

Solution to the Reliability Problem of Radial Electric Distribution Systems Through Artificial Intelligence

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Abstract: In this paper the distribution electric system reliability is recognized like an artificial intelligence problem. How this idea is applied in evaluation of reliability is detailed. Concepts as Intelligence Matrix and Inter-feeder Route are defined. From the last one a reliability prediction strategy for medium voltage networks is proposed and tested.

Keywords: Artificial intelligence, agent, searching, primary route, secondary route

1 Introduction

It has been established that within an electric system, nearly 80% of the faults occur in the distribution system, (Billinton and Allan, 1998). Legal aspects protect the costumers from faults in the electric system. So it's necessary, for electrical companies, to guarantee a high level of security, quality and reliability in the service. Companies are not only affected by the demanding norms but also by high financial lost due to energy non-sell and penalties. The reliability is evaluated using the markovian models (Brown and Gupta, 1998; Asgapoor and Mathine, 1997 Brown, et al., 1997 Brown and Ochoa, 1998) or different analytic methods (Billinton y Wagn, 1999), that, according to the past behavior, they make an extrapolation of its future one. This paper is based in developing a method that makes possible the prediction of distribution system's behavior in terms of reliability, addressing it to the Artificial Intelligence (AI). This is capable of giving information in terms of representative indexes in the points of loading and overall system, including alternative supply in case of the principal feeding's failure. When considering the AI, we intent to model the distribution system's reliability and developing concepts to be used in the solution of a generic problem that requires topological analysis. Therefore, emphasis is made in searching problems as AI's tasks.

Within the AI's wide world we find the searching's problems (Russell and Norvig, 1996). Once the problem is defined (this action is called the "abstraction") the process starts from an initial state. Then, operators are applied to the present state, resulting in a new set of states. This process is called "expansion" state. The essence of the search is to choose one option and to put all the others aside to be expanded afterwards, just in case the first election does not reach solution. The dilemma of which state to be expanded first is determined by the "strategy of search". The process of searching can be included as the construction of a search tree that is superposed on the space of states where the node of roots is the initial state whereas the nodes leaves are states that do not have successor in the tree. (because they have not been expanded yet or because they have already been expanded but they generate an empty state). An efficient strategy of search is named "depth-first search". This strategy always expands one of the nodes at the deepest level of the tree and only when the search finds its end (a goal state or one without expansion) the search continues expanding nodes of less deeper level.

2 Proposed method

The algorithm has the mission or purpose of finding the failure modes of the system. The hypotheses are: The elements of protection are a 100% reliable. The fault is determined by first order cut. The first step of the method is to make a protocol of nodal assignation. It consists in labelling a bus or node of distribution with number 1 and the branches with ascendant (rising) numbers from the departure node to full stop of load, in the form shown by the arrows in figure 1.

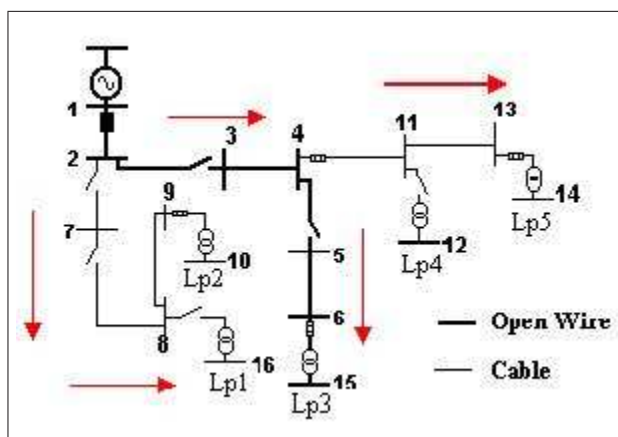


Figure 1: Basic System

Next the space of state is defined, the one that corresponds to the environment in which the agent can move to find the solution. According to the above for the basic system of test (BS), figure 1, the states are defined by each one of the buses of the system. The BS consists of 16 buses and 5 points of load (Lp). There are 16 possible states by which the agent can "travel" with the purpose of satisfying the test of goal. The information related with the topology of the BS is in the so called "Intelligence Matrix"(IM) which forms the base of the algorithm of search. Part of the IM corresponding to the BS is shown in figure 2

