An Artificial Immune Approach for Service Restoration in Smart Distribution Systems

Oliveira, D. Q., Zambroni de Souza, A. C., Almeida, A. B., Lima, I.
Federal University of Itajuba
Itajuba - Brazil
denissonqo@gmail.com, zambroni@unifei.edu.br, adbaal@yahoo.com.br, isaias@unifei.edu.br

***Abstract*— The power system reconfiguration is a challenging task. As smart grids concepts develop, different approaches try to take advantage of the grid intelligent features and infrastructure to evolve a fast and robust self-healing scheme. At the distribution level, the self-healing schemes are responsible for performing automatic corrective and self-restorative actions. This task includes managing the service restoration by locating and isolating the fault, and reconfiguring the network topology to decrease the harm. This paper presents a self-healing scheme using Artificial Immune System as an optimization tool to solve the service restoration problem in power systems considering faults within the internal switch breakers. To make this approach suitable for bigger systems, the Prim Algorithm is used due to its capacity to generate minimum spanning trees from a graph. The proposed scheme is tested on benchmark systems to investigate the capacity of proposing feasible solutions for faulted systems.**

***Index Terms*--Service restoration, self-healing, Evolutionary Algorithms.**

I. Introduction

The power system recomposition is a challenging task. As the smart grids (SGs) concepts evolve, different approaches try to take advantage of its intelligence and infrastructure to improve the power system control and operation. The self-healing capacity is one of the SGs most promising features. It refers to the ability of the grid to take corrective actions, and to recover itself from any contingencies without or with minimum human interference. Following an outage, the self-healing scheme should carry the system to a normal operating condition and assure a minimal loss of load, keeping the electricity supply to critical loads [1]. This process includes fault location, isolation, reconfiguration and service restoration.

Self-healing on smart distribution systems depends on distribution automation, which is a set of technologies that enable to remotely monitor and operate distribution components in real-time mode from distribution system operator (DSO) center [2]-[3]. The service restoration is achieved by switching normally closed (NC) and normally opened (NO) switches to find a suitable backup feeder or lateral and transfer the loads from the out-of-service areas. This operation aims to minimize the loss of load and is restricted by time and switching restrictions [4]. As stated in [4], self-healing schemes are also possible on less automated systems. But in these cases, the necessary corrective actions are performed manually by DSO operators, which requires more time and harm the system's reliability.

In the literature, several researchers have proposed different tools to support self-healing schemes on smart distribution grids. Due to its combinatorial nature, metaheuristics is usually used to solve this problem. Reference [1] presents an expert system for self-healing on SGs. This expert system has different modules which perform assessments over generation availability, network reconfiguration and system constraints. Reference [4] presents a distributed multiagent framework for self-healing on distribution systems with distributed generation (DG). A hybrid fuzzy-grey relational approach is used in [5] to perform service restoration minimizing switching operations, and feeders and laterals unbalancing. Reference [6] applies dynamic programming to minimize unserved energy, while [7] aims to minimize the cost of unserved energy using subgradient-based lagrangian relaxation. Tabu search is applied in [8] to improve reliability indices during the service restoration and genetic algorithm is used in [9] with the help of fuzzy systems during the fitness step to weight different objectives.

Another option for service restoration is islanding the distribution system into microgrids to achieve a more resilient operation, as described in [10]. However, the islanding option is not as simple as it seems since it demands previous planning studies on power generation availability, load shedding schedules development, and switch breakers location to build the islands.

Considering this background, this paper presents an approach for a self-healing scheme on smart distribution systems using the Artificial Immune Systems (AIS) as an optimization tool for reconfiguration purposes. The proposed scheme should perform the necessary operations to minimize the loss of load, after fault isolation, without islanding the system. High quality reconfiguration schemes are expected to work properly both on small and big systems. To accomplish this requirement, the Prim Algorithm is also applied during the assessment. The combination between AIS and Prim Algorithm was investigated before in [11] for multiobjective reconfiguration in normal conditions. This paper investigates this approach in faulted conditions, since the Prim Algorithm always gives feasible radial solutions for normal operation.

