to environmental permit processes and geographic constraints. In this context, optimal conductor selection presents a viable alternative to network upgrades. This approach aims to replace existing conductors with more suitable types to reduce energy losses, enhance current capacity, and improve voltage levels when they drop below acceptable standards[1-4].The authors of [10] introduced a Mixed-Integer Linear Programming Model along with a heuristic approach to determine the Pareto front for the conductor size selection problem. In [11], a Mixed-Integer Nonlinear Programming (MINLP) formulation for optimal conductor selection was demonstrated and solved using the General Algebraic Modeling System (GAMS) and the DICOPT solver. Additionally, the authors of [12] developed an exact nonlinear model, which was addressed using existing MINLP solvers to identify the optimal conductors. Furthermore, a MINLP model specifically for optimal conductor selection in DC radial distribution systems was proposed by the authors of [13].The optimal placement of capacitor banks in distribution systems is essential for minimizing voltage drops and reducing line losses. This essentially involves installing capacitors at strategic locations within the network to compensate for reactive power demands and enhance technical performance. Proper distribution of reactive power within the system not only helps decrease overall power consumption but may also lead to lower electricity costs due to reduced losses in the system.. In [17], a heuristic methodology based on graph search was proposed to optimally size and allocate reactive compensation in distribution networks. Deterministic methods and Genetic Algorithms (GAs) were employed in [18] to address the optimal placement of capacitors. In [19], the authors utilized a GA for reactive compensation in power systems with varying customer load patterns. A GA was also applied in [20] for optimal capacitor placement, where the authors limited the maximum number of operations for switched capacitive banks to account for equipment aging. In [21], Shannon’s Entropy was leveraged for the optimal allocation of capacitors in distribution networks, taking into consideration multiple criteria. The authors in [22] examined unbalanced networks and implemented a micro-GA to tackle the optimization challenges in radial distribution networks. Additionally, in [23], a Particle Swarm Optimization (PSO) approach was proposed for the optimal placement and sizing of capacitors, while factoring in the effects of harmonics in unbalanced networks. This technique was further applied in [24] for optimal capacitor allocation in microgrids and in [26], considering the impact of switchable capacitive banks. In [27], the authors introduced a multiverse optimizer approach that partially modifies conventional loss sensitivity factors. Multi-stage methodologies have also been explored to address the optimal capacitor allocation problem. A two-stage method presented in [28] incorporates a loss sensitivity technique to identify potential locations for capacitor placement. Planning techniques such as optimal conductor selection, capacitor placement, reconfiguration, the installation of new substations, and the integration of distributed generation (DG) are often examined in isolation. However, in distribution systems with heavily loaded feeders and inadequate voltage profiles, relying on a single technique may not suffice to minimize power losses and enhance voltage levels. Thus, combining these techniques could lead to a more effectively planned system. The optimal conductor selection problem has been integrated with optimal capacitor placement in numerous studies [1,5–16,19,20,23,25]. The main contribution of this paper is the simultaneous modeling of optimal conductor sizing along with the optimal placement of capacitors. In general, attention has focused on reducing cost through optimizing the conductor profile, capacitor cost, and in some cases cost of losses. But in these all, increasing rate of load for coming years is not considered. In addition in most articles available in the literature, there is not any special way to solve the power flow problem in the distribution system and they simultaneously have solved the power flow problem and minimized the objective function, but as it will be shown we have developed a software pack which is able to determine radial distribution system parameters just having line data matrix, and technical data for available capacitors and conductors .further more we have used HGAPSO method for solving the optimization problem, which uses both effective GA and PSO‘s benefits simultaneously. The proposed method is tested on a sample radial distribution network, with 5 types of available conductors and 11 different sizes of capacitors, considering 8 years for load growth. The results show that the proposed objective function minimizes the loss of the system by considering all of the constraints and incorporating capacitors and conductors selection.

The proposed method identifies better solutions than those reported in the reviewed literature. The rest of this document is organized as follows: Section 2 describes the proposed model, and Section 3 describes the method to solve the simultaneous optimization problem in the power distribution network that can be carried out either jointly or separately. Section 4 presents the results of the proposed method applied to a test system. Finally, Section 5 presents the research conclusions.

