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# Multi-Objective Service Restoration for Blackout of Distribution System with Distributed Generators based on Multi-agent GA

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**Abstract**

Service restoration is a problem with multiple objectives and constraints, when the distribution systems with DGs (distributed generators) come up large area blackout. In this article the model of multiple objective service restoration about distribution systems with DGs has been built, considering users' priority, the action times of hand switches or tele-switches and network losses after service restoring. Multi-agent GA can be used to search the Pareto optimal solution set for the multiple objectives service restoration problem. Agent's competitive and selflearning actions reflect the principal of survival of the fittest and diversity. It can reduce complex rate and improve efficiency using challenge match method to form Pareto solution to store populations. At last the calculation example manifests the quickness and precision of the multiple objective service restoration for blackout based multi-agent GA, and it is better suit for the distribution system than single objective method.



*Keywords: Distribution network, Service restoration, Multi-agent GA, Distributed generation, Best Pareto solution*

## 1. Introduction

With the power demand constantly increasing, the complex rate and scale of the modern power system has been greatly increasing. So the blackout probability and area also expand in the distribution system. In order to satisfy users' demand and maintain profit of power supply company, it is necessary to restoring power service as soon as possible [1]. Distribution system is designed in close loop and operated in open loop. So there are sectional switches on distribution lines and interconnecting switches in feeder inlets. Service restoration of distribution system is to operate a set of switches to restore power service [2].

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But there are some questions to be noticed in the process of service restoration:

(1) Try best to restore service.
(2) The time of running program is as short as possible.
(3) Satisfy the constraints of distribution system.
(4) The least times of switches are operated.
(5) Consider priority of loads.
(6) The network losses are as small as possible after service restoring.

Now DG technology has rapidly expand on the world. Based on the transmission system surport, it can bring in DGs in the distribution system near users side. Users can get reliable power with using existing resources and devices. Inserting DGs can not change the structure of distribution system, and delay the large investment for upgrade lines. Meanwhile, it can effective improve reliability of transmission system and increase quality of supply. After the distribution system with DGs faulting, DGs can keep on supplying power in the manner of isolated island of electricity [3-7].

To solve distribution system service restoration problem, there are a lot of methods, for example, simulated annealing algorithm (SA), genetic algorithm (GA), tabu search algorithm and so on[8]. But most of methods are in the form of single objective or multiple objective weighting to single objective. Single objective can not wholly reflect real demand of distribution system service restoration, and weighting method is more dependent on personal experience. It must be as soon as possible for service restoration, but the speed algorithm for multiple objective is not enough quick. In this article Multi-agent GA for multiple objective service restoration has proposed, considered matters in service restoration. Multi-agent GA can be used to search the best Pareto solution set for the multiple objectives service restoration problem, considering users' priority, the action times of hand switches or tele-switches and network losses after service restoring. Agent's competitive and self-learning actions reflect the principal of survival of the fittest and diversity. It can reduce complex rate and improve efficiency using challenge match method to form Pareto solution to store populations. The purpose of the multiple objective service restoration is try to search as many solutions as possible in the quick speed, and offer a solution as service restoration case according real condition for decision maker.

## 2. Mathematical model for large-scale blackout restoration in distribution system with DGs

### *2.1. Simplification for distribution system topology structure*

Distribution system net can be treated as a kind of figure. Feeder switches are as nodes of the figure and the feeders are as sides[2]. Using equivalent load model stands for load between two switches. Then distribution system net mathematical model can be got. When there is a fault in distribution system, DGs supply power in the form of isolated island of electricity with opening GDs' grid-connected switches.

### *2.2. Mathematics model for service restoration in distribution system with dgs*

(1) Objective Function

When large scale blackout happens, it is an important aspect that how to restore loads as many as possible, considering users' loads priority. So restoring loads capacities are used as to objective function:

$$Max\ f = \sum_{i \in N} \lambda Li \tag{1}$$

where $N$ is as $\{1,2,3,\ldots\ldots\}$; $Li$ is the capacity for the $i$th restoring load; $\lambda$ is the $i$th load priority.

