Simultaneous capacitor allocation and conductor sizing in unbalanced radial distribution systems using Differential Evolution Algorithm

Padarbinda Samal
Department of Electrical Engineering
National Institute of Technology, Rourkela, Odisha, India
padarbindasamal87@gmail.

Sanjeeb Mohanty
Department of Electrical Engineering
National Institute of Technology, Rourkela, Odisha, India
sanjeeb@nitrkl.ac.in.

Sanjib Ganguly
Department of Electronics and Electrical Engineering
Indian Institute of Technology, Guwahati, India
sanjib191@gmail.com.

***Abstract*— This paper proposes a planning approach for unbalanced radial distribution systems (URDS) for simultaneous capacitor allocation and conductor size selection. A differential evolution (DE) based algorithm is implemented in order to obtain the optimal location and the ratings of capacitors, and the optimal conductor sizes of the distribution systems. The total system real power loss is minimized without violating the voltage and thermal constraints of each bus and lines. A three-phase load flow algorithm for unbalanced distribution systems is used as a subroutine for power flow calculations. The performance of the proposed method is verified on 19-bus and 34-bus unbalanced radial distribution systems. The results show that significant reduction in total system power loss and improvement in voltage profile of the systems is achieved by simultaneous optimization of capacitor location and ratings and conductor sizes.**

Keywords*— *Unbalanced radial distribution systems, three phase load flow, capacitor, and power loss.

NOMENCLATURE

SB Sending end bus.

RB Receiving end bus.

BN Branch number.

CT Conductor type.

NBR Number of branches/lines.

BL Branch length in mile.

P_a Real power in kW for phase *a*.

Q_a Reactive power in kVAR for phase *a*.

I. INTRODUCTION

In recent years, the capacitor allocation [1-10] and conductor size selection [11-18] has become a promising choice for system loss reduction and voltage profile improvement. The capacitor placement problem consists of determining the optimal location, rating and number of capacitors while satisfying various technical constraints [2]. The conductor size selection involves the determination of optimal conductor sizes without violating the technical constraints [18].

Numerous works have been reported in the capacitor allocation problem. Classifying this problem, in view of objective functions such as: power loss minimization[1-3,6-9], voltage profile improvement [1,3,7], network saving maximization [2], real power loss cost minimization [4], capacitor cost minimization [4], total investment cost minimization [5], network reliability maximization [5], and node voltage deviation minimization [5,8]. The solution methodologies used for capacitor allocation problem can be categorized [10] into two types such as heuristic based [3,6] and artificial intelligence-based (AI) [1-2,5,7-9]. The AI-based techniques are genetic algorithm [1], bat algorithm and cuckoo search [2], particle swarm optimization (PSO) [4], multi-objective PSO [5], non-dominated genetic algorithm version – II [7], honeybee mating optimization [8], and modified cultural algorithm [9].

Over the years, valuable research has been carried out in the field of conductor size optimization [11-18]. The authors in [11] proposed a two-step approach for minimizing the total cost, In [12], a heuristic approach was developed in order to minimize the system power loss and maximize the total saving, a mixed-integer linear programming method [13] was used to minimize the network power loss and investment cost. PSO was used in [14] for the real power loss minimization, The authors in [15], utilized evolutionary strategies for minimization of sum of capital and energy loss cost, In [16], a harmony search algorithm with differential operator was implemented for loss minimization and voltage profile improvement, a load flow method was employed in [17] for minimization of capital investment and real power loss cost. A DE based [18] approach was implemented for phase balancing and conductor size optimization.

978-1-4799-5141-3/14/$31.00 ©2016 IEEE

From the literature, it is observed that network power loss has been reduced considerably, and voltage profile has been improved by separately optimizing the decision variables such as capacitor sizes, locations and conductor sizes using AI-based approaches. This has motivated the authors to simultaneously optimize these variables and see its impact on network power loss and voltage profile with the help of a popular optimization algorithm. Moreover, no work has been reported in the literature for simultaneous optimization of capacitor size and locations, and conductor sizes for unbalanced radial distribution systems.

In this paper, a DE [18] based metaheuristic algorithm is employed to minimize the total system real power loss by obtaining the optimal capacitor location and conductor sizes in unbalanced distribution systems. A three-phase load flow algorithm [19] for unbalanced distribution systems is utilized as a subprogram to compute the power flow solutions. A 19-bus and 34-bus is considered as the test system for validation of the proposed algorithm.

