PLANNING OF UNBALANCED RADIAL DISTRIBUTION SYSTEMS WITH CAPACITOR USING DIFFERENTIAL EVOLUTION ALGORITHM

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Abstract: *This work presents a planning approach for unbalanced radial distribution systems using differential evolution (DE) algorithm so as to determine the optimal capacitor location and phase balancing. Four objective functions are considered in the planning problem. They are the minimization of (i) total system real power loss, (ii) average voltage drop, (iii) total neutral current, and (iv) total negative-sequence voltage unbalance. These objectives are optimized under the constraints of minimum and maximum voltage limits for each bus voltage and thermal limit of each line. A modified three phase forward-backward sweep based load flow algorithm is employed as a supplementary tool for the evaluation of these objective functions. The simulation results obtained with the Indian 19-bus and 34-bus unbalanced radial distribution networks show that significant improvement in power loss, average voltage drop, and total neutral current can be achieved with simultaneous optimization for capacitor location, sizing and phase balancing.*

Key words*: Unbalanced radial distribution networks, three phase load flow, capacitor, differential evolution algorithm.*

1. Introduction

The main aim of distribution system planning is to develop a distribution network that can sustain future demand reliably and efficiently. However, distribution systems are inherently unbalanced due to uneven single phase, three-phase loads. This results in an increase in power loss, neutral current and voltage unbalance and consequently the system performance reduces. Therefore, an appropriate phase balancing is required so as to reduce these effects.

Recent developments show significant phase balancing schemes [1-12]. In [1], the authors have used evolutionary algorithm for minimizing wire replacement cost, transformer positioning cost, load balancing cost, A modified particle swarm optimization algorithm was used in [2] to minimize phase unbalance in a radial distribution system. In [3], a phase balancer device was developed for mitigation of neutral current, and phase unbalance. The authors in [4], utilised mixed integer programming for minimization of phase swapping cost. A population-based algorithm called immune algorithm was employed in [5], to minimize customer service interruption cost, labor cost, and neutral current. The authors in [6], proposed non-dominated sorting genetic algorithm II for minimization of energy loss, neutral current, and number of reconnections. In [7], the authors have reduced the phase unbalancing by changing the transformer winding connections. An expert system was devised in [8], to minimize the total loss cost. A self-adaptive differential evolution algorithm [9] was used for phase balancing of distribution networks. The authors in [10], utilized tabu search algorithm for minimization of total system cost. In [11], simulated annealing was used for minimizing phase swapping cost. The authors in [12], have utilized differential algorithm (DE) for minimization of complex power unbalance, power loss, voltage unbalance, and neutral current.

In recent years numerous works have done in the area of capacitor allocation in distribution networks [13-20]. In [13], the authors have used cuckoo search algorithm for minimizing total system power loss. A system approach was devised in [14] for profit maximization in distribution networks. Cultural algorithm [15] was employed for power loss minimization and voltage profile improvement in distribution networks. The authors in [16] utilized particle swarm optimization for power loss minimization. A bacteria foraging based algorithm was used in [17] for maximizing capacitor saving function, minimizing active power losses, and voltage profile improvement. In [18], genetic algorithm (GA) was employed for minimization of operating costs of the distribution networks. The authors in [19], used GA for annual energy loss minimization. A modified monkey search algorithm was implemented in [20], for loss and investment cost minimization.

As observed from the literature [1-20], the phase balancing and capacitor allocation can reduce the system power loss, neutral current, and unbalance of unbalanced distribution system. In all the scenarios the optimization of phase balancing and capacitor allocation has been done separately and encouraging results have been obtained. Further, no work has been reported for simultaneous optimization of phase balancing and capacitor allocation. Hence, this has motivated the authors to simultaneously optimize the phase balancing and capacitor location and rating

The objective functions are the total power loss, Average voltage drop, total neutral current and total voltage unbalance. Differential evolution (DE) is employed as the solution strategy for minimizing these objective functions to obtain optimal capacitor location, rating and phase balancing. For the evaluation of each objective, a forward-backward load flow algorithm is developed. The proposed approach is demonstrated on the Indian 19-bus and 34-bus unbalanced radial distribution networks.

