International Journal of Power and Energy Systems, Vol. 43, No. 10, 2023
An Open Access Paper

SELF-ADAPTIVE OPTIMAL ALLOCATION STRATEGY OF EMERGENCY RESOURCES FOR POWER DISTRIBUTION NETWORK FAILURES

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Abstract

When the distribution network fails, emergency resources can provide a reliable guarantee for the rapid and smooth progress of emergency repair work. This study presents a self-adaptive optimal allocation strategy for the emergency resources of power distribution network failures. First, matching functions are established to indicate the matching degree of personnel, vehicles, tools, and spare parts with emergency repair workload. Second, a minimum absolute difference allocation algorithm based on the reasonable allocation of resources is proposed. On this basis, a self-adaptive optimisation allocation strategy for emergency resources is designed. The concept of self-adaptive index is introduced to describe the degree of matching between the emergency repair work and resource allocation as well as the impact of related factors on emergency resource allocation. Finally, the IEEE 33 node system is utilised as a simulation example to verify the effectiveness and practicability of the proposed self-adaptive optimal allocation strategy.

Key Words

Power distribution network, emergency resources, optimal allocation, minimum absolute difference, self-adaptive index

1. Introduction

As an important link of electric energy supply, the professional management of power distribution network not only concerns the stability and reliability of power supply quality but also related to consumer satisfaction with power companies [1], [2]. Southern China is especially prone to natural disasters of typhoons, floods, and snow, which will lead to distribution network failures and cause serious losses to production and livelihood in the affected areas [3]. The emergency repair work of distribution network failures is urgent to minimise losses, and the emergency resource scheduling problem faced by the emergency repair work deserves our attention.

The emergency resources, including personnel, vehicles, tools and equipment, and spare parts are limited [4]. The lack of definite allocation principles for those resources will certainly lead to some emergency teams being under-resourced and others having redundant resources. The current research on distribution network faults mainly focuses on fault recovery [5]–[10], emergency repair path optimisation [11], and the application of modern communication technology in distribution network fault emergency repair [12], while there is less research on resource allocation. Chen *et al.* [14] proposed a model to quantify the emergency repair fault tasks, emergency repair teams, and material warehouses of the distribution network. The concept of fitness was also introduced to describe the degree of adaptation between the three to achieve the optimal allocation of each fault task. In this way, a self-adaptive optimal allocation strategy for the emergency resources of power distribution network failures is presented, which mainly contributes to the following two aspects:

1) On the basis of reasonable allocation of resources, a minimum absolute difference allocation model and algorithm is proposed, which can quickly obtain the most reasonable resource allocation plan and improve the fault repair efficiency.
2) The concept of self-adaptive index [13] is introduced to guide the reasonable allocation of emergency resources. A self-adaptive optimal allocation strategy is designed to accelerate the repair of failure points, avoid waste of emergency resources, and solve the problem of uneven resource allocation.

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Recommended by Xiaorong Xie
(DOI: 10.2316/J.2023.203-0453)

2. Description and Conditions of Emergency Resource Allocation

Let $C = \{\mathrm{c1}, \mathrm{c2}, \ldots\}$ be the initial global emergency repair work set, $T = \{\mathrm{t1}, \mathrm{t2}, \ldots\}$ be the emergency team set,

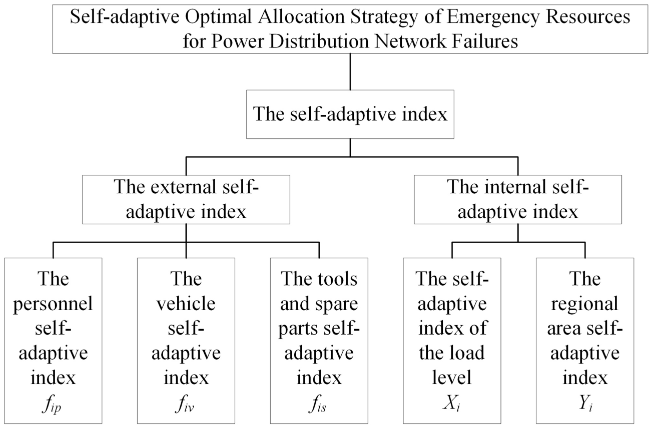

Figure 1. Matching functions of emergency resources.