The paper is organized as follows: In Section II, the problem formulation is described. The proposed solution strategy is presented in Section III. Test results are given in Section IV. Section V concludes the paper.

II. Problem Formulation

In this paper, the minimization of total system power loss [18] is considered as the objective function.

The constraints associated with this objective function are:

i. Bus voltage constraint

$$V_l^{min} \le V_l^{abc} \le V_l^{\max} \tag{1}$$

ii. Branch thermal limit constraint

$$I_m^{abc} \le I_m^{\max} \tag{2}$$

iii. Capacitor size constraint

The capacitor size should be the integer multiple of the smallest capacitor size available [4].

$$QC_t \le L \times QC_0 \qquad \text{L=1, 2,…, N} \tag{3}$$

Where QC_0 denotes, the smallest capacitor size available.

iv. Reactive power demands constraint

The total reactive power injection shouldn't exceed the total reactive power demand of the distribution system [4].

$$\sum_{t=1}^{N} QC_t \le Q_{Net} \tag{4}$$

Where, Q_{Net} represents the total reactive power demand of the system.

III. Solution Strategy

DE algorithm was developed by Price and Storn [20]. This algorithm employs three operations: mutation, crossover, and selection in order to obtain best solutions from a randomly generated initial vectors of population size NOP, having dimension *D*. Numerous variants of DE can be obtained from [21]. In this paper, we have used DE/rand/1/bin strategy as the solution methodology for the planning problem. In DE the population size, NOP is fixed during the evolution process.

The ith vector of the population at iteration (generation) G is given as:

$$y_i(G) = (y_{i1}(G), y_{i2}(G), ..., y_{iD}(G)) \tag{5}$$

A. Mutation Operation

In this operation, a mutant vector $v_i(G+1)$ is created from the target vector $y_{r1}(G)$ as follows:

$$v_i(G+1) = y_{r1}(G) + F.(y_{r2}(G) - y_{r2}(G)) \tag{6}$$

Where indices $r1$, $r2$, and $r3$ are random and mutually different integers generated in the range [1, NP], and also are different from the current trial vector's; $F \in [0,2]$ is a scale factor, which controls the mutation size.

B. Crossover Operation

This operation is performed in order to obtain a trial vector as follows:

$$T_i(G) = (T_{i1}(G), T_{i2}(G), ..., T_{iD}(G)) \tag{7}$$

$$T_{ij}(G+1) = \begin{cases} v_{ij}(G+1) & rand1_{ij} \le CR \ or \ j = j_{rand} \\ y_{ij}(G) & rand1_{ij} > CR \ or \ j \ne j_{rand} \end{cases} \tag{8}$$

Where, CR denotes a crossover constant in the range [0, 1] specified by the user, and j_{rand} is a randomly chosen integer in the range [1, NOP].

C. Selection Operation

The selection operation is performed to compare the fitness value of the target (parent) individual and the trial (child) vector so as to know who goes to the next generation as:

$$y_i(G+1) = \begin{cases} T_i(G+1) & f(T_i(G+1)) < f(y_i(G)) \\ y_i(G) & f(T_i(G+1)) > f(y_i(G)) \end{cases} \tag{9}$$

Where $f(.)$ denotes the fitness function (objective function) to be minimized.

D. Encoding Scheme

In this planning problem, the chromosome representing the decision variable consist of three parts. The locations of capacitors (C_1, C_2..,C_N) represent the first part; followed by the ratings of the capacitors (QC_1 , QC_2,…, QC_t); the conductor sizes (CT_1, CT_2, …, CT_{NBR}) forms the last part of this chromosome, and they are represented as shown in Fig. 1.

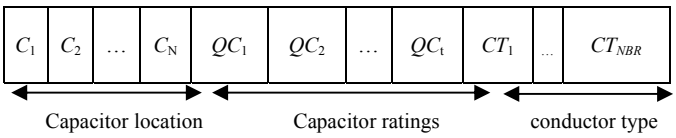

Fig. 1. Encoding scheme for a chromosome in DE

E. Flow chart of the proposed approach

In this subsection, the flow chart of the proposed approach is shown in Fig. 2. A three-phase unbalanced load flow algorithm [19] is used as a subroutine for evaluation of power flow results.

