Journal of Applied Mathematics and Physics, 2025, 13(4), 1061-1072
https://www.scirp.org/journal/jamp
ISSN Online: 2327-4379
ISSN Print: 2327-4352

Entropy Weight TOPSIS-Based Local Load Reallocation Strategy

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How to cite this paper: Guo, D. and Ji, N. (2025) Entropy Weight TOPSIS-Based Local Load Reallocation Strategy. *Journal of Applied Mathematics and Physics*, **13**, 1061-1072.
https://doi.org/10.4236/jamp.2025.134054

Received: March 3, 2025
Accepted: April 4, 2025
Published: April 7, 2025

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Abstract

In complex network systems, load redistribution strategy has become a key means to ensure stable system operation. In practical application, load redistribution strategy needs to comprehensively consider several factors, such as node degree, node residual capacity, and shortest path length. To address this issue, this paper proposes a local load redistribution strategy based on entropy weight TOPSIS method. The entropy weight TOPSIS method combines the advantages of entropy weight method and TOPSIS method, and determines the weights of each index by calculating its entropy value, which can objectively reflect the importance of each index in decision-making and avoid the interference of subjective factors. Meanwhile, the TOPSIS method evaluates the advantages and disadvantages of each node by comparing the distance of each node from the ideal solution and the negative ideal solution, so as to determine the more suitable node as the assignable node. In this paper, the effectiveness of local load redistribution strategy based on entropy weight TOPSIS method is verified on BA scale-free network, WS small-world network, and WS-BA composite network, and the results show that the assignable nodes of the load redistribution strategy based on node's maximum residual capacity and entropy weight TOPSIS have not only higher values of residual capacity, but also their node degree value and shortest path length value, which indicates that the load reallocation strategy is more integrated in selecting the assignable nodes.

Keywords

Cascade Failure, Entropy Weight Method, TOPSIS Model, Load Redistribution

1. Introduction

Under the wave of ever-changing development of science and technology, human society has been surrounded by all kinds of network systems. Infrastructure networks such as financial markets, power networks, communication networks, public transportation networks and air transport networks have emerged [1]. In these networks, the nodes are closely connected and interact with each other, forming an intricate linkage. From the flow of funds in the financial market to the efficient operation of transportation; from the innovation drive in the "Internet +" era to the fine planning of urban layout, financial networks [2]-[4], transportation networks, power networks, urban networks, and other diversified forms of networks have been deeply integrated into and continue to change our daily lives. Being in this highly networked modern society, the various issues involved in the social network have increasingly triggered people's widespread concern and in-depth thinking, and its influence is constantly expanding to all corners of social life, becoming one of the key factors in promoting social development and change. Taking the scenario of resource transfer in resource transportation network, crowd evacuation and herdsmen's transhumance network as an example, in the process of resource transfer, it is necessary to comprehensively and integrally consider various factors of the transfer destination, so as to screen out a more suitable place for transfer. This is not only related to the efficiency and safety of resource transfer, but also closely related to the stable operation and optimal development of the social network, which has become an important link that cannot be ignored in the development of modern society.

The main key parts in the study of cascade failure are node capacity, node initial load and node load redistribution strategy. In recent years, the research on cascade failure has achieved relatively rich results, and the load capacity model [5] [6], binary impact model [7] cascade failure models have been proposed. When a node in a complex network fails, the way to distribute its own load to other nodes in the network is called load redistribution strategy. Among the studies on load redistribution strategies for nodes in the network, scholars have proposed load distribution strategies such as nearest-neighbor distribution strategy [8], region-based distribution strategy [9], and global distribution strategy [10] [11]. Previous studies on cascading failures have mostly used a single metric as the basis for the selection of assignable nodes. However, in the actual network, it is necessary to select the assignable nodes according to different actual situations by considering multiple indicators of the nodes. Therefore, this paper introduces the entropy weight TOPSIS model into the node load reallocation strategy, and utilizes the theoretical knowledge of complex networks to construct a new load reallocation strategy.