978-1-4673-6605-2/15/$31.00 ©2015 IEEE

Some simulations are performed on benchmark systems to evaluate the feasibility of the proposed algorithm.

Section II provides some background on the applied tools to perform the self-healing scheme on a smart distribution system and the proposed methodology. In section III, some simulations and results are provided to show the efficiency and the solutions of the proposed approach on benchmark systems. Finally, the conclusion in Section IV draws some comments about the proposal and its contributions

II. Self-healing on Smart Distribution Systems

Although the disturbances on distribution systems have limited harm in comparison to the whole electric power system load, this level presents the highest fault rates. Some contingencies have a permanent nature, like conductor disruption, and cause a blackout on some areas.

In this situation, the self-healing scheme should, beyond locating and isolating the fault, find a new suitable topology which isolate the affected area and keep the electricity supply for the others unaffected downstream areas. The electricity supply continuity for the highest priority loads is also important.

The AIS-based self-healing methodology proposed for smart distribution systems aims to minimize the unserved load after a fault by finding the best reconfiguration scheme. So, the objective function, which is the minimization of unserved load, is described in (1).

$$\min \sum_{i=1}^{N_Z} P_i \qquad (1)$$

s.t.

- Radial topology should be maintained;
- Voltage minimum and maximum limits:

$V_{min} \leq V \leq V_{max}$;

- Conductors ampacity: $I_j < I_{jmax}$;
- Customers priority.

where:

P_i : Active power load from node i, where $i \in Z$
Z : set of nodes in the out-of-service zone
N_Z : total number of elements in set Z
V_{min} : 0.93 p.u.
V_{max} : 1.05 p.u.
I_j : Conductor's current
I_{jmax} : Maximum conductor's current

The restrictions considered above are important issues for distribution systems operation. They are described as follows:

- The radial topology should be maintained due to the protection devices configuration;
- Technical constraints as voltage limits and feeders' currents are important to avoid overloads and protection devices to trip, increasing the out-of-service area;
- Some customers have higher priority supply than the others. These set includes health services, industrial loads, infrastructure essential services, etc. The priority is evaluated during the process and unserved priority loads add penalties to function cost;

In order to match the load priority, power balance and technical constraints, a load shedding scheme of low priority customers is predicted. The next subsections describe the proposed methodology and some background on the tools used to develop the self-healing scheme in distribution systems.

A. *Artificial Immune Systems*

The Artificial Immune Systems (AIS) is a bio-inspired evolutionary algorithm which mimics the human immune system in a computational way. This optimization approach is robust and fast due to its search process, which, differently from the genetic algorithm and the particle swarm, avoids its convergence for the best individual from the population and keeps looking for new solutions over different regions from shape space. As the other bio-inspired algorithms, AISs also use terms from biology and their original meaning is important to use them properly. For this paper, it is important to explain the following terms:

- Antibody: a candidate solution represented by a vector containing the solution;
- Clone: a copy of one solution;
- Hypermutation: the step from AIS evolutionary process where a random mutation occurs on antibodies.

The AISs have some interesting features for optimization problems, as reinforcement learning, pattern recognition, noise tolerance and memory. More background on AIS and example applications are available on [12]-[16]. Reference [14] presents an AIS-based reconfiguration problem, but using a quantum-inspired technique to improve the performance. Comparing to this, the Prim Algorithm theory is easier to understand and to develop computationally.

B. *Prim Algorithm*

A graph G = (V, E) consists of a set of objects $V = \{v_1, v_2, \ldots\}$ called vertices, and another set $E = \{e_1, e_2, \ldots\}$, whose elements are called edges, such that each edge ek is identified with an unordered pair (v_i, v_j) of vertices. The most common representation of a graph is by means of a diagram, in which the vertices are represented as points and each edge as a line segment joining its end vertices [17].

The concept of a tree is probably the most important in graph theory. A tree is a connected graph without any circuits. A tree T is said to be a minimum spanning tree of a connected graph G if T is a subgraph of G and T contains all vertices of G. There are several methods available for actually finding a minimum spanning tree in a given graph.

