Electric Power Systems Research 95 (2013) 168–174

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Optimal capacitor allocation in radial distribution systems for loss reduction: A two stage method

Ahmed R. Abul'Wafa *

Ain-Shams University, Electric Power and Machines, Cairo, Egypt

ARTICLE INFO

Article history:
Received 27 December 2011
Received in revised form 14 July 2012
Accepted 11 September 2012
Available online 9 October 2012

Keywords:
Capacitor allocation
Radial distribution feeder reconfiguration
Power loss reduction
Cost function
Load flow

ABSTRACT

This paper presents an efficient approach for capacitor allocation in radial distribution systems that determine the optimal locations and sizes of capacitors with an objective of reduction of power loss and improving the voltage profile. A loss sensitivity technique is used to select the candidate locations for the capacitor placement. The size of the optimal capacitor at the compensated nodes is determined simultaneously by optimizing the loss saving equation with respect to the capacitor currents. The performance of the proposed method (*PM*) was investigated on several distribution systems and it was found that significant voltage profile improvement and loss saving can be achieved by optimal allocation of capacitors in the system. However this method is sensitive to the distribution network configuration. In a 28 node feeder the matrix of capacitor sizing becomes close to singular or badly scaled and results may be inaccurate. In 85 node feeder the same matrix becomes singular and no solution obtained. For the 28 node feeder a two stage technique is proposed: a reconfiguration of the feeder in the first stage followed by optimal capacitor allocation as a second stage. For the 85 node feeder a slight movement of the capacitor location was sufficient to reach optimal capacitor allocation. The proposed two stage technique is also applicable to the 85 node feeder for given optimum configuration of the tie switches. Simulations, using genetic algorithm are conducted for the two (28 and 85 nodes) systems allowing detection of loss reduction and voltage improvement due to capacitor placement.

1. Introduction

Optimal allocation of shunt capacitors on radial distribution systems is essential for power flow control, improving system stability, power factor correction, voltage profile management, and losses minimization. The solution techniques for the capacitor allocation problem can be classified into four categories [1]: analytical, numerical programming [2], heuristic [3,4], and artificial intelligence-based (AI-Based). AI-Based methods include genetic algorithms [5,6], simulated annealing [7], expert systems [8], artificial neural networks, and fuzzy logic [9,10]. A survey of all capacitor allocation categories has been presented in [1,11]. Haque [12] proposed a method for minimizing the loss associated with the reactive component of branch currents by placing optimal capacitors at proper locations. The method first finds the location of the capacitors in a sequential manner (loss minimization by a singly located capacitor). The optimal capacitor size at each selected location for all capacitors are determined simultaneously, to avoid over compensation at any location, through optimizing the loss saving equation. Other publications found optimal capacitor size through optimizing cost saving [13,14]. Capacitor locations are determined by two methods: Loss Sensitivity Factor and Index Vector. Capacitor sizes are determined by PSO. Capacitor locations given by two methods are not same and the sizes are also different in both the methods. But, total reactive power used for compensation is almost nearer to each other. Location of the capacitors may be found in sequential manner by loss minimization by a singly located capacitor [12,15]. Also fuzzy expert system may be used for extracting suitability of capacitor location from power loss reduction index and voltage profile [10]. Hsiao et al. [16] present a combination fuzzy-GA method to resolve the capacitor placement problem. The problem formulation considers three distinct objective functions related to minimize the total cost for energy loss and capacitors to be installed, as well as decreasing the deviation of bus voltage and improving the margin loading of feeders. Das [17] presents a genetic algorithm (GA) based fuzzy multi-objective approach for determining the optimum values of fixed and switched shunt capacitors to improve the voltage profile and maximize the net savings in a radial distribution system.

This paper, extending the problem formulation of previous researches on capacitor optimization presents an efficient approach for capacitor placement in radial distribution systems that determine the optimal locations and size of capacitor with an objective of reduction of power loss and improving the voltage

