



Optimal Feeder Reconfiguration of Distribution System with Distributed Generation Units using HC-ACO

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Abstract: The objective of optimal feeder reconfiguration of radial distribution system problem is to obtain the best set of branches to be opened, one each from each loop, such that the resulting radial distribution system has the desired performance. This paper presents a feeder reconfiguration problem in the presence of distributed generators to minimize the system power loss while satisfying operating constraints using Hyper Cube-Ant Colony Optimization (HC-ACO) algorithm. Loss Sensitivity analysis is used to identify optimal location for installation of DG units. Simulations are conducted on 33 – bus radial distribution system at four different cases to verify the efficacy of the proposed method with other recent published approaches reported in the literature. The result shows that the method proposed is fast and effective.

Keyword: Distribution system, radial distribution system, Distribution feeder reconfiguration, Distributed generator, Ant Colony Optimization (ACO) algorithm, Real power loss.

Nomenclature

P_i	Real power flowing out of bus i
Q_i	Reactive power flowing out of bus i
P_j	Real power flowing out of bus j
Q_j	Reactive power flowing out of bus j
P_{Li}	Real power load connected at bus i
Q_{Li}	Reactive power load connected at bus i
P_{Lj}	Real power load connected at bus j
Q_{Lj}	Reactive power load connected at bus j
R_{ij}	Resistance of line section between i and j
X_{ij}	Reactance of line section between i and j
$P_{Lj,eff}$	Effective real power load connected at bus j
$Q_{Lj,eff}$	Effective reactive power load connected at bus j
I_{ij}	Current in line section between buses i and j
I_{ij}^{max}	Maximum current in line section between buses i and j
$V_{i,nom}$	Nominal voltage of bus i
V_i	Voltage of buse i
V_j	Voltage of buse j
V_i^{min}	Minimum value of bus voltage magnitude

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V_i^{\max}	Maximum value of bus voltage magnitude
$P_{Loss}(i, j)$	Real power loss of the line section between buses i and j
$P_{T, Loss}$	Total real power loss
n	Total number of buses
A	Bus incidence matrix
P_{SUB}	Real power injection of substation
Q_{SUB}	Reactive power injection of substation
P_{DG_i}	Real power generation of the DG connected at bus i
Q_{DG_i}	Reactive power generation of the DG connected at bus i
$P_{DG,i}^{\min}$	Lower limit of active power generation of the DG connected at bus i
$P_{DG,i}^{\max}$	Upper limit of active power generation of the DG connected at bus i
$Q_{DG,i}^{\min}$	Lower limit of reactive power generation of the DG connected at bus i
$Q_{DG,i}^{\max}$	Upper limit of reactive power generation of the DG connected at bus i
$p.f._{DG_i}$	Power factor of the DG connected at bus i

1. Introduction

Electrical power distribution system consists of groups of interconnected radial circuits. They have switches to configure the networks via switching operations to transfer loads among the feeders. There are two types of switches used in the distribution system, sectionalizing switches (normally closed switches) and tie switches (normally open switches), whose states determine the configuration of network. The configuration of the distribution system is changed by opening sectionalizing switches and closing tie switches so that the radial structure of the network is maintained and all of the loads are supported and reduced power losses, improve voltage profile, improve power quality, increase system security, relieve overload in the network [1]. However, due to dynamic nature of loads, total system load is more than its generation capacity that makes relieving of load on the feeders not possible and hence voltage profile of the system will not be improved to the required level. In order to meet required level of load demand, DG units are integrated in distribution network to improve voltage profile, to provide reliable and uninterrupted power supply and also to achieve economic benefits such as minimum power loss, energy efficiency and load leveling. Network reconfiguration and DG placement in distribution networks are considered independently. But, in the proposed method, network reconfiguration and then DG installation are done for improved loss minimization and voltage profile.