The direct purpose for network reconfiguration is to reduce net losses in normal condition of distribution system. Service restoration as the network reconfiguration under fault circumstance can also try to reduce net active losses. Its objective function is:

$$Min\ f = \sum_{i=1}^{N} R_i I_i^2 \tag{2}$$

where $N$ is the number of feeders to restore. $R_i$ is the resistance of the $i$th feeder. $I_i$ is the current of the $i$th feeder.

A series of switch operations are certainly happened in restoring service. The cost for one time of switch operation is different between hand switches and tele-switches. In this paper it is defined that one hand switch operation is 1 and one tele-switch operation is 0.5, the formula is as followed:

$$Min\ \ f = SW_1 + SW_2 \tag{3}$$

where

$$SW_1 = \sum_{j=1}^{N_m} | SWM_j - SWMR_j |$$

$$SW_2 = 0.5 \times \sum_{k=1}^{N_a} | SWA_k - SWAR_k |$$

where $SW_1$ is the times of hand switch operations; $N_m$ is the number of hand switches; $SWM_j$ is the $j$th switch state just after fault; $SWMR_j$ is the $j$th switch state just after restoring service; $SW_2$ is the times of tele-switch operations; $N_a$ is the number of tele-switches; $SWM_k$ is the $k$th switch state just after fault; $SWMR_k$ is the $k$th switch state just after restoring service.

Power quality is a aspect being paid more attention in modern power system. Voltage deviation from rated voltage reflects power quality in a certain extent in each point of distribution system. The formula is as followed:

$$\min f = \max\left\{\left|1-\min\left(V_n\right)\right|, \left|1-\max\left(V_n\right)\right|\right\} \tag{4}$$

where $\min\left(V_n\right)$ is the minimum voltage of each bus; $\max\left(V_n\right)$ is the maximum voltage of each bus.

(2) Service Restoration Relevant Constraints

1l Radial network structure should be maintained regardless of DGs.

22 Feeder line power limits should not be violated.:

$$S_i \le S_{i\max}, i = 1, 2, \cdots, n \tag{5}$$

where $n$ is the number of feeders; $S_i$ is the power of the $i$th feeder; $S_{i\max}$ is the capacity of the $i$th feeder.

33 Bus voltage limits should not be violated.:

$$U_{i\min} \le U_i \le U_{i\max}, i = 1, 2, \cdots, m \tag{6}$$

where $m$ is the number of buses; $U_{i\min}$ is the minimum voltage of the $i$th bus; $U_{i\max}$ is the maximum voltage of the $i$th bus; $U_i$ is the voltage of the $i$th bus.

### *2.3. The concept of pareto optimum*

It is hard to make all objective values reach optimum. So the final method to settle service restoration problem is to split the difference from each objective function. Then the optimum can be got as far as possible. Thereby weight coefficient multiple objective algorithm is arose. But this method is more dependent on experiences, and the different unit of each objective is not easy to directly compare. Meanwhile, there are contradictory norms among objectives because of mutual restrictions of decisional variables. So the concept of Pareto optimum is used to solve multiple objective service restoration problem.

For two decisional variables $u$ and $v$, where $u, v \in S$ and $S$ is a decisional variable space. If the non-equality $f_i(u) < f_i(v)$ is consistent for $i \in \{1, 2, \ldots k\}$, it is called that variable $u$ dominates variable $v$, recorded as $u \succ v$[1].