* Tel.: +20 222639022.
E-mail address: Ahmedlaila.nelly.ola@gmail.com

0378-7796/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsr.2012.09.004

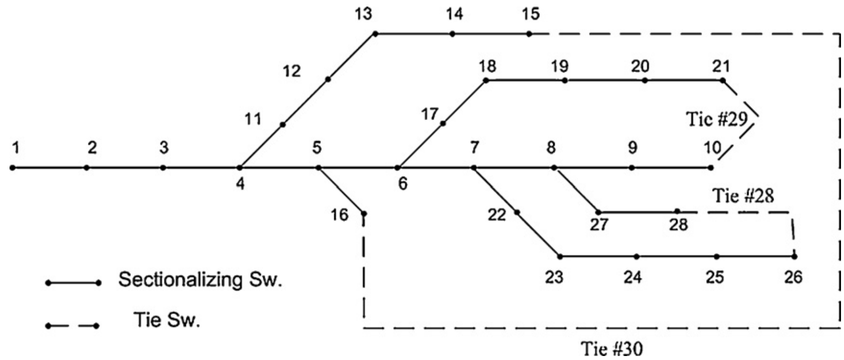

Fig. 1. Single line diagram of 28 node radial distribution feeder.

profile. A loss sensitivity technique is used to select the candidate locations. The size of the optimal capacitor at the compensated nodes is determined simultaneously by optimizing the loss saving equation with respect to the capacitor currents. Sensitivity measured through sequential loss minimization or suitability index extracted from fuzzy expert system gave same location of capacitors along distribution feeders. The performance of the *PM* was investigated on several distribution systems (15 node [18], 28 node [19], 33 node [15], 34 node [1], 69 node [3] and 85 node [18] feeders) and it was found that significant voltage profile improvement and loss saving can be achieved by optimal allocation of capacitors in the system. Two incidents were met where the configuration of distribution network may hinder the solution of capacitor allocation problem. In a 28 node feeder the matrix of capacitor sizing becomes close to singular or badly scaled and results may be inaccurate. In 85 node feeder the same matrix becomes singular and no solution obtained. For the 28 node feeder a two stage capacitor allocation technique is applied: a reconfiguration of the feeder in the first stage [20] followed by optimal capacitor allocation as a second stage resulting in problem solution. For the 85 node feeder a slight movement of the capacitor location is proposed to avoid matrix singularity. The proposed two stage technique is also applicable to the 85 node feeder for given optimum allocation of the tie switches.

2. Proposed method

The load flow algorithm described in [21] is used for calculation of active and reactive power loss. Note that for a given configuration of a single-source radial network, the active power loss cannot

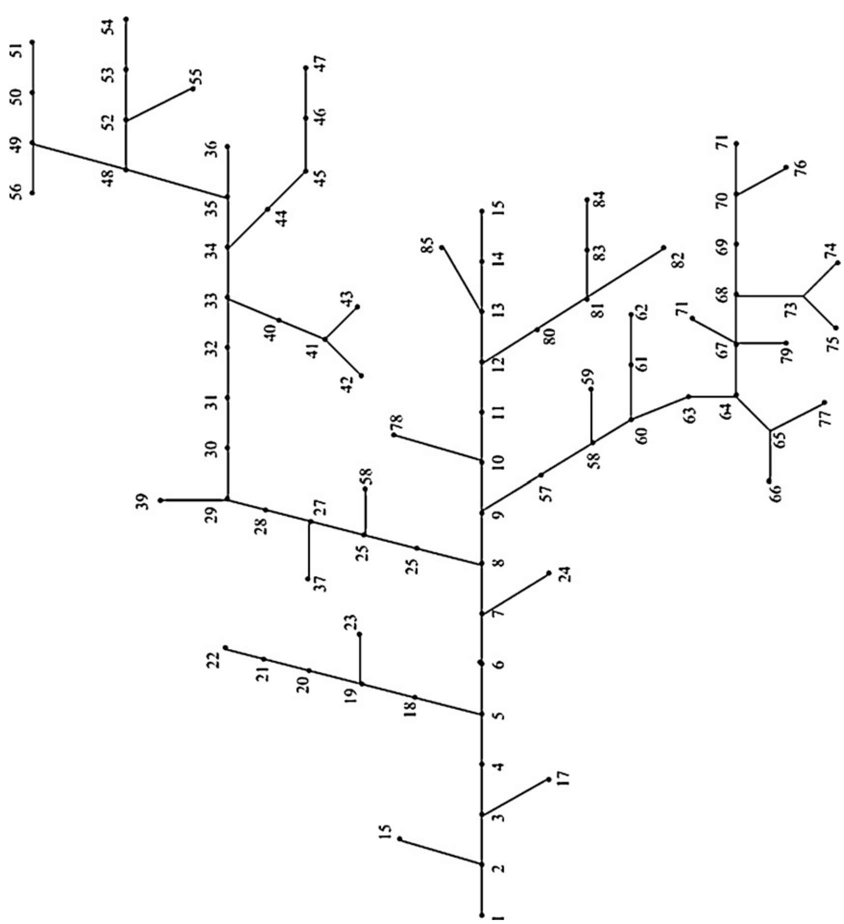

Fig. 2. Single line diagram of 85 node radial distribution feeder.

