# SERVICE RESTORATION IN DISTRIBUTION AUTOMATION SYSTEM USING PARALLEL HYBRID GENETIC ALGORITHM-TABU SEARCH

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Abstract: This paper presents an application of parallel hybrid Genetic Algorithm-Tabu Search (GA-TS) in searching the optimal service restoration solution in an electric power distribution system, a discrete optimization problem. In this investigation, parallel hybrid GA-TS was developed for the service restoration of a distribution system. For parallel computing, a PC-cluster system consisting of 8 PCs was developed. Each PC employed a 2 GHz Pentium IV CPU, and was connected with others through Ethernet-switch-based fast Ethernet.

The newly developed algorithm was tested with a practical distribution system in Korea. From the simulation results, the proposed method found the optimal fault restoration strategy. The obtained results were the same as those of the explicit exhaustive search method (Wu, Tomsovic, and Chen, 1991). Also, it was found that the proposed algorithm is efficient and robust for distribution system service restoration in the solution quality, speed-up, efficiency, and computation time. 

Keywords: Service Restoration, Distribution Systems, PC Clustering, Tabu Search(TS), Genetic Algorithm(GA), Parallel Hybrid Genetic Algorithm-Tabu Search(GA-TS)

## 1. INTRODUCTION

In recent years, because of the quickly growing size and complexity of the distribution networks, rapid restoration of out-of-service areas and a speedy return to normal operating conditions following a fault has become more critical in order to improve the reliability of distribution systems. Also, in distribution system operation, service interruption frequency, interruption duration, power loss and voltage drop should be reduced, through the introduction of automation techniques in order to increase customers' satisfaction.

The main objective of service restoration of distribution systems when a fault or overload occurs is to restore as much load as possible by transferring the de-energized load in the out-of-service area via network reconfiguration to the appropriate adjacent feeders at minimum operational cost without violating operating constraints. The objective function is usually defined as the number of switching operations, the minimal amount of the unreserved load, the load balance of transformers and feeders, and other factors. The constraints which should be considered are radial configuration constraints, feeder loading constraints, voltage-drop constraints, main transformer loading constraints, and line capacity constraints.

The service restoration problem is a complicated combinatorial optimization problem with non-linear constraints, because the number of variables and constraints involved in restoration planning is large. To resolve this problem, various approaches have been investigated. These algorithms are based on knowledge of the features of a distribution system.

Heuristic approaches (Morelato and Monticelli, 1989), a branch exchange method (Castro, Bunch, and Topka, 1980), and an expert system (Natata, Sasaki, and Yokoyama, 1989) have been developed to quickly determine restoration plans. Also, Fuzzy reasoning has been used to implement the operator’s empirical knowledge of service restoration (Brauner and Zabel, 1994). However, these methods are likely to produce sub-optimal solutions.

Therefore, an algorithm with the global searching capability of GA and the local search capability of the branch exchange method (Oyama, 1996), as well as GA with a fitness function calculated by the fuzzy satisfying method (Hsiao and Chien, 2000) were proposed to solve the service restoration problem. Recently, several hybrid algorithms by parallelizing of GA, Simulated Annealing (SA), and TS were proposed to obtain better solutions and to reduce the computation time by combining the advantages of each algorithm for the combinatorial optimization problem (Nara, Gojyo, Ito and Kaneda, 2002).

In parallel computing, GA, SA, and TS divide the problems into several subproblems, and allocate them to each processor. This reduces the computation time and enhances the computation efficiency. To realize the parallel algorithm, parallel computers like transputers have been used. But parallel computers are expensive to use. Recently, PC clustering, one of the types of parallel or distributed processing systems, which is composed of a collection of interconnected workstations or PCs working together as a single, integrated computing resources, has been used for parallel computing.

In this paper, parallel hybrid Genetic Algorithm-Tabu Search (GA-TS) was developed for the service restoration of distribution systems. In parallel hybrid GA-TS, GA and TS operators are executed for each processor. To prevent solution of low fitness from appearing in the next generation, strings below the average fitness are saved in the tabu list. If best fitness of the GA is not changed for several generations, TS operators are executed for the upper 10% of the population to enhance the local searching capabilities. With migration operation, best string of each node is transferred to the neighboring node after predetermined iterations are executed. For parallel computing, a PC cluster system consisting of 8 PCs was developed. Each PC employs a 2 GHz Pentium IV CPU, and is connected with others through an Ethernet-switch-based fast Ethernet.