	1	2	3
1		L	
2	L		L
3		S	

Figure 2: Part of IM for the Basic System

The numbers for the rows and columns are the nodes or buses. The procedure to enter the data consists of entering the components between two consecutive nodes, identifying it with a letter and associating it with the respective element of the IM. For BS, between the node 1 and 2 there is a line, indicated by an L in the position of the element [1,2] of the matrix. The same for the element [2,1]. When there is a switching or protection device (as between nodes 2 and 3) or when there is a line and a disconnects, the element, [2,3], is defined with an L (line). In the position [3,2] you enter an S (disconnects) indicating that the switching device is closer to bus 3. This directional quality or differentiation of the common elements of the system with those of switching and/or protection is conclusive in the optima resolution of the problem, this is the reason of the name "Intelligence Matrix". Specially, for the evaluation of the indicator of future reliability, en the BS are identified:

Initial State: The search begins from the point of load to evaluate.

Operators: The agent can "jump" or "travel" from a particular state towards the next closer, i.e., from [3,2] to [2,1]. In direction to the node of generation (ascending form) or towards the other point of load (descending form).

State Space: The states extended by the agent from the load point (initial state).

Route: The route from one state to another within the space of states.

Goal Test: It corresponds to have extended all the possible states in which any eventual fault may produce a lost in supply energy to the load point evaluated.

Cost of Route: Unit cost in order to travel from one state to the next nearest one.

Solution: It corresponds to the result of the algorithm of search once the goal is fulfilled.

In accordance to the above the complete IM for the BS is shown in figure 3. The non-existence of elements in the system is indicated with blank spaces in figure 3. In order to find the failure modes of system, the algorithm must identify the primary route and the secondary route (López et al, 1998). The IM of the BS shows that the diagonal divides the information of the different routes. The last one, due to the arranged assignation of the number of nodes. On the other, the algorithm uses the "best first search", then, the best expanding option occurs at first. In this case, it corresponds to the primary route. It leaves, in "waiting queue", the secondary routes for the next expansion.

2.1 Getting the Primary Route

The primary route is the minimal cost one from the load point to the feeding node. The information about the primary route is contained under the principal diagonal of the IM. The primary route of each load point is stored in a matrix called "matrix of primary route" (MPR). Though each row will contain the primary route corresponding to a load point. The MPR is of order $m \times n$ (load point \times nodes) and initially is a null matrix. Its formation is ordered and it is starting with the agent in the first load point (Lp1). In the intelligence matrix the row corresponding to the node number, that has the load point, is checked. Then the elements contained under the diagonal are examined. When finding an element within the search sector, in the row of the matrix of primary routes, the number of the next node that corresponds is entered. The number of the column that corresponds to the found element gives this node. Then, is verified the row corresponding to the next node of the primary route and so on, until arriving at node 1 of the feeding. The figure 4 outlines the way of how to find the primary route for the load point Lp1. It corresponds to the node 16. Figure 5 shows the BS's matrix of the primary route (MPR of BS). Regarding to the agent like an "problem-solving agent" (Russell and Norvig, 1996) and one state as a structure of simple data, the agent is placed in a problem of determining the route. The agent corresponds to an algorithm of resolution that uses a sequence of actions to follow in order to obtain its goal. The "resolutor-agent" of the simplified problem, in order to find the primary route, corresponds to figure 6. This agent is executed for each load point (Lp) and ends or gets to the goal, when finding the feeding node (node 1). The route of the agent corresponds to the one shown above in figure 4. It is observed in figure 6 that the agent has two rules (if condition, then action). They take step from a basic and incipient system to an expert one that has the particularity to provide a great flexibility by the time of incorporating new knowledge. The incorporation of a new rule is enough for it, which don't need to change the algorithm's behavior.