$P = \{\text{p1, p2, } \dots\}$ be the personnel set, $V = \{\text{v1, v2, } \dots\}$ be the vehicle set, and $S = \{\text{s1, s2, } \dots\}$ be the spare parts collection. For set C, each emergency repair work requires a different number of personnel, vehicles, tools, and spare parts. Allocation of those resources needs to meet the following conditions [14].

Realise the mapping of the optimal number of personnel, vehicles, tools, and spare parts for emergency repair work. The demand for emergency resources, including emergency personnel, vehicles, tools, and spare parts varies with different emergency repair work. The optimal allocation of emergency resources realised by assigning the most matching number of personnel, vehicles, tools, and spare parts to each emergency repair work helps to complete the emergency repair work quickly and effectively.

Give priority to the emergency repair work of fault points with high load levels. Due to different load levels of the power distribution network, the losses and impacts caused by failures are also different. Emergency repairs at the fault points with high load levels first can minimise power outage loss and improve the efficiency of the repair work.

Ensure that the emergency response team in the larger area responsible for the emergency repair area is allocated more emergency resources to better complete the emergency repair work.

3. Optimal Allocation Model and Algorithm of Emergency Resources

As shown in Fig. 1, the adaptive indicators corresponding to the self-adaptive optimal allocation strategy for distribution network fault emergency resources include external adaptive indicators and internal adaptive indicators. External adaptive indicators include: personnel adaptive indicators, vehicle adaptive indicators, and tool adaptive indicators; internal adaptive indicators include: load level adaptive indicators and area range adaptive indicators.

To enhance the practicability of the optimal allocation strategy for emergency resources in the power distribution network, the matching functions of emergency personnel, vehicles, tools, and spare parts are established, respectively. Then, the emergency repair area scope of each emergency team is divided. On this basis, the least absolute difference algorithm for reasonable allocation of resources is proposed in this section (On a monthly basis, and without regard to resource reuse).

3.1 Matching Functions of Emergency Resources

3.1.1 The Matching Function of Personnel

The principle of personnel allocation is to reasonably allocate personnel according to the emergency repair workload in the area of responsibility of each emergency team is responsible. The matching function of emergency personnel is:

$$f_p = \sum_{i=1}^{k} \left| \frac{p_i}{N_P} - \frac{N_i}{N} \right|, 1 \leq p_i < N_P \tag{1}$$

where, f_p is the matching function, indicating the matching degree of personnel allocation and emergency repair workload; p_i is the number of people assigned to each emergency team; N_i is the emergency repair workload of each emergency team; N_P is the total number of personnel set P; N is the total workload, and k is the number of emergency repair work. The calculation formulae of N_i and N are as follows:

$$N_i = \sum_{j=1}^{n} n_g n_p t_j \tag{2}$$

$$N = \sum_{i=1}^{k} N_i \tag{3}$$

where n is the number of emergency teams; n_g is the frequency of each type of failure; t_j is the repair time of each emergency repair work; n_p is the number of personnel required for each emergency repair work, and k is the number of emergency repair work.

3.1.2 The Matching Function of Vehicles

The principle of vehicle allocation is to allocate vehicles reasonably according to the number of vehicles in the area of responsibility of each emergency team. The matching function of vehicles is:

$$f_v = \sum_{i=1}^{k} \left| \frac{v_i}{N_V} - \frac{M_i}{M} \right|, 1 \leq v_i < N_V \tag{4}$$

where f_v is the matching function, representing the matching degree of vehicle allocation and the number of vehicles; v_i is the number of vehicles allocated to each emergency team; M_i is the number of vehicle attendance of each emergency team; N_V is the total number of vehicles in the set V, and M is the total number of attendances.

The calculation formulae of M_i and M are as follows:

$$M_i = \sum_{j=1}^{n} n_g n_v \quad (5)$$

$$M = \sum_{i=1}^{k} M_i \quad (6)$$

where n_v is the number of vehicles required for each emergency repair work.

