The optimized allocation of emergency resources for power system restoration

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Abstract. In recent years, there have been frequent blackout accidents in foreign countries. For power system, the configuration of emergency resources affects the process of the power system restoration. It is the key to ensure the smooth restoration of power system that the emergency generating vehicle and the operations staff arrive at the substation in time after the blackout. In this paper, the optimal allocation scheme of the emergency generating vehicle considering the comprehensive importance of load nodes and traffic network constraints is proposed. The comprehensive importance degree of nodes is calculated by considering the spectral importance degree, the importance degree of load amount and the comprehensive importance degree of load of nodes. The blackout economic loss of node is evaluated by node's comprehensive importance degree. In addition, the cost of configuration and maintenance of the emergency generating vehicle and the transmission cost under the constraint of traffic network are considered to establish the optimal configuration model of the emergency generating vehicle. Finally, the Discrete Binary Particle Swarm Optimization (DBPSO) is used to obtain the optimal configuration location of emergency generating vehicle and the optimal route for recovery. The validity and feasibility of the proposed method are verified by the results of IEEE39.

1.Introduction

With the rapid development of society and economy, the degree of informatization and modernization is getting higher. The power system blackout will not only affect people's normal life, but may also cause great economic losses or casualties. The modern power system is equipped with a large number of advanced safety automatic devices and protection equipment. The blackout itself is a small probability event, but it happens frequently in recent years, such as the 2009 blackout in Brazil, 2011 Tokyo power grid blackout, The 2012 blackout in India, 2015 Turkey blackout, The 2018 blackout in Brazil, 2019 Venezuela blackout. Therefore, the allocation of emergency resources and the formulation. The modern power system is equipped with a large number of advanced safety automatic devices and protection equipment of emergency measures are very important for power system.

In the process of system restoration, the emergency generating vehicle and operations staff are the core of emergency resources. The emergency generating vehicle has strong mobility and environmental adaptability, and is not affected by geographical location and the emergency generating vehicle has strong mobility and environmental adaptability environment, and could respond immediately to catastrophic accidents. It is a generator set independent of normal power supply [7]. However, its cost and maintenance cost are high, and it is affected by traffic network connectivity and congestion [8]. This

paper optimizes the configuration of emergency generating vehicle in power system recovery. In the configuration of the emergency generating vehicle, the investment cost of the emergency generating vehicle, the cost of a blackout at a substation and the operation and maintenance cost of the emergency generating vehicle should be considered comprehensively, so as to reduce the power network loss after the blackout to the maximum limit. Secondly, as the transmission process of the emergency generating vehicle is affected by the traffic network, the configuration of the emergency generating vehicle should consider the connection of the traffic network and traffic congestion to reduce the transmission time cost of the emergency as much as possible. In conclusion, this paper proposes an optimal configuration scheme for the emergency generating vehicle considering the comprehensive importance of load nodes and the traffic network constraints. The comprehensive importance degree of nodes is calculated by considering the spectral importance degree, the importance degree of load amount and the comprehensive importance degree of load of nodes. The node blackout economic loss is evaluated by node's comprehensive importance degree. This paper also considers the configuration cost of the emergency generating vehicle and the transmission cost under the constraint of the traffic network to establish the optimal configuration of the emergency generating vehicle. Finally, the DBPSO is used to calculate the optimal location of emergency generating vehicle and the optimal route for power system restoration.

2. Evaluation index of node comprehensive importance

The nodes in the power system are divided into load node and non-load node according to whether the load is received or not. The emergency generating vehicle is mainly connected to the load node to prevent a sudden blackout affecting the load power supply and increase the economic loss. In this paper, the comprehensive importance degree of load nodes is obtained by considering the spectral importance degree, the importance degree of load amount and the comprehensive importance degree of load of nodes. The definition and calculation of each degree of importance are described in detail below.

2.1. The node spectrum importance

The power system has many properties of complex network and Laplace spectrum analysis is more suitable for network topology analysis. After blackout, priority should be given to restoring important load nodes to reduce power loss as much as possible. According to the theory in reference [9], the node spectrum importance is calculated by the following formula:

$$\text{Imp}_i = 1 / \left\| X_i - X_{cluster} \right\| \tag{1}$$

Where, X_i is the coordinate of i node in the high-dimensional feature space, $X_{cluster}$ is the high-dimensional spatial coordinate of the center of clustering, Imp_i is the spectral importance of node i.