2.2 Secondary Routes

At the moment the "resolutor agent" of the primary route crosses the system and full the matrix of primary route, MPR. A vector is added that stores the quantity of nodes including each primary route. This vector is called "cont". By knowing the dimensions of each primary route (cont) the agent can track the secondary routes 'looking' for it in the superior diagonal of the IM. The last one for each one of the nodes that the primary route contains. Extending the first secondary routes nearer to the feeding and leaving in delay the rest of the routes in the nearest nodes to the load point does this. For this, the MPR in inverse form is crossed. For example, for the load point Lp1 the first secondary routes that are originated in node 1, then those of node 2, 7, and 8 are extended, to arrive to node 16 which corresponds to the node that contains the load point. The search of these routes is similar to which is made in the primary routes, but with some restrictions.

One of them is that the agent must finish the search at the moment a fuse is found and must begin to extend the following one that is in delay. As secondary routes are subdivided in different branches, it is

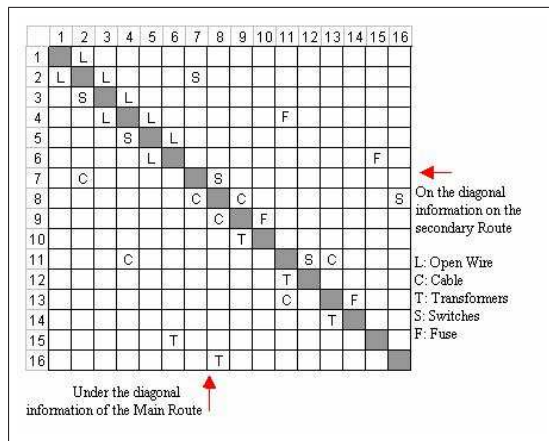


Figure 3: Intelligence Matrix corresponding to BS

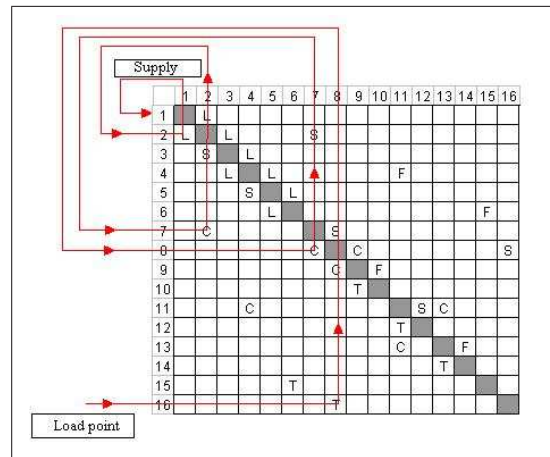


Figure 4: Searching the primary route for Lp1 (node 16)

necessary to store the nodes that at the moment of the distance traveled (on the diagonal of the matrix) will have to wait until the previous one in its deeper level extends (point of neighboring or fusible load). For this, it is strictly necessary to store four data of the node to expand:

Lp1	→	16	8	7	2	1	0	0	...	0
Lp2	→	10	9	8	7	2	1	0	0	0
Lp3	→	15	6	5	4	3	2	1	0	0
Lp4	→	12	11	4	3	2	1	0	0	0
Lp5	→	14	13	11	4	3	2	1	0	0

Figure 5: Matrix of primary route (MPR) for the BS

- The preceding node is required in case that there is a switching or protection device in the arrival of the node. These elements can involve the end of the route searching or a change in the repairing time to switching time.
- The node to expand, is the node that indicates in which row of the intelligence matrix, to look for the elements that form the secondary route and if there are more elements that will be needed to expand more ahead.
- The node towards which the agent travels, gives the direction in which the search takes place.
- Condition in which it is found, considering the time of repairing or switching, essential condition for the calculus of the unavailability.