The Prim Algorithm is one of these methods to build minimum spanning trees in a simple way. In every Prim's algorithm iteration, an edge must be found that connects a vertex in a subgraph to a vertex outside the subgraph. The Prim Algorithm does not require listing all edges in order of decreasing weight or checking at each step if a newly selected edge forms a circuit.

Since graph G is connected, there will always be a path, and only one path, to every vertex. The output Y of Prim's algorithm is a Tree, because the edge and vertex added to Y are connected. Then Y is a minimum spanning tree. The algorithm continuously increases the size of a tree, one edge at a time, starting with a tree consisting of a single vertex, until it spans all vertices [17].

C. *Self-healing proposed methodology*

1) *Assumptions*

Let consider the system branches and loads between two switches as an area, as in [18]. This assumption comes from the fact that in radial and convex networks, the different areas connect to each other through switches. This concept is depicted on Fig. 1, where the 7-node network is represented by a 5-area diagram.

As demonstrated before, according to graph theory this 5-area diagram may be considered as a tree. Each area is a node and the switch is the edge between two nodes. Giving arbitrary weights to the edges, it is possible to build a minimum spanning tree linking all the nodes. The continuous lines represent closed switches while the dashed lines represent open switches. This concept is used during the self-healing process.

2) *Fault location and isolation*

The available data sent by advanced metering infrastructure help with the fault location and isolation process. The power protection devices, as relays, automatic reclosers and switching breakers, perform the sensing through impedance-based algorithms assessed with voltage and current measures and isolate the affected area. Works on fault location methods are available in [18]-[21]. Since fault location is not the concern here, it is considered that any approach may be applied.

3) *System reconfiguration*

After fault location and isolation from previous steps, it is time to reconfigure the system topology in order to achieve the objective of (1). This is accomplished following these steps:

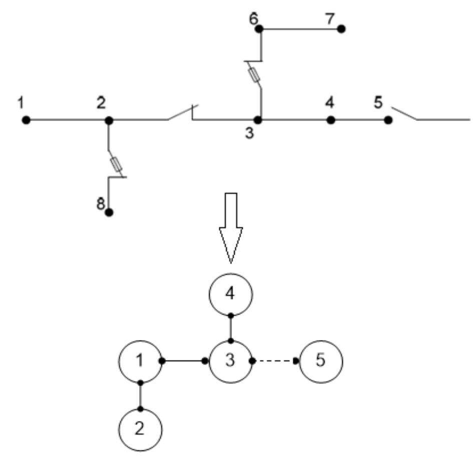


Figure 1. Areas delimited by switches on a distribution network

a) *Initial population*

The first step of AIS-based reconfiguration process is to create the initial population of antibodies. The antibody is a vector of the switches status, which could be 0 when it is opened or 1 if it is closed. On a given graph built according to the distribution network topology, the edges receive arbitrary weights. After this step, it is possible, through the Prim Algorithm, to create a set of minimum spanning trees. These trees are important due to their radial topology, which is a considered constraint.

b) *Hypermutation*

First, the original antibodies are cloned ‘n’ times. On the hypermutation step, each clone has some features changed randomly to introduce some variability in the population. These mutations correspond to changes in switches status, which create new topological solutions.

Different from the original process, in this case the hypermutation is divided into two steps: in the first step, a mandatory mutation is applied. According to the data received during the previous fault locating and isolating step, the information about the area where the fault occurred is available now. This information is used to apply a mutation in each clone aiming to create new solutions that have those areas disconnected from the system. This is done by giving a high weight to the edges that link this area to the rest of the graph.

In the second step, the clone suffers a random mutation on switches status according to a mutation probability. This mutation consists of changing the edges’ weights. The mutation probability is assessed according to the amount of out-of-service zones the original antibody has.

c) *Fitness*

Now, in the fitness step, the clones created before are tested to evaluate their feasibility to the problem. This is done using the Prim Algorithm again to create minimum spanning trees with the information of each clone. As the clone has a high weight edge between the out-of-service area and the other areas, the algorithm understands that this area should be islanded from the system.