Since network reconfiguration is a complex combinatorial, non-differentiable constrained optimization problem, many algorithms are proposed in the past. Merlin and Back [2], first proposed network reconfiguration problem and they used a branch-and-bound-type optimization technique. The drawback with this technique is the solution proved to be very time consuming as the possible system configurations are, where line sections equipped with switches is. Based on the method of Merlin and Back [2], a heuristic algorithm has been suggested by Shirmohammadi and Hong [3]. The drawback with this algorithm is simultaneous switching of the feeder reconfiguration is not considered. A heuristic algorithm [4] was suggested, where a simple formula was developed to determine change in power loss due to a branch exchange. The disadvantage of this method is only one pair of switching operations is considered at a time and reconfiguration of network depends on the initial switch status. An algorithm [5] was presented based on the heuristic rules and fuzzy multi-objective approach for optimizing network configuration. The disadvantage in this is criteria for selecting membership

functions for objectives are not provided. A solution using a genetic algorithm (GA) [6] was presented to look for the minimum loss configuration in distribution system. A refined genetic algorithm (RGA) [7] was presented to reduce losses in the distribution system. In RGA, the conventional crossover and mutation schemes are refined by a competition mechanism. Harmony Search Algorithm (HSA) [8] was proposed to solve the network reconfiguration problem to get optimal switching combinations simultaneously in the network to minimize real power losses in the distribution network.

Many methods are proposed for the best placement and sizes of DG units which is also a complex combinatorial optimization problem. An analytical method [9] was introduced to determine optimal location to place a DG in distribution system for power loss minimization. A Lagrangian based approach to determine optimal locations for placing DG in distribution systems considering economic limits and stability limits was presented by Rosehart and Nowicki [10]. A multi-objective algorithm using GA [11] was presented for siting and sizing of DG in distribution system. Placement and penetration level of the DGs under the SMD framework was discussed by Agalgaonkar [12].

This paper is to propose a 33- bus radial feeder reconfiguration technology based on the Hyper-Cube (HC) Framework Ant Colony Optimization (ACO) algorithm with DG to minimize system real power loss and bus voltage deviation in the distribution network without violating operation constraints and maintaining the radial structure. The HC-ACO algorithm is a useful evolutionary algorithm with strong global search ability. The characteristics of the HC-ACO algorithm include positive feedback, distributed computation and a constructive greedy heuristics. Positive feedback makes sure of a rapid search for a global solution; distributed computation avoids premature convergence, and constructive greedy heuristics help find acceptable solution as soon as possible. These properties are counterbalanced by the fact that, for some applications, the HC-ACO can outperform other heuristics.

The rest of the paper is organized as follows: In section II, modelling of power flow in radial distribution network is discussed. Modelling of DG units are given in section III. Sensitivity analysis for DG installation is given in section IV. In section V, the problem formulation is described. The Ant Colony Optimization is briefed in section VI. In section VII, application of Ant Colony Optimization in the Hyper-Cube (HC) Framework to solve problem is described. The test system, numerical results and discussion are presented in section VIII and Section IX, concludes this paper.

2. Modeling of power flow using backward and forward sweep method

In this paper, network topology based backward and forward sweep method [13] is used to find out the load flow solution for balanced radial distribution system. Conventional NR and Gauss Seidel (GS) methods may become inefficient in the analysis of distribution systems, due to the special features of distribution networks, i.e. radial structure, high R/X ratio and unbalanced loads, etc. These features make the distribution systems power flow computation different and somewhat difficult to analyze as compared to the transmission systems. Various methods are available to carry out the analysis of balanced and unbalanced radial distribution systems and can be divided into two categories. The first type of methods is utilized by proper modification of existing methods such as NR and GS methods. On the other hand, the second group of methods is based on backward and forward sweep processes using Kirchhoff's laws. Due to its low memory requirements, computational efficiency and robust convergence characteristic, backward and forward sweep based algorithms have gained the most popularity for distribution systems load flow analysis. The voltage magnitude and phase angle of the source should to be specified. Also the complex values of load demands at each node along the feeder should be given. Starting from the end of the feeder, the backward sweep calculates the line section currents and node voltages (by KCL and KVL) back to the source. The calculated voltage at the source is compared with its original specified value. If the error is beyond the limit the forward sweep is performed to update the node voltages along the feeder. In such a case, the specified source voltage and the line section currents already calculated in the

previous backward sweep are used. The process keeps going back and forth until the voltage error at the source becomes within the limit. The shunt admittance at any bus to ground is not considered. It is assumed that the three-phase radial distribution network is balanced and can be represented by their equivalent single-line diagram. Figure 1 represents the electrical equivalent of a typical branch of a distribution system.

