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Robust Reconfiguration Scheme for Distribution Networks using Biogeography Based Optimization

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ABSTRACT

Network reconfiguration is an operation problem, which entails altering the topological structure of the distribution feeders by rearranging the status of open switches in order to obtain an optimal configuration that minimizes the network real power loss (RPL). This paper presents a new reconfiguration algorithm that reduces the RPL using biogeography based optimization (BBO) without incurring any additional cost for installation of capacitors and tap-changing transformers. The BBO, inspired from the geographical distribution of biological species, searches for optimal solution through the migration and mutation operators. Test results on a 33 and 69-node distribution networks reveal the superiority of the developed method.

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Nomenclature:

BBO biogeography based optimization
$[C]$ branch-to-node matrix that describes the topological structure of the distribution network
HSI habitat suitability index
h_i i^{th} habitat
$[I_L]$ vector of load currents
$[i_b]$ vector of branch currents
$I_{L,m}$ equivalent load current at node- m
$i_j^{\max}$ maximum permissible current through j^{th} branch
$Iter^{\max}$ maximum number of iterations for convergence check
nn number of nodes
nb number of branches
neh number of elite habitats
P^{mod} habitat modification probability
P_m mutation probability
$P_{L-m} + jQ_{L-m}$ real and reactive power load at node-m
$r_l + jx_l$ resistance and reactance of branch-l
RPL real power loss
$S^{\max}$ maximum species count
SIV suitability index variable
T_j binary variable that represents the topological status of j-th branch. It equals '1', if the tie/sectionalizing switch is closed, else its value is set as '0'
$V_m \angle \delta_m$ voltage at node-m
$V_o \angle \delta_o$ voltage at source node
Vmin lowest node voltage seen in the network
$[v_b]$ vector of branch voltage drops
limit
w_b penalty factor for handling violation of line flow constraint
$[z]$ diagonal matrix containing the self-impedances of all the branches
λ immigration rate
μ emigration rate
$\Re$ a set of branches, whose current flow exceed the respective thermal

INTRODUCTION

Distribution networks provide the final link between the high voltage transmission network and the consumers. They normally use primary or main feeders and lateral distributors. The main feeder

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originates from the substation and passes through the major load centers. The lateral distributors connect the individual load points to the main feeder through distribution transformers. Most distribution networks used in practice have only a single feeder and are defined as radial distribution networks. Radial networks are popular because of their simple design and low cost. They deliver power to a variety of loads in the residential, industrial and commercial sectors with a view of satisfying the customers' demand in a more economical and reliable manner. There are two types of switches in distribution networks, sectionalizing switches that are used to isolate the faulty network and tie switches are utilized to restore power to customers through another route in order to reduce interruption duration abnormal operation conditions. Each load point of the distribution network is fed by a route through the network components to the substation. Therefore changing the status of these switches will alter the power flow to loads and consequently affect the power loss.

Network reconfiguration is a process of altering the topological structures of the distribution feeders by changing the open/close status of the sectionalizing and tie switches. During normal operating conditions, networks are reconfigured to reduce network RPL, achieve load balancing and relieve network overloads. The network reconfiguration problem was first solved for loss reduction using branch-and-bound-type optimization technique by Merlin and Back in the year 1975 (Merlin, A. and H. Back, 1975). In that method, all network switches are initially closed to form a meshed network and then the switches are successively opened to restore radial configuration. Deterministic mathematical approaches involving Benders decomposition (Khodr, H.M. and J. Martinez-Crespo, 2009), and mixed-integer programming (Jabr, R.A., 2012; Taylor, J. A. and F.S. Hover, 2012) have been proposed. A switch exchange method has been outlined in (Civanlar, S., 1988) and further modified in (Goswami, S. and S. Basu, 1992). A heuristic type algorithm to find the tie-switch position in each loop to reduce the RPL has been proposed (Shirmohammadi, D. and H. Hong, 1989) These algorithms start with a radial configuration of the network and modify the network configuration using heuristic formulas in order to reduce the RPL. They are usually fast but may not achieve the optimal configuration. Therefore, metaheuristic algorithms such as hyper-cube ant colony optimization (Abdelaziz, A.Y., 2012), bacterial foraging optimization algorithm (Sathish Kumar, K. and T. Jayabarathi, 2012), particles swarm optimization (Andervazh, M.R.,2013), artificial immune systems (De Oliveira, L.W., 2014), adaptive imperialist competitive algorithm (Mirhoseini, S.H., 2014), and genetic algorithms (Gupta, N., 2014) have been gradually applied for reconfiguration to reduce the network RPL. Metaheuristic optimization methods can solve the reconfiguration problem without any or fewer restrictions on the shape of the cost function curves due to their ability to seek the global optimal solution. Moreover, these algorithms do not depend on the first and second differentials of the objective function.

