Optimal Placement of Line Switches for Distribution Automation Systems Using Immune Algorithm

Chao-Shun Chen, Member, IEEE, Chia-Hung Lin, Member, IEEE, Hui-Jen Chuang, Member, IEEE, Chung-Sheng Li, Ming-Yang Huang, and Chia-Wen Huang

Abstract—To enhance the cost effectiveness of the distribution automation system (DAS), this paper proposes the immune algorithm (IA) to derive the optimal placement of switching devices by minimizing the total cost of customer service outage and investment cost of line switches. The reliability index of each service zone defined by the boundary switches is derived to solve the expected energy not served due to fault contingency, and the customer interruption cost is then determined according to the customer type and power consumption within the service zone. To demonstrate the effectiveness of proposed IA methodology to solve the optimal placement of line switches, a practical distribution system of Taiwan Power Company (Taipower) is selected for computer simulation to explore the cost benefit of line switch placement for DAS.

Index Terms—Distribution automation system (DAS), immune algorithm (IA), outage management system (OMS).

I. INTRODUCTION

WITH the economic development and computer application, the power quality has become a more and more critical concern for utility customers. The power companies have to improve overall customer satisfaction through enhancement of service quality in order to maximize the customer retention. For this reason, distribution automation systems have been implemented in Taipower as an intelligent technology to enhance the reliability and operation efficiency of distribution systems.

Among all functions to be achieved by the distribution automation system (DAS), the fault detection, isolation, and restoration (FDIR) is considered to be the most important one, with the objective to reduce the service restoration time from an average of 58 min to less than 20 s for the permanent fault contingency of distribution feeders. Table I illustrates the reliability indexes of system average interruption duration (SAIDI) and SAIFI of Taipower system from 1998–2003. It is found that the system average interruption duration index (SAIDI) in 2003 is 39.7 min/customer-year. With the application of DAS to shorten the outage duration time, it is expected that system SAIDI can be reduced to be 21 min/customer-year in 2008 [1]. To achieve this purpose, a fully integrated DAS in Fig. 1 is designed to include a master station (MS) with application software, remote terminal units (RTUs) in the substations, feeder terminal units (FTUs), and automatic line switches along primary feeders [2].

With so many feeders and sectionalizing switches in the Taipower distribution system, the placement of line switches becomes a very difficult and tedious problem to be solved by the conventional optimization techniques because of voluminous combinations to be investigated. With the installation of line switches in the distribution system, the reliability indexes of customer service zones can therefore be evaluated according to the installation locations of line switches.

Several approaches have been proposed to solve the problem of switch placement for distribution systems, which are 1) a decomposition approach [3]; 2) a reliability cost/worth approach [4]; and 3) a value-based method [5]. However, most of these efforts deal with the manual line switch placement by considering the customer interruption cost or system reliability enhancement. In this paper, the placement of both manual and automatic line switches is considered for a distribution system with...
DAS function. The reduction of customer interruption cost due to FDIR action and investment costs of automatic line switches and master station are included in the objective function.

The effectiveness of the immune algorithm (IA) to solve complicated optimization problems has been illustrated in many previous case studies [6]–[11]. In this paper, an economically-based fitness function is used for the IA to determine the optimal locations of automatic switches and normal open tie switches for the existing distribution system with 11 feeders. Besides, the IA is also applied to solve the number of automatic/manual switches for an actual Taipower distribution system with 11 feeders. By comparing to the genetic algorithm (GA), the IA does provide the following advantages to solve the optimization problems.

1) The memory cell is maintained without applying operators, such as recombination, selection, etc., to the population.
2) It operates on the memory cell that guarantees the fast convergence.
3) The diversity of the immune system is embedded by means of affinity calculation.

In this paper, the objective function with constraints to be subjected for the optimal placement of line switches is expressed as the antigen inputs. The feasible solutions are represented as the antibody for the IA to solve the optimization problem. A binary/integer mixed coding system is developed to accelerate the speed to obtain the high-quality solution without using a long binary string. The genetic operators, including crossover and mutation, are then processed for the production of antibodies in a feasible space. With the operation of IA on the memory cell, the very fast convergence will be obtained during the searching process by applying the information entropy as a measure of diversity for the population to avoid falling into a local optimal solution. The effectiveness of the proposed IA to solve line switch placement is then verified by comparing to the classical GA.