3.1.3 The Matching Function of Tools and Spare Parts

The principle of tools and spare parts allocation is based on the frequency of use of tools and spare parts in the area for which each emergency team is responsible. The matching function of tools and spare parts is:

$$f_s = \sum_{i=1}^{k} \left| \frac{s_i}{N_S} - \frac{Z_i}{Z} \right|, 1 \leq s_i < N_S \quad (7)$$

where f_s is the matching function, which shows the matching degree between the distribution of tools and spare parts and the number of use of tools and spare parts; s_i is the number of tools and spare parts allocated to each emergency team; N_S is the total number of spare parts for set S; Z_i is the number of use of tools and spare parts of each emergency team; and Z is the total number of uses. The calculation formulae of Z_i and Z are as follows:

$$Z_i = \sum_{j=1}^{n} n_g n_s \quad (8)$$

$$Z = \sum_{i=1}^{k} Z_i \quad (9)$$

where n_s is the number of tools and spare parts required for each emergency repair work.

3.2 The Minimum Absolute Difference Algorithm Based on the Reasonable Allocation of Resources

After establishing the above-mentioned emergency resource allocation models, a minimum absolute difference algorithm based on the reasonable allocation of resources is proposed [15]–[18] to obtain the most reasonable resource allocation plan. Taking personnel as an example, the objective function is:

$$\min f_p = \min \sum_{i=1}^{k} \left| \frac{p_i}{N_P} - \frac{N_i}{N} \right| \quad (10)$$

To minimise f_p, $p_i = N_P N_i / N$, and $f_p = 0$. p_i is an integer, and f_p is not 0 in general. Now, p_i is rounded to obtain

$$p_{i0} = \mathrm{int}(N_P N_i / N) \quad (11)$$

That is, the value of p_i can only be either p_{i0} or $(p_{i0}+1)$, and the objective function can be rewritten as:

$$\begin{aligned} f_p &= \sum_{i=1}^{k} |p_i/N_P - N_i/N| \\ &= \sum_{p_i=p_{i0}} |p_{i0}/N_P - N_i/N| \\ &\quad + \sum_{p_i=p_{i0}+1} |(p_{i0}+1)/N_P - N_i/N| = f_{p0} + f_{p1} \end{aligned} \quad (12)$$

where

$$\begin{aligned} f_{p0} &= \sum_{i=1}^{k} |p_{i0}/N_P - N_i/N| \\ f_{p1} &= \sum_{p_i=p_{i0}+1} [|(p_{i0}+1)/N_P - N_i/N| \\ &\quad - |p_{i0}/N_P - N_i/N| \,] \end{aligned} \quad (13)$$

As f_{p0} is a constant, to minimise f_p, f_{p1} should be minimised.

Let $d_i = |(p_{i0}+1)/N_P - N_i/N| - |p_{i0}/N_P - N_i/N|$, which represents the absolute difference of the emergency personnel assigned by the ith emergency team. The steps of the algorithm are as follows:

a) Calculate the value of $p_i = N_P N_i / N$.
b) If p_i are all integers, p_i personnel will be assigned to the ith emergency team, and the assignment will be completed; otherwise, proceed to step c).
c) Calculate the absolute difference d_i of the emergency teams and rank them from smallest to largest.
d) As shown in Fig. 2, calculate the value of $P' = N_P - \sum p_{i0}$, *i.e.*, the number of remaining personnel. The remaining personnel are assigned to the first P' emergency teams with the smallest d_i, one for each team, and the allocation is completed.

4. Self-adaptive Optimal Allocation Strategy of Emergency Resources

After proposing the above-mentioned emergency resource allocation models and the minimum absolute difference allocation algorithm, a self-adaptive optimal allocation strategy is presented. Self-adaptive in this study means that the allocation of emergency resources changes automatically with the change of the emergency repair workload, the frequency of vehicle attendance, and the use of tools and spare parts.

4.1 The Self-adaptive Index

To realise aforementioned three conditions of emergency resource allocation, the concept of self-adaptive index is proposed. f is set as a self-adaptive index for emergency repair work, which is composed of an external self-adaptive index and an internal self-adaptive index.