Recently, a Biogeography-Based Optimization (BBO), a population based meta-heuristic optimization technique sharing information between candidate solutions based on their fitness values, has been suggested for solving optimization problems by Simon. It has been applied to a variety of power system optimization problems and found to yield satisfactory results.

This paper attempts to apply BBO in solving the reconfiguration problem with a view of obtaining the global best solution with lower computational burden. The method is tested on 33- and 69-node radial networks and the results are presented.

Biogeography Based Optimization:

BBO, based on the concept of biogeography, is a stochastic optimization technique for solving multimodal optimization problems. In BBO, a solution is represented by a habitat-i consisting of solution features named Suitability Index Variables (SIV), which are represented by real numbers. It is represented for a problem with nd decision variables as

$$h_i = [SIV_{i,1}, SIV_{i,2}, SIV_{i,3}, \cdots, SIV_{i,nd}] \quad (1)$$

The suitability of sustaining larger number of species of a habitat-i can be modeled as a fitness measure referred to Habitat Suitability Index (HSI) as

$$HSI_i = f(h_i) = f(SIV_{i,1}, SIV_{i,2}, SIV_{i,3}, \cdots, SIV_{i,nd}) \quad (2)$$

High HSI represents a better quality solution and low HSI denotes an inferior solution. The aim is to find optimal solution in terms of SIV that maximizes the HSI .

Each habitat is characterized by its own immigration rate λ and emigration rate μ . A good solution enjoys a higher μ and lower λ and vice-versa. The immigration and emigration rates are the functions of the number of species in the habitat and defined for a habitat containing k -species as

$$\mu_k = E^{\max}\left(\frac{k}{n}\right) \quad (3)$$

$$\lambda_k = I^{\max}\left(1-\frac{k}{n}\right) \quad (4)$$

When $E^{\max} = I^{\max}$, the immigration and emigration rates can be related as

$$\lambda_k + \mu_k = E^{\max} \quad (5)$$

A population of candidate solutions is represented as a vector of habitats similar to any

other evolutionary algorithm. The features between the habitats are shared through migration operation, which is probabilistically controlled through habitat modification probability, P^{mod}. If a habitat h_i in the population is selected for modification, then its λ is used to probabilistically decide whether or not to modify each *SIV* in that habitat. The μ of other solutions are thereafter used to select which of the habitats in the population shall migrate randomly chosen *SIVs* to the selected solution h_i .

The cataclysmic events that drastically change the *HSI* of a habitat is represented by mutation of *SIVs*. The mutation operation modifies a habitat's *SIV* randomly based on mutation rate P_m and tends to increase diversity among the population, avoids the dominance of highly probable solutions and provides a chance of improving the low *HSI* solutions. Mutation rate of each solution set can be calculated in terms of species count probability using the following equation:

$$P_m = m^{\max}\left(\frac{1-P^k}{P^{\max}}\right) \tag{6}$$

Proposed Method:

Reconfiguration is necessary in distribution networks not only for minimizing the RPL but also improving the voltage profile (VP). The proposed BBO based reconfiguration method (PRM) involves the problem formulation, representation of a habitat, which represent the problem variables and formation of a *HSI* function.

Problem Formulation:

Distribution Power Flow:

The equivalent load current at node-m ($I_{L,m}$) of the distribution network can be computed from the specified real and reactive power loads ($P_{L-m} + jQ_{L-m}$) as

$$I_{L,m} = \left(\frac{P_{L-m} + jQ_{L-m}}{V_m \angle \delta_m}\right)^* \qquad m = 1, 2, \cdots nn \tag{7}$$

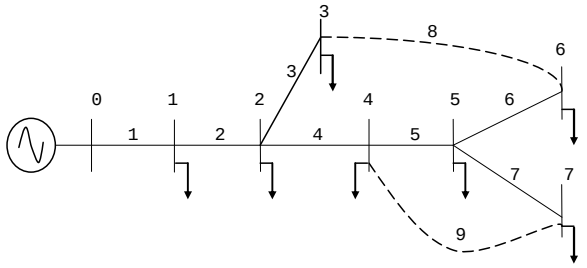

Fig. 1: Eight node example network.