This paper focuses on the study of node load reallocation strategy. TOPSIS is a ranking method that approximates the ideal solution, and ranks the results of the measurement by measuring the distance between the evaluation object and the positive ideal solution and the negative ideal solution [12]. Entropy weighting method is an objective assignment method widely used in various fields, which reweights different indicators according to the amount of information of different assessment indicators, and can avoid the differences between the evaluation indicator data to reduce the difficulty of evaluation and analysis [13]. Considering the comprehensive consideration of many factors to select the assignable nodes, the entropy weight TOPSIS model is introduced in the node load redistribution strategy, and the load redistribution strategy based on the maximum residual capacity of the nodes and entropy weight TOPSIS is proposed. Secondly, the local load reallocation strategy based on entropy weight TOPSIS is analyzed on the model network in terms of arithmetic cases.

2. Node Load Redistribution Strategy

2.1. Local Load Redistribution Strategy Based on Maximum Remaining Capacity of Nodes

In the course of previous studies, when defining the capacity of the network nodes, it is generally based on the fact that the capacity of the nodes and the initial load of the nodes are proportional to each other as mentioned in the ML load-capacity model, which is calculated as Eq:

$$C_i = (1+\alpha) L_i(0) \tag{1}$$

where C_i is the capacity of the node i; is the capacity parameter of the node and is greater than 0.

Most of the relationships between capacity and load in real networks are nonlinear, and the ML model is not applicable to real networks. Therefore, some scholars improved the ML model and proposed a nonlinear load-capacity model:

$$C_i = L_i(0) + \beta L_i(0)^{\alpha} \tag{2}$$

where $\alpha > 0$, $\beta > 0$. α and β are capacity tuning parameters. When $\alpha = 1$ is the ML model.

Most of the complex network studies use the degree that reflects the local information of the network to define the initial load [14]. The initial load of a node in a network is related to the degree of the node [8] [11] [15]. The load of a node is defined as the sum of the weights of its connected edges defines the initial load:

$$L_i(0) = \sum_{j \in \Gamma_i} w_{ij} \tag{3}$$

he selection of assignable nodes in the actual network requires comprehensive consideration of multiple factors of the nodes according to the demand, and among multiple evaluation methods, the TOPSIS method is a comprehensive evaluation and analysis method suitable for multiple indicators, which is applicable to the multi-objective decision analysis, and combined with the entropy weight method for the evaluation indexes of each node, the evaluation indexes of each node are empowered, eliminating the variability of the indexes of the aspect of the outline, which makes the empowered more accurate and objective, and then the entropy weight TOPSIS method is suitable for the research of this paper. The entropy weight TOPSIS method is suitable for the research of this paper, so the entropy weight TOPSIS method is introduced into the node load reallocation strategy.

When the load from the failed node is distributed, it is generally considered that the larger the remaining capacity of the node the more load should be distributed to the assignable node, which is more in line with the actual situation [16]. Therefore, defining the proportion of load distribution that a node receives from a failed node is then:

$$p_{ij} = \frac{C_i - L_i(0)}{\sum\limits_{m \in \Gamma_{k_j d}} C_m - L_m(0)} \tag{4}$$

where, is the node capacity of the node; is the initial load of the node; is the shortest path between the node and the node; is the set consisting of all the assignable nodes, when the node fails, the nodes within the range of the shortest path less than the node will be selected, and the former node with higher residual capacity is selected as the assignable node.

When the load reallocation strategy is applied, the remaining capacity of the nodes is used as the criterion to select the nodes for load allocation, however, when a comprehensive evaluation of multiple indicators is required, it is easy to ignore other key factors due to a single indicator; in addition, for the dynamically changing system state, a dynamic load reallocation strategy is required to adjust in real time to cope with unexpected situations. For this phenomenon, this paper combines the entropy weight TOPSIS method with the load reallocation strategy, and proposes a local load reallocation strategy based on entropy weight TOPSIS.

2.2. Improved Node Load Redistribution Strategy

The load redistribution strategy considers these two main issues: finding assignable nodes that accept loads; and determining the load distribution ratio. The specific selection of assignable nodes and determination of load distribution ratio are as follows:

2.2.1. Selection of Assignable Nodes

The addition of entropy weight TOPSIS method in assignable selection enables the load redistribution strategy to comprehensively evaluate the performance of each node by considering a variety of key indicators of the node, such as load capacity, node priority, distance from the failed node, etc., which effectively avoids the one-sidedness of the evaluation of a single indicator. Among them, the specific steps for assignable node selection are as follows:

1) Selection area of assignable nodes. If the selected node is too far away, it will affect the load transfer, so the selection of assignable nodes must be selected within a certain range. The selection area of assignable nodes is divided into nodes within the range of the shortest path length not exceeding from the failed node.