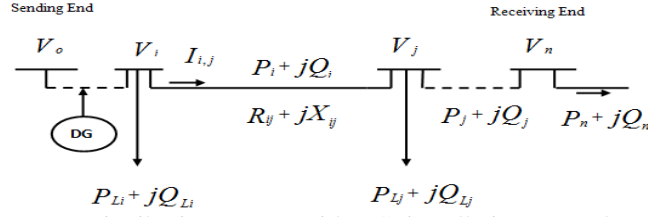


Figure 1. Distribution system with DG installation at any location.

A. Backward Sweep

By starting from the ending buses and moving backward to the slack bus (substation bus), the power flow through each branch is expressed by the following set of recursive equations:

$$P_i = P_j + P_{Lj} + R_{ij} \cdot \frac{P_j'^2 + Q_j'^2}{|V_j|^2} \quad (1)$$

$$Q_i = Q_j + Q_{Lj} + X_{ij} \cdot \frac{P_j'^2 + Q_j'^2}{|V_j|^2} \quad (2)$$

$$|V_i|^2 = |V_j|^2 - 2(R_{ij} \cdot P_j + X_{ij} \cdot Q_j) + (R_{ij}^2 + X_{ij}^2) \cdot \frac{P_j'^2 + Q_j'^2}{|V_j|^2} \quad (3)$$

Where $P_j' = P_j + P_{Lj}$ and $Q_j' = Q_j + Q_{Lj}$

B. Forward Sweep:

By starting from the slack bus (substation bus) and moving forward to ending bus, the active and reactive power flows at the receiving end of branch (P_j and Q_j) and the voltage magnitude at the receiving end ($|V_j|$) are expressed by the following set of recursive equations:

$$P_j = P_i - P_{Lj} - R_{ij} \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (4)$$

$$Q_j = Q_i - Q_{Lj} - X_{ij} \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (5)$$

$$|V_j|^2 = |V_i|^2 - 2(R_{ij} \cdot P_i + X_{ij} \cdot Q_i) + (R_{ij}^2 + X_{ij}^2) \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (6)$$

Hence, if the V_o, P_o, Q_o at the first bus of the network are known, then the same quantities at the other nodes can be calculated by applying the above branch equations.

By applying the backward and forward update methods, we can get a power flow solution. The real power loss of the line section connecting between buses i and j is calculated as

$$P_{Loss}(i, j) = R_{ij} \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (7)$$

The total real power loss of the all lines sections in n bus system ($P_{T, Loss}$) is calculated by adding up the losses of all line sections of the feeder, which is described as

$$P_{T, Loss} = \sum_{i=1}^{n-1} P_{loss}(i, j) \quad (8)$$

3. Mathematical model of Distributed Generation Units

A distributed generation (DG) unit can be modeled as either a voltage-controlled bus (PV bus) or as a complex power injection (PQ bus) in the distribution system. If DGs have control over the voltage by regulating the excitation voltage (synchronous generator DGs) or if the control circuit of the converter is used to control P and V independently, then the DG unit may be modeled as a PV type. Other DGs, like induction generator – based units or converters used to control P and Q independently, are modeled as PQ types. The most commonly used DG model is the PQ model. In this work, the PQ-DG units are represented as a negative PQ load model delivering active and reactive power to a distribution system. This gives flexibility in modeling various types of DG. DG can be classified into four major types[14] based on their terminal characteristics in terms of active and reactive power delivering / consuming capability as follows:

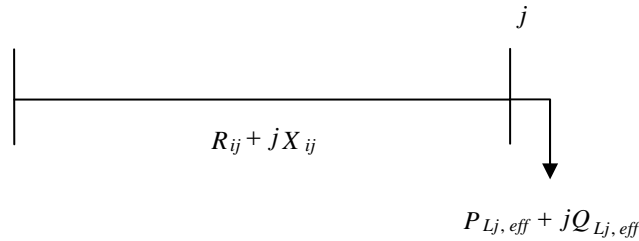
- *Type 1*: DG capable of injecting real power (P_{DG_i}) only (Photovoltaic, $p.f_{DG}=1$)
- *Type 2*: DG capable of injecting both real power (P_{DG_i}) and reactive power (Q_{DG_i})
(Micro Turbine, $0 < p.f_{DG} < 1$)
- *Type 3*: DG capable of injecting real power (P_{DG_i}) but consuming reactive power (Q_{DG_i})
(Wind Turbine, $0 < p.f_{DG} < 1$)
- *Type 4*: DG capable of injecting reactive power (Q_{DG_i}) only
(Synchronous condenser, $p.f_{DG}=0$)

