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Research Article

Real-Time Multifault Rush Repairing Strategy Based on Utility Theory and Multiagent System in Distribution Networks

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The problem of multifault rush repair in distribution networks (DNs) is a multiobjective dynamic combinatorial problem with topology constraints. The problem consists of archiving an optimal faults' allocation strategy to squads and an admissible multifault rush repairing strategy with coordinating switch operations. In this article, the utility theory is introduced to solve the first problem and a new discrete bacterial colony chemotaxis (DBCC) algorithm is proposed for the second problem to determine the optimal sequence for each squad to repair faults and the corresponding switch operations. The above solution is called the two-stage approach. Additionally, a double mathematical optimization model based on the fault level is proposed in the second stage to minimize the outage loss and total repairing time. The real-time adjustment multiagent system (RA-MAS) is proposed to provide facility to achieve online multifault rush repairing strategy in DNs when there are emergencies after natural disasters. The two-stage approach is illustrated with an example from a real urban distribution network and the simulation results show the effectiveness of the two-stage approach.

1. Introduction

Distribution network (DN), as the end of the entire power system, is connected with the users directly, and the normal and economical operation of the DN is crucial [1]. Snowstorms, earthquakes, and other natural disasters have brought great damage to the distributed network in recent years. The power equipment failure, tower collapsed, substation damaged, and even partial paralysis of the grid have caused serious influence on the production and life of the damaged areas. Huge losses of life and property of the people will be caused if the power supply can not be restored quickly. The repairing personnel and resource may be insufficient on the rush repairing site due to the diversity of the outage load. Coupled with the emergencies, the existing researches can not fully meet the needs of the rush repair. In order to deal with the emergencies on repairing site to minimize the outage loss and total repairing time, it is important to carry out researches on rush repairing strategy with limited repairing personnel and resource.

There has been many investigations on power system restoration and fault diagnosis, while studies on multifault rush repair in distribution systems are quite limited, and existing literatures are to develop the repairing strategies ahead of time based on the deterministic fault message [2–5]. But in the actual rush repair, the prestrategy is feasible only when the relevant forecast information is consistent with the actual information. However, many unexpected events may occur during an actual rush repair, which will result in the prestrategy becoming unreasonable or even unfeasible. Therefore, this paper proposes to research on how to adjust the multifault rush repairing strategy in real-time considering the uncertainty of the emergencies on rush repairing site.

The real-time adjustment reflects the characteristics of automation and intelligence of the multifault rush repair. Agent is an intelligent entity with a high degree of autonomy capability that keeps running in a dynamic environment. According to their own resources, status, capacity, relevant knowledge and knowledge rules, and the external environment information acquired, they can perceive the environment, accomplish specific tasks independently, and achieve the intended target by planning, reasoning, and decision-making [6, 7]. MAS has become hot for more than 20 years. In the field of power systems, there are many researches and applications of multiagent technology, and the agent component can be increased flexibly based on the actual demand, which is consistent with the functional requirements of power dispatching automation system [8]. A MAS is proposed to manage the power dispatch in DN dynamically to balance the supply and demand by considering the variability of DGs and loads through five types of autonomous agents in [9]. A novel distributed algorithm is presented for service restoration with distributed energy storage support following fault detection, location, and isolation in [10]. A MAS including communication of agents is presented to restore a power system after a fault in [11]. Considering the excellent performance of MAS, this paper introduces multiagent theory to solve the real-time adjustment problem of the multifault rush repairing strategy in distribution network.

In the existing literatures on multifault rush repair of distribution network, researches can be divided into two parts: the allocation of the fault tasks and the model of multifault rush repair in DN. For the first part, a multifault rush repairing strategy optimization model with a single squad is established in [2], which can not be applied to the actual multisquad collaboration; a multisquad cooperation mechanism is given in [5], which considers the allocation of resources and a repairing scheduling multiagent approach is proposed to archive an emergency repairing plan quickly, as well as a resource grouping scheme. For the second part, the tie switch is taken as a virtual fault and a multifault rush repairing model is built in [3, 4], which assumes the repairing personnel and resource are enough and assigns fault tasks to each squad randomly. It seemingly simplifies the repairing model, but it has some drawbacks. (1) It increases the search scope of the solution space greatly, resulting in "curse of dimensionality" problem, reducing the formulation speed of the repairing strategy, and disobeying the characteristic of urgency of the actual rush repair. (2) It does not match with the actual role of tie switches in DN. (3) Only achieving restoration of the load is the main content of fault recovery, but the rush repair needs to ensure all faults repaired.

In response to these problems, this paper first introduces utility theory to achieve an efficient allocation of fault tasks, divides fault level, and develops repairing principle. Then a real-time adjustment of repairing strategy multiagent system (RA-MAS) is established considering two cases: when there are no emergencies, repairing squads complete the entire intelligent repair following the prestrategy; when unexpected events occur, it determines the real-time adjustment decision, ultimately achieving the repairing target of restoring the maximum load power supply with minimum time cost.

The remainder of the paper is organized as follows. In Section 2, a multisquad dynamic allocation of the fault tasks based on utility theory is discussed. The distribution network multifault repairing model and DBCC algorithm are introduced in Section 3. In Section 4, a multiagent system model for real-time adjustment of repairing strategy is presented. Simulation results are analyzed to demonstrate the performance of the proposed approach in Section 5. Conclusions and some possible paths for future researches are finally drawn in Section 6.

2. Multisquad Dynamic Allocation of the Fault Tasks Based on Utility Theory

2.1. Goals of Allocation of the Fault Tasks. It is assumed that after multiple faults occur in the DN the repairing tasks collection is $T = \{t_1, t_2, \dots, t_j, \dots, t_n\}$, where n is the number of faults; the repairing squad collection is $R = \{r_1, r_2, \dots, r_i, \dots, r_m\}$, where m ($m < n$) is the number of repairing squads, which are equipped with the repairing personnel and resource. ρ is the task allocation solution set.