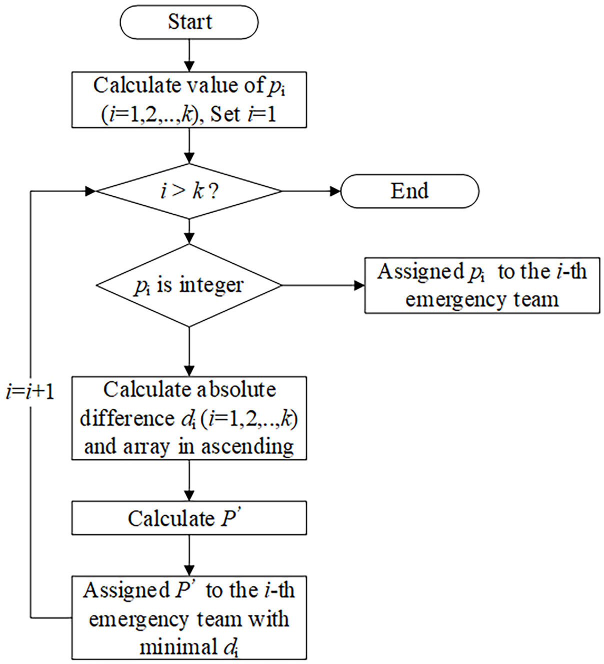

Figure 2. Flowchart of minimum absolute difference algorithm for personnel.

4.1.1 The External Self-adaptive Index

The external self-adaptive index is considered from the degree of adaptation of emergency resources. It reflects the degree of matching of emergency personnel, vehicles, tools, and spare parts with emergency repair work. The greater the index, the more reasonable the allocation of resources. The external self-adaptive index, consisting of the personnel self-adaptive index, vehicle self-adaptive index, and tools and spare parts self-adaptive index, is introduced to meet the first condition of the above emergency resource allocation.

The personnel self-adaptive index f_{ip} represents the degree of adaptation between personnel and emergency repair work, reflecting the degree of matching between personnel and emergency repair work. The larger f_{ip}, the more reasonable the resource allocation. f_{ip} can be defined as:

$$f_{ip} = 1/\left|p_i/N_P - N_i/N\right| \tag{14}$$

The vehicle self-adaptive index f_{iv} represents the degree of adaptation between the vehicle and the emergency repair work, reflecting the degree of matching between the vehicle and the emergency repair work. The larger f_{iv}, the more reasonable the resource allocation. f_{iv} can be defined as:

$$f_{iv} = 1/\left|v_i/N_V - M_i/M\right| \tag{15}$$

The tools and spare parts self-adaptive index f_{is} indicates the degree of adaptation between tools and spare parts and emergency repair work, reflecting the degree of matching between tools and spare parts and emergency repair work. The larger f_{is}, the more reasonable the allocation of resources. f_{is} can be defined as:

$$f_{is} = 1/\left|s_i/N_S - Z_i/Z\right| \tag{16}$$

As the calculation formula of the external self-adaptive index is a dimensional expression, which is not advantageous to comparison, normalised it as follows:

$$f'_{ip} = f_{ip}/\sum f_{ip} \tag{17}$$

$$f'_{iv} = f_{iv}/\sum f_{iv} \tag{18}$$

$$f'_{is} = f_{is}/\sum f_{is} \tag{19}$$

The expression f_{iE} of the external self-adaptive index can be obtained averaging the above three self-adaptive indexes, which reflects the degree of matching between emergency resources and emergency repair work. f_{iE} can be defined as:

$$f_{iE} = ({f'}_{ip} + {f'}_{iv} + {f'}_{is})/3 \tag{20}$$

4.1.2 The Internal Self-adaptive Index

The internal self-adaptive index is considered from the emergency repair work. It reflects the sequence of the emergency repair work and the scope of the emergency repairs that each emergency team is responsible for. The internal self-adaptive index consists of the self-adaptive index of load level and the self-adaptive index of area, which meets the last two conditions of the above emergency resource allocation mentioned.