These data are stored in a matrix of 4 rows and a undetermined number of columns. It is filled during the route and it is an uncertain number at first. This matrix has the name of "extend" and determines the end of the process of searching as the last element in delay expands. The simplified agent to find the secondary routes is summarized in figure 7. This agent is executed for each primary route, i.e., for each load point it finds all the corresponding secondary routes. It is also observed that it conditions on switching time the rest of the route in case of finding a disconnects (S) and ends the route when finding a fuse (F). The end of this agent corresponds to the extension of the last secondary route (on the primary route) and that there aren't any nodes in delay waiting to be extended.

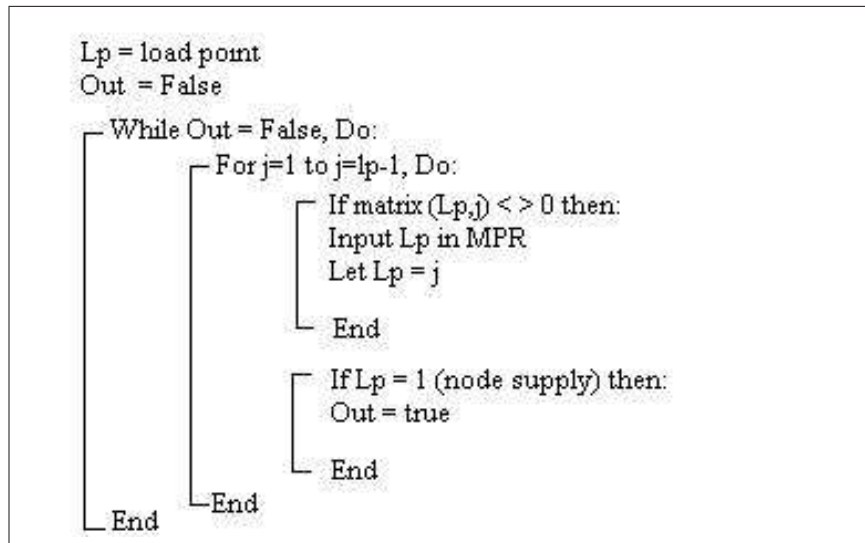


Figure 6: Simplified agent to find the primary route

2.3 Rate of failure and Unavailability

For a load point it is possible to calculate its rate of failure and its unavailability by adding those that correspond to primary or secondary routes. The time of shut down is the quotient between the total unavailability of the load point and its corresponding rate of failure.

$$\text{Rate of failure : } \lambda(lp) = \lambda_{pr}(lp) + \lambda_{sr}(lp) \quad (1)$$

$$\text{Unavailability : } U(lp) = U_{pr}(lp) + U_{sr}(lp) \quad (2)$$

$$\text{Outage time : } r(lp) = \frac{U(lp)}{\lambda(lp)} \quad (3)$$

In the primary route: the information stored is checked in the MPR. A rate of failure is assigned to each element. This information has been entered in a routine of parallel data entrance, to the IM. The sum of the rates individual failures provide the rate of failure of the primary route for the load point $\lambda_{pr}(lp)$. The unavailability of the primary route is the sum of individual unavailability of the elements involved in it, without considering the presence of the switching devices.

In the secondary routes: while the search is made the rates of individual failures of the elements in this route are added. At the same time, the unavailability of the secondary routes is being calculated. At the beginning, the unavailability is related to the repair time of the element, when a switching device is found the unavailability is associated to the switching time and this is kept from this node to the end of the corresponding secondary route. As long as one advances in the search the individual unavailability's are added. At the end of the process the results are the unavailability, $U_{sr}(lp)$ and the rate of failure $\lambda_{sr}(lp)$ of the secondary routes by load point. The way in which the algorithm is worked is shown in figure 9 (getting the mode of failure for the Lp1). With a different color the point where the disconnects is indicated, which conditions to use the time of switching for the rest of the route.