2. Problem Formulation

1.1. Power flow

Load flow is very important and fundamental tool for analysis of any power system and is used in the operational as well as planning stages. Certain application, particularly in distribution automation and optimization of power system, requires repeated load flow solution. In these applications, it is very important to solve the load flow problem as efficiently as possible. The Newton-Raphson and the fast decoupled power flow solution techniques and a host of their derivatives have efficiently solved for “well behaved” power systems. Researchers however have been aware of the shortcomings of these algorithms when they are generally implemented and applied to ill conditioned power systems.

Power flow in a distribution system obeys physical laws such as (Kirchhoff laws and Ohms law) which became part of the constraints in the capacitor placement problem. The distribution system power flow solution is to be used as a subroutine in each iteration. Therefore, it is essential to have a computationally efficient and numerically robust method for solving the distribution system power flow. By radial distribution system, we mean a system which has a single simultaneous path of power flow to the load. We have used a method, that exploits the radial structure of the distribution network and the relationship between the bus powers and branch powers is expressed as a non-singular square matrix known as element incidence matrix.

The power flow equations for a radial distribution system are derived as the relationship between the specified complex bus powers and the bus voltages.

Let Sijis the complex power flowing from bus ‘i’ to bus’j’:

$$S_{ij} = P_{ij} + jQ_{ij} = V_i\,(V_i^* - V_j^*)Y_{ij}^* \tag{1}$$

The ‘i’th bus powers are expressed as:

$$\begin{aligned} P_i + Q_i &= \sum_{i\epsilon k(i)} P_{ij} + Q_{ij} \\ &= \sum_{i\epsilon k(i)} V_i\,(V_i^* - V_j^*)Y_{ij}^* \end{aligned} \tag{2}$$

k(i) is the set of nodes connected to node i, and Pi /Qi denotes the real/reactive power at node i. The above complex nonlinear equations are to be solved to determine the bus voltages. The real and imaginary parts of the equations are separated and solved using numerical methods.

1.2.Formulation of used method

The basis for the method is that an N bus radial distribution network has only N-1 lines (elements) and the branch currents (powers) can be expressed in terms of bus currents (powers). For an element ij connected between nodes ‘i’ and ‘j’ the bus current of node j can be expressed as a linear equation.

$$I_j = I_{ij} - \sum I_{jk(j)} \tag{3}$$

k(j) is the set of nodes connected to node j. For the slack bus the power is not specified so it is excluded and the relationship between bus currents and branch currents are derived as a non-singular square matrix.

$$\begin{aligned} I_{bus} &= kI_{branch} \\ I_{bus} &= [I_{b2} I_{b3} \cdots I_{bn}]^T \end{aligned} \tag{4}$$

The matrix K is element incidence matrix. It is a non singular square matrix of order N-1.The elemental incidence matrix is constructed in a simple way same like bus incidence matrix. In this matrix K each row is describing the element incidences. The elements are numbered in conventional way i.e. the no of element ‘ij’ is j-1.

1. The diagonal elements of matrix K are one. The variable j is denoting the element number.

K(j, j) =1

2. For each ‘j’th element let m (j) is the set of element numbers connected at its receiving end.

K(j, m(j)) = -1

3. All the remaining elements are zero. It can be observed that all the elements of matrix K below the main diagonal are zero.

$$I_{branch} = k^{-1} I_{bus} \tag{5}$$

The relationship between the branch currents and bus currents can be extended to complex branch powers and bus powers. The sending end power and the receiving end powers are not same due to transmission loss. The transmission loss is included as the difference between the sending end/receiving end powers. The relationship between branch powers and bus powers is established in same way of bus/branch currents. Multiplying both sides by element incidence matrix K:

$$\begin{aligned} S_{bus} &= K[S_{branch}^{sending} - TL_{branch}] \\ S_{branch} &= K^{-1}.S_{bus} \\ &\quad + TL_{branch} \end{aligned} \tag{6}$$

The power flow equations are complex quadratic equations. These are solved as [2]and the results we can get are voltage magnitude, voltage angle, active and reactive losses, and complex current of branches. The advantage of this method is that it does not require a flat start. The formulation can be extended to unbalanced three-phase networks. The reactive power injections at multiple ends can be effectively calculated to improve the voltage profile.