According to the actual operation of the power grid, the grid topology model is established:

1) The transformer, switch, circuit and other devices that can be put into operation are included in the network, and the substation is equivalent to one point.

2) Select the line with low voltage level and low reactive power as the reconstructed line between substations. Since the driving path of the generating vehicle is the highway between each node, the distance between each node is calculated from the node data, and the distance data of the geographic wiring diagram in the actual power system is taken as the line weight:

$$W_{ij}=L \tag{2}$$

According to the grid topology model established, the importance degree of node spectrum based on Laplace spectrum is calculated as follows:

1) Build the power system network topology model, and calculate the weight of each line by formula (2) according to the actual traffic line parameters;

2) According to the network topology, the adjacency matrix and degree matrix are established, and the Laplace matrix of the standard form is calculated

3) Calculate the eigenvectors of the standard Laplace matrix, take the first and second minor non-trivial eigenvectors, and construct the eigenspace.

4) Set the number of clustering as 1, and use k-means clustering algorithm to calculate the coordinates of the center of all nodes of the clustering.

5) According to literature [9], the node spectrum importance was calculated in the feature space.

2.2. *The node load amount importance*

In grid topology, each node has close relationship with the surrounding nodes. For the regional network, there are important nodes, such as hospitals, military, etc, which need to ensure reliable power supply. If there is a temporary interruption in the surrounding nodes, the connected interruptible load can be temporarily interrupted to supplement the important load. Therefore, it is necessary to identify such load nodes and make them recover first. In this paper, the node load importance degree be defined and calculated according to the power system node load size, based on PageRank algorithm.

The web pages in the Internet can be calculated offline by PageRank algorithm to obtain their corresponding PR value. According to this value, web pages can be divided into 0 to 10 levels. The higher the PR value, the higher the importance of the web page [10]. Existing studies show that both Internet and power grid belong to complex networks, and they have certain commonalities [11]. Analogies can introduce some algorithms based on directed graphs from the Internet into the power grid. Based on PageRank algorithm, this paper defines the node load amount importance, whose size is the PR value of each node after normalization. The weight of web page is replaced by the amount of load the power system. The calculation formula of the improved PR value is:

$$PR(P_i) = \mu \sum_{p_j \in M_{p_i}} \frac{PR(P_j)}{D(P_j)} + \frac{1-\mu}{N} \tag{3}$$

In equation (3), $PR(P_j)$ represents the load size of linked P_j, $D(P_j)$ is the load size of all connected nodes of node j. μ is the weight of node j in M_{p_i}, N is the sum of nodes.

2.3. *comprehensive importance of node load*

The higher the load importance and the larger the capacity of the node, the higher the importance of the node and the higher the cost of load loss. And when the emergency generating vehicle is configured in the node, the loss recovery is higher. For the comprehensive importance degree of nodes, it is necessary to consider not only the size of load received by nodes but also the importance of load is connected. For power system, the load has primary load, secondary load and tertiary load. The power system requires that in case of serious power failure, the power supply of all primary loads must be guaranteed, otherwise the regional economy and life will be greatly affected. As far as possible, the supply of secondary load can be guaranteed, and the tertiary load can be temporarily cut off [12]. The economic loss and social influence are different when the blackout happens. Studying how to restore the power supply of important load as soon as possible is an important measure to improve the disaster resistance ability of power grid and reduce the loss of power outage.

$$Z_{L_i} = (\kappa_1 \alpha_i + \kappa_2 \beta_i + \kappa_3 \gamma_i) + \frac{P_i}{p} \tag{4}$$

Where, Z_{Li} is the comprehensive importance degree of node load, and the node load is calculated according to active power. α_i, β_i, γ_i namely the specific gravity of primary load, secondary load and tertiary load, respectively. In this paper, different specific gravity is generated through random function, where $0.1 \leq \alpha_i \leq 0.2$, $0.25 \leq \beta_i \leq 0.45$, $\gamma_i = 1 - \alpha_i - \beta_i$. κ_1, κ_2, κ_3 are the proportion of blackout loss of primary load, secondary load and tertiary load respectively, which are set as 1,0.5 and 0.1 in this paper. P_i Is the power of node i, P is the power sum of all nodes.