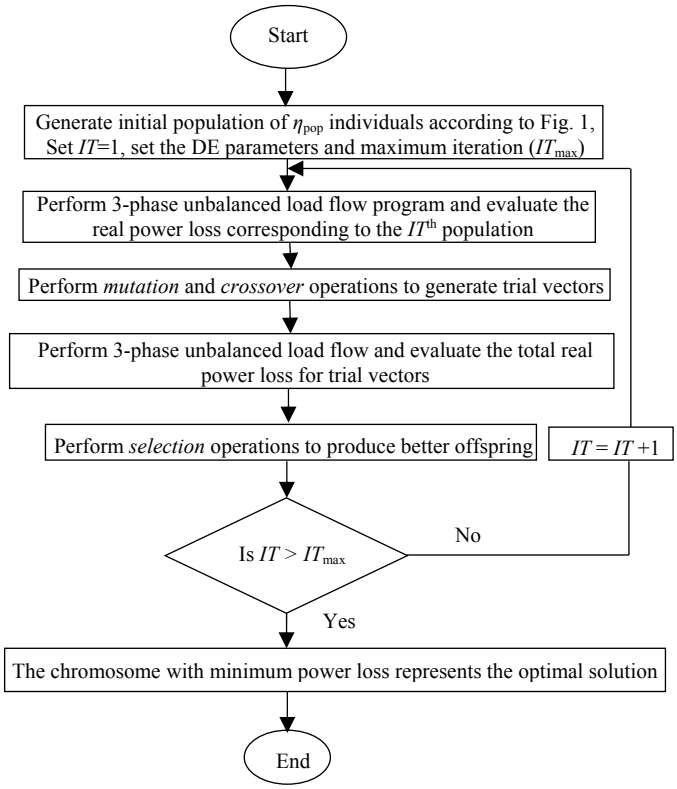

Fig. 2. Flow chart of the proposed planning approach

IV. Test Results

The simulations are carried out with MATLAB 8.0 software. The effectiveness of the proposed algorithm is verified on two unbalanced radial distribution systems, i.e. 19-bus and 34-bus system. The parameters of the DE are taken from [18]. In this, work, three different planning cases are studied such as:

- *Case A:* planning for optimal capacitor allocation.
- *Case B:* planning for optimal conductor sizes.
- *Case C:* Simultaneous planning for optimal capacitor allocation and conductor sizes.

First, simulations are performed for these two systems without considering capacitor allocation and conductor size optimization. The results (voltage and power loss) obtained with these simulations are termed as base case results. Then, simulations are carried out for the case mentioned above.

A. 19-bus unbalanced radial distribution system

The load data and line data of the 19-bus system are taken from [22]. The base kV and MVA of the system are considered as 11 and 1 respectively [22]. The total real and reactive power demand of this system are 1219.8 kW and 590.9 kVAR respectively. The results obtained with the proposed approach for different case studies are shown in Table I. It is observed that power loss has reduced by 75. 3% and also the minimum bus voltage (p.u.) has improved by 4.3% in comparison to base case results for Case C planning when three shunt capacitors of rating 150 kVAR each are placed at bus number 10 (optimal location) of the system. It is worth mentioning that, the total reactive power injection (450 kVAR) is not exceeding the total reactive power demand (590.9 kVAR) of the system. The voltage profile of the system for phase a, b, and c for Case A, B, C, and base voltage are shown in Figs. (3)-(5). From these figures, it can be clearly seen that voltage magnitude at all buses has improved significantly in comparison to base case voltage magnitude for Case C optimization planning.

TABLE I. Simulation results for the 19-bus system

Objective	Case			
	Base	***A***	***B***	***C***
PL(kW)	50.1072	40.9893	27.6998	12.3778
Capacitor location	-	11	-	10
Capacitor rating (kVAR)	-	150	-	150
	-	150	-	150
	-	150	-	150
Minimum bus voltage (p.u.)	0.9460	0.9555	0.9706	0.9869
	0.9439	0.9534	0.9693	0.9864
	0.9447	0.9542	0.9708	0.9868
Conductor type	1	1	4	4
	2	2	5	4
	3	3	3	4
	4	4	5	4
	5	5	2	4
	5	5	3	8
	2	2	5	4
	1	1	5	4
	6	6	5	4
	3	3	9	4
	3	3	7	4
	2	2	9	4
	5	5	8	8
	6	6	5	4
	1	1	3	8
	7	7	1	4
	8	8	3	8
	9	9	4	4