The final configurations are tested using the respective adjacency matrix, given by the clone. The adjacency matrix has topological information about the system. By inspection, it is possible to assure the radiality constraint and to avoid islanded and meshed topologies. The antibodies have their unserved load assessed by (1) and sorted according to them.

In each generation, the best clone is chosen to join the next generation population. The other clones are deleted to avoid memory overflow. After a maximum number of generations or if there is not any improvement in unserved load for an arbitrary number of consecutive generations, the antibody with the lowest unserved load is chosen as the new solution for the system.

III. Simulations and results

Some simulations are performed on IEEE 123 node test system [22], Civanlar system [23] and Baran system [24] to test the proposed methodology. Their data are available in the respective reference. This section provides the results and some discussion on each case.

A. *IEEE 123-node*

The proposed methodology is applied to IEEE 123 node test system according to the approach described before. However it is a simple system, it is a good example to describe the methodology in the first time.

First, it is necessary to divide the system into areas limited by switches. The original topology and its respective graph representation are depicted below, in Fig. 2. According to it, it is possible to divide the system into seven areas. The continuous edges represent closed switches, while the dashed edges represent open switches. However it has seven different zones, there are few options to reconfigure the system and only one source node.

For this case, the initial population has ten antibodies. During the process, it is considered ten clones at each generation and a maximum of five generations. If there is not any improvement in three consecutive generations, the search process stops and the antibody with the lowest loss of load, assessed according to (1), is chosen as the new solution.

Some cases are depicted in Table I, considering different faulted zones in column 1. The respective unserved load assessed for each case is in column 2, and the final best configuration is depicted in column 3. When the contingency occurs in zones 2 and 4, the situation is more severe due to the lack of alternative paths.

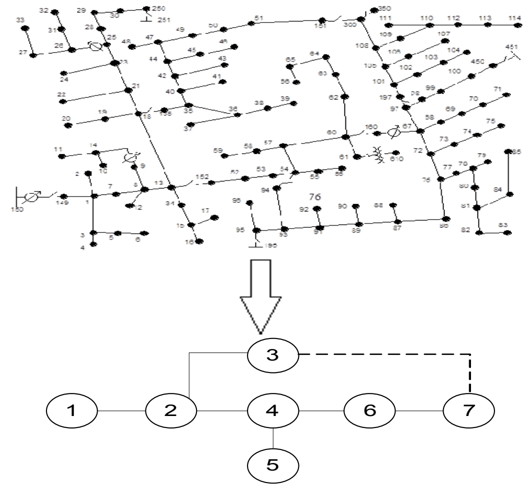
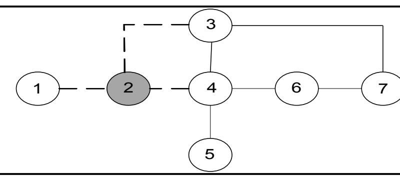
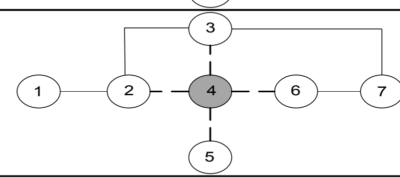
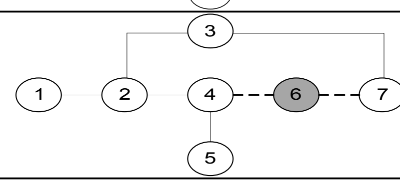


Figure 2. Original IEEE 123-node and its respective graph

TABLE I. Antibodies for 123 node test system

Out-of-service area	Unserved load (%)	Best antibody (solution)
2	98.85	
4	47.42	
6	31.66	

B. *Civanlar System*

The Civanlar system is depicted in Fig. 3. It has three feeders connected to the same substation and tie-lines between them. But, if the proposed approach is applied directly, this system only has three different zones. So, let consider that each branch is a switching device such a way that each node becomes a different zone. So, it is possible to disconnect a zone from the others if there is a contingency on it. Now, there are 16 different zones, represented by enumerated circles. For this example, let consider the highest priority loads connected to nodes 4, 12 and 16.