The proposed algorithm can be used in the event of a fault or overload of transformers and feeders. The output of the algorithm is a n best list of candidate solutions and the corresponding switching sequences. An index of each result helps operators to make the final decision on how to restore the out-of-service area.

The developed fault restoration algorithm has been tested on a practical distribution system restoration problem in Korea. The obtained results were compared to those of the explicit exhaustive search method (Tanese, 1992). It was found from the test results that the proposed method is capable of achieving a proper restoration plan in a very efficient manner.

## 2. PROBLEM FORMULATION

The main objective of service restoration when a fault or overload occurs is to restore as much load as possible by transferring de-energized loads in the isolated areas to other feeders that can take the extra load. When transferring loads, candidate solutions are evaluated based on 3 criteria: the number of switching operations, load balancing to minimize the risk of overload and minimize the amount of forced outage load. Also, one has to check whether the operating constraints are satisfied. Since the feeders in practice are usually operated radially, the radiality of the system topology is an important constraint in the problem. There are also constraints that must be considered for each feeder: voltage drop limits, line/transformer capacity limits, and feeder load limits. The service restoration problem is formulated as follows.

- switching operation costs

$$IC^h = N_s \tag{1}$$

where, $N_s$ is no. of switches operated

- load balancing index

$$ILB^h = \begin{cases} \exp(-Max(y_{cap} - y_{nax})/\alpha_{ILB} & \text{if } y_{max} > 0.75 y_{cap} \\ 0.1 * \exp(-Max(y_{cap} - y_{nax})/\alpha_{ILB} & \text{otherwise} \end{cases} \tag{2}$$

where, $y_{cap}$ is the maximum capacity of i-th tie feeder

$y_{max}$ is maximum possible tie-feeder load after restoration

$\alpha_{ILB}$ is the constant

- power of unrestored load

$$IP^h = p \sum_{i \in a_p^h} P_i^h + q \sum_{i \in a_q^h} p_i^h \tag{3}$$

where, $a_p^h$, $a_q^h$ is set of normal and priority customer

p, q is weighting factor

$P_i^h$ is i-th section load

- voltage drop constraint index

$$IV^h = \underset{i}{Max}[\exp(a_{IV} \cdot \frac{V_r^h - V_{ij}^h}{V_r^h}) - 1] \tag{4}$$

where, $V_r^h$ is feeder voltage

$V_{ij}^h$ is voltage of j-th section of i-th feeder

$n_f$ is no. of feeder i=1,2,…, $n_f$

$n_{si}$ is no. of section of i-th feeder j=1,2,…, $n_{si}$

$a_{IV}$ : constant

Constraints considered in this paper are as belows:

- main transformer loading constraint

$$S_{TSi}^h \le S_{TSi}^n \tag{5}$$

where, $S^n{}_{TSi}$ is max capacity of i-th main transformer

$S^h{}_{TSi}$ is current capacity of i-th main transformer

- feeder loading constraint

$$I^h_{ij} \le I^n_{ij} \qquad (6)$$

where, $I^h{}_{ij}$ is current of j-th section in i-th feeder

$I^n{}_{ij}$ is current ratings of j-th section in i-th feeder

The integral objective function is defined by the following expression.

$$\text{obj}= p_1 \cdot IC^h + p_2 \cdot ILB^h + p_3 \cdot IV^h + p_4 \cdot IP^h \qquad (7)$$

For more than one feasible plan, the degree of preference is determined by the weighting factors, $p_1$ to $p_4$.

## 3. PARALLEL HYBRID GENETIC ALGORITHM-TABU SEARCH USING PC CLUSTERING

### *3. 1 PC CLUSTER SYSTEM*

After the mid-1980s, high performance computers have been required in parallel with the development of large-scale science and engineering. Since supercomputers are expensive, they have been replaced by cluster systems having the availability of inexpensive high-performance PCs and high-speed networks as well as the development of integrated circuits.

PC cluster systems provide higher availability as well as greater performance with lower costs by interconnecting several PCs or workstations. PC cluster systems are very competitive with parallel machines in the ratio of cost to performance because clustering is one of the types of parallel or distributed processing systems, that are composed of a collection of interconnected low-cost PCs working together as a single and integrated computing resource. Also, it is easy to add nodes to construct a PC cluster. A basic construction diagram for a PC cluster is shown in Fig. 1.

