

Research Article

Optimal Capacitor Placement in the Unbalanced Distribution Networks Contaminated by Harmonic through Imperialist Competitive Algorithm

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Abstract: This study presents a new approach in order to determine the optimal location and size of capacitors in unbalance distribution systems including harmonic loads for reduction of power losses, improvement of voltage profile and release of system capacity. Achieving such benefits is dependent to the quality of optimal capacitor installation. Capacitor placement is a nonlinear problem including equal and unequal constraints. In our study, the Imperialist Competitive Algorithm (ICA) method has been used for solving optimal capacitor harmonic contaminations problem. The results obtained for IEEE standard unbalanced 26-bus system including the nonlinear loads show proposed method applicability and good performance.

Keywords: Capacitor placement, harmonic distortion, Imperialist Competitive Algorithm (ICA), unbalanced network

INTRODUCTION

The studies show that almost 13% of power generated in the distribution systems is spent for power losses. On the other side, upon increase of load demand, the voltage profile is dropped along the distribution feeders and placed below the acceptable range. Considering the power losses and voltage drop and increase of electricity demand, restructuring is required. The parallel capacitors may aid the improvement of distribution systems function intensively (Abdel-Salam *et al.*, 1994). The distribution systems are unbalanced inherently due to several reasons; firstly the distribution systems supply the single phase and three phase loads by means of transformers; secondly transmission lines phases not include the equal Loads; thirdly the over head distribution systems have not been displaced similar to the transmission lines, therefore the capacitor size and location shall be determined according to the load value and topology of each phase. Due to expanding the use of harmonic generating equipments in the distribution systems and its inappropriate impacts such as losses and resonance, the significance of this subject is revealed in the capacitor placement. Plenty of optimization methods have been explained for capacitor placement so far. In the most mentioned cases, the capacitor placement has been applied for the balanced distribution networks including the linear Loads, in

references (Hooshmand and Ataei, 2007; Dlfanti *et al.*, 2000; Sundharajan and Pahwa, 1994). Genetic algorithm has been used for solving the problem. In Huang *et al.* (2008) and Su and Tsai (1996), immune algorithm has been used for capacitor placement. In references (Bhattacharya and Goswami, 2009; Su and Tsai, 1996; Das, 2008), the combination of fuzzy logics to revolutionary optimization methods has been used. In (Eajal and El-Hawary, 2010; Rao and Narasimham, 2009) particle swarm optimization algorithm has been used. In the most studies applied on capacitor placement, the studied systems were balanced whilst in this study, the unbalanced distribution system has been analyzed considering the mutual inductance. As well as, the inappropriate impacts of harmonic contaminations have been noticed. To solve the capacitor placement problem, imperialist competitive algorithm is used that is a new and powerful optimization algorithm. This algorithm is coded in binary form and by its optimization process avoids placing in the local minimum instead of total minimum, as well as upraises the optimization speed. The objective functions applied in the problem include the cost of all power loses and capacitor placement energy and cost, and voltage range and maximum harmonic distortion have been assumed as constraint. The method presented in this study has been applied on the unbalanced 26-bus system including harmonic loads.

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DEFINITION OF PROBLEM

In capacitor placement problem, the suitable place for capacitor installation and optimal size of capacitors in the selected buses are noticed that includes equal and unequal constraints and raised as below:

Objective functions: The objective function in capacitor placement problem includes reduction of losses cost of studied system as well as minimizing the capacitor banks cost considering the voltage constraints and harmonic contaminations. The objective function is defined as follows:

- **Total active power losses:** The first objective function includes reducing the active power losses of a distribution system that includes two fundamental and harmonic elements (Eajal and El-Hawary, 2010) which is explained as the following equation:

$$f_1 = \sum_{i=1}^{nb} Ploss_i^{(1)} + \sum_{i=1}^{nb} \sum_{h=h_0}^{h_{max}} Ploss_i^{(h)} \quad (1)$$

Nb = The number of network branches
 Ploss_i^h, Ploss_i = The losses of fundamental and harmonic frequency
 h₀, h_{max} = The minimum and maximum harmonic order

- **Cost of capacitor placement:** The other purpose of minimization is capacitor placement cost that is explained as below:

$$f_2 = \sum_{j=1}^{nc} k_c \cdot Q_j \quad (2)$$

In this equation, Q_j is the cost of capacitor i and k_c the annual reactive power injection cost.

- **Minimizing the voltage deviation:** In this objective function, the buses voltage deviation is reduced from the specified value of 1pu that is explained as below:

$$f_3 = \sum_{i=1}^{nb} (V_n - V_{rated})^2 \quad (3)$$

- **Cost function:** The total objective function or cost function is sum total of costs due to losses and capacitor placement that is explained as below:

$$F = k_p \cdot f_1 + f_2 + k_v \cdot f_3 \quad (4)$$

K_p: The annual cost for per KW of power losses and K_v the penalty factor for minimizing the voltage deviation.