This paper is organized as follows: Problem Formulation is presented in section 2. In Section 3, the implementation of proposed planning approach using DE is described. The simulation results are presented in section 4. Section 5 concludes the paper.

2. Problem Formulation

The aim of this planning problem is the minimization of numerous objective functions subject to some technical constraints. These objective functions are as follows:

(i) *Total Power Loss* (PL)[12]*:* The total power loss of a system is expressed as follows

$$PL = \sum_{\alpha=1}^{NBR} \sum_{p\in\{a,b,c\}} PL_{\alpha}^{p} \tag{1}$$

Where, *NBR* is the number of line/branch sections.

(ii) *Average voltage drop* [12] *(AVD):* The Average voltage drop is formulated according to Eqs. (2)-(3)

$$AV_d = \frac{1}{NB}\sum_{k=1}^{NB} VD_k \tag{2}$$

$$VD_k = \frac{1}{3}\sum_{p\in a,b,c}\left|\frac{V_{rated} - V_k^p}{V_{rated}}\right| \times 100\% \tag{3}$$

(iii) *Total neutral current (TNC)* [12]*:* The total neutral current is defined as below.

$$I_N = \sum_{j=1}^{NBR} \sum_{p\in a,b,c} I_j^p \tag{4}$$

Where, I_N denotes total neutral current and I_j^p represents current of branch *j* of phase *p*.

(iv) Total negative-sequence voltage unbalance (*NSUF*) [12]: The voltage unbalance is computed as follows:

$$TVU = \sqrt{\frac{1}{NB}\sum_{k=1}^{NB}(d_{2,k})^2} \tag{5}$$

Where,
$$d_{2,k} = \frac{V_k^{(2)}}{V_k^{(1)}} \tag{6}$$

All these objectives are aggregated as weighted sum follows:

$$FIT = \begin{pmatrix} 0.25\times\left(\frac{PL}{PL_o}\right) + 0.25\times\left(\frac{MVD}{MVD_o}\right)0.25 \\ \times\left(\frac{TNC}{TNC_o}\right) + 0.25\times\left(\frac{TVU}{TVU_o}\right) \end{pmatrix} \tag{7}$$

Where, PL_0 denotes base case power loss of the system.

Where, $h_1+h_2+h_3+h_4=1.0$ (8)

In which, h_w denotes the weighting factor and h_1, k_2, h_3, and h_4 are considered to be 0.25.

The fitness function (FIT) for DE is assigned as follows:

Minimize *FIT* (9)

This fitness function is minimized under the following constraints [12]:

i. Voltage constraint: The voltage at each bus must lie between the lower and upper bound limit in order to avoid under voltage and over voltage problem.

$$V_s^{min} \le V_s^{abc} \le V_s^{\max} \tag{10}$$

ii. Thermal constraint: The current flowing through each branch shouldn't exceed the maximum current-carrying capacity of the conductor for all the phases.

$$I_j^{abc} \le I_j^{\max} \tag{11}$$

ii. Capacitor power generation constraint: The capacitor reactive power generation must remain within the limits:

$$Q_i^{\min} \le Q_i \le Q_i^{\max} \qquad (12)$$

3. Implementation of DE algorithm for the planning problem

The proposed planning approach with DE utilizes a three-phase load flow algorithm as a supplementary program to obtain bus voltage magnitudes and power loss of a system. DE algorithm is used to update the chromosome representing decision variables such as phase loading, capacitor location and rating. The load flow algorithm including capacitor is explained in Section 3.1 and application of DE is described in Section 3.2.