The self-adaptive index of the load level X_j represents the sequence of execution of emergency repair work, reflecting the load level of the j-type emergency repair work. The larger X_j, the higher the load level, and the higher the execution priority of this type of emergency repair work. The average value of the self-adaptive index X_j of the load level of the emergency repair work in the emergency repair range of each emergency team is taken as the self-adaptive index of the load level of the emergency repair team, denoted as X_i. The value of X_i is not given arbitrarily but determined by the loss caused by the failure [19]–[23] considering the impact of the load level on the allocation of emergency resources.

The regional area self-adaptive index Y_i reflects the scope of emergency repairs that each emergency team is responsible for. In general, the larger the area, the more emergency repair work and the more emergency resources needed.

The above two self-adaptive index components are weighted and combined to obtain the expression of the internal self-adaptive index. f_{iI} is set as the internal self-adaptive index, reflecting the impact of emergency repair work on the allocation of emergency resources. f_{iI} can be defined as:

$$f_{iI} = w_a X_i + w_b Y_i \tag{21}$$

where w_a and w_b are the weight coefficients of the self-adaptive index of load level and the self-adaptive index of regional area, respectively, and $w_a + w_b = 1$.

4.2 Process and Steps of Self-adaptive Optimal Allocation Strategy

Weighting the external self-adaptive index and internal self-adaptive index defined above, the total self-adaptive index f_i of each emergency team can be obtained. The larger f_i, the more reasonable the resource allocation. f_i can be defined as:

$$f_i = w_E f_{iE} + w_I f_{iI} \tag{22}$$

where w_E and w_I are the weight coefficients of the external self-adaptive index and internal self-adaptive index, respectively, and $w_E + w_I = 1$.

After proposing the above models and self-adaptive index, the self-adaptive optimal allocation strategy proposed in this paper has the following constraints:

a) The emergency personnel assigned to each emergency repair work can complete the emergency repair work.
b) Emergency resources can meet the needs of all emergency repair work, that is, emergency resources are adequate.
c) Each emergency repair work is completed by the emergency team responsible for the area.
d) The emergency teams carrying out emergency repair work must complete the tasks that are currently being performed before new emergency repairs can be carried out, and must ensure that emergency resources are not wasted.

The process and steps of the self-adaptive optimal allocation strategy are as follows:

a) Determine the number of emergency teams and emergency resources, and divide the regional scope of each emergency team.
b) Determine the emergency repair work that each emergency team is responsible for, such as the fault object, the load level of the fault point, the number of occurrences per month, the processing time, and the type and quantity of emergency resources required.
c) Preset the load level self-adaptive index and the regional area self-adaptive index of each emergency repair work to determine the internal self-adaptive index.
d) Figure 3 is the process and steps of the self-adaptive optimal allocation strategy. Calculate the total self-adaptive index of each emergency team according to the formula. When the value reaches the maximum, the optimal resource allocation strategy can be achieved.

5. Case Simulation

Assuming there are ten emergency repair works, Table 1 shows the type of failure and the number of occurrences per month for each emergency repair work. Table 2 shows the type and quantity of required emergency resources.

Table 1
Types of Failures and the Number of Occurrences Per Month for Each Emergency Repair Work

C	Fault Object	Occurrences Per Month
c1	Low-voltage branch box	3
c2	Low-voltage metering equipment	6
c3	Low-voltage distribution box	3
c4	Low-voltage line	2
c5	Home entry device	6
c6	Customer internal	8
c7	Transformer	1
c8	Medium-voltage cable line	1
c9	Medium-voltage overhead line	1
c10	On-column equipment	1

Taking the IEEE 33 node system as an example, the system diagram is renumbered, and the emergency repair area of each emergency team is divided as shown in Fig. 4(a)–(c), respectively, represent the emergency repair area range of the emergency team t1, t2, and t3, and numbers 1–10 indicate the emergency repair work points.

Suppose there are three emergency teams t1, t2, and t3, with 100 emergency personnel, 20 vehicles, and 400 tools and spare parts. In Fig. 5, the number of resource allocations for each emergency team, the self-adaptive index values of each load level (set by experts based on experience: 0.6 for the first level; 0.4 for the second level; and 0.2 for the third level), the self-adaptive index for the area of the emergency team (set by experts based on experience: 0.4 for t1 and t2 and 0.5 for t3) are presented. Let $w_a = 0.6$, $w_b = 0.4$, $w_E = w_I = 0.5$, and the value of each self-adaptive index will be calculated according to the formula.