2.4. *comprehensive importance of nodes*

When the emergency generating vehicle is equipped, the load node should be given priority. Due to the high cost of the emergency generating vehicle, important nodes should be given priority. As shown in

the preceding 2.1~2.3, The spectral importance, the comprehensive importance of node load and the load amount importance of nodes are evaluated from different aspects. In this paper, these different evaluation indexes are integrated to obtain the formula of the comprehensive importance of nodes as follows:

$$L_i = \lambda_1 \mathrm{Imp}_i + \lambda_2 PR(\mathrm{P}_i) + \lambda_3 Z_{L_i} \tag{5}$$

Where, L_i is the comprehensive importance degree of node i, λ_1, λ_2, λ_3 are weight coefficients of different importance respectively.

3. The fuzzy treatment of traffic congestion

This paper deals with the traffic network congestion in a fuzzy way. The level of traffic congestion can reflect the running state of traffic flow and people's subjective feelings about the degree of congestion. Two indexes, driving efficiency and low speed driving rate, are selected as the basis to judge the level of congestion. These two indexes are transformed into the level of congestion by fuzzy inference. The driving efficiency is expressed as X_1, respectively are A~F, A represents the best, F represents the worst. The low speed driving rate is X_2, divided into low, medium and high grade. The crowding level is Y. X_1, X_2 are the preconditions of Y. The interval of X_1 and X_2 is [0,1]. According to the *Urban Traffic Management Evaluation Index System* issued by the ministry of public security, there are four types of congestion: unblocked, slightly congested, congested and severely congested. According to driving efficiency and low speed driving rate, the traffic jam state under fuzzy treatment can be obtained in this paper. Figure 1 shows the congestion level corresponding to each level.
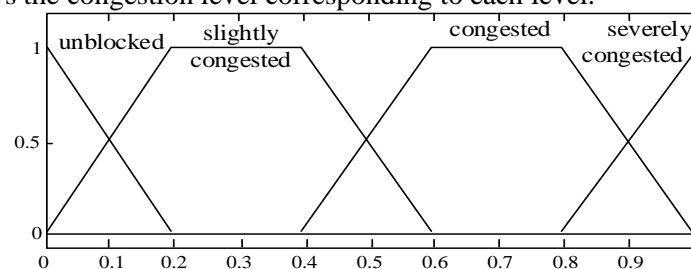

Figure 1. The function of membership degree of congestion state

W_{ij} is defined as the multiple of extended driving time caused by the obtained congestion state as the congestion coefficient, and its corresponding evaluation is shown in table 1.

Table 1. Value of congestion level and congestion coefficient

Congestion Level	Travel time	w_{ij}
unblocked	drive according to the speed limit	$w_{ij=1}$
slightly congested	time is 0.2 times longer	$w_{ij=1.2}$
congested	time is 0.5 times longer	$w_{ij=1.5}$
severely congested	time is 0.8 times longer	$w_{ij=1.8}$

4. Mathematical model of optimal configuration of emergency generating vehicle

The goal of the configuration of the load node of the emergency generating vehicle in the power grid is to minimize the economic losses after the occurrence of major blackout in the power grid. In other words, the configuration of the emergency generating vehicle will recover the most loss. The objective function is expressed as follows:

$$\max F = F_1 - F_2 - F_3 \tag{6}$$

Where, F is the total economic loss recovered after the configuration of the emergency generating vehicle, F_1 is the total economic loss of the load node after the blackout, and F_2 is the total cost of the configuration of the emergency generating vehicle. F_3 is the transmission cost of the emergency generating vehicle considering traffic network constraints.

(1)   The total economic loss of load nodes after blackout

$$F_1 = \sum_{i=1}^{n} L_i X_i P_i \tag{7}$$

Where L_i is the comprehensive importance of node i, X_i is whether node i is equipped with an emergency generating vehicle. If node i is equipped with an emergency generating vehicle, X_i is 1, otherwise it is 0. P_i is the active power of node i.