The assignment of fault tasks needs to achieve the following objectives: ① ensuring that a repairing squad has sufficient capacity to repair a fault; ② ensuring that each squad's mission is broadly balanced; ③ ensuring the repairing squad with better expertise repairing their types of fault in priority, where "better" means a relatively short period of time to repair the same fault; ④ ensuring that faults with high urgency are repaired in priority, where the urgency is consistent with the level of outage loads; ⑤ guaranteeing that the time of faults waiting to be repaired is as short as possible; ⑥ guaranteeing that faults assigned to the same squad are repaired as continuous as possible in order to reduce the squad's waiting time.

Targets ①~③ can be realized by the utility model so that a fault task allocation scheme can be quickly developed dynamically [12]. Targets ④~⑥ need the automation of MAS to achieve the adjustment of the rush repairing strategy actually according to the emergency.

2.2. Utility Theory. The utility theory is proposed by economists to characterize consumers' consumption decision and decision scheme and provide a mathematical tool to calculate the relative value of different indicators [13]. Recently, utility theory has been used by many researchers in various fields to obtain the optimal decision [14, 15]. Utility usually represents the user's satisfaction to accept a service or resource. The economic Cobb-Douglas utility function is often used to describe the individual utility as it can better reflect the tradeoffs among the model variables. The types of the utility function contain linear type, conservative type (exponential type), adventure type, and long type, and the proper types need to be selected according to actual event characteristics and the nature of the utility function [16].

In the multifault rush repair problem, the early assignment of fault tasks can select the appropriate squad based on the features of faults' demands and repairing squads' capabilities. So the utility theory is introduced to characterize the heterogeneity of faults' demands and repairing squads' capabilities by constructing a utility function in this paper. Utility values reflect the competence for squad r_i to repair fault t_j, that is, the satisfaction obtained by fault t_j to be repaired by squad r_i, resulting in a fault task allocation scheme with higher satisfaction and overall utility. Attribute vector is applied to characterize the features of faults' demands and repairing squads' capabilities in this paper.

2.3. Attribute Vector

2.3.1. Repairing Squad's Capability Vector

Definition 1 (repairing squad preference). Due to the limitations of squad location, traffic conditions among faults, natural conditions, and different human factors, repairing squads have different wills to complete the repairing mission; that is, repairing squads' preferences are different [17]. Set the level of preference of squad r_i to repair fault t_j as δ_i^j $(0 \leq \delta_i^j \leq 1)$ and $(\delta_i^j)_{\min}$ as the minimum level of preference; then squad r_i may choose to repair fault t_j when $\delta_i^j \geq (\delta_i^j)_{\min}$, otherwise not.

In order to quantify squad's capability, we classify it into k intuitive atomic capabilities c_i and constitute the capability set $C = \{c_1, c_2, \ldots, c_k\}$ [18]. Define the quantified description of the squad capability vector C_i^r for the atomic capabilities of squad r_i as follows:

$$C_i^r = \left[\alpha_{i1}c_1, \alpha_{i2}c_2, \ldots, \alpha_{ik}c_k\right]^T, \tag{1}$$

where α_{ik} $(\alpha_{ik} \geq 0)$ is squad's capability coefficient, which is a relative value and dimensionless, reflecting the relative degree of squad r_i to have atomic capability c_k. Squad r_i does not have the atomic capability c_k when $\alpha_{ik} = 0$.

Definition 2 (failure degree). After each fault has been repaired, the squad's resources will reduce and repairing efficiency will decline, where the fault also has some "damage" to the squad during the repair process. Therefore, the capability drop of squad r_i is defined as the failure degree μ_i^r $(0 \leq \mu_i^r \leq 1)$ of its atomic capability to reflect the damage cost that the squad suffered during the repairing process.

Failure degree indicates that α_{ik} is not a constant but will show a decreasing trend in the repairing process.

2.3.2. Fault's Demand Vector. On the actual rush repairing site, each fault has a demand vector to quantify the degree of its demand for different atomic capabilities and the demand vector C_j^t of fault t_j is as follows:

$$C_j^t = \left[\beta_{j1}c_1, \beta_{j2}c_2, \ldots, \beta_{jk}c_k\right]^T, \tag{2}$$

where β_{jk} $(\beta_{jk} \geq 0)$ is fault's demanding coefficient, which is a relative value and dimensionless, reflecting the relative demand degree of fault t_j for atomic capability c_k. Fault t_j does not need the atomic capability c_k when $\beta_{jk} = 0$.

It is necessary to reduce the dimension of the repairing squad's capability vector and the fault's demand vector to simplify the utility function model and develop the fault task allocation scheme quickly. So the resources needed are processed into four groups according to the fault type: transformer failure resource group, backup power failure resource group, cable failure resource group, and overhead line failure resource group. Squads' ability for these resources corresponds to squads' atomic capabilities $c_1 \sim c_4$ in turn and the physical meaning of α_{ik} is the comprehensive strength of squad r_i to equip c_k.

The squad's repairing efficiency is corresponding to atomic capability c_5 and its physical meaning is the efficiency of different squads to repair the same fault when the resource is consistent.

2.4. Utility Model

2.4.1. Utility Function Model

Definition 3 (capability condition matrix $V_{m\times n}$). It is a matrix that reflects whether squad r_i has the capability to repair fault t_j alone. Thus, the expression of element v_{ij} is given in the form of Boolean variables.

$$v_{ij} = \begin{cases} 1, & \text{if } \delta_i^j \geq \left(\delta_i^j\right)_{\min}, \ \forall a, \alpha_{ia} \geq \beta_{ja}, \\ 0, & \text{others.} \end{cases} \tag{3}$$

Considering both the repairing squad's preference and capability vector, we can find that only when $v_{ij} = 1$ does squad r_i have the capability to repair fault t_j alone and fault t_j can not be assigned to squad r_i when $v_{ij} = 0$. Then it will avoid the infeasible allocation of faults and greatly reduce the search space dimension of the fault allocation scheme.