3.1 Three phase forward-backward sweep load flow algorithm incorporating capacitor

The proposed algorithm [21] utilizes three matrices *A*, *B* and *C* to obtain power flow solutions. The downstream buses connected to a particular bus are determined using matrix *A*. The end buses are identified with the help of matrix *B* and matrix *C* is developed to obtain the branch currents. This load flow algorithm basically consists of two steps. In the first step, the backward sweep is executed to find out the branch currents as follows:

$$\bar{I}_j^{x\in a,b,c} = \left(\frac{P_j^x - iQ_j^x}{\bar{V}_j^{x*}} \right) \qquad (13)$$

Where, $\bar{I}_j^{x\in a,b,c}, \bar{V}_j^{x*}$, P_j^x, and Q_j^x are the load current and voltage conjugate (in phasor form), active and reactive power demand at bus *j* for phase *x*

Then, the forward sweep is executed to obtain the bus voltages. More details of the algorithm can be obtained from [21].

3.1.1 Incorporation of Capacitor model in distribution load flow

To incorporate the capacitor model, the reactive power demand at the bus at which a Capacitor unit is placed, say, at bus *i*, Eqs. (13) are modified by:

$$Q_{D_{jp}}^{C} = Q_{D_{jp}}^{base} - Q_{jp}^{C} \qquad (14)$$

Where, $Q_{D_{jp}}^{C}$ are the reactive power demand for p^{th} phase of j^{th} bus with a Capacitor unit and $Q_{D_{jp}}^{base}$ is the reactive power demand for p^{th} phase of j^{th} bus of the base-case network; Q_{jp}^{C} is the active power generated by the capacitor unit placed at p^{th} phase of j^{th} bus.

3.2 Proposed Planning Approach Using DE

DE is employed as the solution strategy for the planning problem of unbalanced radial distribution networks. This algorithm obtains the optimal solution by employing selection, crossover, and mutation operation. More details about DE algorithm can be found in [12].

3.2.1 Decision variable representation

The parameters (decision variables) for DE in this planning problem consists of three decision variables and is represented as a vector *D* as follows:

$$D = [\mathrm{NC}, \phi, \mathrm{APD}] \qquad (20)$$

$$\phi = [\phi_1, \phi_2, .., \phi_N] \qquad (21)$$

$$\mathrm{ADP} = [APD_{a,b,c}, APD_{a,b,c}, \ldots, APD_{N}] \qquad (22)$$

Where ϕ denotes the vector of capacitor locations; APD vector represents the active and reactive power load for phases a, b, and c for bus *N*, and NC represents the number of capacitors.

3.2.2 Flow chart of the proposed methodology

The flow chart of the solution strategy for the planning problem is provided in Fig. 1.

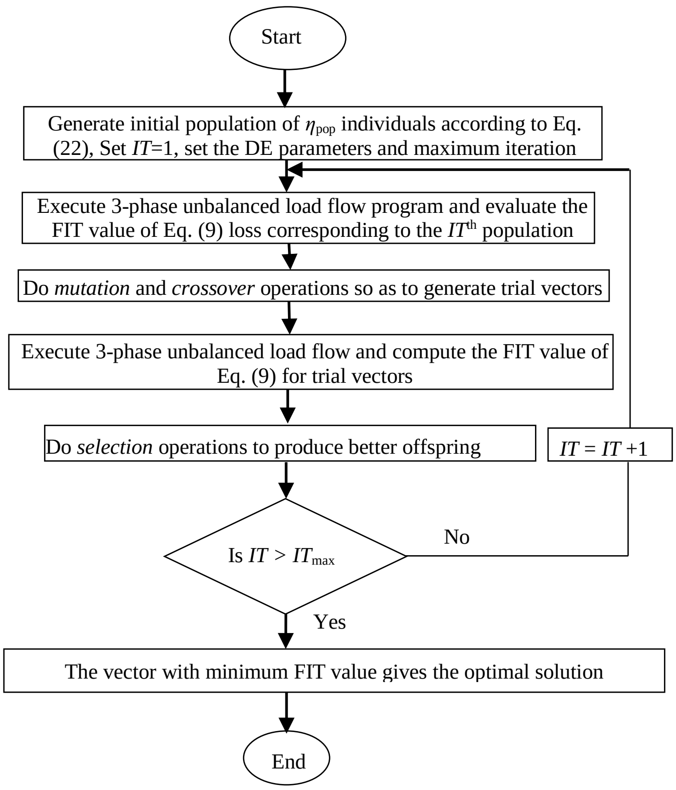

Fig. 1. Flow chart of the proposed planning approach

4. Simulation Results and discussions

The simulations are carried out with MATLAB 8.0 software. The effectiveness of the proposed algorithm is verified on two unbalanced radial distribution networks, i.e. 19-bus and 34-bus system. The base case results for the 19- and 34-bus networks are provided in Table 1. The parameters of the DE are taken from [12]. In this, work, three different planning cases are studied such as:

- *Case A:* planning for optimal phase balancing
- *Case B:* planning for optimal capacitor allocation.
- *Case C:* Simultaneous planning for optimal phase balancing and capacitor allocation.

Table 1: Base case values for 19- and 34-bus networks

Objective	Indian 19-bus network	34-bus network
PL (kW)	50.1072	578.3774
TNC(p.u.)	7.9849	53.3436
AVD (%)	3.3678	7.0538
NSUF (%)	0.0316	0.3898

A. 19-bus unbalanced radial distribution system

The load data and line data of the 19-bus system are taken from [24]. The base kV and MVA of the system are considered as 11 and 1 respectively [24]. 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 2. It is observed from this table that, the power loss, neutral current, and Average voltage drop has been reduced by 21.92%, 9.64%, and 13.65% respectively with Case C optimization.

Table 2: Results obtained with different planning cases using DE for 19-bus network

Objective	*Case A*	*Case B*	*Case C*
PL (kW)	45.6309	40.9893	39.1230
TNC(p.u.)	7.6208	7.3328	7.2144
AVD (%)	3.5127	3.0328	2.9081
NSUF (%)	0.0077	0.0305	0.0302

The optimal location of the capacitor is found as bus number 11 with Case C planning, and the ratings are 150 kVAR for phase a, b, and c respectively. The voltage profile of the system for phase a, b, and c for Case A, B, C, and base voltage are shown in Figs. (2)-(4). 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.

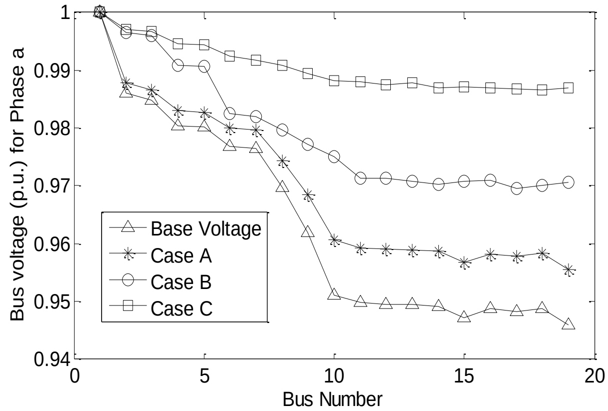

Fig. 2. Voltage magnitude for phase a for different planning cases obtained with DE for 19-bus system

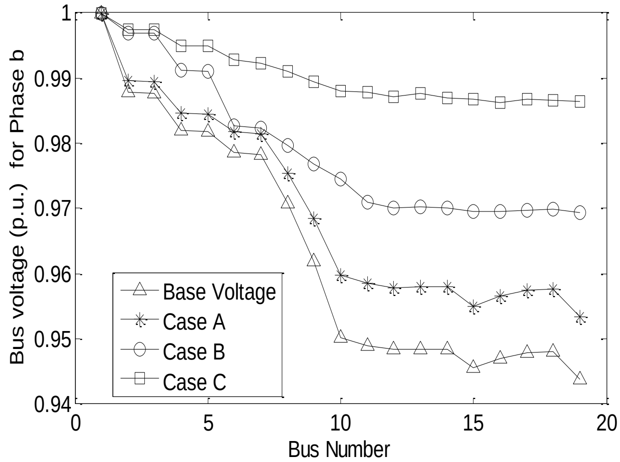

Fig. 3. Voltage magnitude for phase b for different planning cases obtained with DE for 19-bus system

