Engineering Innovations
ISSN: 2813-1002, Vol. 9, pp 31-38
doi:10.4028/p-5yiHYg

Submitted: 2023-08-27
Revised: 2023-11-18
Accepted: 2023-11-24
Online: 2024-02-12

Optimal Location of Capacitor in a Radial Distribution System Using New Hybrid Method

Hassane OUSSEYNI IBRAHIM[1,a*], Arouna OLOULADE[2,b], Moussa GONDA[1,c] and Francois-Xavier FIFATIN [2,d]

[1]University Institute of Technology, University Dan Dicko Dankoulodo, of Maradi, BP 465. Maradi, Niger

[2]Polytechnic School of Abomey-Calavi (EPAC), University of Abomey-Calavi, BP 123. Cotonou, Benin

[a]hassane2025@yayoo.fr, [b]olouarou@yahoo.fr, [c]ahmad.nai2011@gmail.com, [d]fifatinf@gmail.com

Keywords: Reactive power compensation; Capacitors; Radial distribution network; Compensator placement; Optimal position

Abstract. Reactive power compensation in the electricity system helps maintain transmission and distribution performance. This can be done by compensator placement; if reactive power is not properly managed, there is a risk of multiplying network losses, overloading facilities and generating unacceptable and unstable voltage levels. This paper solves the problem of optimal position of capacitors in radial distribution network using a new hybrid method combining a new stability index and a genetic algorithm to improve the loss and voltage stability. The Bus Voltage Stability Index BVSI is used to determine the locations and the genetic algorithm GA to calculate the size. The GA-BVSI analytical-metaheuristic method, compared with existing methods, is more suitable and recommended for operators who are faced with the problem of sizing capacitors to improve the technical performance of their network.

1. Introduction

Voltage is regulated on the radial distribution network by means of load tap changers (LTC) in HV/MV source substations, the placement of capacitors in distribution substations, the positioning of flexible alternating current transmission systems (FACTS), and so on. In view of the rapid growth in loads on electrical installations, some of the above-mentioned devices are proving to be slow and ineffective in monitoring changes in these loads and dynamically adjusting voltage. For example, LTC are made up of coils positioned on the primary windings of transformers in HV/MV source substations. Their role is to modify the transformation ratio to improve the secondary voltage if the load changes. the transition from one turn to another is always accompanied by electric arcs, which are the cause of certain equipment failures recorded on these types of transformers. In the event of rapid load growth, the controllers freeze and are no longer able to adjust effectively to correct the impact of load growth. Capacitors placed in HV/MV source substations or in MV/LV distribution substations, with the aim of providing reactive power to compensate for the overall network, do not effectively and sustainably improve the technical performance of electricity networks. These empirical methods of capacitor positioning do not demonstrate their effectiveness. Consequently, the reagent must be supplied locally and optimally to the consumer loads by reconfiguring the shunt capacitors. The positioning and operating costs of FACTS devices in networks raise issues that need to be studied in order to highlight their technical contribution and profitability in terms of their application in distribution networks. There are several methods in the literature for solving these problems. The effectiveness obtained varies from one method to another. This paper will study the optimal positioning of capacitors, using a new hybrid method, to improve the technical performance of the radial distribution system. There are many different algorithms for placing capacitors in distribution systems [1]. The total number of publications specific to capacitor allocation problems is close to 400 [2,3]. The methods developed include analytical methods, numerical programming, heuristic methods, metaheuristic methods based on artificial intelligence and a combination of techniques [4]. These latest have become attractive in power system optimisation techniques, and in most cases combine a stability index and a metaheuristic.

2. Problem Formulation for Optimal Capacitor Sizing

The aim of installing capacitors in distribution networks is to improve the technical and environmental reliability of the power system. This problem is formulated as that of a multi-objective function with several criteria and constraints, including the stability index, the cost of lost energy, the voltage at the nodes, the current in the branches, and so on. The optimisation criteria and constraints are described below:

2.1. Bus voltage stability index

BVSI, a new concept defined in reference [5], BVSI is used to designate candidate buses for capacitor placement. The exploration zone and the optimisation process are considerably reduced

$$\mathrm{BVSI} = \frac{3V_{i+1} - V_i}{2V_{i+1}} \tag{1}$$

The nodes with the lowest BVSI will be given priority as candidates for the installation of compensation devices.