Set the utility function $u_j(i) = 0$ when $v_{ij} = 0$, yet we need to quantify the competent degree of squad r_i for fault t_j to get the optimal-utility fault allocation scheme set when $v_{ij} = 1$, thus getting higher satisfaction of fault t_j. Faults' demands and squads' capabilities will change with the repairing environment changes and the repairing process performances, and the competent degree is also changed accordingly. Thus, $u_j(i)$ is a function of the squad's capability and fault's demand:

$$u_j(i) = \begin{cases} U_j\left(C_i^r, C_j^t\right), & v_{ij} = 1, \\ 0, & v_{ij} = 0, \end{cases}$$
$$U_j\left(C_i^r, C_j^t\right) = \sum_{p=1}^{k} \omega_p \cdot f_p\left(\alpha_{ip}, \beta_{jp}\right), \quad (k = 5), \tag{4}$$

where ω_p is the utility weight of a fault's atomic demands and $\sum_{p=1}^{k} \omega_p = 1$. Its value is determined through a method (characteristic value method) that is a combination of subject and object.

$f_p(\cdot) = \beta_{jp}/\alpha_{ip}$ is the utility function of the squad's pth atomic capability to the fault's pth atomic demand, reflecting that the closer a squad's capability to a fault's demand is, the higher the overall utility of faults task allocation is under the premise of meeting fault demands.

Set $u_{ij} = u_j(i)$ and get the utility function matrix:

$$U = \begin{bmatrix} U_1 & U_2 & \cdots & U_n \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_m \end{bmatrix} = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1n} \\ u_{21} & u_{22} & \cdots & u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{m1} & u_{m2} & \cdots & u_{mn} \end{bmatrix}. \quad (5)$$

Under the current state, for the same fault, the greater the value of the utility function is, the higher the satisfaction of its acceptance of the squad's repair is; that is, the stronger the squad's capability to repair the fault is, the more competent the squad for the fault is.

Finally, based on the above utility function matrix U, the Roulette Wheel Selection method [19] is applied to allocate the fault mission and ρ will be archived.

2.4.2. Squad Collaboration. The cooperation must be considered when every squad can not repair a fault alone. That is, two or more squads will repair a fault together.

If fault t_j needs to be repaired together by squads r_i and r_l, the repairing process is as follows.

(1) Combine capability vectors C_i^r and C_l^r as C_{i+l}^r. The capability vector C_{i+l}^r of the combined squad r_{i+l} is

$$C_{i+l}^r = \left[\left(\alpha_{i1} + \alpha_{l1}\right) c_1, \left(\alpha_{i2} + \alpha_{l2}\right) c_2, \ldots, \left(\alpha_{ik} + \alpha_{lk}\right) c_k \right]^T. \quad (6)$$

(2) Redevelop a capability condition matrix together with fault's demand vector C_j^t. The capability condition of the combined squad r_{i+l} to complete fault t_j is as follows: $v_{(i+l)j} = 1$ only when $\delta_i^j \ge (\delta_i^j)_{\min}$, $\delta_l^j \ge (\delta_l^j)_{\min}$, $\forall a, \alpha_{ia} + \alpha_{la} \ge \beta_{ja}$.

(3) Establish a new utility function model and a new utility function matrix U'.

3. Distribution Network Multifault Repairing Model

3.1. Classification of Fault Levels and Development of Repairing Principles. The structure of DN is radial and the repairing personnel and resource are limited. So it is particularly important to determine the repairing priority of faults to restore important load when multifaults occur in DN.

According to the three load levels divided in load reliability, the urgency of the need to restore the power supply is also divided into three levels: loads of the first level, the second level, and the third level are corresponding to loads of the highest urgency, the medium urgency, and the low urgency, separately.

Faults are divided into two levels and the minimum fault set $T_{\min}$ is defined. Faults with the highest urgency are the first level faults and other faults are the second level faults. The first level faults are included in $T_{\min}$, where $T_{\min} = \{t_1, t_2, \ldots, t_q\}$ $(q \le n)$. With the premise of contact switch operation, all loads with the highest urgency can be restored as long as q faults in $T_{\min}$ are repaired.

Thus, the actual rush repair should follow the following repairing principles: repair the first level fault in priority and then the second level fault after all loads with the highest urgency have been restored; faults in the same level need to optimize the repairing order according to their objective values.

3.2. Objective Function. The multifault rush repair should achieve the following four objectives: each squad ① repairs the nearest fault to reduce the delay on power restoration caused by drive; ② completes the repairing plan in advance, rather than postponing it; ③ restores loads of highest urgency in priority to reduce the outage loss; ④ ensures that the repairing process is affected as little as possible when emergencies occur; for example, the repairing route is damaged or a new fault occurs.

According to repairing principles, faults in $T_{\min}$ should be repaired prior to restore loads of highest urgency as quickly as possible. Thus the repairing order of the first level loads should be repaired with the shortest time. Meanwhile, in order to ensure the maximum satisfaction of all faults, the repairing efficiency is considered in the repairing time. The total repairing time of the first step can be expressed as follows:

$$\min f_1\left(X_2\right) = \max\left\{D_1, D_2, \ldots, D_m\right\}, \quad (7)$$

where X_2 is the repairing sequence of faults; D_m is the time of squad m to complete its repairing task; the time of squad i to repair fault x_j is $T_{i(x_j)} + T_B(x_j)/\alpha_{i5}$, $T_{i(x_j)}$ is the driving time, and $T_{B(x_j)}$ is the expected repairing time of fault x_j.

The objective of the repairing order of other faults is to minimize comprehensive outage loss, and the total outage loss in the second step can be described as follows:

$$\min f_2\left(X_2\right) = \sum_{i=1}^{m} \sum_{j=1}^{n-q} \left(T_{i(x_j)} + \frac{T_B\left(x_j\right)}{\alpha_{i5}} \right) \cdot \sum_{dj=2}^{3} \beta_{dj}\left(x_j\right) L_{dj}\left(x_j\right), \quad (8)$$

where $\beta_{dj}(x_j)$ is the level coefficient of outage load and $L_{dj}(x_j)$ is active power of outage load caused by fault x_j.

Constraints in the model are introduced as follows:

$$g_k \in G_R, \quad (9)$$

$$|P_k| \leq P_{k\max}, \quad (10)$$

$$U^a_{\min} \leq U^a \leq U^a_{\max}, \quad (11)$$

$$R_s \leq R. \quad (12)$$

The constraints listed above include radial network topology constraint (9), branch current capacity constraint (10), node voltage constraint (11), and repair resources constraint (12).