Table 1
Summary of compensation by a multiple capacitors.

System	Power losses compensated/uncompensated (kW)	Capacitor location (node) and size (kVAr)		Power loss reduction (%)	Minimum voltage (pu) compensated/uncompensated	Money saving ($)	CPU time (s)
15 Node	32.7697/61.7803	3 6	925 375 Total = 1300	46.96	0.9725/0.9445	15567.31	2.593
	32.4262/61.7803	3 6 4	175 375 750 Total = 1300	47.51	0.9695/0.9445	15763.13	2.783
33 Node	146.6393/210.7977	7 29	850 875 Total = 1725	30.44	0.9245/0.9038	35284.88	2.868
	144.0420/210.7977	7 29 30	850 25 900 Total = 1775	31.67	0.9251/0.9038	36728.07	2.945
34 Node	363.8938/471.3114	21 20	1050 775 Total = 1825	22.79			
	363.5452/471.3114	21 20 19	1125 625 75 Total = 1825	22.87	0.8968/0.8822	60066.89	3.496
	385.9952/471.3114	21 20 19 6	600 1175 1375 25 Total = 3175	18.10	0.9041/0.8822	46264.39	3.496
69 Node	149.2920/224.6893	19 62	225 1100 Total = 1325	33.59	0.9284/0.9092	42046.14	4.899
	148.9139/224.6893	19 62 63	225 900 225 Total = 1350	33.75	0.9289/0.9092	42243.02	5.361

be minimized because all active power must be supplied by the source at the root node. However, the reactive power loss can be minimized by supplying part of the reactive power demands locally. The *PM* first identifies a sequence of nodes to be compensated. A loss sensitivity technique is used to select the candidate capacitor locations. Loss reduction index is found in sequential manner by loss minimization by a singly located capacitor. As cross check fuzzy expert system is used for extracting suitability of capacitor location from power loss reduction index and improving the voltage profile within voltage constraints. The optimal capacitor sizes at selected locations are determined simultaneously, to avoid over compensation at any location, through optimizing the loss saving equation. This involves the solution of a set of linear algebraic equations.

2.1. Capacitor sizing

The reactive power loss in the original *n*-branches system is given by

$$P_{Lr} = \sum_{i=1}^{n} I_{ri}^2 R_i \tag{1}$$

Let us consider the following:

k, is the number of capacitor nodes
$\boldsymbol{I_c}$ is the k-dimensional vector consisting of capacitor currents
$\boldsymbol{\alpha}_j$ is the upstream branches from the jth capacitor node to the source node ($j = 1, 2, \ldots, k$)
$\boldsymbol{D}$ is a matrix of dimension n by k

The elements of $\boldsymbol{D}$ are considered as:

$D_i = 1$; if branch $i \in \alpha$
$D_i = 0$; otherwise

When the capacitors are placed in the system, the new reactive component of branch currents are given by

$$[\boldsymbol{I_r^{new}}] = [\boldsymbol{I_r}] + [\boldsymbol{D}][\boldsymbol{I_c}] \tag{2}$$

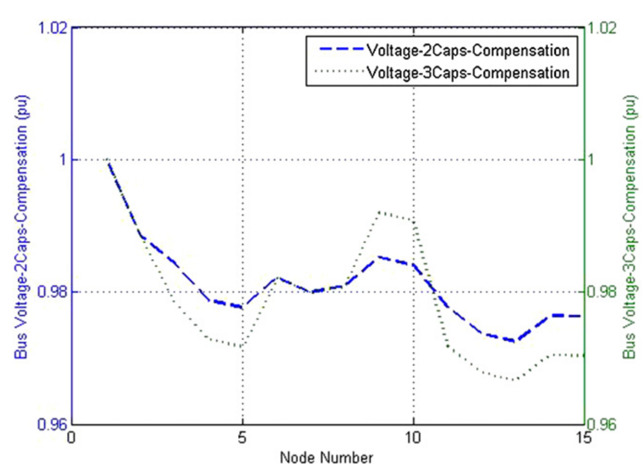

Fig. 3. Voltage profiles on the compensated 15 node feeder with 2 and 3 capacitors.