Variable $x$ is a feasible solution for multiple objective optimization problem and $x \in S$. If and only if $S$ space doesn't exist $y$ making $y \succ x$ come into existence, it is called that $x$ is the Pareto optimal solution for multiple objective optimization problem. What is called Pareto optimum is that there is not better solution that at least one objective is best and others are not disappointing than present. Generally Pareto optimum of multiple objective optimization problem is a solution set. The final solution for the real condition which must be dependent on how much known about the problem and decision maker's preference is selected from Pareto optimum [1]. So the key step to solve multiple objectives is to seek for Pareto optimal solutions as many as possible.

## 3. Multi-agent GA For Service Restoration Distribution System

### *3.1. GA and multi-agent system*

GA has strong ability of overall optimal search. It has been using to search solution in traditional repeated structure of distribution system. But there are still some shortages:

1l GA only considers competitiveness among organisms, but not cooperating probability. It has been demonstrated that competitiveness and cooperation exit at the same time and they both speed up evolutionary process in biology.

2l Biological evolutionary process is one learning rules in ecological environment. This includes innate genetic learning or duplicate and acquired personal learning. But GA according to 'generated detection' doesn't make the best use of father generation evolutionary experience and ignores self learning.

From what have said, we can get the conclusion that it is not enough to simulate living beings dealing with things just using GA. So it is necessary to study deeply and take advantage of biological resource.

In recent years, calculation based on Agent from distributed aritificial intelligence has been successfully apply to power system. Multiple Agents System (MAS) is what multiple agents want to attain special aim to mutual effect to form. Three factors must be taken into account to solve problem: environment agent living, purpose of every agent and behaviour that can be taken.

Multi-agent GA based perception to environment and ability of reaction will stand for a kind of service restoring solution fixed on grid. In order to increase self energy, every agent competes with region and learns personally.

### *3.2. Encoding for agent*

The aim of service restoration of distribution system is to get a set of switch operation strategies. Switches only have both open and close two states. So we can use binary system to encoding. Power supply lines (stride from blackout area to normal area) and buses in blackout area are ordered in nature sequence and as the approved operation lines (not include lines of unitary island or multi-users' island).

Then switch in every line that can be operated according to pre-order is defined to be a gene in agent. It can be expressed as:

$$\alpha = \left(a_1, a_2, \cdots, a_n\right) \in S \quad (7)$$

where $a_i$ is equal to 0 or 1; $i$ is not less than 1 and not more than $n$; $\alpha$ presents a agent; n is the number of operated lines; $S$ stands for searching space of service restoration of distribution system.

### *3.3. Energy ,purpose and living environment of agent*

Energy of agent is equal to function value from formula (1) , meaning $Energy(a) = f(a)$. The purpose of agent is to maximum its energy.

Living environment of agent is a annular grid which is called agent grid, represent by $L$. The size of agent grid is supposed to be $L_{SIZE}$ by $L_{SIZE}$. Its form is shown as figure 1. Every box presents a agent. Numeral stand for row and column which agent is in. $L_{ij}$ means agent $ij$ is in row $i$ and in column $j$. every agent occupies a grid pot and can't move, but it can fell environment around and has interaction with other agent around which are decided by $R_s$ (parameter of perceptible scope). The agent which has interaction with agent L is $L_{kl}$, where $\alpha$ presents a agent; $k$ is not less than $i–R_s$ and not more than $i+R_s$; $l$ is not less than $j–R_s$ and not more than $j+R_s$. Agent grid is annular, so:

$$k = \begin{cases} k + L_{size}, & k < 1 \\ k - L_{size}, & k > L_{size} \end{cases}, \quad l = \begin{cases} l + L_{size}, & l < 1 \\ l - L_{size}, & l > L_{size} \end{cases} \quad (8)$$

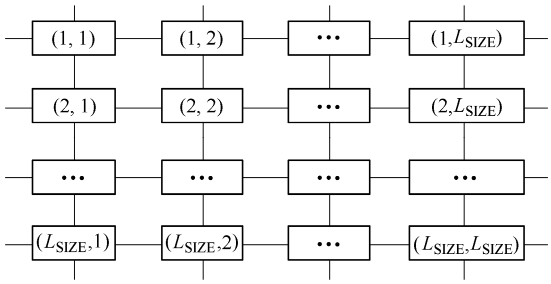


Fig. 1.Structure of the agent environment

Neighbour region which has interaction with agent $L_{ij}$ is recorded as $N_{ij}$. For different behaviours of agent, its perceptible scope is different, so its neighbour region is not alike.