In the above constraints, g_k is network topology of the area which has been restored, and G_R is the set of radial network structure under consideration. If ith fault has been repaired, the connection status between both sides of the fault will be changed by switch operation. Constraint (9) is to prevent ring network operating. P_k is the power flow through branch k which is calculated by back/forward sweep method, $P_{k\max}$ is the maximum power flow capacity limit of branch k, U^a is node voltage in the repairing process, $U^a_{\min}$ is the lower limit of the node voltage, $U^a_{\max}$ is the upper limit of the node voltage, R_s is the required resources when multiple faults occur, and R is resources available.

For these two objectives, the double-level mathematical optimization model of distribution network multifault rush repair is established. The optimal faults allocation scheme and repairing order from ρ will be archived through the improved DBCC algorithm.

3.3. The Improved Discrete Mechanism of BCC Algorithm. BCC algorithm is an intelligent optimization algorithm for continuous variables and has been widely used in the continuous problem field [20, 21]. However, the control variables in the multifault rush repairing order optimization is a sequence of discrete variables, and its value represents only the code of the fault rather than the position of bacteria in the solution space. Existing BCC algorithm is only applicable to optimization problems with continuous variables. Thus, the following method is applied to discretize the BCC algorithm.

The bacteria dimension is taken to be n since there are n faults in DN. Represent the n faults by random numbers $a_1, a_2, \ldots, a_n$ with values taken within 0~1 and calculate the initial position of bacteria by unitary processing as follows:

$$x_i = \frac{a_i}{\sum_{i=1}^{n} a_i}, \quad (i = 1, 2, \ldots, n). \quad (13)$$

Now sort $x_1, x_2, \ldots, x_n$ in descending order and the order of x_i represents the sequence of fault repairing.

4. Multiagent System Model for Real-Time Adjustment of Repairing Strategy

4.1. Architecture of the RA-MAS. The RA-MAS is made up by such three types of agents as coordination agent (CA), assist agent (AA), and execution agent (EA). Figure 1 shows a simple structure diagram charactering RA-MAS's operating characteristics. It can be seen that CA can share information simultaneously with EA and AA; AA can only exchange information with CA and its assisting role for EA can be only achieved through CA; parts of EA can also exchange information between each other.

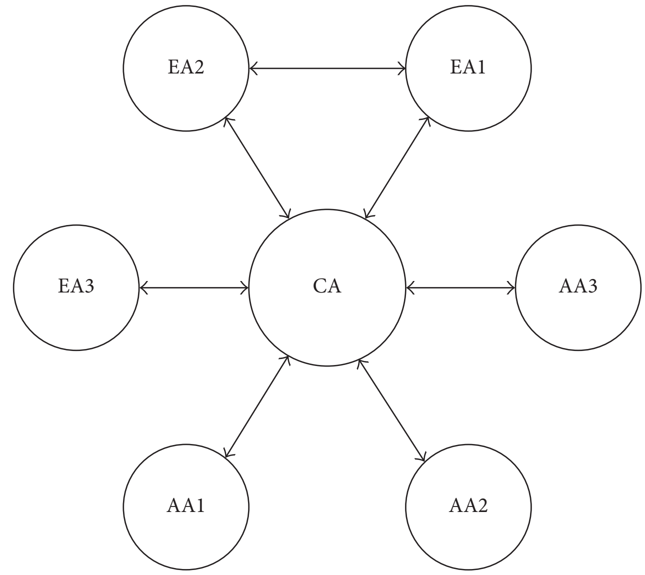

Figure 1: A simplified structure of RA-MAS.

Multifault rush repair is actually the service of squads for faults; thus this article presents the concept of unit-task and service entity to facilitate characterization.

Unit-task is the basic unit of the fault task and its demand for the resource is more than one type. It is necessary to specify such attributes as the maximum expected time to complete the repair process, the resource needed, and so forth. The number of the unit-tasks will be reduced as a fault is repaired and increased as a new fault occurs suddenly.

Service entity is the basic unit of the repairing squads and its capability is more than one type. It is necessary to specify such attributes as the repairing efficiency, the resource needed, and so forth. The number of the service entities will be reduced as a squad needs a rest and increased as a squad return to the repairing process.

The multifault rush repair in DN in this paper includes fault tasks allocation, fault recovery, and repairing sequence optimization and information coordination which are implemented by CA, AA, and EA. The working processes of CA, AA, and EA are described as follows.

(1) Coordination Agent (CA). CA consists of the control center agent (CCA), the background data processing (BDP) platform, and the blackboard. Their communication is shown in Figure 2. The BDP platform is mainly responsible for the two tasks: fault tasks allocation and emergency information processing; thus it consists of the utility model unit (UMU) and the emergency processing unit (EPU).

When faults occurred in DN after a disaster, CCA will analyze the information obtained from the information acquisition system. Then CCA writes the information into

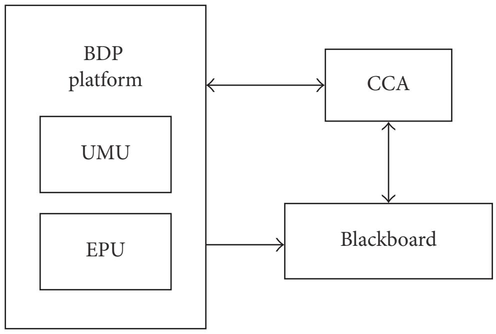

Figure 2: A simplified structure of CA.

the blackboard for other agents to read and transmits it to the BDP platform. The information includes the DN topology information, geographical information of the outage zone, the load information, the repairing squad information, the fault information, the DG and emergent power-vehicle information, and the possible unexpected event information.

CCA analyzes and processes the geographical information of the outage zone, the repairing squads' information, and the faults' information and then predicts the driving time F_B and the fault repairing time T_B. At last CCA transmits them to the DP platform and the blackboard.

UMU of the BDP platform integrates the DN topology information, the repairing squads' information, and the faults' information. Then it will provide attribute vectors C_i^r and C_j^t, the utility model, and the utility function matrix. At last it will obtain the task allocation solution set ρ via the roulette wheel selection method and write it into the blackboard.

