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Involvement of cost savings and voltage stability indices in optimal capacitor allocation in radial distribution networks using artificial bee colony algorithm

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ABSTRACT

This article applies the artificial bee colony algorithm to define and allocate static shunt capacitors along radial distribution networks. The objective function is adapted to maximise net yearly savings and to enhance the overall system static voltage stability index with weighting and magnifying factors. Load variations have been considered to optimally size the fixed and switched capacitors required. Nodes with higher loss sensitivity factors and lower voltage stability indices are initially identified for capacitor allocations. The proposed algorithm ascertains optimal sizing and placement, and takes the final decision for optimum locations among the number of buses nominated. The realised numerical results are compared with those found by other recent heuristic methods and show that the proposed method is capable of producing high-quality solutions and validated its viability and applicability.

Introduction

Technical losses are happened because of the physical nature of the equipment and infrastructure of the power distribution systems, such as power losses in the cables, overhead lines, distribution transformers, switches, connections and bus bars [1]. It should be emphasized that non-technical losses are difficult to quantify. Technical power losses can be categorised into active and reactive power losses. Since these losses are a function of current flow through the line [1]. The real and reactive power losses in the distribution network are given by:

$$P_{\text{Loss}} = \sum_{1}^{n} |I_i|^2 \cdot R_i \quad Q_{\text{Loss}} = \sum_{1}^{n} |I_i|^2 \cdot X_i \qquad (1)$$

Numerous authors have discussed different aspects of power loss minimisation and voltage profile enhancement. Many methods have been developed for reducing the network losses and improving the voltage profile in distribution systems: network reconfiguration and load balancing [2,3], high voltage distribution system [4], distributed generations [5–7] and shunt capacitor allocations [8–23]. Reactive power compensation can be beneficial only when correctly applied. Correct application means choosing the correct position and size of the reactive power support. It is not possible to achieve zero losses in a power system, but it is possible to keep losses to a minimum to reduce the system overall yearly costs. Algorithms for enhancing voltage stability of electrical systems by OCA have been developed and described [24–27].

Many evolutionary/stochastic methods that assist in solving optimisation problems that were previously problematic or unmanageable have been proposed and developed in the last decade. To attain a loss reduction package in distribution systems, it is necessary to use effective and efficient computational tools that allow quantifying the loss in each different network element for system losses reduction.

Many researchers have focused on various types of heuristic optimisation techniques to solve the optimal capacitor allocation (OCA) problem such as heuristic strategies (HS) [8], genetic algorithms (GA) [9], tabu search [10], particle swarm optimisation (PSO) [11], big bang–big crunch optimisation [12], harmony search algorithm [13], ant colony search [14], fuzzy-real coded GA [15], bacterial foraging solution [16], immune optimisation technique [17], differential evolution and pattern search (DE–PS) [18], teaching learning based optimisation [19], plant growth simulation algorithm (PGSA) [20], artificial bee colony (ABC) [21,22] and cuckoo search algorithm (CSA) [23].

The ABC algorithm has been proposed for optimising numerical complex problems [28]. It simulates the intelligent foraging behaviour of honey bee swarms. It is a very simple, robust and

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Nomenclatures

$\lvert I_i \rvert$	magnitude of the branch current in line i
n	total number of lines
R_i	resistance of line i
X_i	reactance of line i
P_{loss}	total network active loss
Q_{loss}	total network reactive loss
VSI(j)	voltage stability index of bus j
R_{ij}	resistance of line i–j
X_{ij}	reactance of line i–j
$\lvert V_i \rvert$	voltage magnitude of bus i
$\lvert V_j \rvert$	voltage magnitude of bus j
P_j	total effective real power load fed through bus j
Q_j	total effective reactive power fed through bus j
C_e	rate of energy cost
ΔT_i	time period for load level slot i
$P_{L_a}(i)$	total active power loss after compensation for certain load level i
$P_{L_b}(i)$	total active power loss before compensation for certain load level i
C_{Ci}	cost rate of capacitor installation/location
N_B	number of candidate effective buses (that have compensations with values > 0)
N	number of network buses
C_C	purchase cost of the capacitor
C_{CO}	yearly operating cost of the capacitors/location
σ	depreciation factor
μ_F	magnifying factor
$L(i)$	the ith load level
W	weighting factor ($0 \leqslant W \leqslant 1$)
m	number of load level slots
n_l	number of load buses
P_{Slack}	active power supplied from the slack bus
Q_{Slack}	reactive power supplied from the slack bus
$P_D(i)$	active power demand of load at bus i
$Q_D(i)$	reactive power demand of load at bus i
$P_L(j)$	active power loss of branch j
$Q_L(j)$	reactive power loss of branch j
$Q_C(i)$	amount of reactive power of installed capacitors at bus i
$V_{i,\min}$	lower permissible voltage limit at bus i
$V_{i,\max}$	upper permissible voltage limit at bus i
$Q_{Ci}^{\min}$	lower reactive power limit of compensated bus i
$Q_{Ci}^{\max}$	upper reactive power limit of compensated bus i
S_{li}	actual line flow of line i
S_{li}^{rated}	rated line transfer capacity
$PF_{\min}$	lower limit of overall system power factor at substation (slack bus)
$PF_{\max}$	upper limit of overall system power factor at substation (slack bus)
MCN	maximum cycle number
SN	colony size