II. TECHNICAL WORK PREPARATION PROBLEM DESCRIPTION AND FORMULATION

To evaluate the service reliability of the Taipower distribution system, the number of customers affected and outage duration time for each fault contingency is generated in the data logging of the outage management system (OMS). By performing the statistic analysis of service outage, the customer interruption cost (CIC) of a distribution system is expressed as [5]

\[
\text{CIC} = \sum_{i=1}^{n} \text{IC}_{i} = \sum_{i=1}^{n} \lambda_{i} \left( \sum_{j=1}^{m} C_{ij} L_{j} \right)
\]

where \(n\) is the total number of line segments, \(\text{IC}_{i}\) is the interruption cost per year due to outages in line Segment \(i\), \(\lambda_{i}\) is the outage rate (failure/km-year) of line Segment \(i\), \(L_{j}\) is the length of line Segment \(i\), \(C_{ij}\) is the interruption cost of load at Segment \(j\) due to an outage at Segment \(i\), and \(L_{j}\) is the total load of line Segment \(j\).

The \(C_{ij}\) in (1) represents the integrated interruption costs of different types of customers, which have been derived for the residential, commercial, and industrial customers, respectively [12]. Besides, three different categories of key customers with high service priority levels are considered in this paper. The higher hierarchy level of customers denotes the more critical power service.

Level 1: the customers with power outage could be affected by inconvenience or public concern (schools, supermarkets, sport and entertainment facilities, etc.)

Level 2: the customers with power outage could result in serious financial damage (banks, oil refineries, high technology plants, etc.)

Level 3: the customers with power outage could jeopardize the public security (hospitals, police stations, fire stations, important telecommunications, etc.)

\[
C_{ij} = (\text{Res}_{j} \cdot f_{R}(r_{ij}) + \text{Com}_{j} \cdot f_{C}(r_{ij}) + \text{Ind}_{j} \cdot f_{I}(r_{ij}) + \sum_{l=1}^{3} \text{Pri}_{l} \cdot f_{P}(r_{ij}))
\]

where \(\text{Res}, \text{Com}, \text{Ind},\) and \(\text{Pri}\) are the load percentages of residential, commercial, industrial, and key customers; \(f_{R}, f_{C}, f_{I},\) and \(f_{P}\) are the interruption cost functions of residential, commercial, industrial, and key customers; \(r_{ij}\) is the duration of service interruption of Segment \(j\) due to a outage at Segment \(i\); and \(l\) is the hierarchy level of key customers.

To solve the load percentages of Res, Com, Ind, and Pri customers within each service zone, the customer-to-transformer mapping is retrieved from the facility database of the OMS system. Besides, the daily load patterns of different customer classes are derived by a load survey study [13], and the energy consumption of each customer is retrieved from the customer information system (CIS) database. The hourly loading of each service zone is then obtained by integrating the power profiles of all customers served. Fig. 2 shows the overall structure of reliability assessment for distribution systems.

As described previously, the objective of service reliability improvement is to reduce customer service outage cost by proper placement of line switches. To solve the problem, the distribution system has to be reconfigured by rearranging the normally close/open switches and replacing part of the manual switches by automatic switches to achieve fast restoration of customer service by remote operation of automatic line switches. In this paper, the total cost of reliability (TCR) to be minimized is defined as

\[
\text{Minimize } \text{TCR} = \text{CIC} + \text{INVC}
\]
and feeders. In the Taipower distribution system, the rated loading levels of main transformers and feeders are defined as 450 and 1450 A, respectively.

2) The voltage drop of line conductors along the feeders has to be less than 5% after the proposed switching operations. In order to avoid large circulation current to cause further tripping of distribution feeders after closing the open tie switching for non-interruptible load transfer, the phase sequences must be the same, and the difference of voltage magnitudes and phase angles between both sides of the open tie switch must be less than 10% and 10°, respectively.

III. IMMUNE ALGORITHM

The immune algorithm (IA) has been widely used to solve the optimization problems by applying the same operating principle of the human immune system. The capability of the IA method for pattern recognition and memorization does provide a more efficient way to solve the discrete optimization problem as compared to the GA. The objective function and limit constraints are represented as antigen inputs, while the solution process is simulated by antibody production in the feasible space through the genetic operation mechanism. The calculation of affinity between antibodies is embedded within the algorithm to determine the promotion/suppression of antibody production. Through the IA computation, the antibody that most fits the antigen is considered as the solution for the optimization problem.