According to the proposed self-adaptive optimal allocation strategy, the self-adaptive index of each emergency team is obtained. Figure 6 represents the value of internal self-adaptive index; Fig. 7 represents the value of external self-adaptive index, and Fig. 8 represents the value of total self-adaptive index.

It can be seen from Fig. 7, regardless of the impact of emergency repair work on resource allocation, the allocation of tools and spare parts for emergency team t1 is more reasonable than that for t2. However, considering the influence of factors, such as load level and area of emergency repair, the allocation for t2 is more reasonable than that for t1. This shows that the repair work has a certain impact on the allocation of emergency resources [24], [25]. Figure 8 shows that the emergency team with the most reasonable personnel allocation is t1, followed by t2, and then t3. The emergency team with the most reasonable allocation of vehicles is t1, followed by t3, and

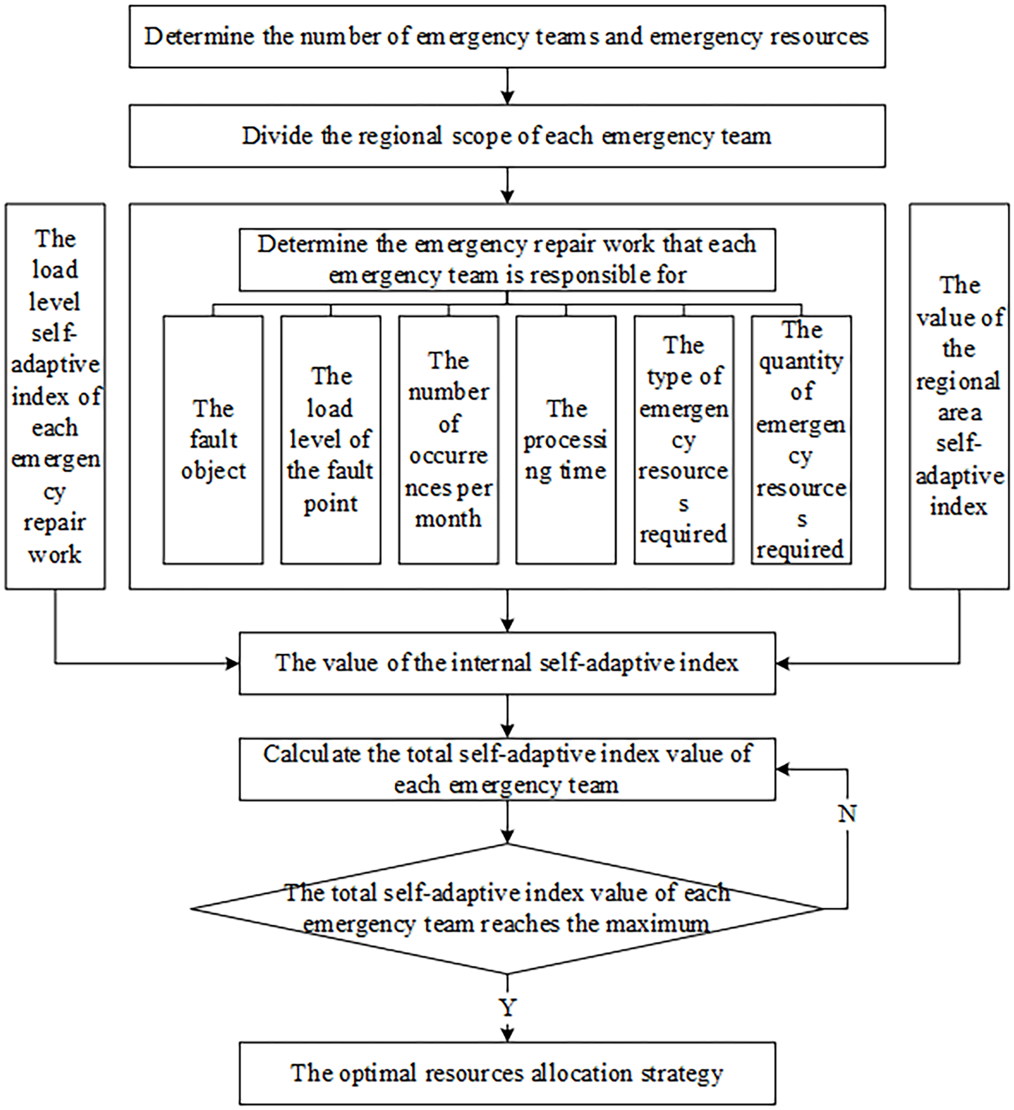

Figure 3. Processes and steps of the self-adaptive optimal allocation strategy.

Table 2
Processing Time, Load Level, and Emergency Resources Required for Each Emergency Repair Work

C	Processing Time (h)	Load Class	Emergency Resources Needed
c1	2.0	2	4 personnel, 1 vehicle, 14 tools, and spare parts
c2	1.0	2	2 personnel, 1 vehicle, 6 tools, and spare parts
c3	2.0	3	4 personnel, 1 vehicle, 14 tools, and spare parts
c4	2.5	2	6 personnel, 3 vehicles, 29 tools, and spare parts
c5	1.0	1	4 personnel, 1 vehicle, 6 tools, and spare parts
c6	1.0	3	2 personnel, 1 vehicle, 8 tools, and spare parts
c7	2.5	2	6 personnel, 3 vehicles, 45 tools, and spare parts
c8	3.0	1	10 personnel, 3 vehicles, 54 tools, and spare parts
c9	3.5	2	10 personnel, 4 vehicles, 59 tools, and spare parts
c10	2.5	1	8 personnel, 3 vehicles, 24 tools, and spare parts

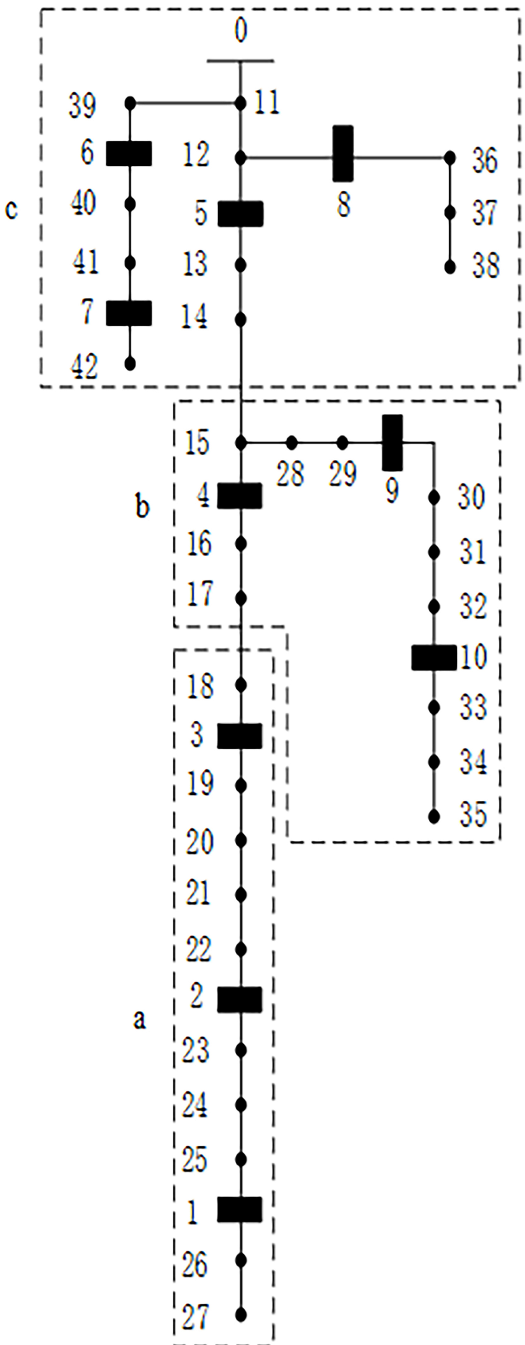

Figure 4. IEEE 33 node system and area division.