B. 34-bus unbalanced radial distribution system

The network diagram of 34-bus unbalanced radial distribution systems is shown in Fig. 6. The system load and line data are given in Table II and III, respectively. This system has total real power load and reactive power load of 9250 kW and 4871.4 kVAR, respectively. The base kV and MVA of the system are considered as 24.9 and 2.5, respectively. The simulation results are shown in Table IV. It is observed that power loss has been reduced by 148.163 kW from base case -

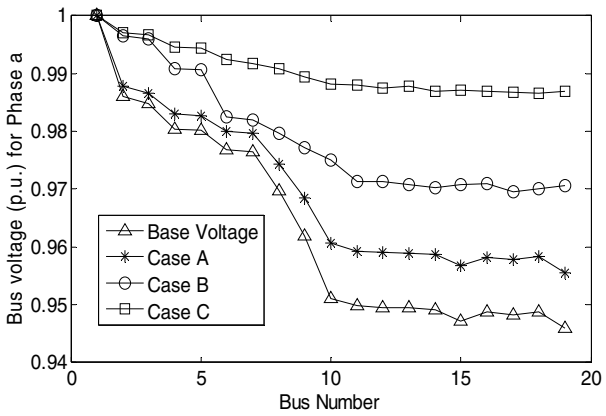

Fig. 3. Voltage magnitude for phase a for different planning cases obtained with DE for 19-bus system

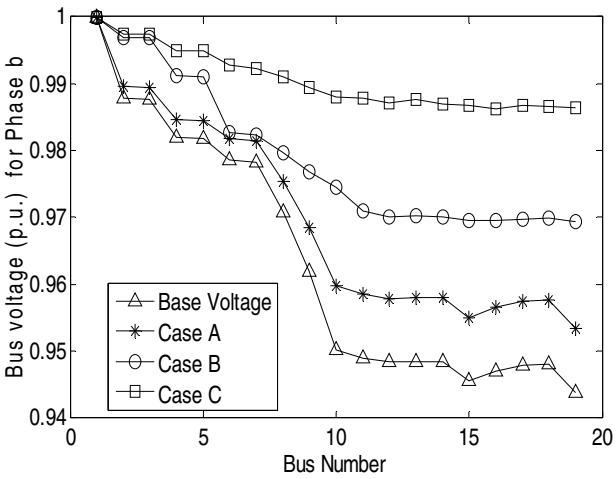

Fig. 4. Voltage magnitude for phase b for different planning cases obtained with DE for 19-bus system

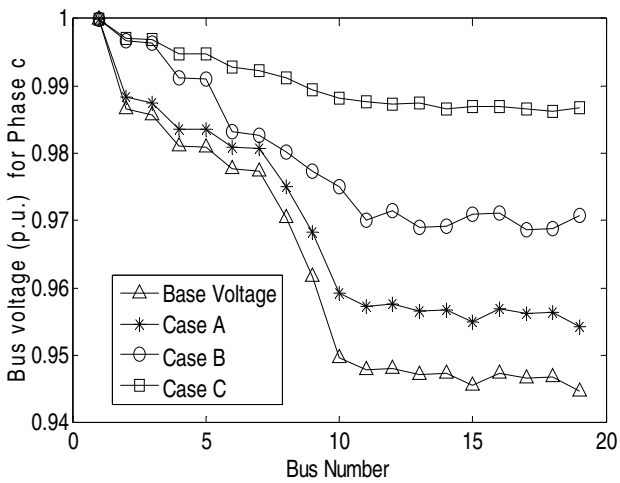

Fig. 5. Voltage magnitude for phase c for different planning cases obtained with DE for 19-bus system

power loss and also the minimum bus voltage magnitude has improved considerably with Case C planning when, three shunt capacitors of kVAR rating of 1350 each is allocated at bus number 20 (optimal location), of the system.

It can be seen that the net reactive power injection remains (4050 kVAR) remains well within the reactive power demand (4871.4 kVAR) of this system. However, the percentage reduction in power loss is less as compared to the 19-bus system. It is expected as the conductor sizes of the 34-bus system are higher as compared to the 19-bus system. The results obtained with DE for different case studies for phase a, b, and c are depicted in Figs. (7)-(9), respectively. As seen from these figures, the voltage profile of the system has improved in comparison to base case results.