An IA-based decision making [14] is proposed in this paper to find the optimal locations of manual switches to be automated for the existing distribution system and to solve the optimal placement of automatic/manual line switches for the new developing distribution system. The population of memory cells is a collection of the antibodies (feasible solutions) accessible toward the optimality, which is the key factor to achieve fast convergence for global optimization. In this paper, the genetic coding structure for the IA is adopted, and the diversity and affinity of the antibodies are calculated during the decision-making process to find the optimal switching placement. The data structure of genes can be depicted as shown in Fig. 3, where Sw-No(i) represents the candidate solution of automatic/manual switching placement. For a feeder pair with N possible strategies of switching placement with M switches, it will generate N antibodies having M genes in the antibody pool.

By applying the immune algorithm to solve the optimal placement of line switches, the attributes of line switches, such as operation status (open/close), type (automatic/manual), and installation locations, are combined and represented as a three bits with binary/integer mixed coding in each gene structure, as shown in Table II.

A. Diversity

The diversity is measured between the antibodies, and it is increased to prevent local optimization during the optimal switching placement search. For each evolving generation, the new antibodies are generated to strengthen the diversity of antibody population in the memory cell. With the data structure of genes in Fig. 3, the entropy $E_j$ of the $j$th gene ($j = 1, 2, \ldots, M$) is defined as [15]

$$E_j = - \sum_{i=1}^{N} P_{ij} \log P_{ij}$$

where $N$ is the quantity of antibodies, and $P_{ij}$ is the probability that the $j$th allele comes out at the $j$th gene. If all alleles at the $j$th gene are the same, the entropy of the $j$th becomes zero. From
(4), the diversity of all genes is calculated as the mean value of informative entropy

$$E = \frac{1}{M} \sum_{j=1}^{M} E_j$$

(5)

B. Affinity

The affinity of antibodies is an important index for the IA during the optimization process. If the affinity of some antibodies is the same during the immune process, it will influence the searching efficiency of optimization for the planning of switch placement. Two types of affinity are calculated for the proposed IA in this paper. One is the affinity between antibodies

$$\text{Affinity between antibodies } (AB)_{ij} = \frac{1}{1 + E(2)}$$

where $E(2)$ is the information entropy of these two antibodies. The genes of the $i$th antibody and the $j$th antibody will be the same when $E(2)$ is equal to zero. The affinity between the $i$th antibody and the $j$th antibody, $(AB)_{ij}$, will be within the range $[0, 1]$.

The other one is the affinity between antibody (candidate of optimal placement of line switches) and antigen (the objective function)

$$\text{Affinity between antibody (candidate of optimal placement of line switches) and antigen } (Ag)_i = \frac{1}{1 + \text{TCR}_i}$$

(7)

where TCR$_i$ is the total cost of reliability evaluated by (3) to represent the connection between the antigen and antibody $i$. The antigen with the maximum affinity $(Ag)_i$ will be the optimal switch placement within the feasible space.

C. Computation Procedures

The process to solve the objective function for optimal placement of line switches is simulated by the interaction of antibody and antigen in the immune algorithm. During the evolution of genes, the candidates of switch placement planning with high affinity are selected and included in the memory cells, which will be used to generate new candidate planning. The computation procedure of the IA method is executed as follows.

Step 1—Recognition of Antigens: To solve the optimal switch placement planning, the total cost of reliability of each possible solution subject to operation constraints is calculated in this step. The binary/integer mixed coding is adopted for the antigen pattern to represent the relationship of genes and physical switching placement planning in the objective function for the computation process.

Step 2—Production of Initial Antibody Population: A random number generator is applied to generate the antibodies in the feasible space. All of antibodies and a group of genes are considered to form the antibody pool. Some of the antibodies will be from the memory cells with higher affinity during the searching process to generate a new set of antibodies. Each pair of gene and antibody represents a possible solution for the optimal switching placement in a feeder pair, respectively.

Step 3—Calculation of Affinity: In this step, the affinity between antibodies $(AB)_{ij}$ and the affinity between antibodies and antigens $(Ag)_i$ are calculated by (6) and (7), respectively, as the references in the following evaluation process.

Step 4—Evaluation and Selection: The antibody having high affinity with the antigen is added to the new memory cells. To maintain the size of memory cells and ensure the speed of convergence, the diversity of memory cells is calculated, and the antibody with high affinity (namely, $(AB)_{ij}$ close 1) is removed so that the violation of the size constraint of memory cells can be prevented. A roulette selection algorithm is implemented by considering the affinity of antibodies to form a new antibody pool by spinning the desired roulette. Since most of the selected antibodies have higher affinities with the antigen, the average affinity of the new population pool will be higher than that of the original pool to obtain better evolution during the IA optimization process.