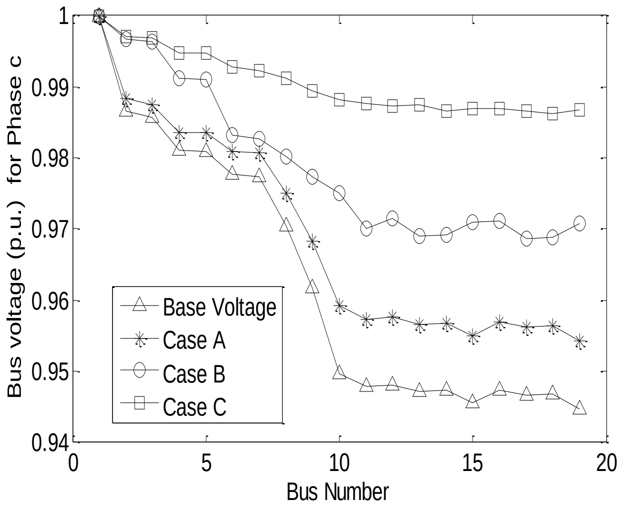

Fig. 4. Voltage magnitude for phase c for different planning cases obtained with DE for 19-bus system

B. 34-bus unbalanced radial distribution system

The network diagram of 34-bus unbalanced radial distribution networks is shown in Fig. 5. The system load and line data are given in Table 3 and 4, 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.

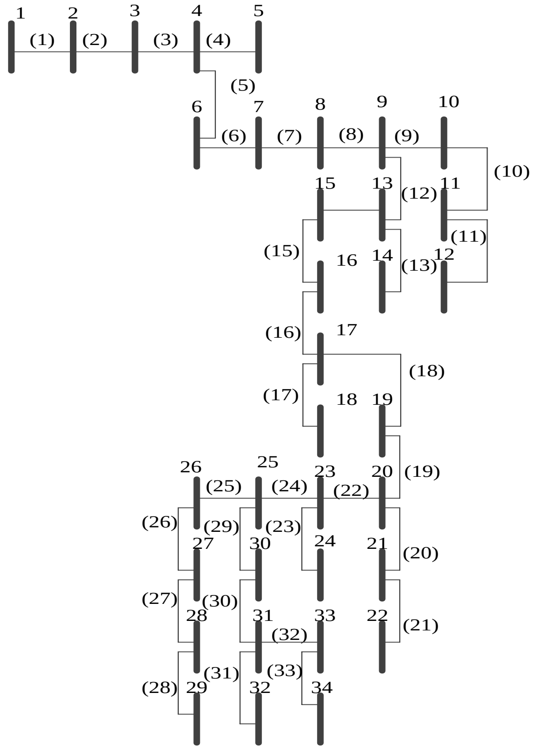

Fig. 5. A 34-bus unbalanced radial distribution system, (a) 1,2,3…,34 denotes bus number (b) (1), (2),(3),…,(33) denotes branch numbers (c) All the branches are considered as three-phase.

The simulation results for different case studies are shown in Table 5. It can be observed from Table 5 that power loss, neutral current, and Average drop has been reduced by 23.85%, 17.22%, and 55.9% for Case C planning. The best place for capacitor placement for Case C planning is found to be bus number 12, and ratings are 1350 kVAR for phase a, b, and c respectively. The results obtained with DE for different case studies for phase a, b, and c are depicted in Figs. (6)-(8), respectively. As seen, from these figures, the voltage profile of the system has improved in comparison to base case results.

Table 3: Load data for the 34-bus networks

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

Where, SB, RB, BN, CT, BL, P_a , and Q_a represents sending end bus, receiving end bus, branch number, conductor code, branch length in mile, active load in kW for phase a, and reactive load in kVAR for phase a respectively.