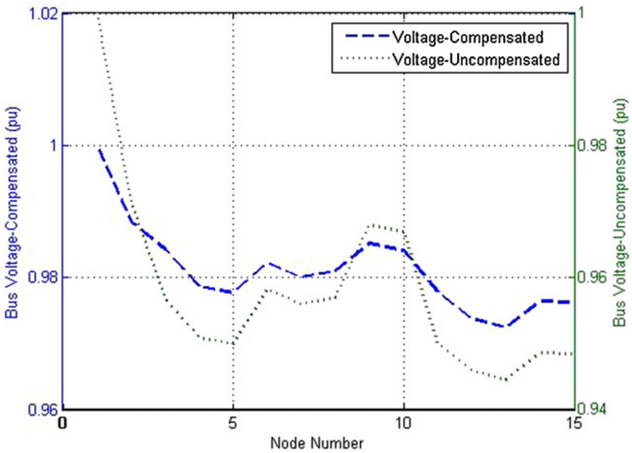

Fig. 4. Voltage profiles on the 15 node feeder before and after compensation.

Table 2
Optimal power-loss in each loop, tie-switch closed and sectionalize-switches open in the 28 bus reconfigured feeder.

Tie switch (closed)	Sectionalize switches open between nodes	Power loss (kW)
29	9–10	68.3371
	8–9	68.0205
30	5–6	67.8443
28	25–26	64.5119
	24–25	63.9701
	23–24	64.1047

Last switching is not acceptable.

And the corresponding reactive power loss P_{Lr}^{comp} is

$$P_{Lr}^{comp} = \sum_{i=1}^{n}\left(I_{ri} + \sum_{j=1}^{k} D_{ij} I_{cj}\right)^2 R_i. \tag{3}$$

The loss saving S obtained by placing the capacitors is the difference between Eqs. (1) and (3) and is given by

$$S = -\sum_{i=1}^{n}\left[2I_{ri}\sum_{j=1}^{k} D_{ij} I_{cj} + \left(\sum_{j=1}^{k} D_{ij} I_{cj}\right)^2\right] R_i \tag{4}$$

The optimal capacitor currents for the maximum loss saving can be obtained by solving the following equation:

$$\frac{\partial S}{\partial I_{c1}} = 0;\ \frac{\partial S}{\partial I_{c2}} = 0;\ \ldots;\ \frac{\partial S}{\partial I_{ck}} = 0 \tag{5}$$

After some mathematical manipulations, Eq. (5) can be expressed by a set of linear algebraic equations as follows:

$$[\boldsymbol{A}][\boldsymbol{I_c}] = [\boldsymbol{B}] \tag{6}$$

where $\boldsymbol{A}$ is a k by k square matrix and $\boldsymbol{B}$ is a k-dimensional vector. The elements of $\boldsymbol{A}$ and $\boldsymbol{B}$ are given by

$$A_{jj} = \sum_{i \in \alpha_j} R_i \tag{7}$$

$$A_{jm} = \sum_{i \in (\alpha_j \cap \alpha_m)} R_i \tag{8}$$

$$B_j = \sum_{i \in \alpha_j} I_{ri} R_i \tag{9}$$

The capacitor currents for the highest loss saving can be obtained from Eq. (6).

$$[\boldsymbol{I_c}] = [\boldsymbol{A}]^{-1}[\boldsymbol{B}] \tag{10}$$

Once the capacitor currents are known, the optimal capacitor sizes can be written as

$$[\boldsymbol{Q_c}] = [\boldsymbol{V_c}][\boldsymbol{I_c}] \tag{11}$$

Here $\boldsymbol{V_c}$ is the voltage magnitude vector of capacitor nodes. The saving in the compensated system can be estimated from Eq. (4) using the value of $\boldsymbol{I_c}$ given by Eq. (10). If the matrix of capacitor sizing, due to peculiar locations of capacitors becomes close to singular or badly scaled solution may be inaccurate. When the matrix is singular no solution will be obtained. A slight movement of the capacitor location will insure problem solution. However a two stage solution method is proposed as generic approach.