2) Determine evaluation indicators. According to the different needs of load shifting, determine suitable indicators as indicators for judging each node in the selection area.

3) Determine the weight of each indicator.

Step 1: Data collection and pre-processing. Collect the values of each evaluation indicator for each node in the selection area and organize the data to construct a decision matrix.

Step 3: Determine the weights of indicators under the entropy weight TOPSIS method. Use the entropy weight method to construct the evaluation index system matrix based on the relevant index data; standardize the data; calculate the information entropy of each index; calculate the weight of each index based on its information entropy.

Step 4: Calculate the posting progress of each node. Determine the positive and negative ideal solutions; Calculate the distance of each node from the positive ideal solution and the negative ideal solution; Calculate the posting progress of each node.

Step 5: Determine the assignable nodes. Sort each node by the level of closeness and select the top k nodes with higher closeness as assignable nodes.

2.2.2. Determination of Load Distribution Ratios

Assuming that node j is still a failed node and that node i receives the load distribution ratio from node , then p_{ij}:

$$p_{ij} = \frac{C_i - L_i(0)}{\sum_{m \in \Gamma_{Tk_j d}} C_m - L_m(0)} \tag{5}$$

where, $C_i - L_i(0)$ is the remaining capacity of node i and $\Gamma_{Tk_j d}$ denotes the set of all assignable nodes. When the node j fails, all the nodes within the shortest path from the node j not exceeding d are searched for, and the nodes in the selection area are evaluated comprehensively by entropy-weighted TOPSIS model, and the first k_i nodes with higher closeness are selected as the assignable nodes.

The load ΔL_{ij} obtained by the node j is:

$$\Delta L_{ij} = \frac{C_i - L_i(0)}{\sum_{m \in \Gamma_{Tk_j d}} C_m - L_m(0)} L_i(0) \tag{6}$$

The load of node j after accepting the load from the failed node i is:

$$L_i = L_i(0) + \Delta L_{ij} \tag{7}$$

Load on node i versus node capacity C_i:

1) If $L_i > C_i$ is present, node i will not function properly as a new failed node if node i exceeds the capacity of the node it is carrying after receiving additional load.

2) If $L_i \le C_i$ is present, then node i has not exceeded the capacity of the node it is carrying after receiving additional load and node i will operate normally.

3. Calculus Analysis

3.1. Evaluation Indicators

1) Remaining node capacity

Each node in the network can bear the load is limited, the maximum it can withstand that is its node capacity, node residual capacity for the node's actual load and its node capacity of the difference between the node's capacity, the node's residual capacity (Remaining Capacity of Nodes, RC) is:

$$Rc_i = C_i - L_i \tag{8}$$

where, C_i is the node capacity of node i; L_i is the node load of node i.

2) Shortest path length

A path in a network that passes through the least number of edges from node i to node j is called a geodesic. The Shortest Path Length (i.e., geodesic distance) (Shortest Path Length, SPL) d_{ij} is the minimum number of edges experienced by node i to node j.

3) Nodal degree

The node degree (Degree, D) refers to the number of edges in the network that are directly connected to it. The node i has a node degree k_i:

$$k_i = \sum_{j=1}^{n} A_{ij} \tag{9}$$

where, n is the total number of nodes in the network; A_{ij} is the neighbor matrix of the network. The higher the node degree value, the closer the connection with its neighboring nodes, and the more efficient the nodes are in communicating and transferring with each other.

3.2. Selection Scheme for Assignable Nodes

Most of the real-world network models satisfy the small-world property and scale-free property, and in this section, the node load redistribution strategy proposed in this paper is analyzed in an arithmetic case on BA scale-free network, WS small-world network and its composite network to validate the distribution strategy, where deliberate attacks are chosen as the attack on the network.