The present studies were considered with *Type 1* DGs only. By considering the properties of these resources and in order to modeling them in the mentioned optimization problem, the injected active powers at bus i are modeled as follows:

Type 1:

$$P_i = P_{DG_i} - P_{L_i} \text{ and } Q_i = -Q_{L_i} \quad (9)$$

4. Sensitivity analysis for DG installation



Consider a line section consisting an impedance of $R_{ij} + jX_{ij}$ and a load of connected $P_{Lj,eff} + jQ_{Lj,eff}$ between i and j buses as given above.

The real power loss of the line section connecting between buses i and j is given by

$$P_{loss} = \frac{(P_{Lj,eff}^2 + Q_{Lj,eff}^2)R_{ij}}{V_j^2} \quad (10)$$

The loss sensitivity factor (LSF) can be defined with the equation

$$\frac{\partial P_{loss}}{\partial P_{Lj,eff}} = \frac{2 * P_{Lj,eff} * R_{ij}}{V_j^2} \quad (11)$$

Using (11), LSFs are calculated from load flows and values are arranged in descending order for all buses of the given system. The LSFs decide the sequence in which buses are to be considered for DG unit installation. The size of DG unit at candidate bus is calculated using HC-ACO.

5. Problem Formulation

The objective function is a constrained optimization problem to find an optimal arrangement of feeder for the distribution system and DG placement in which the value of function $f(x)$ is minimized.

A. Objective Function

The objective function $f(x)$ consists of 2 goals: reducing the real power losses and improving the voltage profile in a given radial distribution system while satisfying all constraints for a fixed number of DGs and specific total capacity of the DGs.

A.1. Minimization of the real power losses (f_1):

The real power loss of the line section connecting buses i and j can be computed as

$$P_{Loss}(i, j) = R_{ij} \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (12)$$

The total real power losses of the all lines sections is described as

$$f_1 = P_{T, Loss} = \sum_{i=1}^{n-1} P_{Loss}(i, j) \quad (13)$$

A.2. Minimization of Voltage deviation or Improvement the voltage profile (f_2):

The objective function for minimization of voltage deviation is defined as

$$f_2 = VD = \sum_{i=1}^n |V_i - V_{i,nom}| \quad (14)$$

B. System Constraints

The objective function is subjected to the following constraints:

B.1. Power balance constraints

$$P_{SUB} + \sum_{i=1}^n P_{DG,i} = \sum_{i=1}^n P_{Li} + P_{T,Loss} \quad (15)$$

$$Q_{SUB} = \sum_{i=1}^n Q_{Li} + Q_{T,Loss} \quad (16)$$

B.2. Bus Voltage limit

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (17)$$

B.3. Thermal Limits

$$I_{ij} \leq I_{ij}^{\max} \quad (18)$$

B.4. Radial structure of the network

$$\det(A) = 1 \text{ or } -1 \text{ (radial system)} \quad (19)$$

$$\det(A) = 0 \text{ (not radial)} \quad (20)$$

B.5. Power limits of DG :

$$P_{DG,i}^{\min} \leq P_{DG,i} \leq P_{DG,i}^{\max} \quad (21)$$

6. General description of ant colony optimization algorithm

Ant Colony Optimization (ACO) is a recently proposed metaheuristic approach for solving hard combinatorial optimization problems. The inspiring source of ACO is the pheromone trail laying and following behavior of real ants which use pheromone as a communication medium. In analogy to the biological example, ACO is based on the indirect communication of a colony of sample agents, called artificial ants, mediated by artificial pheromone trails. The pheromone trails in ACO serve as distributed, numerical information which the ants use to probabilistically construct solutions to the problem being solved and which the ants adapt during the algorithm's execution to reflect their search experience [15, 16 & 17].

Artificial ants used in ACO are stochastic solution construction procedures that probabilistically build a solution by iteratively adding solution components to partial solution by taking into account (i) heuristic information on the problem instance being solved and (ii) artificial pheromone trails which change dynamically at run time to reflect the agents' acquired search experience [15, 16 & 17].

The concept of ACO is clear but the algorithm is not unique. The model of selection of a proper algorithm depends on the application. The proposed ACO algorithm that is introduced here is shown in the flow chart of figure 2. The following steps give explanations to the flow chart of figure 2.