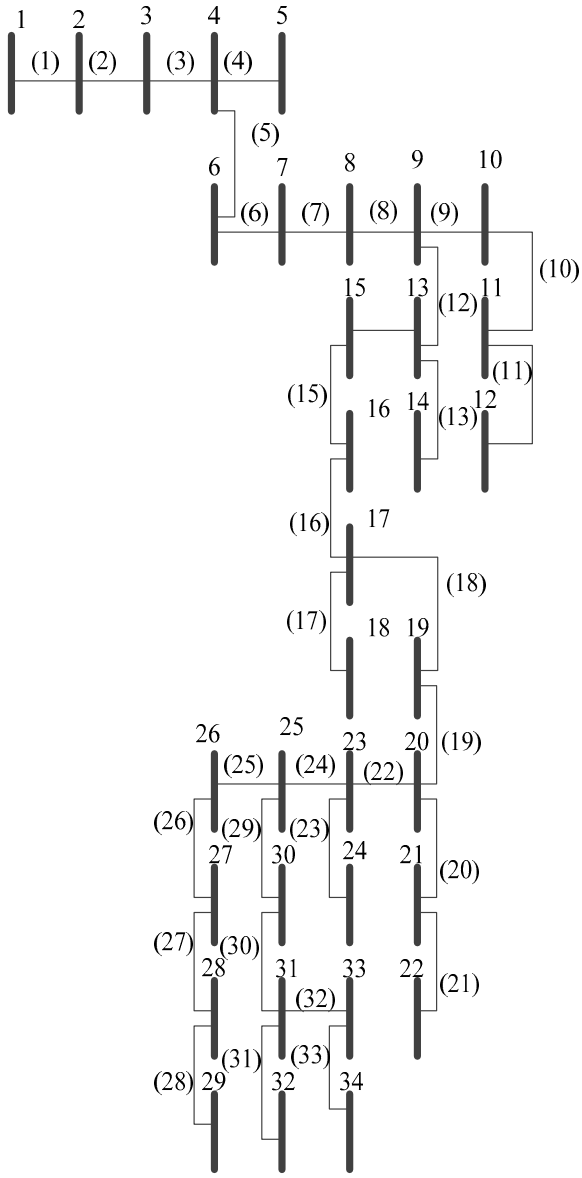

Fig. 6. A 34-bus URDS, (a) 1,2,3…,34 denotes bus number (b) (1), (2),(3),…,(33) denotes branch numbers (c) All the branches are considered as three-phase.

TABLE II. LOAD DATA OF 34-BUS SYSTEM

SB	RB	BN	CT	BL	Receiving end power					
					P_a	P_b	P_c	Q_a	Q_b	Q_c
1	2	1	1	0.4895	46.67	46.67	46.67	24.50	24.50	24.50
2	3	2	1	0.3277	46.67	46.67	46.67	24.50	24.50	24.50
3	4	3	1	1.1334	73.33	73.33	73.33	38.62	38.62	38.62
4	5	4	2	1.1063	100	100	100	52.67	52.67	52.67
4	6	5	1	0.2672	70	70	70	36.87	36.87	36.87
6	7	6	1	0.9955	50	50	50	26.33	26.33	26.33
7	8	7	1	0.3410	50	50	50	26.33	26.33	26.33
8	9	8	1	0.0587	100	100	100	52.67	52.67	52.67
9	10	9	2	0.3238	150	150	150	79.01	79.01	79.01
10	11	10	2	2.9062	150	150	150	79.01	79.01	79.01
11	12	11	2	1.9818	300	300	300	158.03	158.03	158.03
9	13	12	1	0.6911	50	50	50	26.33	26.33	26.33
13	14	13	2	0.5740	90	90	90	47.41	47.41	47.41
13	15	14	1	0.1591	86.67	86.67	86.67	45.65	45.65	45.65
15	16	15	1	1.2430	83.33	83.33	83.33	43.89	43.89	43.89
16	17	16	1	0.7200	83.33	83.33	83.33	43.89	43.89	43.89
17	18	17	2	1.3120	100	100	100	52.67	52.67	52.67
17	19	18	1	0.1430	50	50	50	26.33	26.33	26.33
19	20	19	1	0.7162	76.67	76.67	76.67	40.38	40.38	40.38
20	21	20	2	0.7347	140	140	140	73.74	73.74	73.74
21	22	21	2	2.0004	180	180	180	94.82	94.82	94.82
20	23	22	1	0.3067	40	80	80	21.07	42.14	42.14
23	24	23	2	0.3069	100	100	100	52.67	52.67	52.67
23	25	24	1	1.1044	33.33	33.33	33.33	17.55	17.55	17.55
25	26	25	2	0.0530	40	90	90	21.07	47.41	47.41
26	27	26	2	0.8773	283.33	283.33	283.33	149.25	149.25	149.25
27	28	27	2	0.6896	43.33	43.33	43.33	22.82	22.82	22.82
28	29	28	2	0.7219	20	70	70	10.53	36.87	36.87
25	30	29	1	0.1030	53.33	53.33	53.33	28.09	28.09	28.09
30	31	30	1	0.6215	46.67	46.67	46.67	24.50	24.50	24.50
31	32	31	2	0.1629	130	130	130	68.48	68.48	68.48
31	33	32	2	0.0530	60	65	65	31.60	34.24	34.24
33	34	33	2	0.9206	60	60	60	31.60	31.60	31.60