1.3. Objective Function

In each optimization problem, objective function should be defined. In the proposed approach, objective function can be formulated as following equation; The proposed objective function aims at minimizing the total annual cost due to capacitor placement, conductor selection and power losses considering load growth in period of instrument life, with constraints that include limits on voltage, maximum permissible carrying current of conductors, size of installed capacitors and type of selected conductors, and maximum permissible reactive current to be injected to avoid over voltage.

$$\begin{aligned} \mathrm{J} = & \sum_{\mathrm{l}=0}^{\mathrm{n_S}} \mathrm{L_l} \times \mathrm{C(con_l)} + \sum_{\mathrm{j}=1}^{\mathrm{J}} \mathrm{K_j^c} \times \mathrm{Q_j^c} + \\ & + \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{P_{loss,i}} \times \mathrm{C_E} \times \mathrm{P_W^i} \times 8760 \times \mathrm{LSF_i} + \\ & + \sum_{\mathrm{k}=1}^{\mathrm{m}} \{\max(0, \mathrm{V_{min}} - \mathrm{V_k})^2 \\ & \qquad + \max(0, \mathrm{V_k} - \mathrm{V_{max}})^2\} \\ & \qquad + \\ & + \sum_{\mathrm{l}=1}^{\mathrm{n_S}} (\mathrm{I_l} - \mathrm{I_{max}^l})^2 + \sum_{\mathrm{j}=1}^{\mathrm{m}} (\mathrm{Q_j^c} - \mathrm{TQlossj})^2 \end{aligned} \tag{7}$$

where:

$$P_W = \left(\frac{1 + Intr}{1 + \mathrm{Inf}r}\right) \tag{8}$$

According to the mentioned constraints we should have:

$$I_{max}^{l} = \begin{cases} I_{\max(ConType_l - 1)} & if \quad \begin{matrix} I_{\max(ConType_l)} \leq |I_l| \\ ,ConType_l \neq 1 \end{matrix} \\ I_{\max(ConType_l)} & \qquad\qquad else \end{cases} \tag{9}$$

$$V_{min} \leq |V_i| \leq V_{max} \tag{10}$$

$$I_l \leq I_{\max(l)} \tag{11}$$

While computing the cost by defined objective function, load growth is considered as (12):

$$load_i = \begin{cases} load \times (1+r)^i & i = 1,2,3,\dots,M \\ load \times (1+r)^M & i = M+1,\dots,N \end{cases} \tag{12}$$

Where, load i is the load in i'th year, r is the annual growth rate and M is a plan period up to which the feeder can take load growth.

The peak load growth during the planning period is illustrated in figure 1.

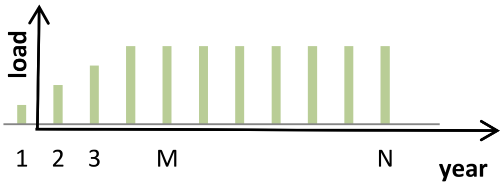

Fig1. Peak load growth during planning period

Variation of load is considered with loss factor parameter in objective function.

The objective function includes six statements which are described as followed:

Statement1: The cost of power losses considering load growth,

Statement2: the cost of the installed capacitors,

Statement3: the cost of the installed conductors,

Statement4: the constraint of voltage limit,

Statement5: the constraint of maximum permissible carrying current of the conductors,

Statement 6: the constraint to avoid over-voltage, or having sufficient capacitor installation.

3. Proposed Computational Algorithm

3.1.HGAPSO algorithm

In GA, a candidate solution for a specific problem is called an individual or a chromosome and consists of a linear list of genes. Each individual represents a point in the search space, and hence a possible solution to the problem.

A population consists of a finite number of individuals. Each individual is decided by an evaluation mechanism to obtain its fitness value. Based on this fitness value and undergoing genetic operators, a new population is generated iteratively with each successive population referred to as a generation. The GAs use three basic operators (reproduction, crossover, and mutation) to manipulate the genetic composition of a population.

The PSO conducts searches using a population of particles corresponding to GA individuals. A population of particles is randomly generated, initially. Each particle represents a potential solution and has a position represented by a position vector$\bar{x}_i$,A swarm of particles moves through the problem space, with the moving velocity of each particle represented by a velocity vector $\bar{v}_i$, At each time step, a function f_i representing a quality measure is calculated by using $x_i$as input. Each particle keeps track of its own best position, which is associated with the best fitness it has achieved so far in a vectorv_i. Further, the best position among all the particles obtained so far in the population is kept track of as p_g. At each time step t, by using the individual best position$p_i(t)$and global best position $p_g(t)$, a new velocity for particle i is updated as follows:

$$\bar{v}_i(t+1) = \chi[(\bar{v}_i(t) + c_1\varphi_1\{\bar{p}_i(t) - \bar{x}_i(t)\} + c_2\varphi_2\{\bar{p}_g(t) - \bar{x}_i(t)\}] \qquad (13)$$