Problem constraints: The capacitor placement problem includes equal and unequal constraints as follows.

Voltage constraint: The total effective voltage for each bus including the fundamental and harmonic elements should be placed within the acceptable range of maximum V_{max} and minimum V_{min}. This acceptable range is explained according to standard IEEE-519 (Masoum *et al.*, 2004). There in V_{max} = 1.1 pu and V_{min} = 0.9 pu.:

$$V_{min} \leq \sqrt[2]{\sum_h (V_i^h)^2} \leq V_{max} \quad (5)$$

- **Constraint of total harmonic distortions:** The total harmonic distortions of each bus should be lower or equal to the acceptable value of harmonic levels:

$$THD_{v,i} = \left(\frac{\sqrt[2]{\sum_{h=1}^{\infty} (V_i^h)^2}}{V_i^1} \right) \cdot 100\% \leq THD_{v,i}^{max} \quad (6)$$

- **Number of constraints and capacitors size:** The parallel capacitors in the industry are available discretely. The parallel capacitors are achieved as the integer multiple of the available lowest capacitor capacity:

$$Q_{ci} = L \cdot Q_0 \quad (7)$$

Q₀: The smallest capacitor capacity, on the other side, because of economic problems and limitation of installation area, total capacity of capacitors available in per bus should not exceed an acceptable range:

$$\sum_{i=1}^{nc} Q_{ci} \leq Q_T \quad (8)$$

Q_T: Acceptable range of reactive power

In this study, the smallest capacitor capacity is 150 KVar and acceptable number of capacitor in each bus is 15.

Load flow of distribution system: load flow of distribution system due to the intensive use in optimization trend should have a high speed and appropriate performance. In this study, backward-forward sweep method has been used for load flow.

- **Load flow in the fundamental frequency:** In this section, a load flow is used in the fundamental system frequency and for determination of buses voltage and lines current and actual losses of

distribution system. In this study, backward-forward sweep load flow method has been used because of its high speed and good performance. This load flow has been formed based on two matrices [BIBC] Bus-Injection to Branch-Current matrix and [BCBV] the branch-current to bus-voltage matrix. The buses voltage and lines voltage is calculated as per a repetitive process as follows:

$$[V]^k = [V_0] - [BCBV] \cdot Z \cdot [BIBC] \cdot [I]^k \quad (9)$$

V_0 : Slack bus voltage vector, Z initial network impedance matrix assuming [I] load current vector, [V] buses voltage vector.

- **Load flow for unbalanced network:** In the unbalanced network, each phase has the load and topology different from other phases. Also, the impact of mutual inductance caused by the other phases on the voltage drop of each phase is significant. Therefore, in the unbalanced network, the load should be distribution as three phase and distribution network may not be analyzed as single line. Consequently, the impedance matrix includes 3 phases and mutual inductance and the primary voltage vector will vary as follows:

$$[V_0] = [V_0^a \cdot e^{-i0}, V_0^b \cdot e^{-i\frac{2\pi}{3}}, V_0^c \cdot e^{+i\frac{2\pi}{3}}] \quad (10)$$

- **Load flow in the harmonic frequencies:** In the above frequencies, a precise model is available for distribution systems and parallel capacitors. Each one of distribution system elements should be modeled in the harmonic order including the details. In the different harmonic levels, the system admittance and consequently the impedance of each section are changed. Ignoring the skin impact of feeder impedance in the harmonic frequency and parallel capacitors reactance, the following equation is raised:

$$Z_{i,i+1}^h = R_{i,i+1} + jhX_{i,i+1} \quad (11)$$

$$X_c^{(h)} = \frac{V_k^2}{hQ_c} \quad (12)$$

In the high frequencies, the linear Loads are modeled as a resistance with parallel reactance (Pesonen, 1981):

$$Z_{ii} = \frac{1}{\frac{P_{ii}}{|V_{ii}^2|} - j \frac{Q_{ii}}{h|V_{ii}^2|}} \quad (13)$$

Nonlinear Loads (harmonic generating Loads) cause harmonic injection in the distribution systems and

are modeled by harmonic current sources, the size of current source of a harmonic load is obtained based on the harmonic spectrum current and nominal load current in the fundamental frequency:

$$I^{(h)} = I_{rate} \frac{I_{h-spectrum}}{I_{1-spectrum}} \quad (14)$$

where, h-spectrum specifies the harmonic spectrum of nonlinear load, the harmonic Loads are modeled by constant power. The nominal current of nonlinear loads is obtained in the fundamental frequency. Harmonic current phase is obtained as per following equation (Task Force on Harmonics Modeling and Simulation, 1996):

$$\theta_h = \theta_{h-spectrum} + h(\theta_1 - \theta_{1-spectrum}) \quad (15)$$