2.4 Considering the Alternative Feeding

A system with alternative feeding diminishes the times of unavailability to the customer. Before making any calculus, it necessary to know where the alternative feeding is. For the previous, the "Inter-

feeding route" that joins the main feeding with the alternative feeding is defined. The corresponding agent is similar to the *"resolutor agent"* that finds the primary route (under the diagonal of the matrix). But instead of beginning at the load point (Lp), it starts its nodal search where the alternative feeding is. This route is stored in a vector called *"ralt"*. In the first place, the inter-feeding route is located. Then, it is compared with the primary routes for each load point settling down the intersection point among them. Then, a pursuit between the main feeding and the intersection point is done, where the agent has to realize if there is a switching device in this sector. If not in this route, a calculus is made in a traditional way, without affecting the alternative feeding. If there is a switching device between the main feeding and the intersection point of the routes, this conditions all the elements that are found between the switching device and the main feeding, in case of a possible fault to only consider the time of switching, since this one is isolated, connecting the alternative supplies. This lightens the search, since the agent leaves the search of other switching devices in that sector to assign times. The rest of the system is analyzed as if there is no alternative feeding. Considering the BS with alternative feeding in the node 11, nodes-1 - 2 - 3 - 4 - 11 form the inter-feeding route for that configuration. For the LP3 (node 15), the intersection of the primary routes, the Inter-feeding and the switching device in [3,2] are shown in figure 11 The existing switching device conditions a great part of the system to a time of switching. This same example is considered, in terms of evaluating the Lp1 (node 16). The primary route of this load point only intersects in node 2 with the inter-feeding route and there is no switching device between node 2 and the main feeding, in which the alternative supply does not influence the index calculus.

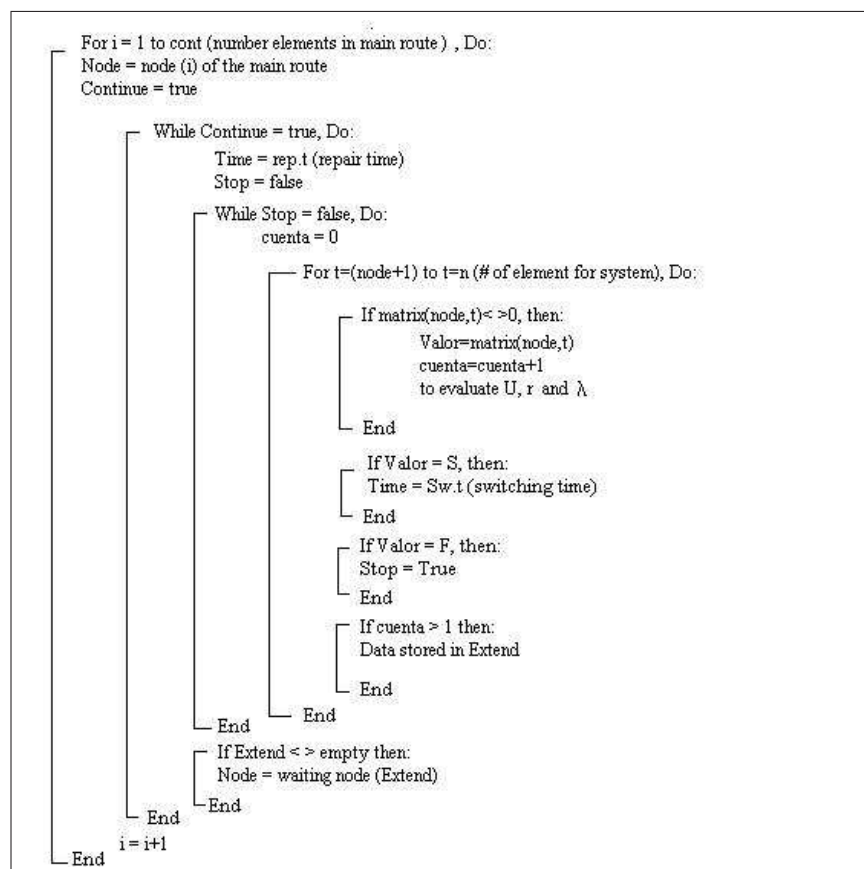


Figure 7: Simplified agent finding the secondary routes

3 Applications

The algorithm was applied to several distribution systems. In this document 4 of them are presented: the basic system (BS), two RBTS feeders (Billinton and Kumar, 1989; Allan et al., 1991) and a real system.