TABLE III. LINE DATA OF THE 34-BUS SYSTEM

ct	Self-impedance per mile (Ω)	Mutual impedance per mile (Ω)
1 (3-ϕ)	$Z_{aa} = 0.7443 + j\,1.2106$	$Z_{ab} = 0.1594 + j\,0.4822$
	$Z_{bb} = 0.7651 + j\,1.1815$	$Z_{bc} = 0.1624 + j\,0.4398$
	$Z_{cc} = 0.7482 + j\,1.1970$	$Z_{ca} = 0.1546 + j\,0.3878$
2 (3-ϕ)	$Z_{aa} = 1.3196 + j\,1.3521$	$Z_{ab} = 0.1939 + j\,0.5477$
	$Z_{bb} = 1.2760 + j\,1.3306$	$Z_{bc} = 0.1973 + j\,0.5070$
	$Z_{cc} = 1.3240 + j\,1.3434$	$Z_{ca} = 0.2028 + j\,0.4547$

TABLE IV. SIMULATION RESULTS FOR THE 34-BUS SYSTEM

Objective	Case			
	Base	*A*	*B*	*C*
PL(kW)	578.373	443.265	566.697	430.210
Capacitor location	-	20	-	20
Capacitor rating (kVAR)	-	1350	-	1350
	-	1350	-	1350
	-	1350	-	1350
Minimum bus voltage (p.u.)	0.9013	0.9420	0.9024	0.9432
	0.9009	0.9388	0.9022	0.9403
	0.9025	0.9443	0.9039	0.9459
Conductor type	1	1	1	1
	1	1	1	1
	1	1	1	1
	2	2	1	1
	1	1	1	1
	1	1	1	1
	1	1	1	1
	1	1	1	1
	1	1	1	1
	2	2	1	1
	2	2	1	1
	2	2	1	1
	2	2	2	1
	1	1	1	1
	2	2	1	1
	1	1	1	1
	1	1	1	1
	1	1	1	1
	2	2	2	2
	1	1	1	1
	1	1	1	1
	2	2	1	1
	2	2	2	2
	1	1	1	1
	2	2	2	2
	1	1	1	1
	2	2	1	1
	2	2	1	1
	2	2	2	1
	2	2	1	1
	1	1	1	1
	1	1	1	1
	2	2	1	1
	2	2	1	1
	2	2	1	1

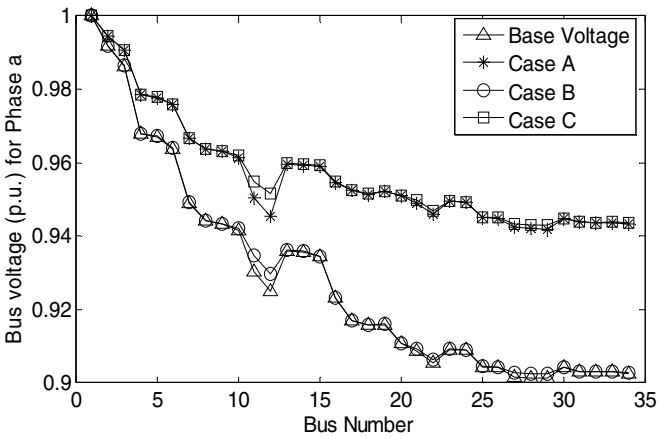

Fig. 7. Voltage magnitude for phase a for different planning cases obtained with DE for 34-bus system

