Optimal Placement and Sizing of Capacitor Banks Using Fuzzy-Ant Approach in Electrical Distribution Systems

Brahim GASBAOUI 1*, Abdelkader CHAKER2, Abdellah LAOUFI1, Abdessalam ABDERRAHMANI 1 and Boumediène ALLAOUA1

1 Faculty of the sciences and technology, Department of Technology, Bechar University B.P 417 BECHAR (08000), Algeria.
2Laboratory of SCAMRE, ENST, University of Oran, Oran (31000), Algeria.
E-mail(s): brahim_gasb@yahoo.com; chakeraa@yahoo.fr; elec_allaoua2bf@yahoo.fr
(*Corresponding author: Phone: +213 – 762-336-415.)

Abstract
Among optimizations of reactive power are minimization of total active power losses and control of voltage in the real-time. This can be achieved by placing the optimal value of capacitor at proper locations in electrical distribution systems. The proposed methodology is an intelligent fuzzy-ant approach of critical buses detection for optimal placement and sizing of capacitor banks in electrical distribution systems the critical nodal is determiner using fuzzy controller and the sizing of capacitor banks is obtained based on ant colony system. Calls up to the ant colony system which are use for complexes combinatorial problem minimizes the cost function. Voltage constraints are considered. The proposed fuzzy-ant approach is has been evaluated on a 25 and 30 buses.

Keywords
Critical Nodal Detection; Capacitor Placement and Sizing; Fuzzy-Ant Approach; Ant Colony System; Power Flow.
Introduction

Power distribution from electric power plants to ultimate consumers is accomplished via the transmission sub transmission, and distribution lines. Studies have indicated that as much as 13% of total power generated is consumed as $R^2I^2$ losses at the distribution level. The $R^2I^2$ losses can be separated to active and reactive component of branch current, where the losses produced by reactive current can be reduced by the installation of shunt capacitors. Capacitors are widely used in distribution systems to reduce energy and peak demand losses, release the KVA capacities of distribution apparatus and to maintain a voltage profile within permissible limits. The objective of optimal capacitor placement problem is to determine the size, type, and location of capacitor banks to be installed on radial distribution feeders to achieve positive economic response. The economic benefits obtained from the loss reduction weighted against capacitors costs while keeping the operational and power quality constraints within required limits.

Fuzzy logic provides a remedy for any lack of uncertainty in the data. Furthermore fuzzy logic has the advantage of including heuristics and representing engineering judgments into the capacitor allocation optimization process.

The ACS is a meta-heuristic motivated by the behaviour observed in colonies of real ants for finding the shortest path from a food source to their nest. Ants can find the shortest path because they deposit pheromones on paths they visit and they follow paths with higher pheromone trails. In [2], the ACS was proposed to solve the travelling salesman problem (TSP) by generating successively shorter feasible tours using information accumulated in the form of a pheromone trail deposited on the edges of the TSP graph.

Many of the previous strategies for capacitor allocation in the literature are also limited for the application to planning, expansion or operation of distribution systems. Very few of these capacitor allocation techniques have the flexibility of being applicable to more than one of the above problems. Hence, this paper presents a fuzzy-ant approach to determine suitable locations for capacitor placement and the sizing of the capacitor. This approach has the versatility of being applied to the planning, expansion, and operation studies of distribution systems. The proposed method was tested on electrical distribution systems consisting of 25 buses distribution system.
Mathematical Formulation

The principle of method is presented in Fig.1.

\[
\text{Minimize } \left\{ F = K_{\text{PL}} P_L + \sum_{j=1}^{N} K_{Cj} B_j \right\}.
\]

Constraint of voltage:
\[
V_{i}^{\text{min}} \leq V_i \leq V_{i}^{\text{max}} \quad i = 2, 3, \ldots N
\]

where:
- \( F \): Total annual cost function [S],
- \( K_{\text{PL}} \): Annual cost per unit of power losses [S/kW],
- \( P_L \): Total active power loss [kW],
- \( K_{Cj} \): Capacitor annual cost [cost/KVar],
- \( B_j \): Shunt capacitor size placed at bus \( j \) [kVar],
- \( N \): Number of buses,
- \( V_{\text{min}} \): Minimum permissible rms voltage,
- \( V_{\text{max}} \): Maximum permissible rms voltage.