3.1 Basic system

This system was created to replace the necessity of having a small distribution system (DS) that had the complexity and diversity of a real one. The system has 5 load points and a primary feeding in node 1. The elements corresponding to a conventional DS are also present, such as: line, cables, fuses, transformers, switching devices, and so on. The modes of failure, the times of switching and repairing used correspond to those indicated in the IEEE St. 493 (1990). The results are indicated in Table 1.

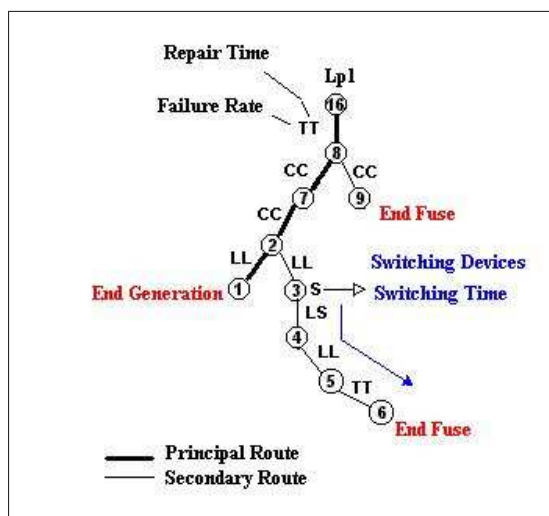


Figure 8: Mode of failure Lp1 (node 16)

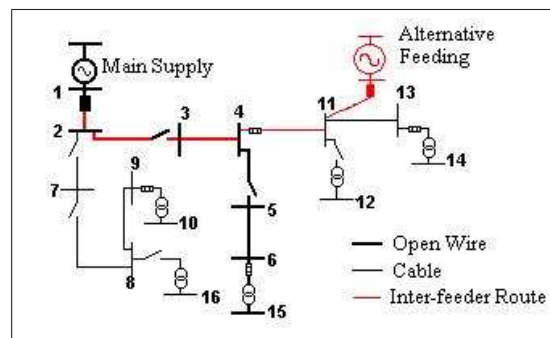


Figure 9: Inter-feeding Route. Alternative supplies in 11

3.2 RBTS System (Roy Billinton Test System)

This is a test system that is divided in 6 buses. Bar 1 is the feeding of the system, whereas bus 2 to 6 correspond to the load buses. The whole system shows different level of tension which it works 220, 138, 33, and 11 kV. With the purpose of proving the algorithm, the reliability of the feeder 1 of buses 2 and 4 are evaluated, corresponding to a level of 11 kV. Table 2 gives the result of the reliability indexes.

3.3 The CGE's Feeder

This feeder is inserted in the CGE's distribution system. This has 70 elements and 33 load points. For its evaluation the same considerations of the experimental feeder are applied. Three evaluations to the system were made. Case 1: Future Reliability Evaluation. Case 2: Future Reliability Evaluation considering the Alternative Feeding in node 27. Case 3: Future Reliability Evaluation considering the Alternative Feeding in node 55. Table 3, show the results of the reliability evaluation for the three different cases given.