The branch currents in terms of equivalent load currents of all the nodes of the example network of Fig. 1 can be written as

$$\begin{bmatrix} i_{b,1} \\ i_{b,2} \\ i_{b,3} \\ i_{b,4} \\ i_{b,5} \\ i_{b,6} \\ i_{b,7} \\ i_{b,8} \\ i_{b,9} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{L,1} \\ I_{L,2} \\ I_{L,3} \\ I_{L,4} \\ I_{L,5} \\ I_{L,6} \\ I_{L,7} \end{bmatrix} \tag{8}$$

That is,

$$[i_b] = [C]\,[I_L] \tag{9}$$

The voltage drop across all branches can be computed from the relation

$$[v_b] = [z]\,[i_b] \tag{10}$$

Similar to Eq. (3), the node voltages can be written in terms of branch voltages by the relation

$$V_i \angle \delta_i = V_o \angle \delta_o - \sum_{j=1}^{nb} T_j\, C_{ji}\, v_{b,j} \;, i = 1, 2, \cdots, nn \tag{11}$$

Objective Function:

The objective of the reconfiguration problem is to minimize the RPL and can be formulated as

$$Minimize \quad RPL = \sum_{j=1}^{nb} T_j \left|i_j\right|^2 r_j \tag{12}$$

The above objective can be calculated from the branch currents, obtained through iteratively solving the distribution power flow algorithm of Eqs. 7, 9, 10 and 11 for a given load data, and status of tie and sectionalizing switches.

Radial Topology Constraint:

The switching operation may sometimes make certain nodes disconnected from the live network, thereby making the configuration not radial. A check is therefore made for the status of tie and sectionalizing switches so as to confirm whether the resulting configuration is radial. If the network is radial, the entries in the first row of C matrix are binary ones. This can be imposed as a constraint in the reconfigurations problem as

$$\prod_{j=1}^{nn} C_{1,j} = 1 \tag{13}$$

If the above constraint is not satisfied, the network is either not radial or a group of loads is disconnected from service.

Line Flow Constraint:

The resulting flows in the lines should not exceed their respective thermal limits. It is represented by a constraint

$$\left|i_j\right| \le i_j^{\max} \qquad (14)$$

Representation of Design Variables:

The decision variable in BRM is the open-switch numbers. Each habitat of the BBO is therefore represented in vector form to denote the open-switches as

$$h = [TS_1, TS_2, \cdots\cdots TS_n] \qquad (15)$$

The BBO generates real numbers and hence to obtain integer values for open-switches, the real numbers are rounded off to the nearest integer values.

HSI Function:

The HSI function can be built from the problem objective function and radial topology and line flow constraints as

Maximize

$$HSI = \frac{1}{1 + RPL + w_b \sum_{i \in \Re} \left(\left|i_j\right| - i_j^{\max}\right)^2} \times \prod_{j=1}^{nn} C_{1,j} \qquad (16)$$

Solution Process:

An initial population of habitats is obtained by generating random values within their respective limits to every individual in the population. For each habitat in the population, the RPL is calculated by the procedure discussed in section-3, after altering the network topology according to the status of open-switches, and then the *HSI* is computed. The migration and mutation operations are performed for non-elite habitats with a view of maximizing the *HSI* . This process is continued till convergence. The flow of the BRM is shown in Fig. 2.

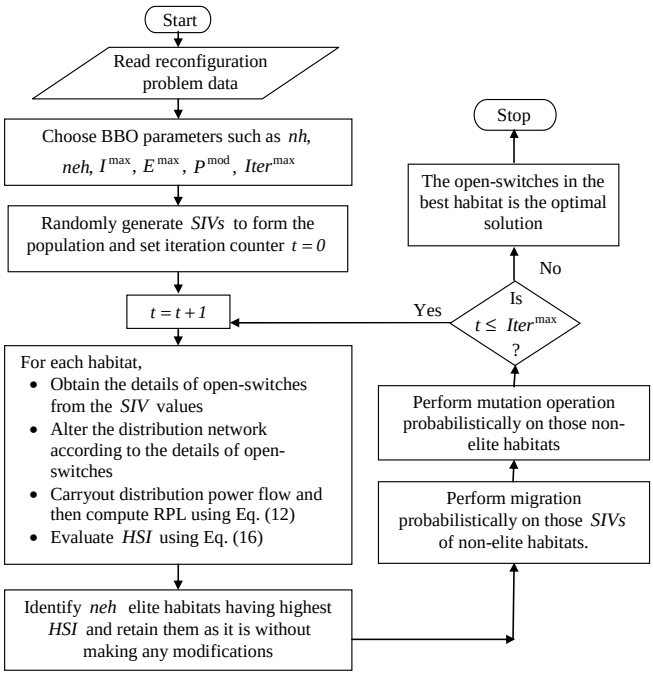

Fig. 2: Flow chart of BRM.