θ_1 : Nominal phase angle in the fundamental frequency.
Imperialist competitive algorithm

IMPERIALIST COMPETITIVE ALGORITHM

This algorithm has been presented for the first time by the Atashpaz-Gargari and Lucas (2007). This algorithm is new optimization strategy based on the human's sociopolitical evolution similar to other evolutionary algorithms, this algorithm begins with some preliminary random population, and each one is called as a country. Some of the best population elements are selected as the colonizer. The remained population is assumed as the colony. The colonizers depending on their power attract these colonies through a specific process. The total power of an empire is dependent to its both constituting parts means the colonizer country as the central core and its colonies. In the mathematical state, this dependence has been modeled by defining the imperial power as the total power of imperialist country plus a rate of its colonies power average. Each empire that fails to succeed in the imperialist competition and increase its power or at least avoid the reduction of its influence will be eliminated from imperialist competition scene. Therefore, the survival of an empire is dependent to its power in attracting the colonies of competitor empires and dominating over them. Consequently, in the imperialistic competitions current, the power of greater empires is increased gradually and the weaker empires will be eliminated. The extremity of imperialistic competition is obtained when we have a united empire in the world (Atashpaz-Gargari and Lucas, 2007).

Imperialist competitive algorithm procedure:

- **Establishment of initial countries:** In this section, the initial population is generated randomly as a vector
- **Selection of the best countries as the colonizer:** To begin the algorithm, some of initial countries are established and out of the best members of

countries including the minimum value of cost function, a group is selected as the colonizer. The remained population of countries forms the colonies

- Attracting the colonies by the colonizer country in each empire (homogenization policy)
- Sudden change in the colonies of each empire (revolution)
- If a colony exists in an empire and has costs lower than the colonizer, the colony and colonizer are replaced by each other
- Calculation of total empire costs
- Imperialist competition between empire
- Separation of weak colonies and possession thereof by the powerful empires
- Eliminating the empires excluding colony
- Repeating the algorithm until only one empire remains

Implementation of algorithm in capacitor placement

problem: Due to the use of capacitors with the discrete capacities, the capacitor placement problem is structured discreetly. Imperialist competitive algorithm is a method for solving the continuous problem. Therefore, considering the problem dimensions, random numbers are generated for the buses and minimum capacitor capacity within the range [0, 1] and upon multiplying by the capacitor capacity and rounding, the variables of problem response are obtained. Algorithm implementation stages are as follows:

- Reading the line and load data
- Load flow for obtaining the line losses and buses voltage
- Implementing the imperialist competitive algorithm to determine the location and capacity of capacitors
- If the algorithm is converged, going to stage 6, unless returning to stage 3
- Load flow and determining the bus voltage and system losses after optimal capacitor placement
- End

SIMULATION RESULTS

In order to show the capability of presented method, simulation has been implemented on the unbalanced 26-bus network, the schematic of which is observed in Fig. 1. The information on this system has been obtained from (Kersting, 1984). The nominal voltage of this system is 11 KV. Total reactive and active Loads of this system are respectively equal to 1855 KVar and 3892 KW. The acceptable maximum and minimum voltage for all buses is, respectively equal to 1.1 and 0.9 p.u. and maximum THD is 5%. The cost of power and energy losses per KW has been considered according to Eajal and El-Hawary (2010),

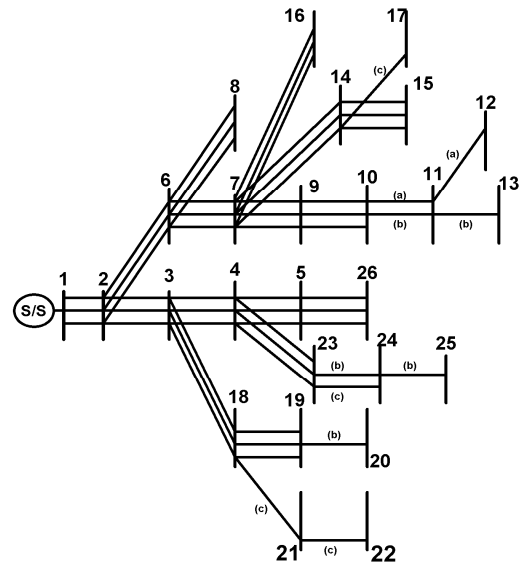


Fig. 1: Schema of unbalanced 26-bus network

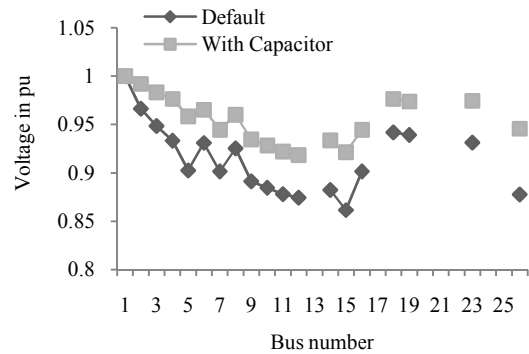


Fig. 2: Phase a voltage profile

168 \$/KW. The cost of reactive power injection has been estimated according to Eajal and El-Hawary (2010). The considered nonlinear load is 6 pulse convertor. This load is three-phase ($p = 400 \text{ KW}$, $Q = 200 \text{ KVAR}$) and has been installed in the 18 bus. Its specification is as per Table 1.