(2)   The total cost of emergency generating vehicle

$$F_2 = \sum_{i=1}^{n} C_1 X_i \tag{8}$$

Where X_i is whether the node is equipped with emergency electric vehicle, C_1 is the total cost of an emergency generating vehicle, which is a constant that takes into account the investment cost, operation cost and maintenance cost of the emergency generating vehicle.

(3)   The transmission cost of the emergency generating vehicle

$$F_3 = \sum_{i=1}^{n} \sum_{j,k \in A}^{n} C_2 X_i x_{jk}^i v_{j,k}^i (t_{j,k}^i w_{j,k}^i + t_j) \tag{9}$$

It is necessary to consider the configuration of the emergency generating vehicle every time. When the emergency generating vehicle resumes the system nodes after a blackout, the purpose is to make its transmission cost lowest. The expression of transmission cost is shown in equation (9). where C_2 is the transmission cost per unit time of the emergency generating vehicle. X_i is whether node i is equipped with an emergency electric vehicle. If node i is equipped with an emergency electric vehicle, X_i is 1, otherwise it is 0. $N = \{1, 2, \ldots n\}, 1, 2, 3\ldots$ represents the node number in the power network. $x_{jk}^i \in \{0,1\}$ is the decision variable, defined as whether the generating vehicle of node i is needed to supply power between node j and node k. $A = \{(j,k): j,k \in N\}$ represents the collection of all traffic network links between nodes. v_{jk}^i is the driving speed of emergency electric vehicle i. t_{jk}^i represents the time of power car i from node to node，which is proportional to the distance of the line. $w_{jk}^i(y)$ represents the congestion coefficient of power supply i on section (j,k) during y period. t_j represents the operating time of line charging. In order to simplify calculation, this paper considers the operating time of line charging to be a certain value.

Path constraint:

$$\sum_{i=1}^{n} \sum_{jk \in A}^{n} x_{jk}^i = 1 \tag{10}$$

Time constraints:

$$\sum_{i=1}^{n} \sum_{jk \in A}^{N} x_{jk}^i \left(t_{j,k}^i w_{j,k}^i + t_j \right) \le s_i \tag{11}$$

The formula (10) indicates that only one generating vehicle is allowed to supply power to a node. Inequality (11) represents the total time limit of the emergency generating vehicle of node i during running.

5. Results and analysis of calculation examples

Figure 2 is the topology structure diagram of IEEE39 nodes, which has 19 load nodes and the rest are non-load nodes. In this paper, the discrete binary particle swarm optimization algorithm is adopted to optimize the configuration of the emergency generating vehicle in the load node. The parameter settings are as follows: $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.3$; C=200; $\kappa_1 = 1$，$\kappa_2 = 0.5$，$\kappa_3 = 0.1$; $\mu = 0.85$; $0.1 \le \alpha \le 0.2$, $0.25 \le \beta \le 0.45$, $\gamma = 1 - \alpha - \beta$. The configuration optimization curve obtained after several iterations is shown in figure 3. It can be concluded that the configuration of the emergency generating vehicle can be optimized after about 60 iterations, and the fitness tends to be optimal after 60 iterations.

The figure 4 shows the emergency path of two vehicles. Among them, the emergency generating vehicle with 39 nodes mainly restores peripheral nodes of the system, which has a small number of nodes but a long route. while the emergency generating vehicle with 39 nodes restores the surrounding internal nodes, with a large number of nodes but a short distance between the nodes. So that the two vehicles recovery time approximation. The calculation results are described in detail below.
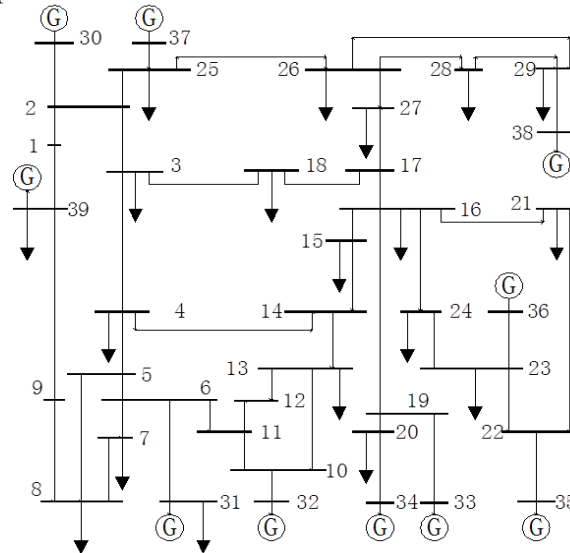