2.2. Objective function

The proposed objective function for the optimal capacitor placement problem is to minimize the total cost, which is determined by the following equation:

$$F = \left[K_e\,(T * P_{T.loss}) + K_T\left(COST_{X_{year}}\right)\right] * \left(\prod_{j=1}^{NL} OC * \prod_{j=1}^{NB} OV\right) \tag{2}$$

Where X represents the device used, which may be a capacitor or other compensator. In this paper we will use capacitors, the annual cost of which is taken from reference [6].

$$COST_{Capacitor_{year}} = (K_I + K_O) * NBC + K_C * \sum_{i}^{NBC} Q_C(i) \tag{3}$$

2.3. Contraints

- Voltage Deviation Limit [6]:

$$OV = \begin{cases} 1; & \text{if } 0.9\text{ pu} \le V_b \le 1.1\text{ pu} \\ \exp(\mu|1 - V_b|); & \text{otherwise} \end{cases} \tag{4}$$

- Line Current Limits [7]:

$$OC = \begin{cases} 1; & \text{if } J \le J_{max} \\ \exp\left(\lambda\left|1 - \frac{J}{J_{max}}\right|\right); & \text{if } J > J_{max} \end{cases} \tag{5}$$

- Reactive power compensation

It is impossible for the capacitor to remain connected, as the reactive power is not only proportional to the square of the voltage at its terminals, but will also be injected constantly even in normal operation, leading to a risk of overcompensation, unacceptable voltage amplitude or premature collapse of the system voltage. To limit these inconveniences, the constraints on the total reactive power injected and the overall power factor of the system will be defined as follows [8]:

$$Q_{capacitor}^{min} \le Q_{capacitor}^{KVAr} \le Q_{capacitor}^{max}, \text{ with step of 50 KVAr} \tag{6}$$

$$\sum_{i=1}^{NBC} Q_{capacitor}^{KVAr}(i) \le \sum_{j=1}^{NB} Q^{KVAr}(j) \tag{7}$$

$$PF_{min} \le PF \le PF_{max} \tag{8}$$

2.4. Net savings

The net savings is the difference between total energy loss cost before installation and total energy loss cost and annual capacitor after installation is given by Eq. (9) as follows:

$$\text{Net savings} = K_e\,(T * P_{T.loss}) - K_e\left(T * P_{T,loss}^{\text{With capacitor}}\right) - COST_{Capacitor_{year}} \tag{9}$$

3. Load Flow

Backward/forward sweep load flow, proposed by Jen-Hao Teng [9], is developed on the Matlab platform for calculating the load flow and the BVSI stability index of the various nodes.
Calculation of current injections at the different nodes as follows:

$$\overline{I_i} = \left(\frac{S_i}{V_i}\right)^* \tag{10}$$

Calculation of branch currents by:

$$[J] = [BIBC].[I] \tag{11}$$

Calculation of the voltage drops in each branch by:

$$[\Delta V^{k+1}] = [BCBV].[J] \tag{12}$$

Calculation of new nodal voltages, $[V^{k+1}]$ by:

$$[V^{k+1}] = [V^0] - [\Delta V^{k+1}] \tag{13}$$

Calculate the BVSI at each node, by:

$$BVSI = \frac{3V_{i+1} - V_i}{2V_{i+1}} \tag{14}$$

Calculate total active loss:

$$P_{T.loss} = \sum_{i=1}^{nl} P_{loss,i} = \sum_{i=1}^{nl} R_i * |J_i|^2 \tag{15}$$

Calculate total reactive loss:

$$Q_{T.loss} = \sum_{i=1}^{nl} Q_{loss,i} = \sum_{i=1}^{nl} X_i * |J_i|^2 \tag{16}$$

4. Hybrid Approach GA-BVSI

The contextualised genetic algorithm is used to optimally size the capacitor. The positions of these capacitors on the network are identified using the BVSI concept designed for this purpose. This hybrid approach consists of creating a population of N chains around the nodes identified by the BVSI so that GA starts in an ideal zone in the solution space. The individuals in the population created are evaluated by calling up the objective function. The best individuals are then selected (roulette) in pairs to reproduce a generation of individuals by running the crossover and mutation operators with a probability of (0.8) and (0.3) respectively, which will be reassessed for the next generation. In this way, the evolutionary loop is repeated until the natural goal is reached. Based on the approximation and research carried out, the pseudo-code and GA-BVSI flowchart in figure 1, for this new approach to optimise the capacitor positioning process are presented below.