The specific load distribution steps are as follows:

The specific steps of the node load redistribution strategy are as follows:

Step 1: Determine the attacked node in the network and attack it to disable it, assuming that the attacked node in the network is the node i.

Step 2: Find all the nodes in the region where the shortest path from the failed node is not more than d and calculate the values of each factor for all the nodes in the selectable region.

Step 3: The entropy weight method is used to assign weights to each factor of the selection, and the value of the closeness of all nodes is calculated using the TOPSIS model. Comprehensive evaluation of all nodes in the selection area is completed.

Step 4: Sorting is done by proximity and the top nodes are selected as assignable nodes for load allocation.

3.3. Example Analysis

The number of nodes of BA scale-free network is 500 and the average node degree is 4. $\alpha = 0.15$, $\beta = 0.27$, $d = 2$ is selected during simulation. Node degree, node residual capacity and shortest path length are selected as evaluation metrics during the experiment, node degree and node residual capacity are very large metrics and shortest path length is very small metric. Deliberate attack on BA scale-free network is carried out to analyze the values of evaluation indexes of assignable nodes under local load redistribution strategy based on maximum remaining capacity of nodes and local load reallocation strategy based on entropy weight TOPSIS, and the values of indexes of assignable nodes under the two load distribution strategies are specified in Table 1 and Table 2.

Table 1. Local load redistribution strategy based on maximum remaining capacity of nodes.

Nodal	D	SPL	RC	Nodal	D	SPL	RC	Nodal	D	SPL	RC
1	6	1	0.332	38	3	1	0.332	72	7	1	0.332
3	11	1	0.332	39	8	2	0.332	73	5	3	0.332
5	4	1	0.332	40	9	2	0.332	74	3	2	0.332
6	32	1	0.332	45	8	2	0.332	76	4	2	0.332
12	3	1	0.332	46	2	3	0.332	79	2	3	0.332
14	32	2	0.332	48	5	1	0.332	80	4	3	0.332
15	3	1	0.332	50	5	3	0.332	82	3	2	0.332
16	28	2	0.332	51	8	1	0.332	83	2	2	0.332
18	14	1	0.332	53	3	3	0.332	84	11	2	0.332
20	17	2	0.332	55	3	2	0.332	85	4	2	0.332
24	4	3	0.332	56	25	2	0.332	86	5	2	0.332
27	3	2	0.332	57	8	2	0.332	87	3	3	0.332
29	10	1	0.332	58	7	3	0.332	89	4	3	0.332
31	16	2	0.332	59	3	3	0.332	90	2	2	0.332
33	10	2	0.332	60	7	1	0.332	92	4	3	0.332
34	5	2	0.332	66	4	3	0.332	94	7	2	0.332
35	6	2	0.332	70	4	2	0.332				
36	10	2	0.332	71	5	3	0.332				

Table 2. Improved node load redistribution strategy.

Nodal	D	SPL	RC	Nodal	D	SPL	RC	Nodal	D	SPL	RC
6	32	1	0.332	15			0.332	31	16	2	0.332
18	14	1	0.332	38			0.332	9	35	1	0.318
14	32	2	0.332	212			0.332	4	32	1	0.318
3	11	1	0.332	258			0.332	84	11	2	0.332

Continued

29	10	1	0.332	324			0.332	33	10	2	0.332
16	28	2	0.332	399			0.332	36	10	2	0.332
51	8	2	0.332	115			0.332	40	9	2	0.332
56	25	1	0.332	150			0.332	21	24	1	0.318
60	7	1	0.332	218			0.332	39	8	2	0.332
72	7	1	0.332	247			0.332	45	8	2	0.332
1	6	1	0.332	275			0.332	57	8	2	0.332
299	6	1	0.332	318			0.332	129	8	2	0.332
48	5	1	0.332	338			0.332	94	7	2	0.332
5	4	1	0.332	400			0.332	35	6	2	0.332
89	4	1	0.332	402			0.332	110	6	2	0.332
244	4	1	0.332	485			0.332	34	5	2	0.332
246	4	1	0.332	490			0.332				
12	3	1	0.332	20			0.332				