When the BDP platform gets any information about emergencies, EPU processes the emergency information and reports it to CCA. CCA reanalyzes and reprocesses large amounts of information and then transmits it to the BDP platform and blackboard.

(2) Assist Agent (AA). AA is comprised of the distribution generator agent (DGA), the emergent power-vehicle agent (EPA), and the switch control agent (SCA). They can exchange information with each other directly and cooperate together to repair the faults.

DGA is in the charge of CCA and in charge of controlling connection states of all DGs in the outage zone to supply power to its maximum ability for the microgrid it belongs to. When the fault is repaired, DG continues to operate in grid-connected state. Meanwhile, DGA monitors and stores DG information and then writes it into the blackboard. DG information includes the amount, type, rated power, utilization rate of fuel, electricity price, and connection state of the device.

EPA is in the charge of CCA and in charge of controlling connection states and power supply positions of the emergent power-vehicles, which supply power temporarily for the first level loads as a priority. When the fault is repaired, the emergent power-vehicles go on working as the principle of the shortest path and the maximum reduced economic loss.

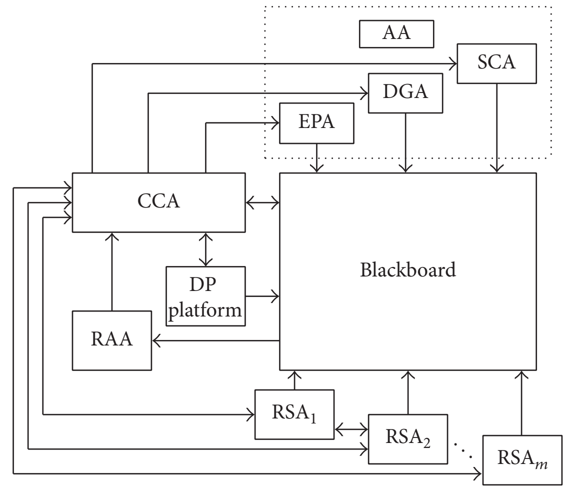

Figure 3: The architecture diagram of RA-MAS.

Meanwhile, EPA monitors and stores the emergent power-vehicle information and then writes it into the blackboard. The emergent power-vehicle information includes the amount, capacity, connection state, current position, and utilization rate of fuel of the device.

SCA is in the charge of CCA and in charge of controlling on-or-off state of the tie breaking switch and the section switch to optimize the cooperative operation strategy for the object of the fault recovery. The improved DBCC algorithm is used in the process. Meanwhile, SCA monitors and stores the switch information and then writes it into the blackboard. Switch information includes the amount, capacity, and on-or-off state of the switch.

(3) Execute Agent (EA). EA includes the real-time adjust agent (RAA) and repairing squad agent (RSA), and RSA is for the service entity.

At first RAA reads ρ and AA's information from the blackboard. Then it optimizes each scheme in phase according to the load level via the improved DBCC algorithm. It reports the best scheme and repairing order directly to CCA at last.

RSA is the real service entity and in charge of repairing unit-tasks and writing the repairing process and local information into the blackboard in the time.

The architecture of RA-MAS is shown in Figure 3.

4.2. Workflow of the RA-MAS. The proposed RA-MAS in this paper is based on the premise of normal communication. The widespread outage after a disaster causes its communication interrupt, so the system will be the first to be repaired. Faults in DN will be repaired after RA-MAS has recovered its communication ability. RA-MAS is a system in the essence that the service entity processes the unit-task in intelligence. Its intelligence mainly embodies developing the prestrategy in advance and adjusting the prestrategy in real-time when emergencies occur. The specific work process is as follows and Figure 4 shows the simplified operation flowchart of RA-MAS.

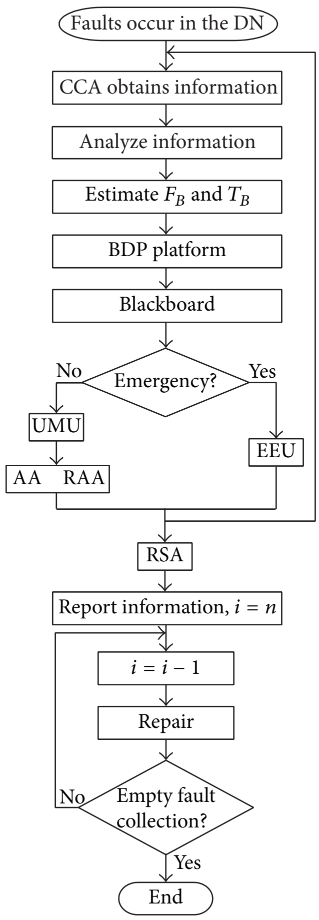

Figure 4: The simplified operation flowchart of RA-MAS.

(1) CCA monitors the current state of DN, obtains information from the information collection system, gives T_B and F_B via the information integration/analysis module, and updates the BDP platform and the blackboard.

(2) After UMU of the BDP platform has integrated and analyzed the above information, the repairing squads' capability vector and the faults' demand vector are obtained. The utility model building module establishes the capability condition judgment matrix according to the attribute vector, builds the utility model, and calculates the utility function matrix. The fault task allocation module starts the roulette wheel selection method to complete the effective allocation of all unit-tasks, generating ρ which is written into the blackboard by the information output unit. If the information repository unit obtains any information about emergencies, turn to step (3); otherwise, go to step (4).

(3) EPU processes emergency information and reports it to CCA. CCA reanalyzes and reprocesses the information:

(a) When a new fault occurs suddenly, it will be added into the queue where the faults are waiting for repairing and the faults' demand information will be modified and then return to step (2).

(b) When a squad needs a rest, its information will be removed and the repairing squads' capability information will be modified and then return to step (2).

(c) When the actual time is inconsistent with the expected time, either the repairing time or the driving time, either in advance or afterwards, the current time will be taken as the starting time and then return to step (2).

(4) AA finishes the following work:

(a) DGA cooperates with the repairing work by controlling connection states of all DGs in the outage zone. When loads in the microgrid that the DG belongs to lose power due to faults, DG is isolated island operation and supplies power independently of its internal loads. After faults have been repaired and the grid recovers normal power supply, DG gets back into the grid-connected state.