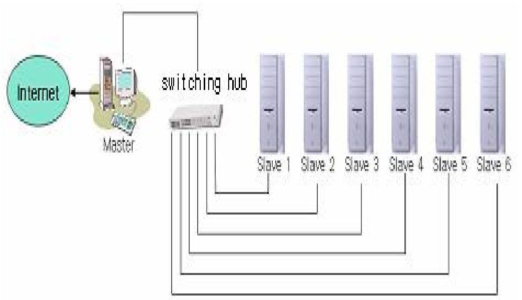



Fig. 1. Construction diagram of PC cluster system

It is important to properly select each of these components to obtain better performance. The PC cluster system implemented in this study is composed of 8 nodes based on Ethernet-switch based fast Ethernet. For the operating system, the master node uses Windows 2000 server, and the slave nodes use Windows 2000 professional. To connect each node, a fast Ethernet card and a switching hub were used. In data communication, an MPI library was used, which, by using a message-passing method through TCP/IP over the Internet is effective for parallel applications.

### *3. 2 PARALLEL HYBRID GENETIC ALGORITHM-TABU SEARCH*

Genetic Algorithm (GA), one of the probabilistic optimization methods, is robust, and is able to solve complex and global optimization problems. However, the disadvantage of GA is that, because of minimal use of prior knowledge and no utilization of local information , it can require excessive computation time before providing an accurate solution (Wu, Tomsovic, and Chen, 1991). In constrast, TS is a meta-heuristic method that guides the search for the optimal solution making a use of a flexible memory system that allows the search history to be taken into consideration (Nara, Shiose, Kitagawa, and Tshihara, 1992). But TS is liable to be affected by the initial solution, and if a local minimum is encountered, it takes much time to execute a diversification operation to escape the local minimum.

In this investigation, parallel hybrid Genetic Algorithm-Tabu Search (GA-TS) was developed, which uses both GA with good global search capability and TS with good local search capability. The proposed algorithm was parallelized by a PC cluster system to enhance both the solution quality and the computation time. Fig. 2 shows the connection structure between the GA-TS nodes. Each node in the PC cluster system is assigned for GA-TS execution. In parallel hybrid GA-TS, GA operators are executed for each node in several iterations. To prevent solution of low fitness from appearing in the next generation, strings below the average fitness are saved in the tabu list. If best fitness of GA is not enhanced during predetermined generations, TS operators are executed for the upper 10% of the population to enhance the local searching capabilities. After the TS operations, the best solutions of those operations are included in the GA populations. To enhance the global search capabilities of GA, strings below the average fitness are stored and prohibited for several generations. A migration operation among GA-TS node with ring topologies makes it possible fore each GA-TS node to enhance the searching capabilities of GA by periodically exchanging the best string between adjacent node.

In this paper, parallel hybrid Genetic Algorithm-Tabu Search (GA-TS) was developed for the service restoration of distribution system. For parallel computing, a PC cluster system consisting of 8 PCs was developed. Each PC employs the 2 GHz Pentium IV CPU, and is connected with others through Ethernet-switch-based fast Ethernet.

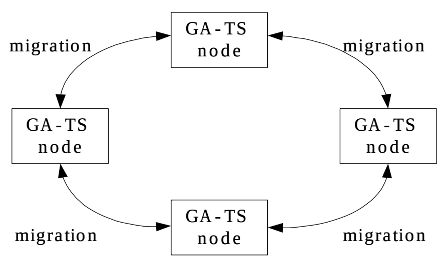



Fig. 2 Connection structure of each node

### *3. 3 PARALLEL HYBRID GENETIC ALGORITHM-TABU SEARCH FOR SERVICE RESTORATION OF DISTRIBUTION SYSTEM*

To implement the proposed parallel hybrid GA-TS for the service restoration of the distribution system, we must determine several parameters of both GA and TS. The parameters are the positions of the opened sectionalizing switches, so this is one of the combinatorial optimization problems.