Pseudo-code GA-BVSI for compensator placement
Inputs: Distribution system data; The objective function Number of generations (n) Constraint limits **Outputs:** Best population; **1 Run** the BIBC load flow;

2 Identify candidate buses for capacitor placement using BVSI;
3 Randomly generate the initial population from the group of BVSI buses identified;
4 i ← 0
5 While i < n AND stop condition not satisfied **Do**
6 Evaluate each individual in the population according to the objective function;
7 Select parents from the selected population;
8 Produce and evaluate the offspring of parents selected by crossover and mutation;
9 Replacing parents with offspring;
10 i ← i + 1
End
11 Return the best population.

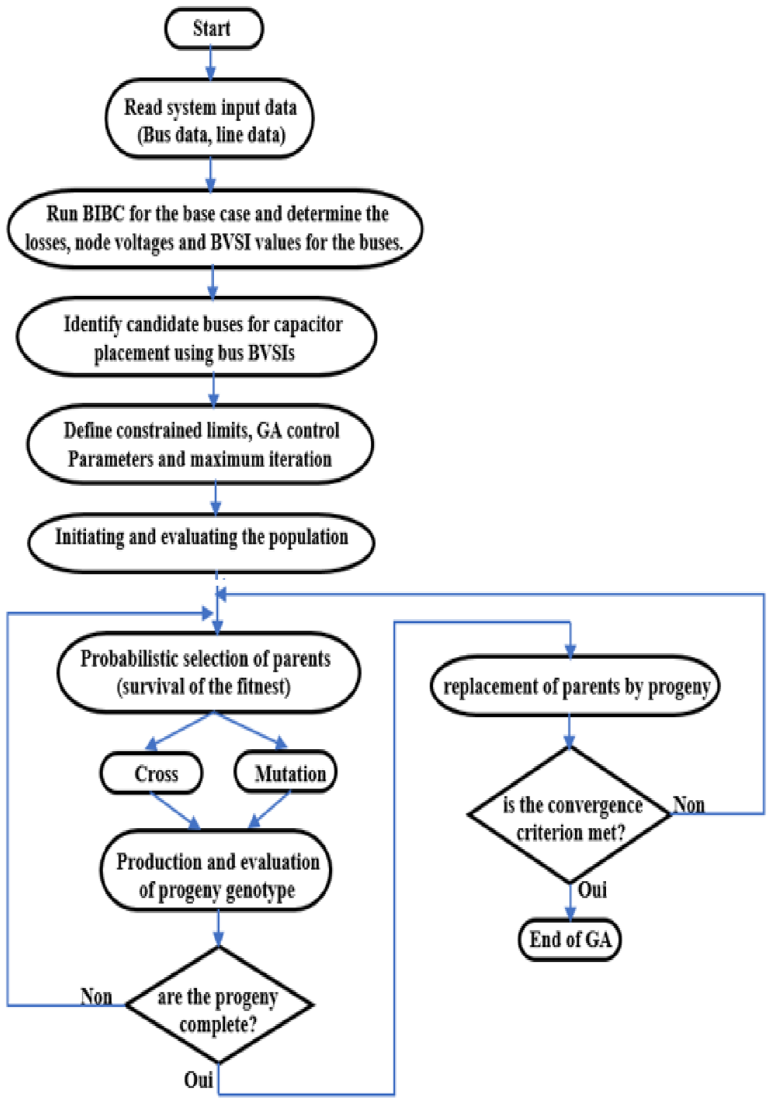

Fig. 1. Flow chart of GA-BVSI.