Step 5—Crossover and Mutation: After the selection of antibody generation, the operations of crossover and mutation for the new generated antibodies are performed. The crossover operation is performed by applying the one-cut-point method,
which randomly selects the mating point and exchanges the gene arrays of the right-hand portion of the mating points between two antibodies. The mating operation will prevent the search process from local optimization by increasing the diversity of the antibody population. According to the predefined mutation rate, mutation is executed to perform the occasional random alteration of the value for an antibody position.

Step 6—Decision of Optimal Switching Placement: During the immune process, the antibody having high affinities with the antigen will be added to the new memory cell, which will be maintained after applying the operation of crossover, mutation, and selection for the population. The search process of optimization continues until no further improvement in relative affinity can be obtained, and the antibody with the highest affinity in the memory cell will be the optimal strategy for line switch placement. Fig. 4 shows the flowchart of the overall solution process to achieve the optimal placement of line switches with the proposed immune algorithm.

IV. NUMERICAL ANALYSIS

In this paper, the proposed immune algorithm is implemented with Matlab on a Pentium-IV personal computer. Based on the sensitivity analysis of simulation test results, the antibody pool, the crossover rate, and the mutation rate are determined as 100, 0.8, and 0.1, respectively, to achieve fast convergence for the optimization of line switch placement by the IA algorithm. A sample distribution feeder pair and one of the Taipower distribution system are selected for computer simulation in this paper.

A. Case 1: Simulation of a Distribution Feeder Pair

Fig. 5 depicts the one-line diagram of a feeder pair with 20 line segments and 19 load points. Besides, two key customers (large-scale hospital) are served at LP10 and LP12, respectively. Each line segment of the feeder-pair is a candidate location for automatic/manual switching placement. A tie switch will be installed between Feeders F1 and F2 for emergency service restoration by load transfer. The failure rate, repair rate, and time required to complete load transfer have been derived by statistic analysis according to the customer outage information retrieved from the OMS system in Table III. The investment costs of overhead automatic/manual switches are US$9071 and US$581, respectively, [16] with life cycle of 15 years. The costs of FTU and communication equipment have also been added to the automatic line switches as the auxiliary equipment for the DAS system.

According to the interruption cost in [12], the outage cost functions of residential, commercial, and industrial customers have been derived by assuming a inflation rate of 3% in Fig. 6. Here, the interruption costs of key customers are determined based on the field survey in Taipower.

For the feeder pair in Fig. 5, the total reliability cost (TCR) for the distribution system by installing a different number of line switches has been solved and illustrated in Fig. 7. It is found that the TCR can be minimized by the placement of three automatic switches and three manual switches for the test feeder pair. The automatic open-tie switch is placed on Segment 11. Table IV shows the reliability indexes of SAIDI, SAIFI, and expected customer interruption cost (ECOST). The SAIDI of Zones 4 and 5 are smaller than that of the other zones when three automatic switches are installed on Segments 9, 10, and 11. Besides, the ECOST of L10 and L12 are larger than other load points because of the larger interruption cost of key customers served.

Fig. 8 shows the reduction of TCR with evolution generations by the proposed IA method and conventional GA [17]. More significant improvement of TCR has been obtained for the first 30 generations. The minimum TCR cost of $204,688/year has
resulted in this paper. Although same optimal placement of line switches has been obtained by both the IA and GA methods, the proposed IA method converges at the 30th generation, while 45 generations are required for the GA method.

### B. Case 2: Simulation of Taipower Distribution System

To demonstrate the effectiveness of the proposed methodology to solve the optimal placement of line switches for an actual distribution system, all of the feeders within the scope of the DAS project in the Fengshan District of Taipower has been selected for computer simulation. Fig. 9 shows the system one-line diagram, which includes 11 feeders, 92 segments, and 90 load points to serve the mixture load of residential and commercial customers with several key customers in the suburban area. There are 34 normal close switches and six normal open tie switches in the system, and all switches are manually operated. To achieve the DAS function, the optimal placement of automatic and manual line switches has to be derived to reduce the customer interruption cost while achieving the cost effectiveness of the investment of line switches.

After solving the optimal switching placement by the proposed IA algorithm to enhance the customer service reliability by the distribution automation system, Fig. 10 shows the Taipower distribution system with the proposed placement of line switches. It is found that 22 manual switches have been replaced by the automatic switches (including six open-tie switches), two more automatic switches are installed for the feeder pair BL34-B526, and one more automatic switch is added for the feeder pair BL43-B533-B536.