To solve the service restoration problem by TS, initial solution for TS is properly selected according to the margin of the adjacent feeders. Moving the open-switch position along the search route generates the neighboring states. Moving the open-switch position changes the direction of the power source of one load section. If this operation overloads the adjacent feeder, we should transfer loads from the adjacent feeder to the secondary feeder in order to remedy the overloading of the adjacent feeder. To illustrate this idea, consider the system in Fig. 3. In Fig. 3, by closing T4 and opening S14, load section L1 is transferred from S/S 2 to S/S 5. Suppose that the fault occurs between switch S1 and S2. If tie switch T1 and T2 are supposed to close, there are three search routes, as shown in Fig. 4.

In the first route, T1 and either S8 or S9 constitute a switching pair. In the second route, T2 and either S4 or S3 constitute a switching pair. If adjacent feeder F2 is overloaded by closing T2, T4 and either S13 or S14 constitute a switching pair.

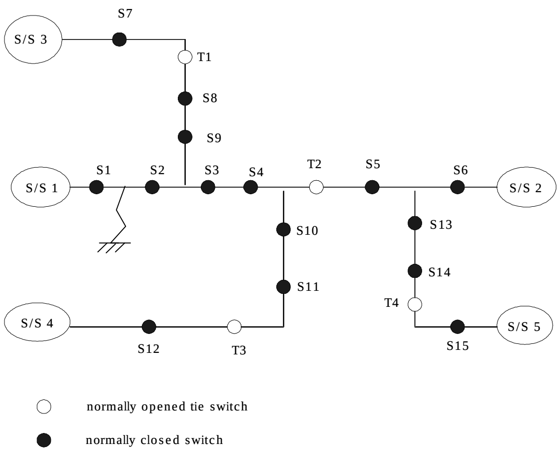



Fig.3 Sample Distribution System

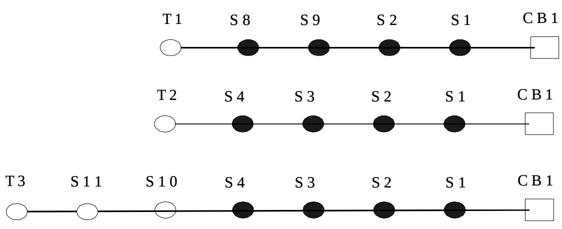



Fig. 4 Search route for sample system

The best solution among neighborhoods, which is not in the tabu list to prevent cycling. In the neighborhood search procedure of TS, TS carries out local search around the current solution. TS represents good global searching capabilities if diversification operation and aspiration criteria procedures are added. By constrast, GA encodes the open-switch position of each loop for the distribution system, and generates an initial population. GA operations, that is, crossover and mutation operations, are applied to the individuals of the present generations to create the next generation. Fig. 5 represents the string architecture of the GA-based node. As shown in Fig. 5, each string represents the closed and open-switch position of each loop in the distribution system.

| | | | | | | |
|---|---|---|---|---|---|---|
| String 1 | T1 | T2 | T3 | T1-T2 | T2-T3 | T1-T3 |
| String 2 | T1 | T2 | T3 | T1-T2 | T2-T3 | T1-T3 |
| | | | | | | |
| String p | T1 | T2 | T3 | T1-T2 | T2-T3 | T1-T3 |

where, Ti : i-th closed switch

Ti-Tj : opened switch between closed tie switch Ti and Tj

p : no. of population

Fig. 5 Coding method of GA for distribution system service restoration

In the GA-TS evaluation procedures, the fitness of each string can be obtained by the following equations. As shown in (8), fitness is composed of integral objective described in (7) and several constraints such as the line/transformer capacity limit, the voltage-drop limit and the radiality constraint.

$$\text{Fitness} = \frac{\alpha}{\text{obj} + \sum_i \text{penalty}_i} \qquad (8)$$

where, *Loss* : system loss [kW]

$penalty_i$ : i-th penalty term, i=1, 2, 3

$$\text{penalty}_1 = \begin{cases} 0 & \text{if} \quad I_a \le I_{Max} \\ \gamma_1 & \text{otherwise} \end{cases} \qquad a = 1.2.\cdots, N$$

$$\text{penalty}_2 = \begin{cases} 0 & \text{if} \quad S^h{}_{TSi} < S^n{}_{TSi} \\ \gamma_2 & \text{otherwise} \end{cases} \qquad a = 1.2.\cdots, N$$

$I_a$ : line current of section a, $I_{max}$ : line capacity

N : no . of sections

$\alpha, \gamma_1, \gamma_2$ : constant

In the reproduction procedure, the next generation population is selected by roulette wheel selection according to the fitness. Crossover, a mutation operation, and elitism are used in the GA operation.