5. Results and Discussion

The superiority of the GA proposed with BVSI is implemented with the IEEE 69-bus test system shown in figure 2. This network comprises 69 buses and 68 branches with a total active and reactive load of 3.80 MW and 2.69 MVAr respectively. The average operating voltage of the network is 12.66 kV. The line and bus parameters are taken from reference [10]. The proposed hybrid algorithm was created using Matlab. The initial active and reactive power losses without compensator are 224.8949 kW and 101.7 kVAr respectively. The minimum voltage is 0.9092 p.u at node 65. Table 1 shows the results of this positioning optimisation compared with references [11], [12] and [13]. It is observed that the total capacitor size evaluated by the proposed GA BVSI method is 1550 kVAr partitioned at node 61 (1250 KVAr) and node 17 (300 KVAr). This size is the smallest and the most optimal to reduce to the lowest value the total cost due to the proposed objective function, i.e. 84250.4 $ compared to the values obtained by the aforementioned references. Similarly, the percentage of net savings with GA-BVSI is the highest compared with the other techniques, at 28.72%. Network losses fell from 224.8949 kW in the initial case to 146.5 kW after compensation, a reduction of 34.85%. In addition, the minimum voltage has been improved from 0.9092 p.u. to 0.9306 p.u. and the maximum current reduced from 386.2727 A to 327.3817 A. Note that in reference [12], using PLI, the authors have evaluated a larger capacitor size of 1650 KVAr partitioned over 5 nodes, the losses are reduced to 146.13 kW and the minimum voltage improved to 0.9327 p.u. However, these differences are relatively insignificant and we can deduce from them the reliability and performance of the GA-BVSI. The system voltage profile is shown in Figure 3 using the installed capacitors. Table 2 shows the settings of the objective function for optimization.

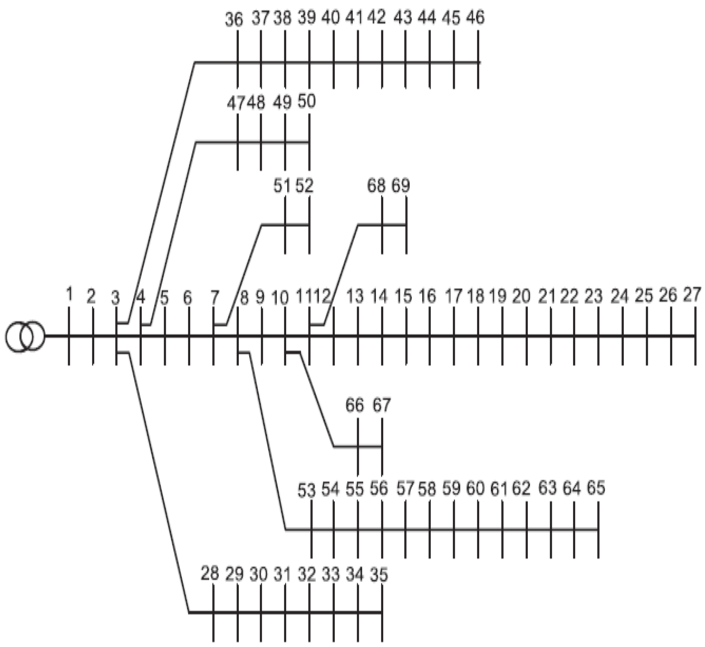

Fig. 2. Single-line diagram of an IEEE standard 69-bus network

Table 1. Results for optimal placement of capacitors on a 69-bus system

Items	Un-compensated	Compensated				
		Fuzzy-GA [11]	DE-LSF [12]	PSO- LSF[13]	DE-PLI [12]	**GA-BVSI**
Total losses (kW)	224.8949	156.62	151.3763	152.48	146.13	146.5
Loss reduction (%)	-	30.4	32.7	32.2	35.02	34.85
Minimum voltage	0.9092	0.9369	0.9311	-	0.9327	0.9306
Maximum Current (A):	386.2727	-	-	-	-	327.3817
Optimal location		59 100	57 150	46 241	61 950	61 1250
and size in kVAr		61 700	58 50	47 365	64 200	17 300
		64 800	61 1000	50 1015	59 150	- -
		- -	60 150	- -	65 50	- -
		- -	59 100	- -	21 300	- -
Total kVAr		1600	1450	1621	1650	1550
Annual cost($/year)	118,204.8	90119.5	88913.4	88606.5	86758.8	84250.4
Net saving ($/year)	-	28085.3	29291.4	29598.3	31446	33954.4
% saving	-	23.8	24.78	25.03	26.6	28.72