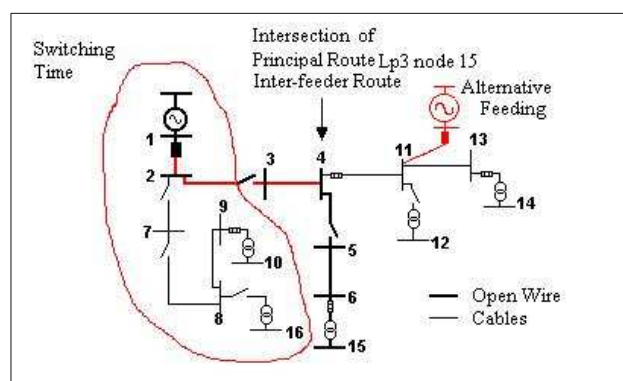


Figure 10: Switching zone and Lp3-alternative supplies

		Alt	Node 5
		Alt	Node 11
NERC indexes			
SAIFI		0.3963	0.3963
SAIDI		4.4847	4.0171
CAIDI		11.3159	10.1359
ENS	MWh/year	21.396	19.102
CIER indexes			
F		0.3964	0.3964
T		4.4576	3.9616
D		11.2442	9.9931
END		21.396	19.102

(CIER: Regional electric inter-american council)

(NERC: National electric reliability council)

Table 1: Reliability indexes of the basic system

4 Analysis of Results

The index of future reliability for each system as the NERC presents was obtained, those that are associated to the client. The index corresponding to the CIER; that referring to the power (kVA) were calculated. These last ones are of great importance due to the fact that these are the authorized by the CNE (national energy council) in Chile through the General Law's Regulation of the Electric Service (1980). Table 1 shows the difference between the alternative feeding in some of the BS's nodes in respect to the same system with only a main feeding. An important improvement is observed in the reliability's index when considering the alternative feeding. If the analysis is centered in one of the index as the average time of fault is, when applying the alternative feeding in node 5 a diminish in time of 11%, can be proved. By applying the same alternative feeding in point 11 the diminishing time of fault was around 7.6%. This is justified whereas node 5 is in the biggest point load of the feeder and there is a switching device immediately before the connection of the new feeding. The RBTS system was useful in confirming the good behavior of the proposed algorithm. This system, though being small, was very easy to follow with a hand calculator, in a addition to the complete results base already given in the Brown et al., (1997). Referring to the results (Table 2) the most important is to see the effect that is produced in the reliability the connection to the client from the main one with a disconnects (bus 2) or with two disconnects isolating the client in both sides (bus 4). A this difference is only remarked by the fact that both bus's feeders consider an alternative feeding. With this specific fact and in similar conditions the

	RBTS 2.1	RBTS 4.1
NERC indexes		
SAIFI	0.2488	0.3021
SAIDI	3.6193	3.4694
CAIDI	14.5443	11.4849
ENS	13.155	12.196
CIER indexes		
F	0.2477	0.3031
T	3.6090	3.4746
D	14.5696	11.4630
END	13.155	12.196

Table 2: Reliability indexes of the RBTS systems

best reliability is obtained in the bus 4’s feeder. This is clear since with the possibility of having an alternative feeding from both ends, the most advisable it is to maintain the client with the switching. This means that before a possible fault, the client can isolate himself of the extreme in which the fault is produced and can keep connected with the other end in which the feeding remains, diminishing therefore the times of unavailability and improving the reliability of the system. For the CGE’S feeder just like the previous cases, got good results being within the established limits for F and T (Ministry of Mining, 1980). In Table 3 it is possible to see that the unavailability index decreases when considering alternative feeding. For the alternative feeding en node 27, the algorithm obtained a decrease of 15.6% en the unavailability. In as much as if the alternative feeding is in node 55, the decrease in the unavailability is of 24,5%. The differences between values is directly related with the amount of the existing switching devices. All results were checked with theoretical or manual analysis to assure the correct execution of the developed algorithm.