### *3.4. Behavior of agent*

The plan of service restoration must be formulated as soon as possible for large area blackout. That is to say that using the least computation gains high-quality solution. So computation is as the resource of agent living environment. Agent's behavior is drove by the purpose of maximum its energy. But resource is finite in environment. This leads to agent take some measures including competition and self learning to enlarge its energy.

1l Competitive behavior

For competitive behavior, perceptible scope of every agent is constant 1 and its neighbour region is competitive neighbour region $N^c$. Agent $L_{ij}$ will compare energy with its competitive neighbour region. If its energy is less than any agent's energy in competitive neighbour region, it will exist or will die. If it dies, its location will be replaced by the largest energy agent in its competitive neighbour region. There are two ways to generate next generation: The first way is that information from $L_{ij}$ and $a_{\max}$ is used to generate descendant. The location of $a_{\max}$ is altered by different locations randomly extracted from $L_{ij}$ and $a_{\max}$; The second way is to use bitwise variation of GA.

22 Self-learning behaviour

For self-learning behavior, perceptible scope of every agent is $R_s$ and its neighbour region is competitive neighbour region $N^t$. A agent can obtain a chance to learn to enlarge its energy, when its energy is less than any agent's energy in its neighbour region[9].

### *3.5. Renovation of infeasible solution*

Because of binary encoding, there will be a large number of infeasible solutions lowering the searching efficiency in processes of competition and slef-learning. It has two kind of infeasible solutions in reconstitution of distribution system: one is closed loop in topological structure and the other is that at least one island not connected with source is existed. In the reconstitution of distribution system based GA, the number of switches opened are not changed before and after reconstitution and this method can't support reconstitution in the condition of load shedding. It is necessary to shed a part of loads for system security in the service restoration of large area blackout. So the number of sectionalizing switches after reconstitution is more than before. The improved strategy based on loop decomposition is proposed and can clear up loop and island.

All loops can be confirmed in the network of distribution system. There are two kinds of loops: the first is the loop starts from one source, passes every bus only once and reaches to another source; the second is the loop starts from a certain bus, passes every bus only once, and then goes back to the start bus. The conception of generalized loop refers to the disconnected loop has at least one bus having a hand in encoding. There is a closed loop without any question when the number of generalized loops don't equal to the number of loops of distribution system. At the moment, randomly opening any switch in closed loop can remove the closed loop. Then all the first kind of loop must be detected one by one. If one island is being in one loop, all first loops including this bus must be checked up having same island or not. If yes, the solution is not feasible. At this time, place value 0 at island bus or value 1 at switch between island bus and source. The two ways are selected randomly. In the process of removing closed loop, new island can be born. So closed loops must be firstly cleared away and then islands.

### *3.6. Rule of formatting pareto solution population*

The strategy using multi-agent algorithm has been designed to solve multiple objective service restoration: there are two populations that one is agents used for solving single objective problem and the other is used to store Pareto solutions. Every agent can be treated as a bus. Competition and self learning are controlled in its neighbour region. The different place is the need to structure a store population of Pareto solution.

The best solution set is achieved by constructing nondominated set of present evolutionary population. In order to reduce time complex rate, challenge match method[10] is used to construct nondominated set and to form populations of store Pareto solution.

### *3.7. Realization of algorithm*

11 DGs in blackout area are operated in the form of unit island or multi-user island after fault.

②Some values must be ascertained, for example: region of blackout, feeders' order for binary encoding of agents, size of population $L_{\text{SIZE}} \times L_{\text{SIZE}}$, neighbour region of competition $N^c$,self-learning neighbour region $N^t$, the largest iterative times $N$, and so on.