**Fuzzy Logic Controller**

Fuzzy logic is expressed by means of the human language. Based on fuzzy logic, a fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database.

First, set the power loss index \( PLI \) and the voltage \( V \) to be the input variables of the fuzzy logic controller. The Capacitor suitable index \( CSI \) is the output variable of the fuzzy logic controller. The structure of fuzzy controller is shown in Fig. 2.
The linguistic variables are defined as \{L, LM, M, HM, H\}, where \(L\) means low, \(LM\) means low medium, \(M\) means medium, \(HM\) means height medium and \(H\) means height. The membership functions of the fuzzy logic controller are shown in Fig. 3, Fig. 4 and Fig. 5. The fuzzy rules are summarized in Table 2. The type of fuzzy inference engine is Mamdani. The fuzzy inference mechanism in this study follows as:

\[
\mu_b(u(t)) = \max_{j=1}^{m} \left[ \mu_{A_j}(PLI), \mu_{A_j}(V), \mu_{B_j}(CSI) \right]
\]

where \(\mu_{A_j}(PLI)\) is the membership function of \(PLI\), \(\mu_{A_j}(V)\) is the membership function of \(V\), \(\mu_{B_j}(CSI)\) is the membership function of \(SCI\), \(j\) is an index of every membership function of fuzzy set, \(m\) is the number of rules and is the inference result. Fuzzy output \(CSI\) can be calculated by the centre of gravity defuzzification as:

\[
u(t) = \frac{\sum_{i=1}^{m} \mu_{B_i}(u_i(t)) \cdot u_i}{\sum_{i=1}^{m} \mu_{B_i}(u_i(t))}
\]

where \(i\) = the output rule after inferring.

**Fuzzy Based Capacitor Location**

Node voltages and power loss indices are the inputs to fuzzy controller to determine the suitability of a node in the capacitor placement problem. The suitability of a node is chosen from the capacitor suitability index (CSI) at each node. The higher values of CSI are chosen as best locations for capacitor placement [1, 2, 3, 4, 5].

The power loss indices are calculated as:

\[
PLI(i) = (LR - L_{MAX})/(L_{MIN} - M_{MAX}), i = 2, 3, ..., N
\]

where: \(LR\) : Loss reduction, \(L_{MIN}\) : Minimum reduction, \(L_{MAX}\) : Maximum reduction, \(N\) : Number of bus.

To determine the critical busses the voltage and power loss index at each node shall be calculated and are represented in fuzzy membership function. By using these voltages and \(PLI\), rules are framed and are summarized in the fuzzy decision matrix as given in Table 1.
Figure 2. Structure of Fuzzy Controller (where: $F = \text{Fuzzification}; F^{-1} = \text{Defuzzification}$)

Figure 3. Power loss indices membership

Figure 4. Voltage membership functions
Algorithm for critical busses identification

Following algorithm explain the methodologies to identify critical busses, which are more suitable for capacitor placement [6, 10].

**Step 1:** Read line and load data of power system.
Step 2: Calculate power flow Newton Raphson methods

Step 3: Determine total active power loss.

Step 4: By compensation the self–reactive power at each node and conduct the load flow to determinate the total active power losses in each case.

Step 5: Calculate the power loss reduction and power flow loss indices.

Step 6: The PLI and the per-unit voltage are the inputs to the fuzzy Controller.

Step 7: The outputs of Fuzzy controller are defuzzified. This gives the ranking of CSI. The nodes having the highest value of CSI are the most suitable for capacitor placement.

Step 8: Stop.

Ant Colony System (ACS)

Overview

The ACO algorithms form a class of meta-heuristic to solve NP-hard combinatorial optimization problems. It has been introduced to solve the travelling salesman problem. The basic idea is to imitate the behavior of real ants foraging for food. In fact, the real ants can found the shortest path from a food source to their nest without visual cue. Indeed, they communicate, in a local and indirect way, through an aromatic essence called “pheromone”, deposed on the ground as they move about. Being very sensitive to this substance, an ant seeking food choose, in a randomly way, the path comprising a strong concentration of this substance. Thus, as more ants take the same path, more than ants will be attracted by this path. By analogy, in ACO algorithm, artificial ants build a solution by applying a probabilistic decision to choose a next destination. The generation of solutions is guided by pheromone trail and information related on the problem specification. Then, the ACO can be defined as an extension of traditional construction heuristics which have to adapt the pheromone quantity during the execution of the algorithm to take, into account, the experiment of research. We note that, in addition to the real ants characteristics, the artificial ants are equipped with a memory, are not completely blind, and the used time is discrete.