Numerical Results:

The BRM is tested on two standard distribution networks. The first one is a 12.66 kV, 33 node network, which consists of 5 normally open switches and 32 normally closed switches. The normally open tie-switches are 33, 34, 35, 36 and 37, and the normally closed switches are 1 to 32. The line data and load data of this network are given in (Baran, M. and F. Wu, 1989), and the total real and reactive power loads on the network are 3715 kW and 2300 kVar, respectively. The initial RPL of this network are 210.97 kW. The second test network is a 12.66 kV, 69 node network comprising of 5 tie-loops. The network data of the initial configuration is available in (Kashem, M., 2001). The total active and reactive network loads are 3802.19 kW and 2694.60 kVar, respectively, and the initial RPL is 225 kW.

The results of 33 node network, containing details of open-switches, RPL, lowest voltage magnitude (Vmin), before and after reconfiguration are compared with those of the existing methods published in (Goswami, S. and S. Basu, 1992; Shirmohammadi, D. and H. Hong, 1989; Mohamed Imran, A. and M. Kowsalya, 2014; Srinivasa Rao Rayapudi, 2011;' Mirhoseini Seyed Hasan, 2014) in Table-1. It is very clear from the results that the

proposed BRM offers the lower RPL of 139.53 kW than those of the existing methods. The VP before and after reconfiguration is pictorially depicted in Fig.3. It is seen from the figure that there is significant improvement in the VP after reconfiguration. It increases the lowest node voltage (Vmin) seen in the network from 0.9038 to 0.9378 per unit.

Table 1: Summary of Results for 33 node network.

	Open-switches	Losses (kW)	Vmin
Initial Configuration	33,34,35,36,37	210.97	0.9038
BRM	7,9,14,32,37	139.53	0.9378
Goswami [6]	7,9,14,33,37	143.69	---
Shirmohammadi [7]	7,10,14,32,37	140.26	---
Mohamed Imran [21]	7,9,14,28,32	139.98	0.9413
Mirhoseini [22]	7,9,14,36,37	145.11	0.9336
Srinivasa Rao [23]	7,10,14,28,36	146.39	0.9336

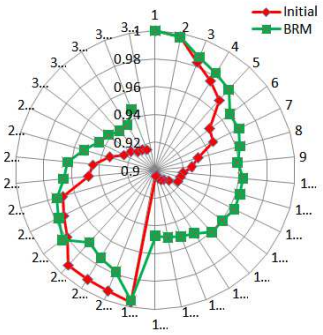

Fig. 3: VP of 33 node network.

Table 2: Summary of Results for 69 node network.

	Open Tie-switches	Losses (kW)	Vmin
Initial Configuration	69, 70, 71, 72, 73	225	0.9092
BRM	14, 57, 61, 69, 70	98.61	0.9495
Shirmohammadi [7]	11, 14, 21, 56, 62	106.67	---
Baran [19]	15, 59, 62, 70, 71	99.62	---
Dong-Li [24]	15, 59, 62, 70, 71	99.62	---
Gomes [25]	14, 56, 62, 70, 71	99.71	---
Zin [26]	15, 59, 62, 70, 71	99.62	---

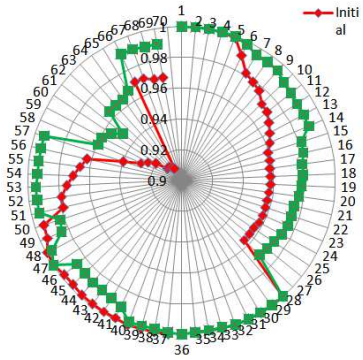

Fig. 4: VP of 69 node network.

The details of open-switches, RPL, Vmin, before and after reconfiguration for 69-node network are compared with those of the existing methods published in (Shirmohammadi, D. and H. Hong, 1989; Baran, M. and F. Wu, 1989; Dong-Li Duan, 2015; Gomes, F., 2005; Zin, A., 2012) in Table-2. It is obvious from the results that the proposed BRM offers the lower RPL of 98.61 kW than those of the existing methods. The VP before and after reconfiguration is pictorially depicted in Fig.4. It can be observed from the figure that there is considerable improvement in the VP after reconfiguration. It increases the Vmin in the network from 0.9092 to 0.9495 per unit.

It is very clear from these results that the proposed BRM offers a better configuration that

reduces network RPL for both the test networks. Even though VP is not considered as an objective, the proposed BRM is able to offer a reasonably good VP.

Conclusion:

A simple BBO based reconfiguration scheme for RPL minimization of radial distribution networks has been developed. This method uses a simple distribution power flow taking into the status of open-switches for calculating the RPL. It uses a simple mechanism for checking the radial nature of the network. The method is able to offer a better VP without any additional infrastructural cost. The algorithm is suitable for practical implementation on networks of any size.

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