2.2. Two-stage optimal capacitor allocation

Capacitor locations in the 28 node feeder presented in Fig. 1 are at nodes 7 and 17. The upstream paths from these nodes are the same resulting in a close to singular or bad scaled $[\boldsymbol{A}^{-1}]$ or/and $[\boldsymbol{B}]$ matrices. In 85 node feeder presented in Fig. 2 the capacitor locations are at nodes 9 and 25. Also the upstream paths from these nodes are the same resulting in singular $[\boldsymbol{A}^{-1}]$ or/and $[\boldsymbol{B}]$ matrices and no solution obtained. For the 28 node feeder a two stage capacitor allocation technique is proposed: a reconfiguration of the feeder

Table 3
Summary of compensation by a multiple capacitors for the 28 and 85 bus feeders.

System		Power losses compensated/uncompensated (kW)	Optimal capacitor locations (nodes) and sizes (kVAr)		Power loss reduction (%)	Minimum voltage (pu) compensated/uncompensated	CPU time (s)
228 Node	Analytical	29.9896/68.75858755	6	225	56.38[a]	0.9633/0.9322[a]	4.0651
			7	475			
				Total = 700			
	GA	35.4486/68.75858	6	500	48.44[b]	0.9532/0.9125[b]	34.9327
			4	150			
			7	25			
				Total = 675			
285 Node[c]	Analytical	6185.2897/344.4759	26	1200	46.21	0.9155/0.8707	5.9427
			9	1200			
				Total = 2400			

[a] Power loss reduction and voltage profile improvement due to feeder reconfiguration and optimal capacitor allocation
[b] Power loss reduction and voltage profile improvement due to optimal capacitor allocation using GA technique.
[c] Optimal capacitor allocation with shifting second capacitor from node #25 to node #26.

Table 4
Comparison of the proposed method results with previous publications.

Items	Compensated/uncompensated					
	[22][a]		[23][a]		Proposed	
(a) 33-Bus System						
Total losses (kW)	135.4/202.67		135/203		144.04/210.80	
Optimal locations and sizes (kVAr)	62829	1200	815202124262728	300	72930	850
		760		300		25
		200		300		900
				300		
				300		
				300		
				600		
				300		
Total kVAr	2160		2700		1755	
Minimum voltage (pu)	N/A		0.9131/0.9349		0.9251/0.9038	
CPU time (s)	N/A		N/A		2.944659	

Items	Compensated/uncompensated									
	[24]	[25]	[26]	[27]	[28]	[29]	[22]	[30]	[23]	[31]	Proposed[b]
(b) 34-Bus System											
Total losses (kW)	168.47/221.67	168.95/221.72	168.95/221.72	169.14/221.72	161.33/221.72	167.91/221.72	168.50/221.67	168.80/221.72	170.00/221.67	168.98/221.67	163.47/221.67
Optimal locations and sizes (kVAr)	26, 11, 17, 4 1400, 750, 300, 250	19, 20, 21, 22, 23, 24, 25 683, 145, 144, 143, 143, 143, 228	18, 21, 19 761, 803, 479	18, 21, 19 1200, 639, 200	8, 18, 25 1050, 750, 750	20, 21, 22, 23, 24, 25, 26 968, 145, 144 143, 143, 143, 228	19, 22, 20 1200, 739, 200	19, 22, 20 900, 986, 150	5, 9, 12, 22, 26 300, 300, 300, 600, 300	24, 17, 7 781, 803, 479	8, 18, 25 25, 2150, 875
Total kVAr	2700	1629	2063	2039	2550	2600	2139	2036	1800	2700	3050
Minimum voltage (pu)	N/A	0.9491/0.9417	0.9496/0.9417	0.9492/0.9417	0.9506/0.9417						0.9494/0.9417
CPU time (s)											2.993898

Items	Compensated/uncompensated									
	[29]		[26]		[23]		[31]	[32]	Proposed	
(c) 69-Bus System										
Total losses (kW)	151.71/225.00		152.48/224.98		147.40/224.98		156.62/224.96	152.72/225.02	148.91/224.79	
Optimal locations and sizes (kVAr)	61	1123	46	781	57	1200	N/A	N/A	19	225
	64	207	47	803	58	274			62	900
			50	479	61	200			63	225
Total kVAr	1330		2063		1674				1350	
Minimum voltage (pu)	N/A		N/A		N/A		0.93693/0.90919	0.9289/0.9092	0.9289/0.9092	
CPU time (s)	N/A		N/A		N/A		N/A	N/A	4.471	

[a] Slight differences in load and line data.
[b] Same load and line data as in [20,23,24,25,26,27,21,28,20,29].

Table 5
Improved results for the 34-Bus System.