	Case 1	Case 2	Case 3
NERC indexes			
SAIFI	0.3222	0.3222	0.3222
SAIDI	2.8079	2.3575	2.1948
CAIDI	8.7139	7.3162	6.8112
ENS	12.410	10.470	9.3700
CIER indexes			
F	0.3198	0.3198	0.3198
T	3.2547	2.7458	2.4573
D	10.176	8.5849	7.6830
END	12.410	10.470	9.3700

Table 3: Reliability indexes of CGE System

5 Conclusions

This paper deals with the problem of the future reliability of a distribution system through AI. The solution considers the process of "searching" placed in the field of the AI. The approach presented in this paper is a powerful tool in distribution system reliability prediction. Its kindness was demonstrated in many evaluations that were made in systems with completely different characteristics. As it was expected, the results obtained were consequent with the theoretical and practical considerations of the

problem. The model proposes the concepts of "Intelligence Matrix" and "Agent". A very remarkable aspect of the conjunction matrix-agent is the facility with which it deals with the elements of protection and switching devices to value the importance of the strategic location of these elements. Furthermore the "Intelligence Matrix" gathers a condition so that the "Agent" works in an efficient way within the topological search. His connections make the run in an efficient and rapid way to complete the layout of the routes that involves the distribution reliability's calculus. This point is the clue of success in the search tree-failure modes.

A second significant contribution corresponds to the route concept "Inter-feeding" helping to harness the model in which it says to be related with the option of alternative feeding. With the help of this a decrease in the unnecessary expenses of time and computer memory was obtained. This, as well, becomes a potential tool of evaluation of the ideal positioning of an alternative point of feeding in a real system of distribution.

From a more general perspective, we can conclude that the use of this model prevents important economical measures, in which the electric companies could commit or incur when not having a suitable control.

Finally, the investigation's development resulted in the necessity to deepen in ordaining the switching and protection devices, that can lead to obtain the best reliability of the system.

References

- [1] Asgarpoor S. y M. Mathine, Reliability Evaluation of Distribution Systems with Non-Exponential Down Times. *IEEE Transactions on Power Systems*. Vol. 12, No. 2, 1997.
- [2] Allan R., R. Billinton, I. Sjarief, L. Goel and K. S. So, A Reliability Test System for Educational Purposes - Basic Distribution System Data and Results, *IEEE Transactions on Power system*, Vol. 6, No. 2, 1991.
- [3] Billinton, R. y Allan, R., Reliability Assessment Of a Large Electric Power Systems. *Kluwer Academic Publishers*, Boston, USA, 1988.
- [4] Billinton R y S. Kumar, A Reliability Test System for Educational Purposes - *Basic Data IEEE Transactions on Power Systems*, Vol. 4, No. 3, 1989.
- [5] Billinton R., y S. Jonnavithula, A Test System for Teaching Overall Power System Reliability Assessment, *IEEE Transactions on Power Systems*, Vol. 11, No. 4, 1996.
- [6] Billinton R., y P. Wang, Teaching Distribution System Reliability Evaluation Using Monte Carlo Simulation, *IEEE Transactions on Power Systems*, Vol.14, No. 2, 1999.
- [7] Brown R., S. Gupta, R. D. Christie, S. S. Venkata y R. Fletcher, Distribution System Reliability Assessment Using Hierarchical Markov Modeling, *IEEE Transactions on Power Delivery*, Vol. 11, No. 4, 1996.
- [8] Brown R., S. Gupta, R. D. Christie, S. S. Venkata y R. Fletcher, Distribution System Reliability Assessment Momentary Interruptions and Storms, *IEEE Transaction on Power Delivery*, Vol. 12, No. 4, 1997.
- [9] Brown R., y J. Ochoa, Distribution System Reliability: Default Data and Model Validation, *IEEE Transactions on Power Systems*, Vol. 13 No. 2, 1998.
- [10] IEEE St 493, *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*, 1990.

- [11] López E., Tardon C., Contreras V., Reliability evaluation of primary distribution systems via search tree, *Procc. of International Congress of ACCA/IFAC Automatic Control Association 2000*, Santiago of Chile, 1998.
- [12] Ministry of Mining, *General Law of Electric Services. Official Newspaper of the Republic of Chile*, 1998.
- [13] Russell S y P. Norvig, *Artificial Intelligence. A Modern Approach*, Editorial Prentice Hall & Hispanoamericana S.A., 1996.

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