Where c1 and c2 are positive constants, φ1 and φ2 are uniformly distributed random numbers in [0,1] interval, andχcontrols the magnitude of v. Changing velocity in this way enables the particle i to search around its individual best position, $\mathrm{p_i}$, and global best position, p_g. Based on the updated velocities, each particle changes its position according to the following equation:

$$\bar{x}_i(t+1) = \bar{x}_i(t) + \bar{v}_i(t+1) \qquad (14)$$

The computation of PSO is easy and adds only a slight computation load when it is incorporated into GA. The detailed design algorithm of HGAPSO consists of three major operators: enhancement, crossover and mutation [4]. In HGAPSO, GA and PSO both work with the same population. Based on the encoding scheme, Ps individuals forming the population are randomly generated. These individuals may be regarded as chromosomes in terms of GA, or as particles in terms of PSO. Then, new individuals on the next generation are created by enhancement, crossover and mutation operations [4]. For clarity, the flow of these operations is illustrated in figure 2.

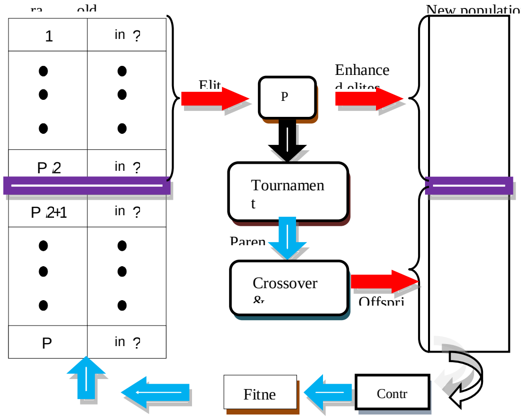

Fig2. Flowchart of the HGAPSO method

Enhancement, crossover, and mutation operators are described as follows:

(a)Enhancement: In each generation, after the fitness values of all the individuals in the same population are calculated, the top-half best-performing ones are marked. These individuals are regarded as elites. Instead of reproducing the elites directly to the next generation as elite GAs do, we first enhance the elites by PSO. By using these enhanced elites as parents, the generated offspring will usually achieve better performance than those bred by original elites. The group constituted by the elites is regarded as a swarm, and each elite corresponds to a particle in it. By performing PSO on the elites, we may increase the search ability. Half of the population in the next generation is occupied by the enhanced individuals, the remainder by crossover operation.

(b)Crossover: To produce well performing individuals, in the crossover operation parents are selected from the enhanced elites only. To select parents for the crossover operation, the tournament-selection scheme is used, in which two enhanced elites are selected at random, and their fitness values are compared to select the elite with better fitness value as one parent. Then the other parent is selected in the same way. Two off springs are created by performing crossover on the selected parents. Two-point crossover operation is used, where two crossover sites are selected randomly within the range of an individual and swapping occurs. These produced offspring occupy half of the population in the next generation.

(c)Mutation: In HGAPSO, mutation occurs in conjunction with the crossover operation. Here, uniform mutation is adopted, that is, the mutated gene is drawn randomly, uniformly from the corresponding search interval. In the following simulations, a constant mutation-probability Pm=0.1 is used.