System	Losses before compensation (kW) and min voltage (pu)	Capacitor location (node)	Capacitor size (kVAr)	Losses after compensation (kW) and min voltage (pu)	Power loss reduction (%)	Money saving (k$/yr)	CPU time (s)
34 Node	221.6750.9417	9, 19 and 26	400 + 1000 + 800 = 2200	162.6360.9505	26.63	32.013	3.256

in the first stage [20] followed by optimal capacitor allocation as a second stage. Simulation, using GA are applied to this feeder to detect power loss reduction achieved only from capacitor placement. For the 85 node feeder a slight movement of one capacitor location was sufficient to reach optimal capacitor allocation. The two stage technique is applicable also to the 85 node feeder.

3. Algorithm

The computational steps involved in finding the optimal capacitor size and location to minimize the loss in a radial distribution system are summarized in following:

1. Run the load flow program [21] and obtain the base case losses. Select a node and find the loss saving from Eq. (4) for the special case of singly located capacitor. Repeat this step for all Nodes in the system, except the source node. Identify the nodes that provides the highest loss saving.
2. Compensate two nodes to get the highest loss saving with the corresponding capacitors found from Eq. (11).
3. Repeat step 2 with three compensated nodes until it is found that no significant loss saving can be achieved by further capacitor placement.
4. If no solution is obtained due to the peculiar capacitor locations, apply the two stage solution method: feeder reconfiguration [20] then optimal capacitor allocation (steps 1–3). Perform simulation using genetic algorithm for the two (28 and 85 nodes) systems having peculiar capacitor locations. This allows detection of loss reduction and voltage improvement solely due to capacitor placement.

4. Simulation results

The *PM* of loss reduction by capacitor placement was tested on several distribution systems and results are given in Table 1. The table presents the corresponding $-saving besides voltage improvement and *CPU* time requirements. Maximum power loss reduction was achieved, with two nodes compensated simultaneously for all investigated feeders. A third capacitor produces slight increase in loss reduction and money saving. However the voltage profile is not as good as with two capacitors in some cases as presented in Fig. 3 for the 15 node feeder. Better voltage profile can be achieved by placing more capacitors in other cases as for the 34 node feeder however this is associated power loss rise. Colored areas in the table are the final optimum solution taking into consideration that extra third/fourth capacitor increases maintenance burden. The shunt capacitors also improve the voltage profile and due to the higher voltage the active component of branch current $\boldsymbol{I_a}$ and hence active power loss for the constant power load model, is also reduced slightly. The voltage profiles along the feeders with multiple capacitor allocation are considerably improved as presented in Fig. 4 for the 15 node feeder. Capacitor locations in 28 node feeder are at nodes 7 and 17. The upstream paths from these nodes are the same resulting in close to singular $[\boldsymbol{A}]^{-1}$ matrix and the solution of Eq. (10) may be inaccurate. In 85 node feeder the capacitor locations are at nodes 9 and 25. The upstream paths from these nodes are the same resulting in singular $[\boldsymbol{A}]^{-1}$ matrix and no solution obtained. For the 28 node feeder the two stage capacitor allocation technique: a reconfiguration of the feeder in the first stage [20] followed by optimal capacitor allocation as a second stage, is applied. Table 2 presents optimal power-loss in each loop, tie-switch closed and sectionalize-switches open as a result of feeder reconfiguration. Simulations, using GA are conducted for this feeder to detect of loss reduction and voltage improvement solely due to capacitor placement. For the 85 node feeder a slight movement of the second capacitor location from node #25 to node #26 was sufficient to reach optimal capacitor allocation. The corresponding results of optimal capacitor allocation for these two feeders are presented in Table 3. The two stage technique is also applicable to the 85 node feeder. It awaits optimum allocation of tie switches. Comparisons of the results of *PM* as applied on the 33-Bus System with those in [22,23], on the 34-Bus System with those in [9,22–30] and on the 69-Bus System with those in [23,26,29,31,32] are detailed in Table 4a–c, respectively. Better or closed results are obtained. Multitude of simulations conducted allows author to declare the following main points affecting optimal capacitor allocation are:

Selection the candidate locations of capacitor: Loss Sensitivity Factor and Index Vector and also fuzzy expert system has been used for extracting suitability of capacitor location from power loss reduction index and voltage profile. Capacitor locations given by three methods are not same and the sizes are also different in the methods.

Bounds of capacitor size selection: Relatively high capacitor steps within declared bound allow higher power loss reduction and better improvement in voltage profiles. Suitable bound of capacitor size, satisfying the constraint limit and also giving best possible result could only be found out by trial and error, which is extremely difficult task.