The Ant Colony System ACS is a particular approach of the ACO, proposed by [12-13] to solve the travelling salesman problem. In the ACS, a set of cooperation agents (ants), initially positioned at a starting point with a number of destination points, cooperate to find
routes according to some rules. In fact, each ant builds a feasible solution by applying a probabilistic function based on the pheromone trail and a heuristic function. While constructing its solution, an ant changes pheromone level of the selected edge by applying a local updating rule. Once all the ants have completed their solution, a global updating rule is performed [11-18].

**Implementation of ant colony system based capacitor sizing**

To apply the ant colony system (ACS) algorithm to a combinatorial optimization problem, is reside to represent the problem by a matrix \( G = [n, r] \).

\[
G = \begin{bmatrix}
C_{11} & C_{12} & \cdots & \cdots & C_{1n} \\
C_{21} & C_{22} & \cdots & \cdots & C_{2n} \\
C_{31} & C_{32} & \cdots & \cdots & C_{3n} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
C_{n1} & C_{n2} & \cdots & \cdots & C_{nn}
\end{bmatrix}
\]

(4)

where: \( n \) = Number of capacitor size; \( r \) = Number of critical busses

An ant positioned on node \( i \) chooses the capacitor \( j \) by applying the rule given by:

\[
j = \arg \max_{q \leq q_0} \left( \frac{\tau_{ij}^\alpha \eta_{ij}^\beta}{\sum_{j} \tau_{ij}^\alpha \eta_{ij}^\beta} \right) \quad \text{if} \quad q \leq q_0
\]

\[
j = \begin{cases} \arg \max_{j \in L_i} \left( \tau_{ij}^\alpha \eta_{ij}^\beta \right) & \text{if} \quad j \in L_i(i) \\ \text{otherwise} \end{cases}
\]

(5)

And \( j \) is a random variable selected according to the probability distribution given by:

\[
j = \begin{cases} \arg \max \frac{\tau_{ij}^\alpha \eta_{ij}^\beta}{\sum_{j} \tau_{ij}^\alpha \eta_{ij}^\beta} & \text{if} \quad j \in L_i(i) \\ \text{otherwise} \end{cases}
\]

(6)

\( \alpha \) and \( \beta \) are parameters that control the relative weight of the pheromone. \( A C_i \) is the set of available Components or capacitors. While constructing its solution, an ant also modifies the amount of pheromone on the visited capacitor by applying the local updating rule: While building a solution of the problem, ants choose elements by visiting element on the matrix \( G \), and change their pheromone level by applying the following local updating rule:

\[
\tau_{ij}^{new} = (1 - \rho) \tau_{ij}^{old} + \rho \tau_0
\]

(7)

where \( \rho \) is a coefficient such that \((1-\rho)\) represents the evaporation of trail and \( \tau_0 \) represent the initial trail of pheromone. Once all ants have terminated their tour, the amount of pheromone on capacitor size is modified an Ant colony system in (by applying the global updating rule): Once all ants have built a complete system, pheromone trails are updated. Only the globally
best ant (i.e., the ant which constructed the best solution from the beginning of the trial) is allowed to deposit pheromone. A quantity of pheromone $\Delta \tau_{ij}$ is deposited on each capacitor size that the best ant has used. Therefore, the global updating rule is:

$$
\tau_{ij}^{new} = (1 - \rho)\tau_{ij}^{old} + \rho \Delta \tau_{ij}
$$

(8)

where $0 < \rho < 1$ is the pheromone decay parameter representing the evaporation of trail and $\Delta \tau_{ij}$ represent the lay of the pheromone in the Capacitor $C (i, j)$. Ants are guided, in building their tours, by both heuristic information (they prefer to choose "less expansive" element), and by pheromone information. Naturally, an element with a high amount of pheromone is a very desirable choice. The pheromone updating rules are designed so that they tend to give more pheromone to element which should be visited by ants.