(b) EPA cooperates with the repairing work by controlling connection states and power supply positions of the emergent power-vehicles. The power-vehicle is dispatched to the capacity-matching and the nearest first level load to supply power, and the power supply time is recorded. When the fault is repaired and the load recovers normal power supply, it will be sent to the next capacity-matching and the nearest first level load till its fuel is depleted or all faults are repaired.

(c) SCA cooperates with the repairing work by controlling the on-or-off state of the tie breaking switch and the section switch, giving the on-or-off command to turn to supply with the maximum loads and ensuring the least operation times. After all faults are repaired, the switches will be restored to the initial state.

(5) RAA reads ρ and AA's information from the blackboard and stores them into the information repository. At first the rush repairing model building module establishes the double-level mathematical optimization model according to the faults' hierarchy. Then the repairing sequence optimization module optimizes the repairing order of each service entity by the improved DBCC algorithm, giving the best repairing route and the specific actions of AA. RAA reports the best scheme and repairing order to CCA finally.

(6) RSA applies for unit-tasks from CCA and repairs faults in turn. After each RSA has finished its unit-tasks, the mission ending information is reported to CCA directly.

Table 1: Detail of load level.

Load level	Load number
The first level	101, 105, 107, 109, 110, 115, 119, 128, 132, 135, 137, 138, 140, 144, 145, 148, 150, 153, 154, 155, 156, 161, 169, 170, 172, 177, 183, 184, 192, 193, 195
The second level	102, 103, 106, 108, 111, 113, 114, 116, 118, 120, 121, 122, 125, 126, 130, 131, 133, 134, 139, 142, 146, 147, 151, 152, 158, 159, 162, 163, 164, 166, 167, 168, 171, 174, 176, 179, 180, 181, 185, 186, 187, 188, 189, 190, 191, 194, 197, 198
The third level	104, 112, 117, 123, 124, 127, 129, 136, 141, 143, 149, 157, 160, 165, 173, 175, 178, 182, 196

Table 2: Preference information of squads.

Squad	Fault										
	43	44	45	46	47	48	49	50	51	52	53
a	0.8	0.94	0.6	0.85	0.9	0.7	0.88	0.8	0.8	0.76	0.85
b	0.78	0.9	0.55	0.85	0.95	0.77	0.92	0.8	0.81	0.75	0.9
c	0.88	0.77	0.5	0.72	0.78	0.68	0.8	0.91	0.9	0.86	0.87

Table 3: Repairing squads' capability vector.

Squad	Atomic capacity				
	1	2	3	4	5
a	1.85	1.97	1.77	1.73	1.93
b	1.84	1.89	1.78	1.63	1.98
c	1.83	1.77	1.85	1.72	1.94

(7) When the fault task set is null, CCA receives all mission ending information from RSA and shuts off RA-MAS.

5. Simulation Results and Discussion

5.1. Parameter Initialization. In order to verify the performance of the proposed RA-MAS method, a computational study is presented in this section. The distribution network of H county [22] is operated and three DGs and eleven faults are randomly added into the system, which is shown in Figure 5. The system contains five distribution lines, five normally open contact switches, and fifteen normally closed section switches. Assuming the power company has three repairing squads and two emergent power-vehicles for sending, respectively, a, b, c and EP1, EP2. Set bacterial population $N = 100$, iterations $K = 50$, $(\delta_i^j)_{\min} = 0.5$, $\mu_i^r = 0.005$, $L_{\text{three}} = 2\,\text{MW}$, and $L_{\text{two}} = 1\,\text{MW}$, and the experiment is simulated via MATLAB 7.1. The detail of load level is shown in Table 1.

According to the working characteristic of RA-MAS, CCA first gets the repairing capability information of three squads, the demanding information of the 11 faults, and other information on repairing site. When the estimated repairing information is consistent with the actual one, UMU builds the utility function matrix model and provides the utility value and the fault task allocation scheme set ρ. Then, RAA establishes the faults' repairing optimization model and provides repairing order with the cooperation of DG, the emergent power-vehicles, and switches. Finally, CCA controls each agent to complete the repairing work, restoring loads with power supply.

Table 4: Faults' demanding vector.

Atomic demand	Fault										
	43	44	45	46	47	48	49	50	51	52	53
1	0	0	0	0	0	0	0	0	0	0	1.83
2	0	0	0	1.68	0	0	0	1.90	0	0	0
3	1.55	1.35	0	0	1.68	0	1.75	0	0	1.56	0
4	0	0	1.57	0	0	1.63	0	0	1.66	0	0
5	1.90	1.84	1.09	1.72	1.82	1.39	1.74	1.94	1.71	1.69	1.86

5.2. Analysis of UMU. The preference values of squads to repair each fault are shown in Table 2. As long as the preference value is more than the minimum preference of squad r_i to repair fault t_j, $(\delta_i^j)_{\min} = 0.5$, r_i would like to choose to repair fault t_j.

Though each squad is willing to repair each fault, its preference to repair fault 45 is small. Because the outage loads 123 and 124 caused by fault 45 are not the first level load and their urge to recover power supply is not high.

Each atomic capability coefficient of repairing squads and each fault's demanding coefficient is presented in Tables 3 and 4, respectively.

After the capability condition judgment to complete the repairing mission according to Tables 2~4, it is found that squad b does not have the ability to repair fault 51 and all squads do not have the ability to repair fault 50, which needs the squads' collaboration. Then the utility function matrix U and the new one U' are obtained, which characterize the utility value of each squad to repair each fault alone and the utility value of each of the two combined squads to repair fault 50, respectively. Finally, considering the effect of μ_i^r, faults are allocated to each squad reasonably before repairing via the roulette wheel selection method. Table 5 shows the task allocation scheme set ρ with 8 dimensions.