Fig. 11 shows the reduction of annual ECOST of different load points after applying the optimal switching placement (OSP). The interruption cost of the commercial customers (such as L4 and L47), and key customers (such as L75 and L82) have been reduced significantly due to the enhancement of service reliability by the proposed line switch placement.

Table V lists the feeder pairs and system reliability indexes (SAIFI and SAIDI) before and after the optimal placement of line switches. The system average interruption frequency has been reduced from 0.231 to 0.157 interruption/customer-year. Besides, the SAIDI has been reduced from 32.233 to 20.872 min/customer-year by the application of the FDIR function with the automatic line switches. It is noted that the improvement of service reliability obtained by optimal placement of line switches is sensitive to the number and locations of line switches to be installed. For example, with two new automatic switches added in segments 19 and 29, the SAIDI of the feeder pair BL34-B526 has been improved from 34.9 to 21.0 min/customer-year, which implies that the customer interruption time has been reduced by 40% with the proposed switch placement.

Table VI illustrates the annual TCR of the distribution system before and after applying the proposed optimal switching placement. The total cost of reliability has been reduced from $460 257/year to $207 754/year. With the installation of automatic line switches at the proposed locations of distribution feeders, the customer interruption cost is dramatically reduced from $454 063/year to $193 438/year. Although same results have been obtained by both algorithms, higher efficiency of the IA algorithm to solve the optimization problem has been illustrated.
Fig. 9. The original Taipower distribution system.

Fig. 10. Taipower distribution system after optimal placement of line switches.
V. CONCLUSIONS

A new approach by using the IA algorithm to solve the optimal placement of line switches for distribution systems has been proposed in this paper. The objective function is formulated by considering the customer interruption cost and investment cost of line switches. The interruption cost of each load point is determined by the load composition of different customer classes and key customers, such as hospitals, etc. The service reliability of each load point has been evaluated according to the failure rate and repair time of primary feeder conductors. With the FDIR function of distribution automation systems in Taipower, the fault contingency can be isolated and unfaulted, but out of service areas can be restored in a short time period by operating the automatic line switches properly. With the proposed placement of line switches, the customer interruption time has been reduced very effectively with the enhancement of service reliability by distribution automation function.

To demonstrate the effectiveness of proposed immune algorithm to solve the optimal line switch placement, a Taipower distribution system with 11 feeders within the service area of the Fengshan DAS project has been selected for computer simulation. The number and installation locations of automatic and manual switches have been determined after solving the optimization problem by the proposed IA algorithm. By comparing to the original system, 22 manual line switches are replaced by automatic line switches, and three automatic switches are added for a feeder pair with key customers. The expected customer interruption cost due to service outage has been derived to investigate the impact of proposed line switch placement to the system service reliability. It is found that the customer interruption cost of the Taipower distribution system has been reduced by 57% or $260,625/year with the annualized investment of $14,326 for the proposed placement of line switches. It is concluded that the optimal placement of line switches by the proposed immune algorithm can therefore enhance the FDIR function of distribution automation system to reduce customer interruption cost for fault contingency in a very cost-effective way.

TABLE V

<table>
<thead>
<tr>
<th>Feeder pairs</th>
<th>before optimal switching placement</th>
<th>after optimal switching placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL24-B532</td>
<td>0.217</td>
<td>0.148</td>
</tr>
<tr>
<td>BL34-B526</td>
<td>0.249</td>
<td>0.161</td>
</tr>
<tr>
<td>BL42-B530</td>
<td>0.221</td>
<td>0.159</td>
</tr>
<tr>
<td>BL43-B533-B536</td>
<td>0.243</td>
<td>0.172</td>
</tr>
<tr>
<td>BL45-B537</td>
<td>0.205</td>
<td>0.166</td>
</tr>
<tr>
<td>System</td>
<td>0.231</td>
<td>0.157</td>
</tr>
</tbody>
</table>

TABLE VI

<table>
<thead>
<tr>
<th>Scenario</th>
<th>w/o optimal switching placement</th>
<th>optimal switching placement with IA</th>
<th>optimal switching placement with GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TJR (8/year) (CIC/INV)</td>
<td>460237 (454063/194)</td>
<td>207754 (199348/14326)</td>
<td>2097754 (199348/14326)</td>
</tr>
<tr>
<td>CPU time (sec)</td>
<td>136</td>
<td>387</td>
<td></td>
</tr>
</tbody>
</table>

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CHEN et al.: OPTIMAL PLACEMENT OF LINE SWITCHES FOR DAS

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