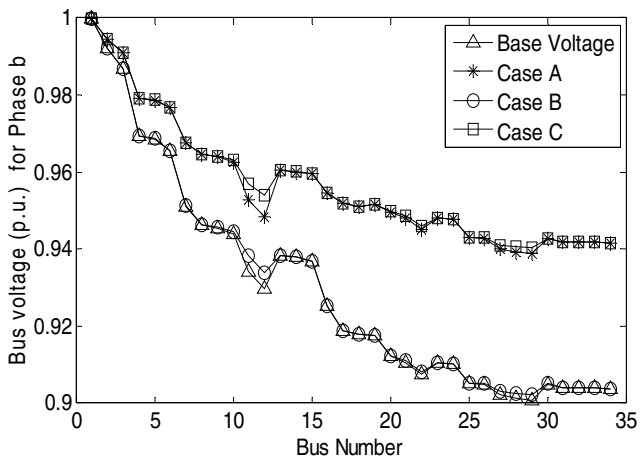

Fig. 8. Voltage magnitude for phase b for different planning cases obtained with DE for 34-bus system

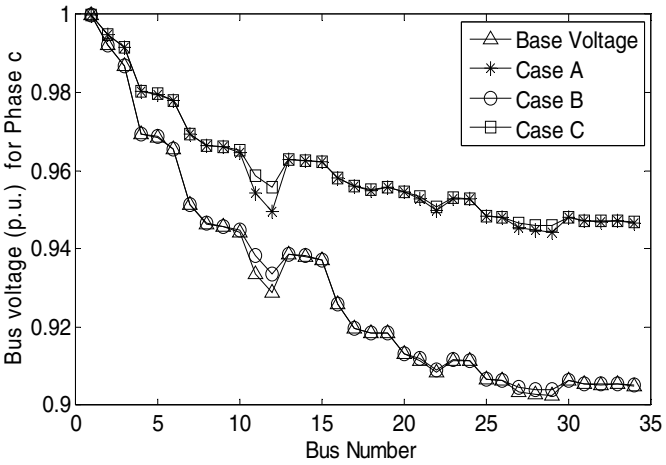

Fig. 9. Voltage magnitude for phase b for different planning cases obtained with DE for 34-bus system

V. Conclusion

In this paper, a planning approach with DE has been proposed for the simultaneous optimization of the capacitor location, sizing, and conductor sizing selection. The total system real power loss minimization has been considered as the objective function for this planning problem. A three-phase unbalanced load flow algorithm has been devised as a subroutine for the evolution of the power flow solutions. The simulation results clearly indicate that the total real power loss of the 19-bus and the 34-bus unbalanced radial distribution systems has been reduced significantly. Moreover, the voltage profile of these systems have improved considerably in comparison to the base case results, for the simultaneous optimization of capacitor location, rating, and conductor sizing.

References

[1] S. Azim and K. S. Swarup, "Optimal Capacitor Allocation in Radial Distribution Systems under APDRP," in *2005 Annual IEEE India Conference - Indicon*, 2005, pp. 614–618.

[2] S. K. Injeti, V. K. Thunuguntla, and M. Shareef, "Optimal allocation of capacitor banks in radial distribution systems for minimization of real power loss and maximization of network savings using bio-inspired optimization algorithms," *Int. J. Electr. Power Energy Syst.*, vol. 69, pp. 441–455, 2015.

[3] V. V. S. N. Murty and A. Kumar, "Capacitor Allocation in Radial Distribution System with Time Varying ZIP Load Model and Energy Savings," *Procedia Comput. Sci.*, vol. 70, pp. 377–383, 2015.

[4] A. A. Eajal and M. E. El-Hawary, "Optimal capacitor placement and sizing in unbalanced distribution systems with harmonics consideration using particle swarm optimization," *IEEE Trans. Power Deliv.*, vol. 25, no. 3, pp. 1734–1741, 2010.