It is found that in the above 8 fault task allocation schemes, fault 51 is never assigned to squad b since its fourth atomic demand for the overhead line failure resource group is 1.66 which is higher than the fourth atomic capacity of squad b. Besides, fault 50 needs squads' collaboration, as its fifth atomic demand for squad's repairing efficiency is relatively the highest as 1.94. However, it is located on the main line and near the power source, so it needs to be repaired as soon as possible to reduce outage economic losses. It is assigned

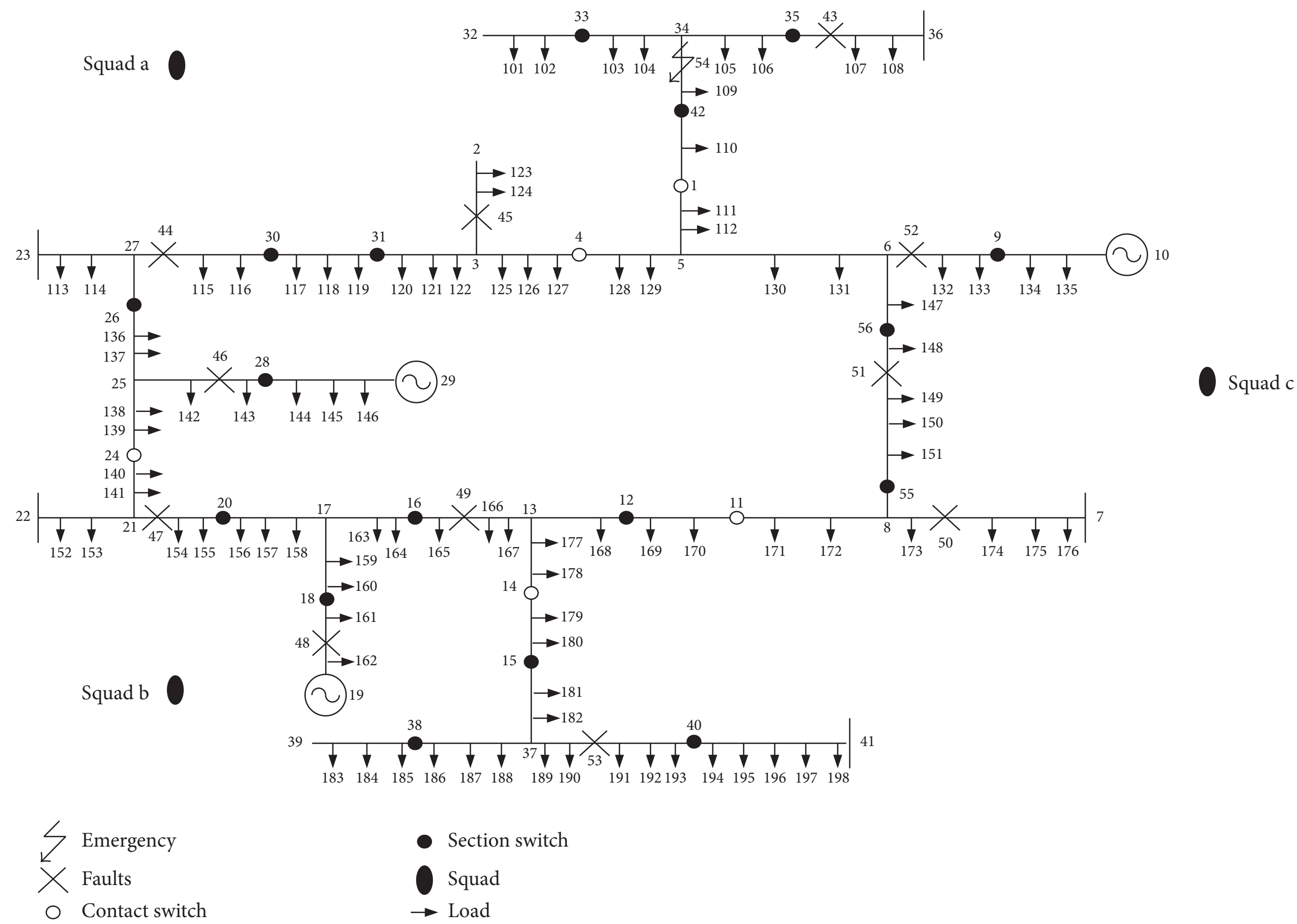

Figure 5: The distribution network with DG of H county.

Table 5: Task allocation solution set ρ.

Scheme	a	b	c
1	44, 45, 48, 49, 50	46, 52, 53	43, 47, 50, 51
2	44, 45, 49, 50, 51	43, 46, 47	48, 50, 52, 53
3	43, 47, 50, 51	44, 45, 48, 49	46, 50, 52, 53
4	44, 45, 50, 51, 53	47, 49, 52	43, 46, 48, 50
5	43, 45, 48, 50, 51	44, 47, 52	46, 49, 50, 53
6	47, 50, 51, 53	43, 44, 46, 48	45, 49, 50, 52
7	45, 46, 49, 50, 51	43, 47, 53	44, 48, 50, 52
8	43, 45, 50, 51, 52	44, 47, 48	46, 49, 50, 53

to squads a and c, which is corresponding to the maximum utility value in U'.

The proposed fault task allocation method based on the optimal utility in this paper has realized the reasonable faults' distribution in DN according to the information of the grid topology, faults, and the repairing squads' capability. Meanwhile, it is suitable for the situation where the squads' collaboration is needed and provides reference for power decision-makers. It also has achieved the rapid development of the task allocation schemes for that it has effectively reduced the searching space of the schemes.

5.3. Analysis of RA-MAS. According to the working characteristic of AA, when multifaults occur in a DN

(1) SCA controls section switches to isolate faults in the first place and opens the 17 section switches and power sources 7, 22, 23, and 36; then the tie switch transfers to on state to supply outage loads as much as possible and restores the initial open state after the faults were repaired;

(2) DGA controls DG10 and DG29 supply power for its internal loads, respectively, and operate again in the grid-connecting mode until the corresponding faults are repaired; that is, DG10 connects to the grid when section switch 9 is charged and DG29 connects to the grid when section switches 26 and 28 are charged;

(3) EPA controls EP1 and EP2 moving to loads of the highest urgency immediately, cooperating with the repair of the first level faults and ensuring restoration of power to the first level loads in the shortest time.

Table 6: The repairing order of three schemes.