In BA scale-free network, node 2 is the node with the largest degree, and node 2 is attacked until it fails. The local load reallocation strategy based on the maximum remaining capacity of nodes selects the assignable nodes, and the 52 nodes with the largest remaining capacity are selected as the assignable nodes, and the values of their specific evaluation indexes are shown in **Table 1**. The local load reallocation strategy based on entropy weight TOPSIS selects assignable nodes, and the 52 nodes with the highest closeness are selected as assignable nodes in accordance with the selection scheme of assignable nodes in Section 3.1, and the values of its evaluation indexes are shown in **Table 1**. Comparing the values of the evaluation indexes of the assignable nodes under the two load allocation strategies, comparing the data in **Table 1** and **Table 2**, it is found that the residual capacity values of the assignable nodes under the two load allocation strategies are almost the same, whereas the node degree value and the shortest path length value of the assignable nodes under the entropy-weighted TOPSIS-based localized load reallocation strategy are higher. The results show that the local load reallocation strategy based on entropy weight TOPSIS in BA scale-free network selects the assignable nodes in a more integrated way, which not only considers the residual capacity, but also takes into account the node degree and shortest path length values of the nodes.

The number of nodes in the WS small world network is 500 and the average node degree is 4. $\alpha = 0.15, \beta = 0.27, d = 3$ is selected during the arithmetic analysis. Deliberate attacks on the WS small world network and the values of the metrics of the assignable nodes under the two load allocation strategies are shown in **Table 3** and **Table 4**, respectively.

Table 3. Local load redistribution strategy based on maximum remaining capacity of nodes.

Nodal	D	SPL	RC	Nodal	D	SPL	RC	Nodal	D	SPL	RC
85	4	3	0.332	183	3	3	0.332	191	4	2	0.332
180	5	3	0.332	184	4	2	0.332				
182	4	3	0.332	187	4	1	0.332				

Table 4. Improved node load redistribution strategy.

Nodal	D	SPL	RC	Nodal	D	SPL	RC	Nodal	D	SPL	RC
266	5	1	0.332	447	4	1	0.332	184	4	2	0.332
187	4	1	0.332	448	5	2	0.332				
366	4	1	0.332	190	5	1	0.332				

In the WS small world network, node 188 is the node with the largest node degree, and node 188 is attacked until it fails. The local load reallocation strategy based on the maximum remaining capacity of nodes selects the assignable nodes, and the seven nodes with the largest remaining capacity are selected as the assignable nodes, and the values of their specific evaluation indexes are shown in **Table 3**. The local load reallocation strategy based on entropy weight TOPSIS selects assignable nodes, and the 7 nodes with the highest closeness are selected as assignable nodes in accordance with the selection scheme of assignable nodes in Section 3.1, and the values of their evaluation indexes are shown in **Table 4**. Comparing the values of the evaluation indexes of the assignable nodes under the two load allocation strategies, comparing the data in **Table 3** and **Table 4**, it is found that the residual capacity values of the assignable nodes under the two load allocation strategies are almost the same, whereas the node degree value and the shortest path length value of the assignable nodes under the entropy-weighted TOPSIS-based localized load reallocation strategy are higher. The results show that the local load reallocation strategy based on entropy weight TOPSIS selects the assignable nodes more comprehensively in WS small-world networks, which verifies the feasibility of the load reallocation strategy.

The number of nodes in the WS-BA composite network is 500 and the average node degree is 4. $\alpha = 0.15, \beta = 0.45, d = 3$ is selected during the analysis of the arithmetic example. The evaluation metrics of the assignable nodes under the two node load distribution strategies are compared and analyzed, and the values of the metrics of the assignable nodes under the two load redistribution strategies are shown in **Table 5** and **Table 6**, respectively.