## 4. NUMERICAL RESULTS

To evaluate the effectiveness of the proposed algorithm, service restoration has been conducted on a 22.9 kV real-life distribution system in Kangdong in Korea. The system has 7 substations, 17 substation transformers, 100 feeders, and 2,558 load sections. The feeder's rated capacity is 10 MVA, and each transformer's capacity is 100 MVA. A program for service restoration was written in C++ and run on an IBM-PC.

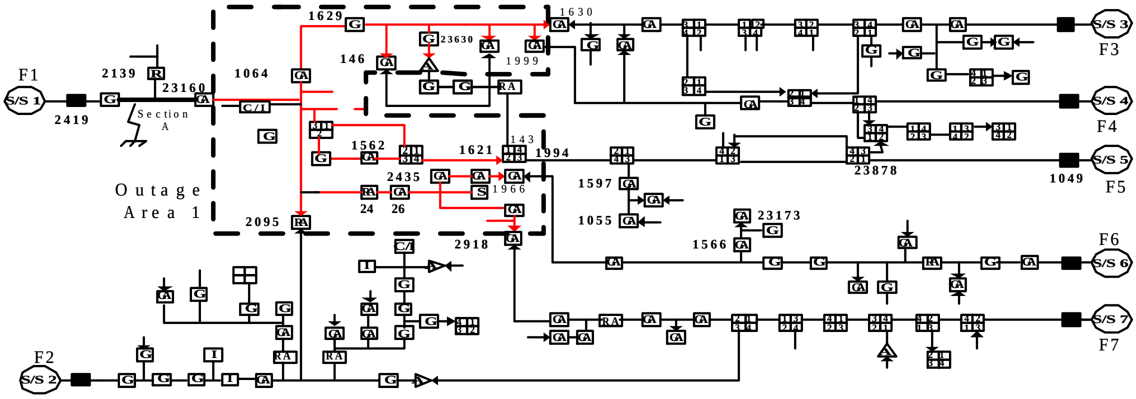



Fig. 5 Distribution system of Kangdong in Korea

Suppose a permanent fault occurs near the CB, as indicated in Fig. 5. To clear the fault, Switch 23160 and Circuit Breaker 2419 are tripped. As a result, Outage Area 1, with a total load of 132.96[A] to be restored, is rendered out-of-service and is connected to 8 feeders through tie switches. Fig. 5 shows a small part of this system. Table 1 describes the simulation parameter in this paper.

Table 1 simulation parameter

| simulation parameter | | value |
|---|---|---|
| $p_1, p_2, p_3, p_4$ | | 1.3, 5.8, 13485.35, 1 |
| p, q | | 1, 2 |
| GA | no. of gen | 200 |
| | no. of population | 80 |
| | crossover prob. | 0.8 |
| | mutation prob. | 0.01 |
| TS | no. of iteration | 400 |
| | tabu length | 30 |

Table 2 ranking list of a restoration plan

| ranking / objective | | Proposed Method | | | conventional Method |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | - |
| Index | $IC^h$ | 3 | 3 | 3 | 3 |
| | $ILB^h$ | 0.2 | 0.2 | 0.23 | 0.2 |
| | $IP^h$ | 0 | 0 | 0 | 0 |
| | $IV^h$ | 0.02 | 0.02 | 0.02 | 0.02 |
| | $IS^h$ | 0 | 0 | 0 | 0 |
| | $IJ^h$ | 0 | 0 | 0 | 0 |
| Integral objective index | | 5.14 | 5.14 | 5.32 | 5.14 |

The result of the ranking list of the restoration plan is described in Table 2. Comparisons between the proposed method and the explicit exhaustive method(Tanese, 1992) show that proposed method and the explicit exhaustive method found the same solution.

The required switching operations for each ranking are described in Table 3. Table 4 describes feeder load changes after restoration. The proposed method recommends to the operator that Tie Switch 24 be opened and 1966, 1630 closed. This transfer restores service to customers of 132.954[A]. In the above scenario, the load of the tie feeders F3 was 212.05[A] and F6 was 170.91[A] after restoration, which makes the switching index and load balance index 3 and 0.2, respectively. The execution time obtained was 16 seconds. This reveals that the proposed algorithm is capable of applying real-time service restoration to a control center operation.