The 34-Bus System has been subjected to further investigations to satisfy Reviewer‘s comments. Results in the manuscripts were obtained allowing 25:25:3000 kVAr capacitors for the program to choose from. Now a test is conducted allowing 300:100:3000 kVAr capacitors for the program to choose from. Higher loss reduction and better voltage profile are obtained and detailed in Table 5.

5. Conclusions

A simple method of minimizing the loss associated with the reactive component of branch currents by placing capacitors in a radial distribution system has been proposed. The method first finds a sequence of nodes to be compensated through finding the highest loss saving by a singly located capacitor. The optimal size of multiple capacitors is then determined simultaneously by minimizing the loss saving equation with respect to the capacitor currents. A two stage optimal capacitor allocation is proposed when the capacitor locations hinder the problem solution. A reconfiguration of the feeder in the first stage followed by optimal capacitor allocation as a second stage resulted in problem solution. Simulations, using *GA* are conducted allowing detection of loss reduction and voltage improvement solely due to capacitor placement. Examples on several distribution networks show the robustness which indicates the method as an appealing alternative to utilities interested in planning radial distribution networks.

References

[1] H.N. Ng, M.M.A. Salama, A.Y. Chikhani, Classification of capacitor allocation techniques, IEEE Transactions on Power Delivery 15 (January (1)) (2000) 387–392.

[2] R.S. Aguiar, P. Cuervo, Capacitor placement in radial distribution networks through a deterministic optimization model, in: 15th PSCC, Liege (22–26 August), Session 6, Paper 5, 2005, pp. 1–7.

[3] I.C. da Silva Jr., S. Carneiro Jr., E.J. de Oliveira, J. de Souza Costa, J.L.R. Pereira, P.A.N. Garcia, A heuristic constructive algorithm for capacitor placement on distribution systems, IEEE Transactions on Power Systems 23 (November (4)) (2008) 1619–1626.

[4] M. Chis, M.M.A. Salama, S. Jayaram, Capacitor placement is distribution systems using heuristic search strategies, IEE Proceedings – C Generation Transmission and Distribution 144 (3) (1997) 225–230.

[5] R. Horacio Diaz, V. Ildefonso Harnisch, H. Raul Sanhueza, R. Romina Olivares, Feeder reconfiguration and capacitor placement in distribution systems: an approach for simultaneous solution using a genetic algorithm, Ingeniare, Revista chilena de ingenieria 18 (1) (2010) 144–153.

[6] S. Sundharaajan, A. Pahwa, Optimal selection of capacitors for radial distribution systems using genetic algorithm, IEEE Transactions on Power Systems 9 (3) (1994) 1499–1507.

[7] C.-T. Su, C.-S. Lee, Feeder reconfiguration and capacitor setting for loss reduction of distribution systems, Electric Power Systems Research 58 (2001) 97–102.

[8] J.R.P.R. Laframboise, G. Ferland, A.Y. Chikhani, M.M.A. Salama, An expert system for reactive power control of a distribution system—Part 2: system implementation, IEEE Transactions on Power Systems 10 (August (3)) (1995) 1433–1441.

[9] H.N. Ng, M.M.A. Salama, A.Y. Chikhani, Capacitor allocation by approximate reasoning: fuzzy capacitor placement, IEEE Transactions on Power Delivery 15 (January (1)) (2000) 393–398.

[10] Md. Sheeraz kirmani, F. Rahman, C. Kumar, Loss reduction in distribution system using fuzzy techniques, International Journal of Advanced Computer Science and Applications (IJACSA) 15 (September (3)) (2010) 15–19.

[11] G.A. Bortignon, M.E. El-Hawary, A review of capacitor placement techniques for loss reduction in primary feeders on distribution systems, in: Canadian Conference on Electrical and Computer Engineering, vol. 2, 1995, pp. 684–687.

[12] M.H. Haque, Capacitor placement in radial distribution systems for loss reduction, IEE Proceedings – C Generation Transmission and Distribution 146 (September (5)) (1999) 501–505.

[13] S.F. Mekhamer, S.A. Soliman, M.A. Moustafa, M.E. El-Hawary, Application of fuzzy logic for reactive power compensation of radial distribution feeders, IEEE Transactions on Power Systems 18 (February (1)) (2003) 206–213.