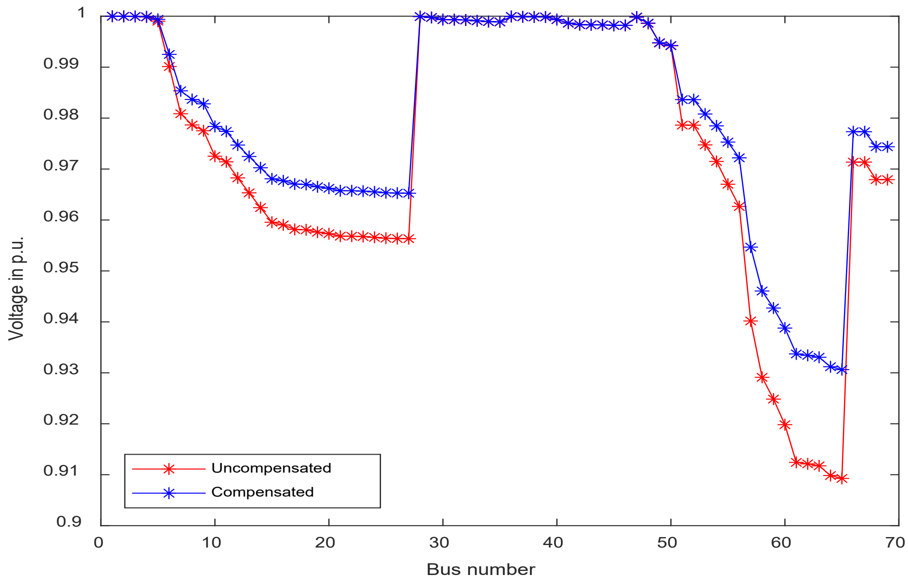

Fig. 3. Voltage profiles of the 69-bus system before and after compensation

Table 2. Objective function parameter settings for optimization

Item	Proposed setting
Number of generations	150
Number of individuals per population	750
Percentage of crossover	0.8
Percentage of mutation	0.3
J_{max}	520A
K_I	\$1000/location
K_O	\$300/year/location
K_c	\$ 3/kVAr
K_T	1
K_e	\$0.06/kWh
PF_{min}	0.9
PF_{max}	1
T	8760 h
μ	1
λ	2

6. Conclusions

The GA-BVSI hybrid method has been developed for the optimum positioning of capacitors in a radial distribution system. Given its accessibility, technical performance and ability to identify weak points in an electrical system, its use can be strongly recommended to distribution network operators. This scientific contribution will provide electricity companies with practical solutions, in particular the reconfiguration of capacitor positioning. Optimal placement and sizing of a shunt capacitor increases voltage stability, and the positioning of multi-capacitors is not expensive. Shunt capacitors are relatively inexpensive and easy to install and maintain. However, they have less function and control over network parameters and have major inconveniences.
In addition, the GA-BVSI analytical-metaheuristic method can be used to optimise the placement of FACTS devices.

Nomenclature

$COST_{X_{year}}$	annual cost of X
K_I	cost rate of capacitor installation/location
K_O	yearly operating cost of capacitors/location
K_c	purchase cost of capacitor