population based stochastic optimisation algorithm. The performance of the ABC algorithm has been compared with those of other well-known modern heuristic algorithms such as GA, DE and PSO on constrained and unconstrained problems [29,30]. The BC algorithm has a well-balanced exploration and exploitation ability and very efficient for multimodal and multi-dimensional functions.

This paper is an extension to the published article [22] which did not take the daily load variations into consideration. However, in this current version the ABC-based algorithm is applied to ascertain the optimal size and select optimum locations of fixed and switched static shunt capacitors. Variations of loading are taken to optimally size fixed and switched capacitors for practical aspect attentions. The magnifying and weight factors have been introduced to attain the same purpose and generalise the objective function formulation. Moreover, a larger system is used to validate the proposed methodology.

In normal practice, high potential buses for capacitor placement are initially identified by the observations of loss sensitivity factor (LSF) and lower voltage stability index (VSI) buses. However, that method has proven less than satisfactory as LSF may not always indicate the appropriate placement. In the proposed ABC approach, the algorithm identifies optimal sizing and placement, and takes the final decision for optimum location within the number of buses nominated. The method has been tested and demonstrated on a variety of radial distribution systems (small and large scales) and detailed results are presented and investigated.

Voltage stability index

Many different indices have been introduced to evaluate the power systems security level from the point of voltage static stability [24–27]. A new steady state VSI is proposed [27] for identifying the node, which is most sensitive to voltage collapse and is expressed in Eq. (2). Fig. 1 shows the simple electrical equivalent of the radial distribution system.

$$\mathrm{VSI}(j) = |V_i|^4 - 4\left[P_j \cdot X_{ij} - Q_j \cdot R_{ij}\right]^2 - 4\left[P_j \cdot R_{ij} + Q_j \cdot X_{ij}\right] \cdot |V_i|^2 \qquad (2)$$

For stable the operation of the radial distribution networks, VSI (j) $\geqslant 0$. The node, at which the value of the VSI has lowest, is prone to collapse. The node with the lowest VSI is the weakest node and the voltage collapse phenomenon will start from that node. Therefore, to avoid the possibility of voltage collapse; the VSI of all nodes should be maximised.

Modelling of the objective function and constraints

Formulation of the objective function

The objective of capacitor placement in the distribution system is to maximise the energy power loss reduction, reduce capacitor purchase, operating and installation costs (i.e. to maximise the annual net savings), and to enhance the system static voltage stability subject to set of specific operating constraints. The objective function is adjusted with weighting and magnifying factors to generalise the mathematical formulation to accept multi-trade objectives. In addition, the objective function is altered to accommodate load variation to scope sizing of fixed and switch capacitor banks. The objective function can be mathematically formulated as defined in Eq. (3):

$$\text{Maximise}\left\{ W \cdot \begin{bmatrix} C_e \cdot \sum_{i=1}^{m} \left(P_{l_b}(i) - P_{l_a}(i)\right) \cdot \Delta T_i - \\ \sigma \cdot \left\langle C_{Ci} \cdot N_B + C_C \cdot \sum_{i=1}^{N_B} Q_C(i) \right\rangle - C_{Co} \cdot N_B \end{bmatrix} + (1 - W) \cdot \mu_F \cdot \sum_{j=2}^{N} \mathrm{VSI}(j) \right\} \qquad (3)$$

The magnifying factor for the specific network under study is calculated:

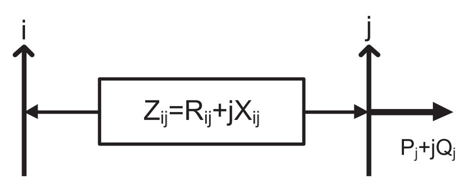

Fig. 1. Line i–j power system model.