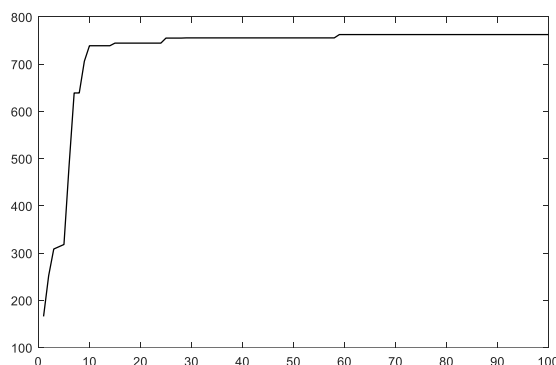Figure 2. The topology structure diagram of IEEE39 nodes

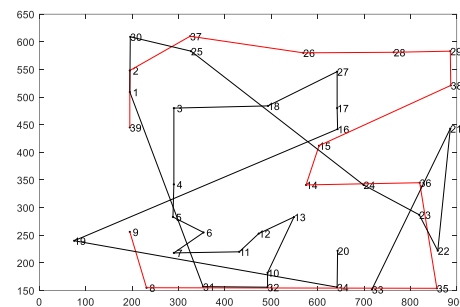Figure 3. Iterative optimization curve   Figure 4. The emergency recovery road map

According to the calculation method in section 4, the comprehensive importance degree of nodes is obtained, as shown in table 2.

Table 2. Comprehensive importance of nodes

Node number	Comprehensive importance	Node number	Comprehensive importance	Node number	Comprehensive importance
3	0.2322	18	0.2319	27	0.4293
4	0.3763	20	0.5686	28	0.4376
7	0.2400	21	0.3079	29	0.6851
8	0.4104	23	0.2965	31	0.5486
12	0.5688	24	0.2624	39	0.5737
15	0.3563	25	0.3734		
16	0.2110	26	0.1311		

After considering the comprehensive importance degree of nodes and the constraint conditions of traffic network, the goal is to minimize the loss of power failure. After iterative calculation, the

emergency generating vehicle is configured for nodes 39 and 20. The emergency recovery routes start from 39 and 20 respectively. The recovery time T1 is the recovery time of the emergency generating vehicle at 39 nodes, and T2 is the recovery time of the emergency generating vehicle at 20 nodes. T1= 7.4410h, T2 =8.5640h, and T= Max (T1, T2) =8.5640h. The optimal recovery path of the emergency generating vehicle is shown in table 3:

Table 3. The optimal emergency path of emergency generating vehicle

Restore the way	Node recovery order
The node 39 emergency generating vehicle delivers power	39-2-37-26-28-29-38-15-14-36-35-8-9
The node 20 emergency generating vehicle delivers power	20-34-19-16-17-27-18-3-4-5-6-7-11-12-13-10-32-31-1-30-25-24-23-22-21-33

6. Conclusion

In this paper, the comprehensive importance degree of nodes is defined. The optimal configuration scheme of the emergency generating vehicle is established considering the comprehensive importance degree of node load and traffic network constraints. The comprehensive importance degree of nodes is calculated by considering the spectral importance degree, the importance degree of load amount and the comprehensive importance degree of load of nodes. The node blackout economic loss is evaluated by node's comprehensive importance degree. The optimal configuration of the emergency generating vehicle is established considering the cost of configuration of the emergency generating vehicle and the transmission cost under the constraint of the traffic network. By means of IEEE39 node data and traffic network data, the discrete binary particle swarm optimization algorithm is used to obtain the optimal configuration location of emergency generating vehicle and the optimal route for power system restoration under the optimal state. The validity and feasibility of the proposed method are verified by the example.

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