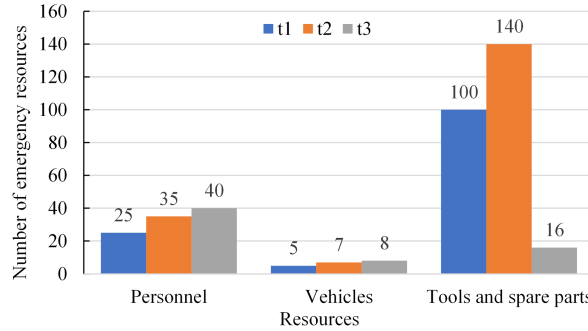

Figure 5. The number of emergency resources allocated by each emergency team.

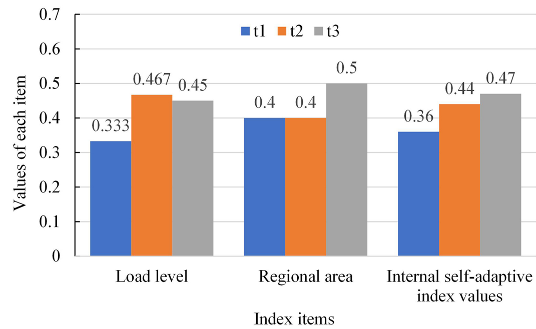

Figure 6. The load level, regional area, and internal self-adaptive index values of each emergency team.

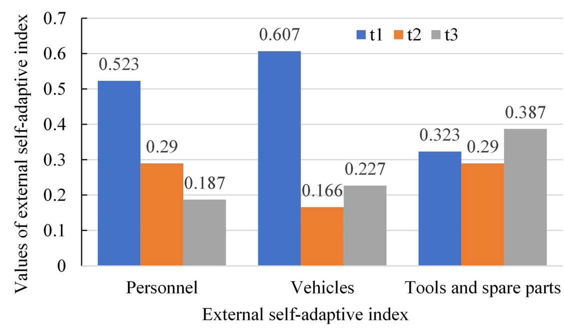

Figure 7. External self-adaptive index values of personnel, vehicles, tools, and spare parts of each emergency team.

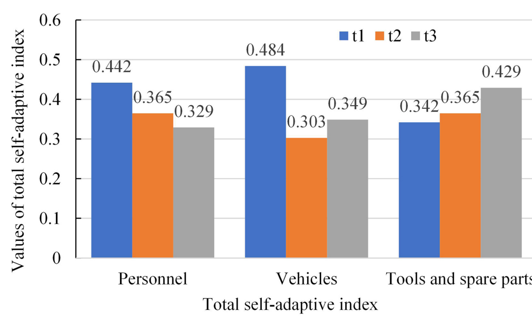

Figure 8. The total self-adaptive index value of the emergency resources of each emergency team.

then t2. The emergency team with the most reasonable allocation of tools and spare parts is t3, followed by t2, and then t1.

To achieve optimal allocation of emergency resources, the total self-adaptive index value should be maximised. According to the minimum absolute difference algorithm based on reasonable allocation of resources proposed above, the optimal resource allocation scheme calculated by simulation is: for the emergency teams t1, t2, and t3, the number of persons is 26, 37, and 37, respectively; the number of vehicles is 5, 6, and 9, respectively, and the number of tools and spare parts is 104, 123, and 173, respectively.

6. Conclusion

An allocation model of emergency resources, including personnel, vehicles, tools, and spare parts is established. The concept of a self-adaptive index is introduced to describe the degree of matching between emergency resource allocation and emergency repair work. An optimal allocation strategy for emergency resources in the power distribution network is put forward, and the effectiveness of this strategy is illustrated by case simulations.

It is proved that in the actual operation process, the self-adaptive optimal allocation strategy of distribution network fault emergency can realise the optimal allocation of emergency resources, avoid the waste of emergency resources, solve the problem of unbalanced resource allocation, and improve the efficiency and quality of emergency repair work. This can provide a guarantee for the realisation of lean distribution network and high-quality services.

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