**Ant colony algorithm for size capacitor computing**

The Ant colony system based capacitor sizing algorithm is given below:

**Step1:** Initializing pheromone an visibility each element of matrix $G$,

For $i = 1:n$
For $j = 1:r$
\[
\tau_{ij} = \tau_{0} \\
\eta_{ij} = 1/F \\
\]
End For
End For

**Step2:** In this phase each ant builds their tours. The tour of ant is stored in tabu list,

While $k \leq p$ (stopping criterion is no wet met)

For $l = i:m$
For $s = l:r$
  - Choose the next element of matrix $G$ according to formula (5) and formula (6),
  - Stored in tabu list,
  - For each chosen element local updating occurs and pheromone is updated using formula (7),
End For

- Evaluate the fitness for each combination according to the objective function (including penalty function). The fitness function includes the total cost investment $F$ and the penalty functions .the penalty function used in implantation is quadratic .It act as a soft constraint .The constraint includes the bus voltage at each bus:
  - Find the minimum $(F_{best})$ among $m_1$ cost functions,
End For
Step 3: In this phase global updating occurs and pheromone is updated,

- Update elements of matrix $G$ belonging to $F_{\text{best}}$ using formula. (8) and $\Delta \tau_{ij} = \frac{I}{F_{\text{best}}}$.

End While.

where: $m =$ Number of ant; $p =$ Number of maximum cycle.

Results and Discussion

The proposed method is illustrated with a system, consisting of 25 bus. The location for placement of capacitors is determined by fuzzy controller and the capacitor sizes are evaluated using ant colony system.

$KPL$ was selected to be 168 $$/kW, and voltage limits on the rms voltage were selected as $V_{\text{min}} = 0.95 \text{ pu}$ and $V_{\text{max}} = 1.10 \text{ pu}$.

Fuzzy-Ant is applied for 25 buses electrical distribution systems the results of approach given above are shows at table 2. Ant colony system parameter setting are show in table 3. In Table we show that the active power losses are decrease for e 29.8913 at 23.2082 MW, decreasing 22.358% and the minimal voltage are improved to 0.9241 at 0.9639 pu.

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<tr>
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<td>After placement of optimal capacitor</td>
<td>Before placement of optimal capacitor</td>
</tr>
<tr>
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<td>9.00</td>
<td>29.8913</td>
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<tr>
<td>Optimal annual cost</td>
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The different voltages of 25 bus electrical network given before ant colony system are illustrated in Fig. 7.
The different voltages of 25 bus electrical network given after ant colony system are illustrated in Fig. 8. The 30 buses electrical network topology is presented in Fig. 9.

Fuzzy-Ant is applied for 30 buses electrical distribution systems the results of approach given above are shows at table 3. Fu Ant colony system parameters setting are show in table 4. In Table we show that the active power losses are decrease for 9.457 at 6.645MW, decreasing 29.67 % and the minimal voltage are improved to 0.959 at 0.968 pu.
Figure 9. The 30 buses electrical network

Table 3. Results of Fuzzy-Ant approach for 30 buses

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<td>After placement of optimal capacitor</td>
<td>Before placement of optimal capacitor</td>
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<tr>
<td>Optimal annual cost</td>
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Table 4. Ant colony systems parameters

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<th>Ant colony system parameter setting</th>
<th>Value</th>
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<td>$\alpha$</td>
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<tr>
<td>$\rho$</td>
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<tr>
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<tr>
<td>$m$</td>
<td>10</td>
</tr>
<tr>
<td>$\eta$</td>
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Conclusions

This paper introduces an intelligent Fuzzy-Ant approach method to determinate a critical busses by fuzzy controller and ant colony system (ACS) for minimization a total cost investment for capacitor this combination reduce active power losses and improve the bus voltage. The main advantage of this approach is robustness of ant colony systems, over modern heuristic is flexibility, robustness of the complex combination problem, sure and fast convergence. As a study case the 25 buses system and 30 buses, the simulation results show that for medium-scale system an ant colony optimization method can give a best result.

Ant colony system parameter alpha, beta and visibility play an important role in the performance of ant colony system and some permutations and combinations of these parameters are to be tested to get the best performance.

References