33 Generate initial population which is $L_{\text{SIZE}} \times L_{\text{SIZE}}$ agents.

44 Energy of every agent is calculated according to formula

55 Population of store Pareto solution must be formed. Structure nondominated set based on challenge match method for agent population $L$, add it to store population $P$ and delete bad solution in $P$. if P>M, delete the crowded solution and the result is recorded as $P$.

66 Every agent in grid must take competitive action in its competitive neighbour region. If $\forall \boldsymbol{a} \in N_{ij}^c$ and $Energy(\boldsymbol{a}) \leqslant Energy(L_{ij})$ , $L_{ij}$ will remain unchanged. Otherwise a new agent will be generate by a competitive way based on parameter $D^h$.

77 Restore unfeasible solution and calculate energy of agents.

88 Every agent in grid must take competitive and self-learning action in its competitive neighbour region.

99 Restore unfeasible solution and calculate energy of agents.

1010 judge stopped condition. If the number of evolutionary generation is equal to $N$, the agent with maximal energy is the optimal solution. Otherwise, turn to step 55 .

1111 Do synchronized operation and combine with system again for the islands in the service restoring area. Or island goes on running independently.

## 4. Calculation Example

### 4.1. Example 1

Numbers with brackets stand for loads and ones without brackets are switches in figure 2. Supposing the line between bus 22 and switch 22 is fault. Setting buses 0, 7 and 41 have enough margin for loads lost power.

Multi-agent GA is used to calculate example 1. The size of agent grid is a ringlike grid 4×4. neighbour region of competition $N^c$ and self-learning neighbour region $N^t$ are both 1. $N$ is equal to 30. In order to improve reliability and reduce losses, the program of service restoration recovers power as soon as possible. So the quickness of the program is directly connected with its practicality. The Pareto optimal solutions can be got in three seconds. A set of solutions is listed in Table I.

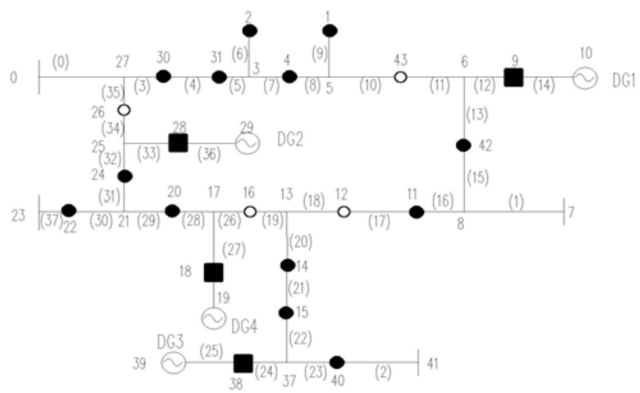


Fig. 2.Distribution system with DGs

A series of service restoring methods can be gained by using multi-agent GA in short time. Case 1 and case 2 have obvious superiority in losses. If decision makers tend to economic operation, they can select one. Case 2 and case 3 have smaller voltage deviation. While the switches operational times are lesser in case 3 and 4. It is thus clear that decision makers can obtain many kinds of cases and select one suitable solution to be the final case for service restoration based on real condition

Table 1. The optimization results of example 1

| Cases | Network losses (p.u) | Operation times of switches | Voltage deviation (p.u) | Number of switch operated |
|---|---|---|---|---|
| Case 1 | 0.04653 | 3 | 0.04529 | Close: 16, 26, 43<br>Open: 20, 31 |
| Case 2 | 0.12196 | 5 | 0.01911 | Close:12, 16, 26<br>Open:14, 24 |
| Case 3 | 0.14422 | 3 | 0.01956 | Close: 26, 43<br>Open: 30 |
| Case 4 | 0.04765 | 3 | 0.04987 | Close: 16, 26<br>Open: 24 |

### *4.2. Example 2*

This example is for complex distribution system in figure 3. Supposing the 16th line has permanent fault and each bus of converting station has enough capacity to recover non-fault loads. A set of restoring cases in table Ⅱ can be gained by using active losses, action time of switches and Voltage deviation to be objectives.