[14] K.V.S. Ramachandra, M. Murthy Ramalinga Raju, G. Govinda Rao, K. Narasimha Rao, Comparison of loss sensitivity factor & index vector methods in determining optimal capacitor locations in agricultural distribution, in: 16th National Power Systems Conference 15th–17th December, 2010.

[15] S. Rao, S.V.L. Narasimham, Optimal capacitor placement in a radial distribution system using plant growth simulation algorithm, Proceedings of World Academy of Science, Engineering and Technology 35 (2008) 716–723.

[16] Y.-T. Hsiao, C.-H. Chen, C.-C. Chien, Optimal capacitor placement in distribution systems using a combination fuzzy-GA method, Electrical Power and Energy Systems 26 (2004) 501–508.

[17] D. Das, Optimal placement of capacitors in radial distribution system using a fuzzy-GA method, Electrical Power and Energy Systems 30 (2008) 361–367.

[18] D. Das, D.P. KothariI, A. Kalam, Simple and efficient method for load flow solution of radial distribution systems, Electrical Power and Energy Systems 17 (5) (1995) 335–346.

[19] R.M. Saloman Danaraj, S.F. Kodad, T. Ram Das, An algorithm for radial distribution power flow in complex mode including voltage controlled buses, Indian Journal of Science and Technology 1 (December (2)) (2007) 1–5.

[20] A.R. Abul'Wafa, A new heuristic approach for optimal reconfiguration in distribution systems, Electric Power Systems Research 81 (2011) 282–289.

[21] A.R. Abul'Wafa, A network-topology-based load flow for radial distribution networks with composite and exponential load, Electric Power Systems Research 91 (2012) 37–43.

[22] K.S. Swarup, Genetic algorithm for optimal capacitor allocation in radial distribution systems, in: Proceedings of the 6th WSEAS Int. Conf. on Evolutionary Computing, Lisbon, Portugal, June 16–18, 2005, pp. 152–159.

[23] A. Kartikeya Sarma, K. Mahammad Rafi, Optimal selection of capacitors for radial distribution systems using plant growth simulation algorithm, International Journal of Advanced Science and Technology 30 (May) (2011) 43–54.

[24] M. Chis, M.M.A. Salama, S. Jayaram, Capacitor placement in distribution system using heuristic search strategies, IEE Proceedings – C Generation Transmission and Distribution 144 (May (3)) (1997) 225–230.

[25] M.D. Reddy, V. Reddy, Optimal capacitor placement using fuzzy and real coded genetic algorithm for maximum savings, Journal of Theoretical and Applied Information Technology, JATIT 4 (3) (2008) 219–226.

[26] K. Prakash, M. Sydulu, Particle swarm optimization based capacitor placement on radial distribution systems, in: IEEE Power Engineering Society General Meeting, 2007, pp. 1–5.

[27] R.S. Rao, S.V.L. Narasimham, Optimal capacitor placement in a radial distribution system using plant growth simulation algorithm, International Journal of Electrical and Electronics Engineering 2 (10) (2008) 651–658.

[28] A. Elmaouhab, M. Boudour, R. Gueddouche, New evolutionary technique for optimization shunt capacitors in distribution networks, Journal of Electrical Engineering 62 (3) (2011) 163–167.

[29] M. Damodar Reddy, N.V. Vijaya Kumar, Optimal capacitor placement for loss reduction in distribution systems using fuzzy and harmony search algorithm, ARPN Journal of Engineering and Applied Sciences 7 (January (1)) (2012) 15–19.

[30] A. Kartikeya Sarma, K. Mahammad Rafi, Optimal capacitor placement in radial distribution systems using artificial bee colony (ABC) algorithm, Innovative Systems Design and Engineering 2 (4) (2011) 177–185.

[31] D. Das, Optimal placement of capacitors in radial distribution systems using a fuzzy-GA method, Electrical Power and Energy Systems 30 (2008) 361–367.

[32] P.V. Prasad, S. Sivanagaraju, N. Sreenivasulu, A fuzzy-genetic algorithm for optimal capacitor placement in radial distribution system, ARPN Journal of Engineering and Applied Sciences 2 (June (3)) (2007) 28–32.

Ahmed Rizk Abul'Wafa received his Ph.D. in 1969 from Moscow power institute. He is currently professor with Faculty of Engineering, Ain-Shams University. He is author of papers on power system analysis, renewable energy, distribution system automation and reliability. He is a member of CIGRE and head of Wafa Consulting Engineers.