Table 3 ranking list of switching operation sequence

| Ranking | Switching operation sequence |
|---|---|
| 1 | 24 open → 1966 close → 1630 close |
| 2 | 24 open → 2918 close → 1630 close |
| 3 | 26 open → 1966 close → 1630 close |

Table 4 Feeder load changes after restoration

| Ranking | Feeder | Load changes |
|---|---|---|
| 1 | F3<br>F6 | 120[A]→212.05[A]<br>130[A]→170.91[A] |
| 2 | F3<br>F7 | 120[A]→212.05[A]<br>135[A]→175.91[A] |
| 3 | F6<br>F3 | 130[A]→167.50[A]<br>120[A]→215.46[A] |

To show the effects of the parallelization by the PC clustering, speed-up and efficiency were evaluated. Speed-up and efficiency are described below.

- speed-up ( $S_p$ )

$$S_p = \frac{T}{T_p} \quad (9)$$

where, T : run time on one processor

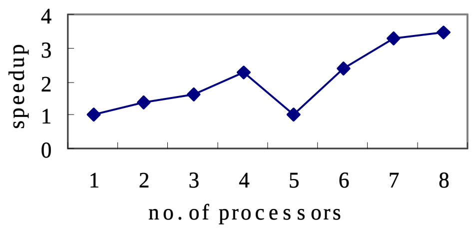
$T_p$ : run time on p processors

- efficiency ( $E_p$ )

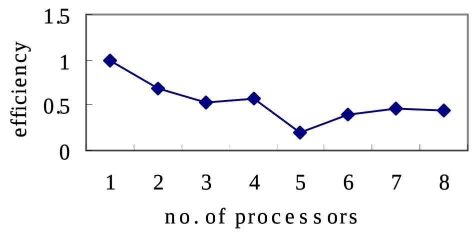
$$E_p = \frac{S_p}{p} \quad (10)$$

where, p : no. of processors

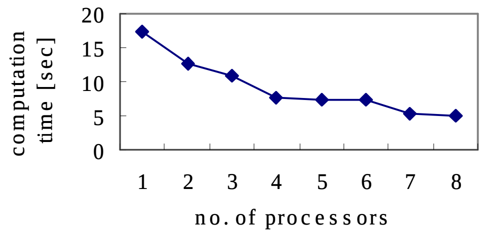
Fig. 8 shows the speed-up, efficiency, and computation time as the number of nodes increases. From Fig. 8, it is found that computation time was decreased while the solution quality was maintained. Speed-up increased almost linearly as the number of nodes increased, but somewhat lowered due to overhead when communication between nodes was executed.



(a) Speed-up



(b) efficiency



(c) computation time

Fig. 8 Speed-up, efficiency, and computation time according to the node number.

## 5. CONCLUSIONS

This paper presents an application of parallel hybrid Genetic Algorithm-Tabu Search (GA-TS) to search an optimal solution for a service restoration in a distribution system. For parallel computing, a PC cluster system consisting of 8 PCs was developed. For compilers of parallel programming, MS visual C++ 6.0 was used under the *Windows* operating system. The proposed parallel hybrid GA-TS uses both GA with good global search capability and TS with good local search capability. The proposed algorithm was parallelized by a PC cluster system to enhance both the solution quality and the computation time, and it is very competitive with parallel machines in cost and performance.

In this study, the service restoration problem in distribution systems was formulated as multiple objective problems in order to minimize switch operations and load balance, to satisfy operational constraints such as transformer capacity constraints, feeder loading constraints, and voltage-drop constraints. To demonstrate the usefulness of the proposed method, it was applied to a practical distribution system in Korea.

As shown in the numerical results, the proposed method has the ability to operate a minimal number of switches, to balance load and to maintain acceptable operating conditions, such as a power flow and system voltage level.

To show the usefulness of the proposed method, the results of the proposed methods were compared with those of GA only and TS only. From the simulation results, it was found that the proposed algorithm is efficient and robust for distribution system service restoration in the solution quality, speed-up, efficiency, and computation time.

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