Load flow in non-compensation mode: In this section, before capacitor placement, the load flow is executed and results are provided in Table 2 whit executes load flow before capacitor placement, it is observed that the voltage of all phases is below 0.9 pu and compensation is required. Also, maximum THD% exceeded the acceptable value.

Results of capacitor placement by imperialist competitive algorithm: After applying the suggested algorithm on the system, the optimal location and value of capacitor banks is obtained as per Table 3 whit execute load flow after capacitor placement, Results are obtained that shown in Table 4 voltage profile for three phase is shown in Fig. 2 to 4.

Table 1: Specifications of respective nonlinear load

Harmonic Order	1	5	7	11
Magnitude (%)	100	20	14.3	90.1
Phase	0	0	0	0
Harmonic Order	13	17	19	23
Magnitude (%)	7.7	5.9	50.3	40.3
Phase	0	0	0	0

Table 2: Results of system load flow before capacitor placement

Total power losses	349.2 KW
Total annual cost	58666 \$
Mini voltage in phase a	0.8616 pu- 15 th bus
Mini voltage in phase b	0.8983 pu- 15 th bus
Mini voltage in phase c	0.8894 pu- 15 th bus
maxi THD%	6.69

Table 3: Results of optimal capacitor placement

Bus number and phase	Size of capacitor per KVar
2-a	450
15-a	300
15-b	300
15-c	300
26-a	300

Table 4: Results of system load flow after capacitor placement

Total power losses	270.5 KW
Total annual cost of losses	45444 \$
Cost of capacitor placement	533 \$
Total cost	45977 \$
Mini voltage in phase a	0.9184 pu- 12 th bus
Mini voltage in phase b	0.9270 pu- 15 th bus
Mini voltage in phase c	0.9181 pu- 15 th bus
maxiTHD%	4.3

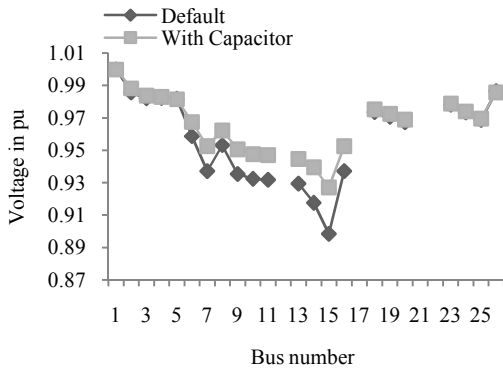


Fig. 3: Phase b voltage profile

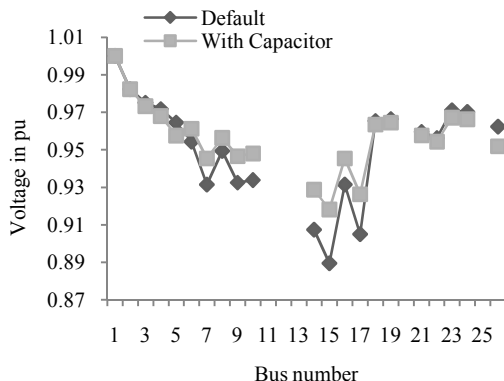


Fig. 4: Phase c voltage profile

After analyzing the unbalanced system, it is observed that before capacitor placement due to the network load and topology unbalance, the network has more intensive voltage drop in phase a to the other two phases. After optima capacitor placement, the voltage profile of all phases has been placed in the acceptable range and active losses and total system costs has been reduced, respectively as 78.8 KW and 12689 \$. Also, the maximum THD% has been placed in the accepted range. The effect of mutual inductance on the voltage drop and voltage profile is obvious in all phases.

CONCLUSION

In this study, the optimal capacitor placement for the unbalanced network has been applied considering the harmonic contamination. To analyze the unbalanced network precisely, three phase load flow of backward-forward sweep has been used considering the mutual inductance in the optimization process. To solve the capacitor placement problem that is a discrete nonlinear optimization problem, imperialist competitive algorithm has been used. The results of simulation demonstrate the high capability of this algorithm for solving the discrete problems. The presented method may be applied as a software package for determining the location and value of parallel capacitors in the unbalanced networks.

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