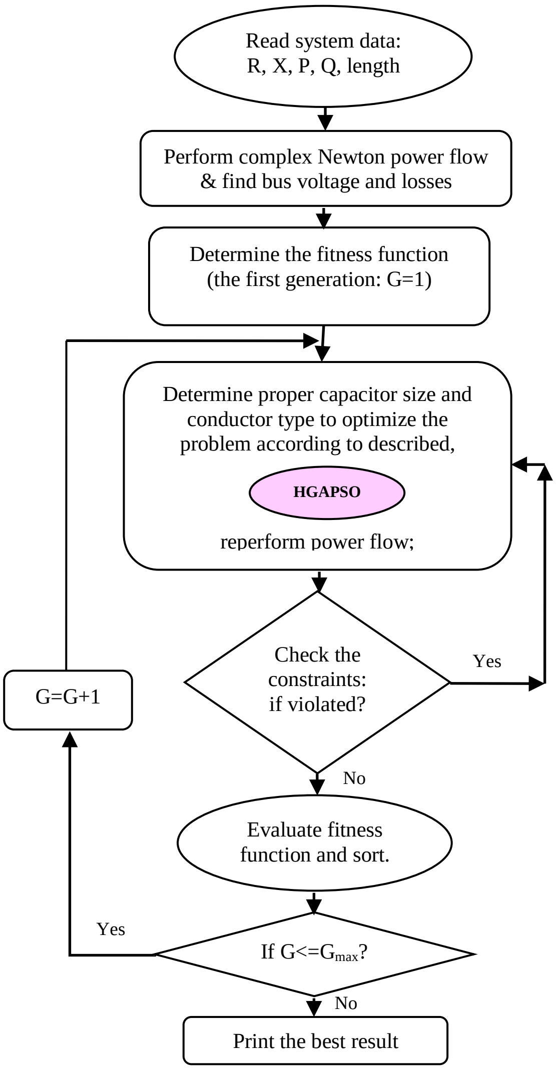

Fig3. Flowchart of the whole proposed method

4. Computational Test

Based on the proposed algorithm, software was developed using MATLAB for proper conductor and capacitor selection considering load growth in distribution networks. The proposed method was tested on a sample distribution network by use of prepared software to evaluate its effectiveness. The test case is a 20 kV radial distribution network that has 13 nodes and 12 sections. Network and load data of radial test feeder are shown in tables 1 and 2.

The technical and economical data of available conductors and capacitors are given in tables 3 and 4, respectively. Other input data needed for evaluating the objective function are as follows:

N: 20, M: 5, Intr: 17%, Infr: 14%, r: 7%,

Vmax: 1.03 pu, V_{min}: 0.95 pu, LSF: 0.63 for all loads, Cost of energy: 50 ($/kWh)

Table1. Data for the test feeder

Sending end(i)	Receiving end(i)	R(Ω)	X(Ω)	Section length(km)
0	1	0.7822	0.2835	0.835
1	2	0.7822	0.2835	0.415
2	3	0.7822	0.2835	0.215
3	4	0.7822	0.2835	0.420
4	5	0.7822	0.2835	0.215
4	6	0.7822	0.2835	0.580
6	7	0.7822	0.2835	0.455
7	8	0.7822	0.2835	0.350
7	9	0.7822	0.2835	0.350
6	10	0.7822	0.2835	0.300
10	11	0.7822	0.2835	0.320
6	12	0.7822	0.2835	0.415

Table2. Load data of the feeder

Bus no.	P(kw)	Q(Kvar)
1	890	468
2	628	470
3	1112	764
4	636	378
5	474	344
6	1342	1078
7	920	292
8	766	498
9	662	480
10	690	186
11	1292	554
12	1124	480

Table3. Technical and economical data of available capacitors

capacitor type	size(kvar)	price($/kvar)
1	0	0
2	150	0.5
3	300	0.35
4	450	0.253
5	600	0.22
6	750	0.276
7	900	0.183
8	1050	0.228
9	1200	0.170
10	1350	0.207
11	1500	0.201

Table4. Technical and economical data of available conductors

conductor type	R(Ω/km)	X(Ω/km)	price($/km)	Max. current
1	0.7822	0.2835	151	500
2	0.0625	0.279	1155	1000
3	0.0353	0.259	1733	1800
4	0.0745	0.285	1026	900
5	0.0429	0.267	1500	1500

5. Results and Discussion

The simulation results are clearly illustrated in following figures and tables. By solving the optimization problem, the size of the capacitor banks, the types of the conductors and the amplitude of the bus voltages are determined. The total cost, power losses, minimum and maximum of the voltages in each node are obtained. Figures4 shows the system performance. Figure5 compares voltage magnitudes before and optimization. Figure 6 compares voltage angles before optimization with them after performing optimization process:

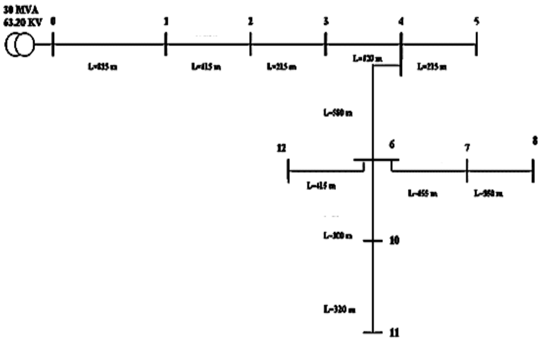

Fig4. The chosen distribution network for implementation of the proposedmethod

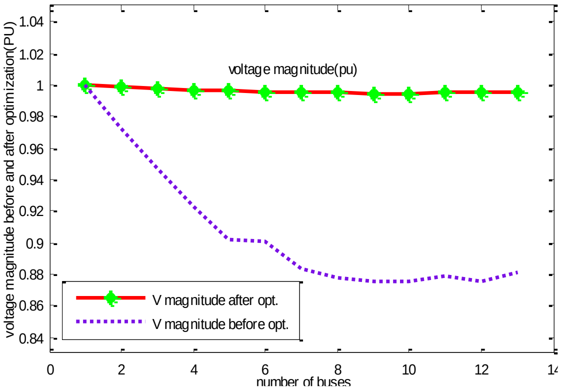

Fig5. Comparison of voltage magnitude before and after performing HGAPSO

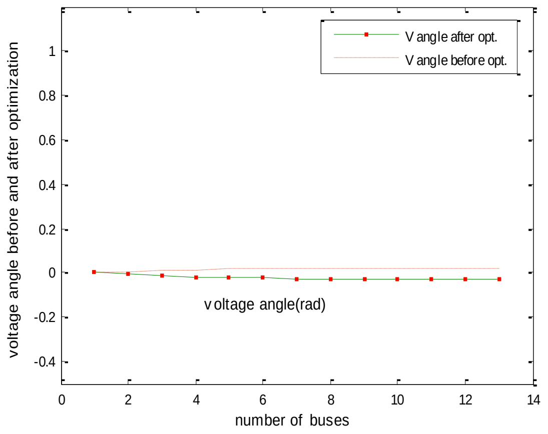

Fig6. Comparison of voltage angle before and after performing HGAPSO

Table5. Comparison of voltage magnitudes before and after performing HGAPSO

Voltage magnitude before optimization	Voltage magnitude after optimization
1.0000	1.0000
0.9722	0.9983
0.9466	0.9971
0.9227	0.9963
0.9017	0.9959
0.9004	0.9956
0.8837	0.9953
0.8774	0.9949
0.8753	0.9946
0.8756	0.9945
0.8787	0.9954
0.8754	0.9948
0.8808	0.9958

Table6. Comparison of power losses before and after performing HGAPSO

	Before optimization	After optimization
TPloss(kw)	1.3219	0.0383
TQloss(kvar)	12.4630	2.0548

Table7. Result of conductor selection and capacitor placement after performing HGAPSO

Sending end(i)	Receiving end(i)	Conductor type	Capacitor type
0	1	3	1
1	2	3	1
2	3	3	1
3	4	5	11
4	5	4	1
4	6	3	1
6	7	3	5
7	8	3	2
7	9	2	2
6	10	3	9
10	11	2	1
6	12	4	11

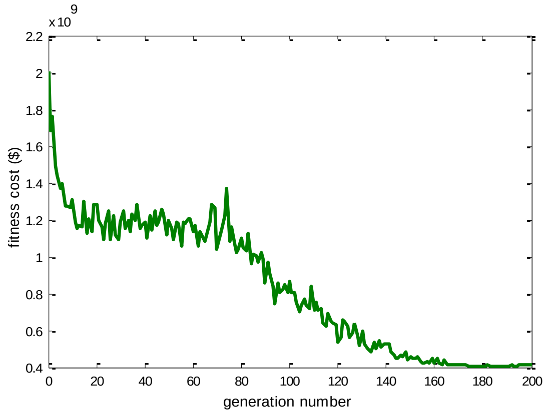

Fig7. Fitness optimized using HGAPSO

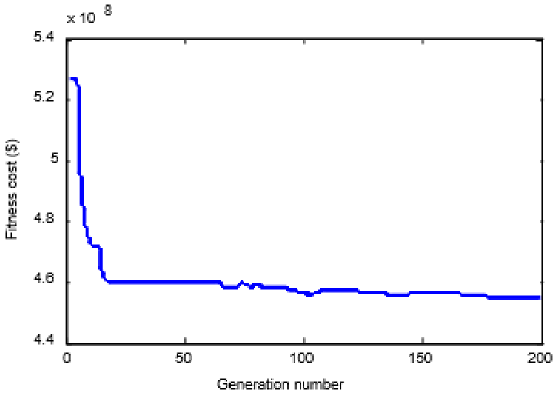

Fig8. Fitness optimized using PSO

Optimization process in HGAPSO, PSO and comparing the two methods are clearly illustrated in figures 8,9. The PSO best cost is 4.52241871*10^8$, and HGAPSO best cost is 3.969713*10^8$. Results obtained from PSO are included in below tables.

