Restoration control decision of distribution network based on dynamic evaluation of restoration value

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Abstract. The power outage scenario, recovery process, and load function in emergency situations will all affect the urgency of the load to restore power supply during distribution network restoration. Usually the importance level of the object to be restored is statically set according to its value of restoration, which restricts the refined management of limited restoration resources. This paper proposes a dynamic evaluation method of bus restoration value that integrates restoration benefits, costs and risks, which considers the influence of the cold load pick-up and the functional coupling relationship between the load on the recovery value of the load unit, the potential recovery value brought by the bus recovery to other surrounding objects to be recovered, and the system power supply shortage, recovery cost and uncertainty of recovery operation. Based on this, a multi-process optimization model for distribution network restoration and a partition parallel restoration decision-making method are established. Finally, simulation analysis verifies that the strategy proposed in this paper can effectively improve the utilization of recovery resources.

1. Introduction

Natural disasters, network attacks, power grid equipment failures and other factors may lead to blackout in distribution network[1]. Restoration control decision-making can optimize the distribution of power transmission and distribution network power capacity to determine the restoration sequence and capacity of various components and equipment in the distribution network under limited backup conditions and dynamically guide the restoration, which has theoretical and practical significance for reducing power outage losses and improving grid resilience.

Usually, the importance of the object to be restored which can guide the decision-making or improve the optimization efficiency after blackout is determined statically by expert experience or power supply level[2]. Rough division of the importance of objects to be restored restricts the fine management of energy in the recovery process, which is not conducive to making full use of resources and obtaining higher recovery benefits in the recovery process. Problems such as power shortage in distribution network, load pick-up, load simultaneity rate and loss of power which change with the scene and duration of power failure, and social demand in emergency environment make the load demand characteristics including capacity and importance in the recovery process very complex and constantly changed with the progress of recovery process. Literature [3-4] considers the cold load pick-up(CLPU) of partial load at the initial recovery stage, and establishes the load recovery demand model. Literature
[5] establishes a multi-period recovery model, aiming at maximizing the load-weighted continuous power supply time, which improves the overall function of key infrastructure in the recovery period. Literature [6] establishes a mathematical model for the energy demand of key infrastructure with coupling relationship, and establishes a mixed integer second-order cone programming model for restoring the optimization decision-making problem with the goal of maximizing the operation capacity of key infrastructure. Obviously, the load pick-up and the functional coupling characteristics between loads will affect the restoration scheme, but they are not reflected in the importance evaluation of the objects to be restored at present. In addition, each node of distribution network is not isolated, and the restoration of power supply of one node will affect the restoration process of other node objects connected with it. It is necessary to establish a unified evaluation index of the importance of the object to be restored, which takes into account the characteristics of load and power supply, so as to guide the restoration order between multiple power supplies to be started and between the power supplies to be started and the load to be restored.

Regarding the issue above, this paper analyzes the CLPU and the functional coupling characteristics between loads, and modifies the unit recovery value of load to reflect the dynamic changes of the unit recovery value of load. Considering the potential restoration value and system power shortage that bus restoration can bring to peripheral equipment power supply restoration, and considering the restoration cost and uncertainty of restoration operation, a dynamic evaluation method of bus restoration value is proposed, which integrates restoration benefits, costs and risks. Furthermore, a decision-making method of power supply restoration in distribution network based on dynamic evaluation of restoration value is proposed, and the effectiveness of the proposed method is verified by simulation.

2. Load demand characteristics in recovery process

2.1. Cold load pick-up

CLPU refers to the load increase during the restart of power equipment after blackout[7]. In terms of load pick-up, the loads in the system are mainly divided into temperature-controlled loads, fixed loads and man-controlled loads[9]. When the temperature control load is re-energized, the load demand is usually different from that before the fault. The demand is unchanged before and after the fixed load failure. The man-controlled load is temporarily not energized when system is re-energized. Therefore, temperature control load affects load diversity.

The heat capacity, power failure time and ambient temperature of temperature-controlled load (such as freezer, refrigerator, air conditioner, etc.) will affect the start-stop state and power demand of the temperature-controlled load after a power outage. This will cause the loss of load diversity during distribution network restoration and the increase of total load demand, which may even reach 4~5 times before failure in local areas and time periods. With the increase of power outage time, the temperature control load in startup state will increase and CLPU will become more and more obvious. The probability that the temperature control load is in the starting state at the recovery time depends on the thermal dynamic characteristics of the temperature control load, so the probability $\beta_i(t)$ of the $i$-th load in the starting state is defined as in equation (1):

$$
\beta_i(t) = \begin{cases} 
1 & \text{the } i\text{-th load is a non-temperature controlled load} \\
\frac{d_s + (t-t_0)}{d_0 + d_s} & \text{the } i\text{-th load is a temperature-controlled load, and } t-t_0 < d_s \\
1 & \text{the } i\text{-th load is a temperature-controlled load, and } t-t_0 \geq d_s
\end{cases}
$$