[5] S. Ganguly, N. C. Sahoo, and D. Das, "Multi-objective planning of electrical distribution systems using particle swarm optimization," *Electr. Power Energy Convers. Syst. 2009. EPECS '09. Int. Conf.*, vol. 46, pp. 65–78, 2009.

[6] A. R. Abul'Wafa, "Optimal capacitor allocation in radial distribution systems for loss reduction: A two stage method," *Electr. Power Syst. Res.*, vol. 95, pp. 168–174, 2013.

[7] M. Farsadi, T. S. Dizaji, and H. Hosseinnejad, "Capacitor allocation in order to maximize the loss reduction benefit and improve the voltage profile based on NSGA-II," *ELECO 2015 - 9th Int. Conf. Electr. Electron. Eng.*, pp. 515–520, 2016.

[8] A. Kavousi-Fard and H. Samet, "Multi-objective Performance Management of the Capacitor Allocation Problem in Distributed System Based on Adaptive Modified Honey Bee Mating Optimization Evolutionary Algorithm," *Electr. Power Components Syst.*, vol. 41, no. 13, pp. 1223–1247, 2013.

[9] V. Haldar and N. Chakraborty, "Power loss minimization by optimal capacitor placement in radial distribution system using modified cultural algorithm," *Int. Trans. Electr. Energy Syst.*, vol. 25, no. 1, pp. 54–71, 2015.

[10] H. N. Ng, M. M. A. Salama, and A. Y. Chikhani, "Classification of capacitor allocation techniques," *IEEE Trans. Power Deliv.*, vol. 15, no. 1, pp. 387–392, 2000.

[11] D. Kaur and J. Sharma, "Optimal conductor sizing in radial distribution systems planning," *Int. J. Electr. Power Energy Syst.*, vol. 30, no. 4, pp. 261–271, 2008.

[12] Z. Wang, H. Liu, D. C. Yu, X. Wang, and H. Song, "A practical approach to the conductor size selection in planning radial distribution systems," *IEEE Trans. Power Deliv.*, vol. 15, no. 1, pp. 350–354, 2000.

[13] J. F. Franco, M. J. Rider, M. Lavorato, and R. Romero, "Optimal conductor size selection and reconductoring in radial distribution systems using a mixed-integer LP approach," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 10–20, 2013.

[14] L. Mohammadian, M. T. Hagh, E. Babaei, and S. Khani, "Using PSO for optimal planning, and reducing loss of distribution networks," in *Electrical Power Distribution Networks (EPDC), 2012 Proceedings of 17th Conference on*, 2012, pp. 1–6.

[15] F. Mendoza, D. Requena, J. Bemal-agustin, and J. Dominguez-navarro, "Optimal Conductor Size Selection in Radial Power Distribution Systems Using Evolutionary Strategies," *2006 IEEE/PES Transm. Distrib. Conf. Expo. Lat. Am.*, vol. 00, no. 1, pp. 1–5, 2006.

[16] R. S. Rao, K. Satish, and S. V. L. Narasimham, "Optimal Conductor Size Selection in Distribution Systems Using the Harmony Search Algorithm with a Differential Operator," *Electr. Power Components Syst.*, vol. 40, no. 1, pp. 41–56, 2012.

[17] R. Ranjan, B. Venkatesh, and D. Das, "A new algorithm for power distribution system planning," *Electr. Power Syst. Res.*, vol. 62, no. 1, pp. 55–65, 2002.

[18] P. Samal, S. Ganguly, and S. Mohanty, "Planning of unbalanced radial distribution systems using differential evolution algorithm," *Energy Syst.*, pp. 1–22, 2016.

[19] P. Samal and S. Ganguly, "A modified forward backward sweep load flow algorithm for unbalanced radial distribution systems," in *Power Energy Society General Meeting, 2015 IEEE*, 2015, pp. 1–5.

[20] K. Price, R. Storn, and J. Lampinen, *Differential Evolution: A Practical Approach to Global Optimization*. Berlin, Germany: Springer-Verlag, 2005.

[21] S. Das and P. N. Suganthan, "Differential evolution—A survey of the state-of-the-art," IEEE Trans. Evol. Comput., vol. 15, no. 1, pp. 4–31, Feb. 2011.

[22] K. Prakash and M. Sydulu, "Topological and primitive impedance based load flow method for radial and weakly meshed distribution systems," *Iran. J. Electr. Comput. Eng.*, vol. 10, no. 1, pp. 10–18, 2011.