Table8. Result of conductor selection and capacitor placement after performing PSO

Sending end(i)	Receiving end(i)	Conductor type	Capacitor type
0	1	3	1
1	2	3	1
2	3	5	6
3	4	3	1
4	5	1	4
4	6	5	11
6	7	3	1
7	8	3	1
7	9	2	10
6	10	3	1
10	11	3	4
6	12	1	1

Table9. Comparison of voltage magnitudes after performing PSO and HGAPSO

Voltage magnitude performing PSO	Voltage magnitude performing HGAPSO
1.0000	1.0000
0.9979	0.9983
0.9963	0.9971
0.9949	0.9963
0.9938	0.9959
0.9929	0.9956
0.9929	0.9953
0.9928	0.9949
0.9924	0.9946
0.9932	0.9945
0.9925	0.9954
0.9924	0.9948
0.9903	0.9958

Table10. Comparison of power losses after performing PSO & HGAPSO

	performing PSO	performing HGAPSO
TPloss(kw)	0.0428	0.0383
TQloss(kvar)	3.2583	2.0548

6. Conclusion

In this paper, using HGAPSO the conductor selection has been incorporated in the conventional optimal capacitor placement, considering load growth in life period of instruments (like capacitors). By solving the optimization problem by the HGAPSO method, the optimal size and place of the capacitors and the conductors are defined. The method has been applied to a sample radial distribution network and the results show the reduction of total loss especially active power loss, in addition to the improvement of voltage profile. According to the results, the bus voltages of the ending buses are in the permissible limits. At last the proposed method is compared with PSO. The obtained results show the efficiency of the hybrid GA and PSO method. The proposed hybrid method has reduced power losses more than PSO, also the cost obtained from HGAPSO is a better answer. In conclusion, the hybrid method performs better than PSO.

References

[1] V. Marvasti, M. Nozari, H. Shariati Dehaghan, J. Azizi,” Combination of Optimal Conductor Selection and Capacitor Placement in Radial Distribution Systems for Maximum Loss Reduction ”,ACM portal,2009.

[2] RM. S. Danaraj, SH.F.Kodad“An algorithm for radial distribution power flow in Complex mode including voltage controlled buses”, Indian Journal of Science and Technology, Vol.1 No.2, 2007.

[3] De Souza, “Micro genetic algorithms and fuzzy logic applied to the optimal placement of capacitor banks in distribution networks”, IEEE Trans. On Power System, vol.19, Issue:2, May 2004, p.942-947.

[4] Chun-Feng Lu, Chia-Feng Juang, “Evolutionary fuzzy control of flexible AC transmission system,” IEE Proc.-Gener. Transm. Distrib, Vol. 152, pp. 441-448, No. 4, July 2005.

[5] H. Falaghi, M. Ramezani, M.-R. Haghifam, K. Roshan milani, ”optimal selection of conductors in radial distribution systems with time varying load” 18th International Conference on Electricity Distribution, Turin, 6-9 June 2005

[6] Ramon. .A. Gallego, and etc, “Optimal capacitor placement in radial distribution”, IEEE Trans. On power systems vol. 16, No.4, November 2001.

[7] Z. Wang, H. Liu, D. C. Yu, X. Wang, H. Song, “A Practical Approach to the Conductor Size Selection in Planning Radial Distribution Systems,” IEEE Transaction on Power delivery, Vol. 15, No. 1, pp. 350-353, 2000.

[8] AJ Rabih ,”Radial Distribution Load Flow Using Conic Programming” , IEEE Transactions on power systems,21,1458-1459.2006.

[9] S.Mandal, A.Pahwa, “Optimal Selection of Conductors for Distribution Feeders,” IEEE Transaction on Power Systems, Vol. 17, Issue 1, pp.192-197, 2002.

[10] R. A. Hooshmand, M.Ataei, “Optimal Capacitor Placement in Actual Configuration and Operational Conditions of Distribution Systems Using RCGA,” Journal of Electrical Engineering, Vol. 58, no. 4, pp. 189–199, 2007.

[11] R.A. Jabr,” Optimal Placement of Capacitors in a Radial Network Using Conic and Mixed Integer Linear Programming, ” Elsevier Ltd, Electric Power Systems Research, vol.78, pp. 941–948, 2008.