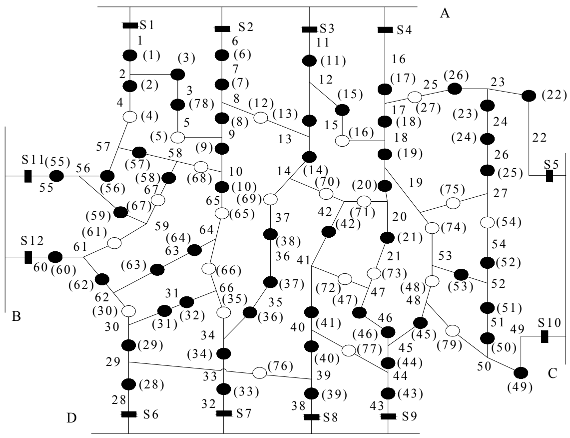


Fig. 3.Complex Distribution System

Multi-agent GA combining multi-agent system and genetic algorithm is easy to realize. An individual in genetic algorithm is treated as a agent having ability of part perception, competition and self-learning in this method. The aim of overall optima comes true through interactions between agents and environment as well as among agents. The competitive and self-learning behaviors of agent are reflected by the characters of survival of the fittest, diversity and self learning. Pareto store population structured based on challenge match method can reduce complex rate and improve efficiency. So from factors what have stated multi-agent GA can well converge to Pareto optimum solution and has good convergence character.

Table 2. The optimization results of example 2

| Cases | Network losses (kW) | The lowest voltage of bus (p.u) | Operation times of switches | Number of switch operated |
|---|---|---|---|---|
| Case 1 | 229.9 | 0.9277 | 1 | Close: 47 |
| Case 2 | 227.6 | 0.9274 | 2 | Close:15, 25 |
| Case 3 | 227.1 | 0.9289 | 2 | Close:42, 20 |
| Case 4 | 227.0 | 0.9290 | 3 | Close:25, 47<br>Open:18 |
| Case 5 | 224.4 | 0.9302 | 3 | Close: 15, 19<br>Open:17 |
| Case 6 | 224.1 | 0.9345 | 3 | Close:15, 25<br>Open:17 |
| Case 7 | 224.6 | 0.9335 | 4 | Close:20, 37, 42<br>Open:14 |
| Case 8 | 223.6 | 0.9347 | 4 | Close:19, 50, 53<br>Open:48 |
| Case 9 | 222.3 | 0.9354 | 5 | Close:25, 41,47<br>Open:18, 46 |
| Case 10 | 229.5 | 0.9351 | 5 | Close:15, 41, 47<br>Open:21,46 |

## 5. Conclusions

In terms of the distribution system with DGs, a multiple objective optimizing model is proposed to solve the service restoration problem and is solved by using method of multi-agent GA. Firstly, a service restoration model is proposed based on loads needing to restore, operational times of switches and network losses. Secondly, multiple objective service restoration problem is settled by using conception of Pareto optimum and come true by the way of multi-agent GA. Multi-agent GA designs agent grid environment and competitive and self-learning behaviours to seek optimal solution for objective function, and achieves overall and quick convergence. Pareto store population structured based on challenge match method can reduce complex rate and improve efficiency. Finally, simulation analysis is carried through real examples. The examples' results indicate that multi-agent GA can well converge to Pareto optimum solution and has good convergence and practicality characters. Decision makers can select one suitable solution to be the best case for service restoration based on real condition. This method has better practicality and is more reasonable than single optimal solution from single objective model.

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