The proposed approach is applied to Civanlar system and some solutions are depicted in Table II. The column 1 shows the location where the fault happens, and the column 2 shows the resultant unserved load in the system. For this simulation, the evolutionary process has 10 antibodies in the initial population, each one generating 10 clones at each generation up to 10 maximum generations, or if any improvement on unserved load does not occur in three consecutive generations.

For Civanlar system, considering the initial topology as depicted in Fig. 3, the proposed methodology find a new suitable topology that isolates only the zone where the fault occurs and keep the electricity supply to the other zones. As expected, this is the optimal solution for the problem. Fig. 4 depicts the case from Table I when the contingency occurs in zone 13, in the third line of Table II. Remember that the dashed edges represent open switches and continuous edges represent closed switches, and the radial topology constraint is matched for all the antibodies. In this case, none of the highest priority loads are disconnected.

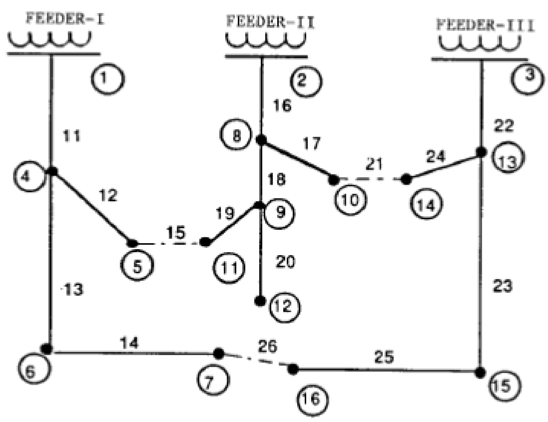


Figure 3. Original Civanlar system [23]

TABLE II. ANTIBODIES FOR CIVANLAR SYSTEM

Out-of-service zone	Unserved load (%)
6	6.96
9	17.42
13	15.68
15	3.48

C. Baran System

Considering the same assumptions made previously for Civanlar system, the Baran distribution system has 33 zones and its original configuration is the graph depicted in Fig. 5. The highest priority customers are connected in zones 15, 21, 28 and 31.

Some results obtained after simulations of contingency at arbitrary nodes are depicted in Table III. The column 2 shows the location where the fault happens, while the column 3 shows the resultant unserved load from each antibody. For this simulation, the AIS initial population has 20 antibodies and at each generation is created 20 clones of each antibody. The process lasts for 15 generations or if there is not any improvement in five consecutive generations.

Like the previous cases, the methodology finds a suitable topology that isolates only the zone where the fault occurs, leading to a low unserved load. As this is the desired behavior, the methodology may be considered satisfactory. There is not any case of load shedding for all cases due to overloading conditions. This is the expected result, as the system does not lose the source node. Priority loads still have their electricity supply when the fault does not occur in the same zone they are located. Regarding to power balance, as all the power flow comes from the substation bus, the load balancing is not a problem at all. The application of Prim Algorithm to build minimum spanning trees enhances the methodology robustness and facilitates its application to big distribution systems without loss of performance.

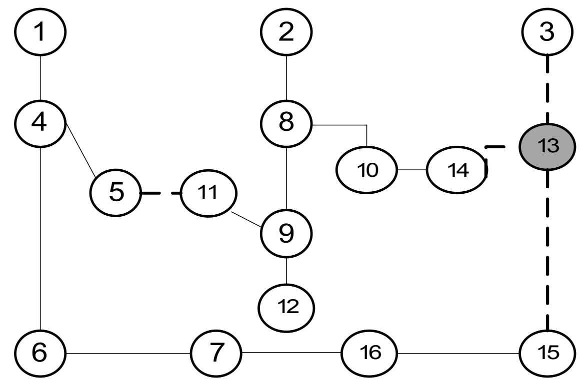


Figure 4. Civanlar system antibody when the fault occurs in zone 13.