In the WS-BA composite network, node 7 is the node with the largest node degree, and node 7 is attacked until it fails. The local load reallocation strategy based on the maximum remaining capacity of nodes selects the assignable nodes, and the 37 nodes with the largest remaining capacity are selected as the assignable nodes, and the values of their specific evaluation indexes are shown in Table 5. The local load reallocation strategy based on entropy weight TOPSIS selects assignable nodes, and the 37 nodes with the highest closeness are selected as assignable nodes in accordance with the selection scheme of assignable nodes in Section 3.1, and the values of their evaluation indexes are shown in Table 6. Comparing the values of the evaluation indexes of the assignable nodes under the two load allocation strategies, comparing the data in Table 5 and Table 6, it is found that the residual capacity values of the assignable nodes under the two load allocation strategies are the same, while the node degree value and the shortest path length value of the assignable nodes under the entropy-weighted TOPSIS-based localized load redistribution strategy are higher, and the two values are more different from each other. The results show that the entropy-weight TOPSIS-based local load reallocation strategy selects the assignable nodes more comprehensively in the WS-BA composite network, which verifies the feasibility of the load reallocation strategy.

In summary, the multifaceted comprehensive evaluation of entropy weight TOPSIS-based local load reallocation strategy makes the load allocation more reasonable, avoids the local optimization but overall imbalance caused by focusing on a certain factor only, and can be flexibly applied to BA scale-free networks, WS small-world networks, and BA-WS composite networks to carry out effective load allocation according to the specific network characteristics and load demand The network can be effectively allocated according to the specific network characteristics and load demand, showing good adaptability.

Table 5. Local load redistribution strategy based on maximum remaining capacity of nodes.

Nodal	D	SPL	RC	Nodal	D	SPL	RC	Nodal	D	SPL	RC
1	19	1	0.554	90	4	3	0.554	170	10	1	0.554
10	13	2	0.554	94	11	3	0.554	175	11	2	0.554
16	18	2	0.554	101	5	3	0.554	181	9	1	0.554
20	19	2	0.554	105	6	3	0.554	185	10	2	0.554
28	17	2	0.554	112	5	1	0.554	191	5	3	0.554
32	11	2	0.554	118	7	3	0.554	201	8	3	0.554
40	9	1	0.554	130	5	3	0.554	207	8	3	0.554
52	8	2	0.554	134	7	2	0.554	213	6	3	0.554
61	5	3	0.554	139	11	2	0.554	218	8	2	0.554
67	11	1	0.554	146	9	2	0.554	224	9	3	0.554
73	10	2	0.554	152	5	3	0.554	229	6	2	0.554
82	10	2	0.554	158	10	2	0.554				
85	7	3	0.554	163	8	1	0.554				

Table 6. Improved node load redistribution strategy.

Nodal	D	SPL	RC	Nodal	D	SPL	RC	Nodal	D	SPL	RC
1	19	1	0.554	300	12	2	0.554	185	10	2	0.554
67	11	1	0.554	321	12	2	0.554	317	10	2	0.554
170	10	1	0.554	352	12	2	0.554	428	10	2	0.554
40	9	1	0.554	441	12	2	0.554	435	10	2	0.554
181	9	1	0.554	446	12	2	0.554	146	9	2	0.554
163	8	1	0.554	453	12	2	0.554	265	9	2	0.554
112	5	1	0.554	32	11	2	0.554	404	9	2	0.554
20	19	2	0.554	139	11	2	0.554	491	9	2	0.554
16	18	2	0.554	175	11	2	0.554	52	8	2	0.554
28	17	2	0.554	393	11	2	0.554	218	8	2	0.554
484	14	2	0.554	73	10	2	0.554	309	8	2	0.554
10	13	2	0.554	82	10	2	0.554				
251	12	2	0.554	158	10	2	0.554				

4. Conclusion

Aiming at the phenomenon that multiple indicators need to be comprehensively evaluated when the load redistribution strategy is applied, this paper applies the entropy weight TOPSIS method to the load redistribution strategy and proposes a local load redistribution strategy based on the entropy weight TOPSIS method. And the effectiveness of the strategy is verified on BA scale-free network, WS small world network and WS-BA composite network. The node degree, shortest path length and node residual capacity are selected as the evaluation indexes during the experimental process, and the results show that the local load redistribution strategy based on entropy weight TOPSIS method not only considers the node residual capacity indexes, but also takes into account the node degree and shortest path length of the nodes under the deliberate attack strategy on the above three networks. The comprehensive evaluation of multiple aspects of the local load redistribution strategy based on entropy weight TOPSIS method makes the load distribution more reasonable, avoids the situation of local optimization but overall imbalance caused by focusing on only one factor, and can be flexibly applied to the network.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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