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

W ith 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
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 a feeder pair to illustrate the simulation process. 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 statistical analysis of service outage, the customer interruption cost (CIC) of a distribution system is expressed as [5]

$$\text{CIC} = \sum_{i=1}^{n} \lambda_i d_i \left( \sum_{j=1}^{m} C_{ij} L_j \right)$$

where \( n \) is the total number of line segments, \( IC_i \) 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 \( i \), \( L_i \) 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 higher 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 refinery plants, high technology plants, etc.)

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

$$C_{ij} = (\text{Res}_j \cdot f_{R}(r_{ij}) + \text{Com}_j \cdot f_{C}(r_{ij})$$

$$+ \text{Ind}_j \cdot f_{I}(r_{ij}) + \sum_{l=1}^{3} \text{Pri}_j^l \cdot f_{P}^{l}(r_{ij}))$$

where Res, Com, Ind, and Pri are the load percentages of residential, commercial, industrial, and key customers; \( f_{R}, f_{C}, f_{I}, \) and \( f_{P}^{l} \) 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

$$\text{Minimize} \quad TCR = \text{CIC} + \text{INVC}$$

where CIC is the customer interruption cost, and INVC is the investment cost of line switches.

To reduce the outage time of customers for fault contingency of distribution systems, the following operation constraints are considered in this paper:

1) The load transfer for service restoration should not introduce an overloading problem for main transformers
the Fengshan DAS project has been selected for computer simulation. With the FDIR function of distribution automation systems in place at Taipower, the fault contingency can be isolated and unfaulted, but out of service areas can be restored in a short time period. With the proposed line switch placement in a radial distribution system, 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.

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 hospital, etc. The service reliability of each load point has been evaluated according to the failure rate and repair time of primary feeder conductor. 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>TCR ($)/year (CIC/INVC)</td>
<td>460257 (454063/194)</td>
<td>207754 (199348/14326)</td>
<td>207754 (199348/14326)</td>
</tr>
<tr>
<td>CPU time (sec)</td>
<td>136</td>
<td>387</td>
<td></td>
</tr>
</tbody>
</table>

CIC: customer interruption cost, INVC: investment cost of line switch

REFERENCES

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