TABLE III. ANTIBODIES FOR BARAN SYSTEM

Out-of-service zone	Loss of Load (%)
5	1.61
10	1.61
18	2.43
30	5.41

D. Further remarks

The presence of distributed generation (DG) may be considered in this approach according to the unit's fault riding through capability. If the unit does not have this capability, it must be switched off. The area where the DG is connected must be considered as a highest priority area that should be connected to the grid.

Regarding to islanding option, it must be previously planned carefully. Enough power generation and energy storage options must be available to assure the customers supply in islanded conditions. In this paper, the islanding option is not considered because the distribution system connection to the bulk power system is still available. So, it is easier trying to reconnect the downstream area to the grid than building an island in the distribution system.

The islanding option is the unique way in some cases, such that described in IEEE 123-node example. When the fault occurs in area 2 or in area 4, the islanding is the unique way to supply the customers from unaffected areas that cannot be reconnected to the grid. In such cases, the recomposition procedure is more complex and time demanding.

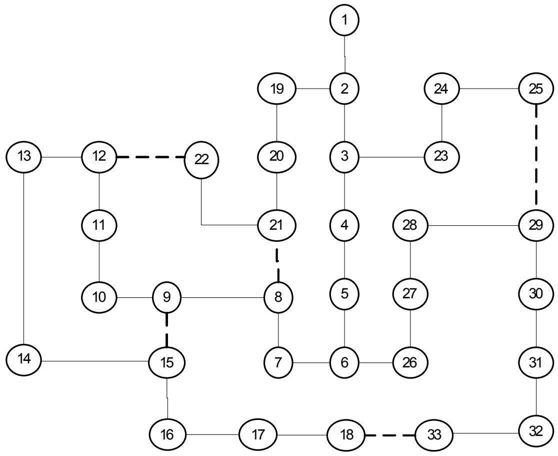


Figure 5. Baran system original configuration.

IV. Conclusions

This paper presents a robust self-healing methodology applying Artificial Immune Systems during the reconfiguration step on a distribution system where a permanent fault occurred. The application of Prim Algorithm enhanced the methodology and allowed its application to a big distribution power system.

The proposed robust self-healing methodology is able to propose radial configurations in restoration problems avoiding the islanding of the system. Through a modification in mutation operator, it is possible to apply the Prim Algorithm on faulted systems and to recognize the faulted zones easily, resulting in a simple and robust approach. Considering the faulted zone connected to the graph with a high edge weight helped on the task, minimizing the need of more actions to disconnect this zone.

References

[1] W. Sun, P. Zhang, Q. Zhou, "Optimization-based strategies towards a self-healing smart-grid", in *Proc. 2012 Innovative Smart-Grid Technologies-Asia*, pp; 1-6, 2012.

[2] J. R. Agüero, "Applying self-healing schemes to modern power distribution systems," in *2012 IEEE PES General Meeting*, pp. 1-4, 2012.

[3] V. Madani, R. Das, F. Aminifar, J. Mcdonald, S. S. Venkata, D. Novosel, A. Bose, M. Shahidehpour. "Distribution Automation Strategies Challenges and Opportunities in a Changing Landscape". *IEEE Transactions on Smart Grid*, V. 6, No. 4, pp. 2157-2165, 2015.

[4] A. Zidan, E. F. El-Saadany, "A Cooperative multiagent framework for self-healing mechanisms in distribution systems*", IEEE Transactions on Smart Grid*, Vol. 3, No. 3, pp. 1525-1539, Sept. 2012.

[5] W. H. Chen, M. S. Tsai, H. L. Kuo, "Distribution system restoration using the hybrid fuzzy-grey method", *IEEE Transactions on Power Systems*, Vol. 20, No. 1, pp. 199-205, Feb. 2005.

[6] R. Pérez-Guerrero, G. T. Heydt, N. J. Jack, B. K. Keel, A. R. Castelhano Jr., "Optimal restoration of distribution systems using dynamics programming", *IEEE Transactions on Power Delivery*, Vol. 23, No. 3, pp. 1589-1596, Jul. 2008.

[7] R. Pérez-Guerrero, G. T. Heydt, "Distribution system restoration via subgradient-based Lagrangian relaxation", *IEEE Transactions on Power Systems*, Vol. 22, No. 1, pp. 1162-1169, Aug. 2008.