[12] A.Seifi, M.R.Hesamzadeh, “A Hybrid Optimization Approach for Distribution Capacitor Allocation Considering Varying Load Conditions,” Elsevier Ltd., Electrical Power and Energy Systems, 2009. (Article in press).

[13] H.M.Khodr, F.G.Olsina, “Maximum Savings Approach for Location and Sizing of Capacitors in Distribution Systems, “Elsevier Ltd., Electric Power Systems Research, vol.78, pp. 1192–1203, 2008.

[14] R. Ranjan, B. Venkatesh, D. Das, “A New Algorithm for Power Distribution System Planning”, Electric power system research, vol. 62, pp. 55-65, 2002.

[15] Jorge Angarita Marquez, Mohammad Ahmad A. Al-Ja’Afreh, GeevMokryani, Sohag Kabir, FelicianCampean, Cuong Dao, Sana Riaz, Optimal planning and operation of distribution systems using network reconfiguration and flexibility services, Energy Reports, Volume 9, 2023, Pages 3910-3919.

[16] Jagtap, K.M., Shukla, A. &Baboria, S.A. Optimal planning for distribution networks considering system uncertainties using pseudo-inspired gravitational search algorithm. ElectrEng (2024). https://doi.org/10.1007/s00202-024-02382-z.

[17] Z. Yang, F. Yang, Y. Shen, L. Su, Y. Lei and F. Yan, "Optimal Planning of Distribution Network Considering Photovoltaic Energy Consumption," *2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2)*, Wuhan, China, 2020, pp. 4133-4137, doi: 10.1109/EI250167.2020.9346975.

[18] Seyed Abbas Taher, Mohammad Hasani, Ali Karimian, A novel method for optimal capacitor placement and sizing in distribution systems with nonlinear loads and DG using GA, Communications in Nonlinear Science and Numerical Simulation, Volume 16, Issue 2, 2011, Pages 851-862.

[19] Gallego Pareja LA, López-Lezama JM, Gómez Carmona O. A MILP Model for Optimal Conductor Selection and Capacitor Banks Placement in Primary Distribution Systems. *Energies*. 2023; 16(11):4340. https://doi.org/10.3390/en16114340.

[20] Ali, H.; Ullah, S.; Sami, I.; Ahmad, N.; Khan, F. Economic Loss Minimization of a Distribution Feeder and Selection of Optimum Conductor for Voltage Profile Improvement. In Proceedings of the 2018 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET), Islamabad, Pakistan, 10–12 September 2018; pp. 1–6.

[21] Kumari, M.; Ranjan, R. Economical Selection of Conductor in Radial Distribution System using PSO. J. Inst. Eng. Ser. B 2022, 103, 1105–1114.

[22] Ravindra, K.; Prasad, K.R.K.V. Optimal Conductor selection and Capacitor Placement for Cost minimization in Distribution Systems. Int. J. Adv. Sci. Res. Manag. 2019, 11–15.

[23] Ismael, S.; Abdel Aleem, S.; Abdelaziz, A. Optimal Conductor Selection in Radial Distribution Systems using Whale Optimization Algorithm. J. Eng. Sci. Technol. 2019, 14, 87–107.

[24] Montoya, O.D.; Gil-González, W.; Grisales-Noreña, L.F. On the mathematical modeling for optimal selecting of calibers of conductors in DC radial distribution networks: An MINLP approach. Electr. Power Syst. Res. 2021, 194, 107072.

[25] Gupta, S.; Yadav, V.K.; Singh, M. Optimal Allocation of Capacitors in Radial Distribution Networks Using Shannon’s Entropy. IEEE Trans. Power Deliv. 2022, 37, 2245–2255.

[26] Navesi, R.B.; Nazarpour, D.; Ghanizadeh, R.; Alemi, P. Switchable Capacitor Bank Coordination and Dynamic Network Reconfiguration for Improving Operation of Distribution Network Integrated with Renewable Energy Resources. J. Mod. Power Syst. Clean Energy 2022, 10, 637–646.

[27] Mtonga, T.P.M.; Kaberere, K.K.; Irungu, G.K. Optimal Shunt Capacitors’ Placement and Sizing in Radial Distribution Systems Using Multiverse Optimizer. IEEE Can. J. Electr. Comput. Eng. 2021, 44, 10–21.

[28] Abul’Wafa, A.R. Optimal capacitor allocation in radial distribution systems for loss reduction: A two stage method. Electr. Power Syst. Res. 2013, 95, 168–174.