HV	High Voltage
J_{max}	maximum current that can flow in the Network lines
KT	time duration proportion
K_e	average energy cost
LV	Low Voltage
MV	Medium Voltage
NBC	The number of compensated buses
NB	The number of total buses
NL	The number of total lines
OC	line over current factor
OV	voltage stability index for buses
PFmin	The minimum power factor
PFmax	The maximum power factor
PF	Power Factor
$P_{T.loss}$	The total power losses after compensation
$P_{T,loss}^{With\ capacitor}$	total power loss after installation of capacitor
$Q_{capacitor}^{min}$	lower reactive power limit of compensated bus i
$Q_{capacitor}^{max}$	upper reactive power limit of Compensated bus i
$Q_C(i)$	amount of reactive power of installed Capacitors at bus i
$Q^{KVAr}(j)$	reactive power demand of load at bus j
T	hours per year
V_{i+1}	voltage magnitude at bus i+1
V_i	voltage magnitude at bus i
μ	small positive constant
λ	small positive constant

Acknowledgement

The authors gratefully acknowledge the reviewers of this paper for their valuable advice and guidance. This research has not been funded in any way.

Competing Interests

Authors have declared that no competing interests exist.

Ethical Approval (not applicable**)**

Availability of Data and Materials
The simulations were carried out with Matlab R2021a.

References

[1] A. K. Bhargava, M Rani, Sweta, Optimal sizing and placement of capacitor on radial distribution system using genetic algorithm, Materials Today: Proceedings, 2023, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2023.03.347

[2] Capacitor Subcommittee of the IEEE Transmission and Distribution Committee, «Bibliography on power capacitors 1975–1980», IEEE Trans. Power Apparatus and Systems, vol. 102, nº 7, p. 2331-2334, juill. 1983.

[3] IEEE VAR Management Working Group of the IEEE System Control Subcommittee, «Bibliography on reactive power and voltage control », IEEE Trans. Power Systems, vol. 2, nº 2, p. 361-370, mai 1997.

[4] H. N. Ng, M. M. A. Salama, et A. Y. Chikhani, « Classification of capacitor allocation techniques », IEEE Transactions on Power Delivery, vol. 15, nº 1, p. 387-392, janv. 2000, doi: doi: 10.1109/61.847278.

[5] H. O. Ibrahim, F. -X. Fifatin, A. Oloulade, A. M. Imano and A. K. Vianou, "Positioning of multicapacitors in a radial distribution network using new analytical methods," 2021 International Conference on Electrical, Computer and Energy Technologies (ICECET), 2021, pp. 1-6, doi: 10.1109/ICECET52533.2021.9698665.

[6] Y. Abdelaziz, E.S. Ali, S.M. Abd Elazim, Optimal sizing and locations of capacitors in radial distribution systems via flower pollination optimization algorithm and power loss index, Engineering Science and Technology, an International Journal, Volume 19, Issue 1, 2016, Pages 610-618, ISSN 2215-0986, https://doi.org/10.1016/j.jestch.2015.09.002.

[7] Saravanan M, Slochanal SMR, Venkatesh P, Abraham JPS. Application of particle swarm optimization technique for optimal location of FACTS devices considering cost of installation and system loadability. Electr Power Syst Res 2007; 77 (3–4): 276–83.

[8] Tahir MJ, Rasheed MB, Rahmat MK. Optimal Placement of Capacitors in Radial Distribution Grids via Enhanced Modified Particle Swarm Optimization. Energies. 2022; 15(7):2452. https://doi.org/10.3390/en15072452

[9] T. Jen-Hao, «A direct approach for distribution system load flow solutions», IEEE Transactions on Power Delivery, vol. 18, nº 3, p. 882-887, juill. 2003, doi: 10.1109/TPWRD. 2003.813818.

[10] S. A. Taher et S. A. Afsari, «Optimal location and sizing of DSTATCOM in distribution systems by immune algorithm», International Journal of Electrical Power & Energy Systems, vol. 60, p. 34-44, 2014.

[11] D. Das, Optimal placement of capacitors in radial distribution system using a Fuzzy–GA method, Int. J. Electr. Power Energy Syst. 30 (2008) 361–367.

[12] A. Elfergany, Optimal capacitor allocations using evolutionary algorithm, IET Proc. Generation Transm. Distrib. 7 (2013) 593–601.

[13] K. Prakash, M. Sydulu, Particle swarm optimization based capacitor placement on radial distribution systems, IEEE Power Engineering Society General Meeting, 24–28 June 2007, pp.1–5, 2007.