Squad	Repairing order		
	1	2	3
a	47, 51, 52, 49	47, 46, 52, 49	49, 51, 52, 43
b	46, 53, 50, 45	53, 44, 50, 45	53, 44, 50, 45
c	44, 43, 50, 48	43, 51, 50, 48	47, 46, 50, 48

The repairing order of the eight schemes mentioned in Table 5 will be optimized and archived according to the proposed double-level mathematical model of multifault rush repair and three optimal schemes will be chosen, as well as the corresponding repairing orders, which are shown in Table 6. Table 7 shows the cooperating operation actions of the section switches and the tie breaking switches after each fault has been repaired.

It is found that the actions of tie breaking switches 1, 11 and 14 are to transfer to on state to supply outage loads temporarily. The switches' actions are open to isolate the faults at first and to restore the original state after a fault is repaired. In addition, the open of section switches 9 and 28 has the role of cooperating with DG's island operation.

Table 8 shows the objectives of the three schemes mentioned in Table 7: $f_1(X)$ is the time to repair the first level faults and $f_2(X)$ is the comprehensive outage loss caused by the second level fault.

According to the optimized principle of the proposed multifault repair double-level mathematical model where the minimum $f_1(X)$ is considered at first, scheme 1 is the best since only for 34.25 hours power supply of all the first level loads can be recovered. And from the perspective of $f_2(X)$, in scheme 1, the comprehensive outage loss caused by the second level fault, 12 501 000 kWh, is not the largest. Therefore, scheme 1 should be implemented and at this point, EP1 and EP2 are, respectively, sent to the first level loads 107 and 161 to supply power until the corresponding faults are repaired or their fuel is insufficient.

Without loss of generality, it is assumed that the power company has carried out the repair as scheme 1 randomly. Squad a has repaired fault 51 with 0.6 hours ahead. When the repair is at the fifth hour, a new fault 54 occurs which is a first level fault. The first level loads 101, 105, 109 and 110 will still be outage loads even though fault 43 has been repaired. EPU processes the emergency information that informs RA-MAS to adjust the rush repairing strategy immediately. At the same time, from the information written to the blackboard by RSA, it is known that faults 44, 46, and 47 have been repaired, squads a and b are on the way to faults 52 and 53, respectively, and squad c is repairing fault 43. At the same time, UMU shows that the current ability of squad b is not enough to complete repairing fault 54 alone, and the fault task demand vector needs to be modified.

Table 9 shows the new fault task allocation scheme for faults 45, 48, 49, 50, 51, 52, 53, and 54 which are waiting for repair when new fault 54 appears suddenly, as well as the corresponding repairing order. Faults having been repaired are shown in brackets.

If the repairing strategy is not updated, let squad c, which finished the original repairing task first, repair the new fault 54. The results of the strategy are shown in Table 10 comparing with results of the repairing strategy in Table 9. It can be seen from Table 10 that the repairing time and outage loss of the strategy which is not updated are bigger than these of the strategy which is updated. In the former strategy, fault 54 is repaired after the other faults by squad c, so the first level loads 101, 105, 109, and 110 will be outage loads until the last. And it is useless to complete fault 43 as some loads are outage loads because of fault 54, which result in bigger outage loss. It can be seen that the RA-MAS will work well when some emergencies occur and the updated strategy can reduce repairing time and outage loss efficiently.

6. Conclusion

In this article, the utility model and real-time adjustment multiagent system are proposed to generate real-time emergency adjustment of multifault rush repairing strategy. This method can solve the dynamic allocation of faults and deal with the emergencies on repairing site. The salient features of this work are as follows:

(1) The proposed method deals with problems caused by the random assignment of faults and the squad cooperation, introducing utility theory to the multifault task allocation problem in DN. Attribute vector has realized to quantify and dynamically update repairing information. Utility function matrix model has achieved the dynamic allocation of faults and the rapid development of allocation schemes.

(2) The article divides faults into two levels and develops faults' repairing principles. The double-level mathematical optimization model of multifault rush repair has been established and DBCC algorithm is used to find the optimal strategy, which has reduced the outage time of the first level loads, as well as the comprehensive outage losses.

(3) Simulation results show that the proposed RA-MAS can not only develop the faults' task allocation scheme quickly, but also effectively cope with on-site emergencies by adjusting repairing strategies in real-time, which can restore power supply quickly and reduce the comprehensive outage losses at the same time.

The future work on this research will focus on uncertain factors in the multifault rush repair process, such as repairing time, the resources needed, and power of renewable energy. The rush repairing work combined with power system restoration will also be further researched in the future. Also the impact of communication ability of the real-time adjustment multiagent system on the repairing model will be investigated.

Competing Interests

The authors declare that they have no competing interests.

Table 7: Switches' operation action.

Fault	Scheme		
	1	2	3
43	Close 33, 35, 42	Close 33, 35, 42	Close 35; open 1
44	Close 30	Close 30	Close 30
45	Close 31	Close 31	Close 31
46	Close 26, 28	Close 26, 28	Close 26, 28
47	Close 20	Close 20	Close 16, 20; open 14
48	Close 18	Close 18	Close 18
49	Close 12, 16; open 11	Close 12, 16; open 11	Close 12, 14
50	Close 11, 55	Close 11,55	Close 55
51	—	—	—
52	Close 9, 56	Close 9, 56	Close 1, 9, 33, 42, 56
53	Close 15, 38, 40	Close 15, 38, 40	Close 15, 38, 40

Table 8: Objective value of each scheme.

Objective	Scheme		
	1	2	3
$f_1(X)$/h	34.25	38.45	37.65
$f_2(X)$/kWh	12 501 000	11 443 000	13 092 000

Table 9: The updated repairing strategy.

Squad	The updated allocation scheme	The updated fault repairing order
a	(47), 49, 51, 54	(47), 51, 54, 49
b	45, (46), 50, 53	(46), 53, 50, 45
c	43, (44), 48, 52	(44), 43, 52, 48

Table 10: Comparison results of two strategies.

Objective	Update	No update
$f_1(X)$/h	35.05	42.35
$f_2(X)$/kWh	13 921 000	16 756 000

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