- 1) Close all the tie and sectionalizing switches in the network to construct meshed loops. The number of meshed loops equal the number of tie switches.
- 2) Generate the number of artificial ants arbitrary.
- 3) Initialize the parameters, heuristic parameter (β), pheromone parameter (α), evaporation parameter (ρ) for local updating rule, evaporation factor (μ) for global updating rule, and initial pheromone values for each switch.

4) State transition rule:

Ants select their next state (switch) according to this rule given by (22)

$$S_k(i, j) = \begin{cases} S_1 & \text{if } q \leq q_0 \\ S_2 & \text{otherwise} \end{cases} \quad (22)$$

$$S_1 = \arg \max [\tau(i, j)^\alpha \cdot [\eta(i, j)^\beta]] \quad (23)$$

Where $S_k(i, j)$ is the state (switch) that an t_k chooses in its next move ; k is the ant ; i and j are the current and next state respectively ; S_1 and S_2 are random variables represent the state (switch) that ant $_k$ selects according to transition state transition rule ; $\tau(i, j)$ is the pheromone deposited by ants during move; q is a random number uniformly distributed in $[0,1]$; q_0 is a parameter between 0 and 1 ($0 \leq q_0 \leq 1$) according to equation (25) ; $\eta(i, j)$ is the heuristic information of the problem ; α is a parameter represents the importance of pheromone ; β is a parameter represents the importance of heuristic.

S_2 is selected according to a pseudo random rule or a pseudo random proportional rule given by (24)

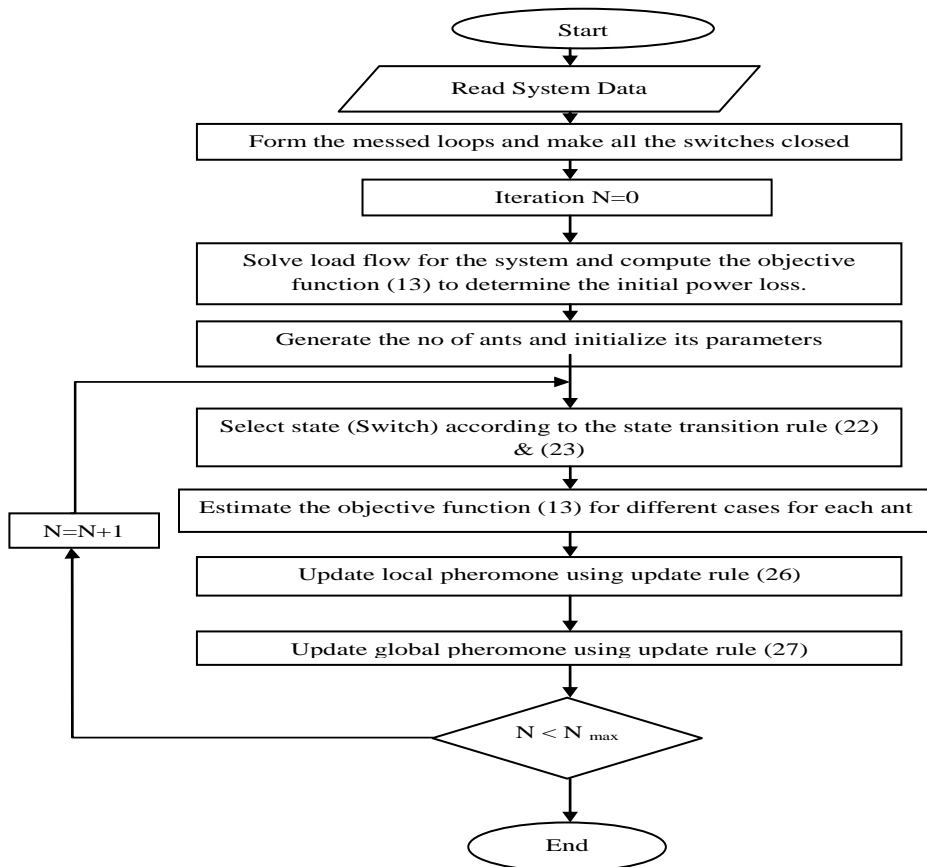


Figure 2. Flow chart of ACO algorithm