[8] M. Boonthienthong, N. Rugthaicharoencheep, S. Auchariyamet, "Service restoration of distribution system with distributed generation for reliability worth", in *Proc. 47th Int. Universities Power Engineering Conference*, pp. 1-5, 2012.

[9] W. Wei, M. Sun, R. Ren, Y. Wang, "Service restoration of distribution systems with priority customers and distributed generation", in *Proc. 2012 IEEE Innovative Smart Grid Technologies-Asia*, pp. 1-6, 2012.

[10] Z. Wang, J. Wang. "Self-healing Resilient Distribution Systems Based on Sectionalization Into Microgrids". *IEEE Transactions on Power Systems*, Vol. 30, No. 6, pp. 3139-3149.

[11] Alonso, F. R., Oliveira, D. Q., Zambroni de Souza, A. C. "Artificial Immune Systems Optimization Approach for Multiobjective Distribution System Reconfiguration". *IEEE Transactions on Power Systems*, V. 30, No. 2, pp. 840-847, 2015.

[12] L. N. de Castro, F. J. Von Zuben, "Learning and optimization using the Clonal Selection Principle", *IEEE Transactions on Evolutionary Computation*, Vol. 6, No. 3, pp. 239-251, June 2002.

[13] D. Q. Oliveira, A. C. Zambroni de Souza, L. F. N. Delboni, "Optimal plug-in hybrid electric vehicles recharge in distribution power systems", *Electric Power Systems Research*, Vol. 98, pp. 77-83, 2013.

[14] N H. Ahmad, T. K. A. Rahman, N. Aminuddin, "Multi-objective quantum-inspired Artificial Immune System Approach for Optimal Network Reconfiguration in Distribution Systems", in *Proc. 2012 IEEE Int. Power Engineering and Optimization Conf.*, pp.1-5, 2012.

[15] T. K. A. Rahman, S. L. Suliman, I. Musirin, "Artificial immune-based optimization for solving economic dispatch in power systems*", Lecture Notes in Computer Science*, Vol. 3931, pp. 338-345, Springer Verlag, 2006.

[16] D. Marujo, D. Q. Oliveira, B. I. L. Lopes, A. C. Z. Souza, "Synchronous machine field voltage blocking using artificial immune systems", *in Proc. X Latin-American Con. on Generation and Transmission*, pp. 1-8, 2013.

[17] N. Deo, "Graph theory with applications to engineering and computer science", Prentice-Hall Inc., 1974, p. 354.

[18]E. P. Bento, N. Kagan,"Algoritmos genéticos e variantes na solução de problemas de configuração de redes de distribuição", *SBA Controle & Automação*, Vol. 19, No. 3, pp. 302-315, Sept. 2008.

[19] S. Das, N. Karnik, S. Santoso, "Distribution fault-locating algorithms using current only*", IEEE Transactions on Power Delivery*, Vol. 27, No.3, pp.1144-1153, Jul. 2012.

[20]T. Ghanbari, E. Farjah, "A multiagent-based fault-current limiting schemes for the microgrids", *IEEE Transactions on Power Delivery*, Vol. 29, No. 2, pp. 525-533, Apr. 2014.

[21] C. Orozco-Henao, J. Mora-Flórez, S. Pérez-Londoño, "A robust method for single phase fault location considering DG and current compensation", in *Proc. 2012 IEEE PES Transmission and Distribution: Latin-America Conference and Exposition*, pp.1-7, 2012.

[22] IEEE PES Distribution System Analysis Subcomitee, [online] http://ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html.

[23] S. Civanlar, J. J. Grainger, H. Lin, S.S.H. Lee, "Distribution feeder reconfiguration for loss reduction", *IEEE Transactions on Power Delivery*, Vol. 3, No.3, pp. 1217-1223, 1988.

[24] M. E. Baran, F. F. Wu, "Network reconfiguration in distribution system for loss reduction and load balancing", *IEEE Transactions on Power Delivery*, Vol. 4, No.2, pp.1401-1407, 1989.