Table 4: Line data for the 34-bus networks

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 5: Results obtained with different planning cases using DE for 34-bus system

Objective	*Case A*	*Case B*	*Case C*
PL (kW)	576.4216	443.265	440.4352
TNC(p.u.)	50.4127	47.2264	44.1568
AVD (%)	6.4178	4.2212	3.1053
NSUF (%)	0.3051	0.2623	0.2620

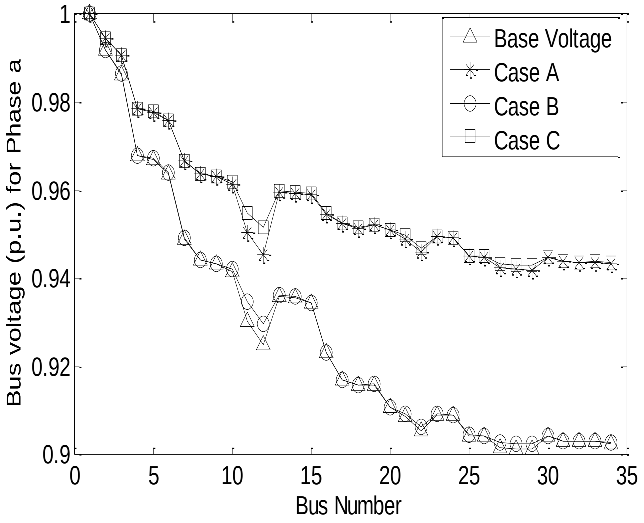

Fig. 6. Voltage magnitude for phase a for different planning cases obtained with DE for 34-bus system

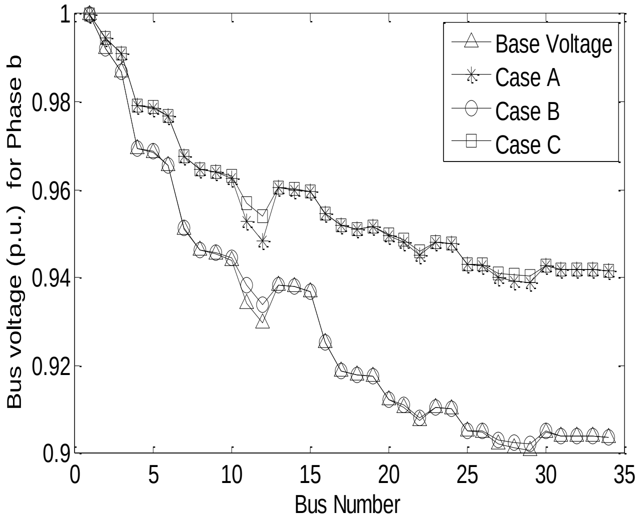

Fig. 7. Voltage magnitude for phase b for different planning cases obtained with DE for 34-bus system

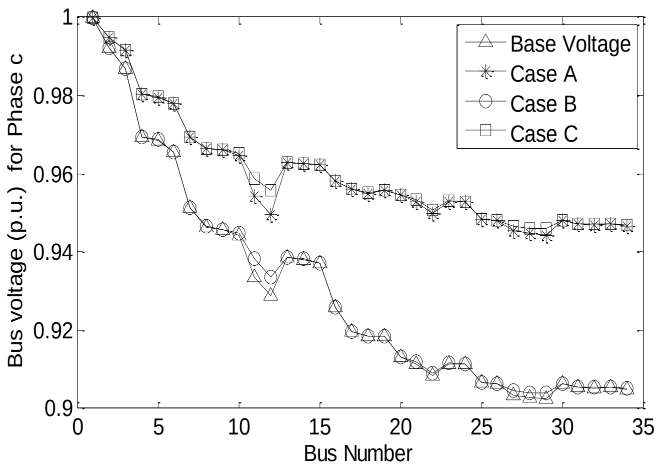

Fig. 8. Voltage magnitude for phase b for different planning cases obtained with DE for 34-bus system

5. Conclusion

This paper proposes a planning approach to determine the optimal phase balancing and capacitor sizes of unbalanced radial distribution networks by optimizing power loss, average voltage drop, negative-sequence voltage unbalance, and neutral current. A three phase forward-backward sweep load flow algorithm is used in the planning approach to compute power flow solutions. DE is used as the solution strategy. The simultaneous optimization for phase balancing, capacitor location and sizing provides a network with better power loss and voltage profile, and lower neutral current.

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