Where $t_0$ is the initial power failure time; $t$ is the evaluation time. The start and stop of the temperature-controlled load in normal operation are controlled by the working temperature. In this paper, the working temperature when the temperature-controlled load starts working is taken as the starting temperature, and the working temperature when it stops working is taken as the stopping temperature. If the difference between the starting temperature and the stopping temperature is twice the return
difference, $d_{i1}$ is the time when the temperature-controlled load works to make its working temperature reach the stopping temperature from the starting temperature; $d_{i0}$ is the time when the temperature-controlled load stops working to restore its working temperature from the load stop temperature to the start temperature, generally $d_{i0} > d_{i1}$.

2.2. Coupling of load functions

Due to the complex social division of labor, the key functions of partial load need the cooperation of spatial multi-point load power supply. It is necessary to consider the interrelation between different load power supply benefits during distribution network restoration. The load function is described as a multi-input-multi-output conversion link, and the necessary condition for the normal exertion of the load function is that each input energy quantity and its proportion in the total input energy are not lower than the corresponding threshold. The load function association model is shown in Figure 1. If the coupling relationship between the functions of load $L_n$ and $L_i$ is expressed as in equation (2) and equation (3), the influence factor of normal power supply by load $L_n$ on the normal function of load $L_i$ after power supply is defined as function correlation factor $\omega_{n-i}$, as in equation (4).

$$y_n = f_n(x_n)$$

$$y_i = f_i(x_i, y_n) = f_i(x_i, f_n(x_n))$$

$$\omega_{n-i} = \frac{x_n}{x_n + x_i}$$

Figure 1. Load function correlation model.

Where $x_n$ is the power supply function of the power system to load $L_n$; $x_i$ and $y_n$ are the functions of power system and load $L_n$ on load $L_i$ respectively; $y_i$ is the self-function that load $L_i$ can realize under the functions $x_i$ and $y_n$ implemented by power system and load $L_n$.

3. Dynamic evaluation of bus restoration value

During distribution network restoration, it is necessary to evaluate the importance of restoring power supply to load bus and unit bus to guide the optimization of power supply path or the allocation of standby power in the decision-making of power supply restoration optimization. The following discusses the value of bus recovery from the perspective of unit recovery value evaluation method of single load or unit.

3.1. Dynamic evaluation of unit recovery value under single load

Unit recovery value of conventional load. In this paper, the ratio of the maximum economic loss caused by the power loss of the $i$-th load after power failure to its power loss is defined as the maximum unit
power loss $\bar{b}_i$ of this single load, which can be used to evaluate the unit recovery value of a single conventional load.

Correction of CLPU for unit recovery value of load. As the objects served by temperature-controlled loads generally have a certain heat capacity, the outage loss of temperature-controlled loads will change with the outage time, that is, the unit recovery value of temperature-controlled loads will change with the outage time. The longer the outage time is, the greater the unit recovery value will be, and eventually it will tend to the maximum unit power loss $\bar{b}_i$ of the load. In addition, the unit recovery value of temperature-controlled loads will also be affected by load types, environmental temperature and other factors. Therefore, considering the CLPU of the temperature-controlled load, the unit recovery value $b_i(t)$ of the $i$-th load at time $t$ is revised as in equation (5):

$$b_i(t) = \beta_i(t)\bar{b}_i\left[1 - \gamma_i e^{-\frac{t}{\tau}}\right]$$  \hspace{1cm} (5)

Where $\gamma_i$ is the load type of the $i$-th load, with a value of 1 indicating temperature-controlled load and a value of 0 indicating non-temperature-controlled load; $\tau$ is the time required for temperature control load to recover to ambient temperature after power failure.

Functional correlation correction of restoration value of load units. Giving full play to the key functions of partial loads requires the cooperation of power supply from other loads, which is of little significance for independent power supply in advance for such loads. These loads with functional coupling relationship should have mutual influence on the importance of restoring power supply. Therefore, it is necessary to consider the related factors of load function in the restoration value of load unit. There are $N$ loads with functional coupling relationship, and this paper defines the unit recovery value $b'_i(t)$ of the $i$-th load at time $t$ considering load functional association correction as in equation (6):

$$b'_i(t) = b_i(t) + \sum_{n=1,n \neq i}^{N} \lambda_n \omega_{n,i} b_n(t), i \in \{1,2,\cdots,N\}$$  \hspace{1cm} (6)

Where $\lambda_n$ is the recovery state of the $n$-th load, with a value of 1 indicating that it has recovered, and a value of 0 indicating that it has not recovered.

3.2. Dynamic evaluation of bus restoration value
The restoration value of bus mainly depends on the benefits brought by the restoration of the bus, and the costs and risks required in the restoration process. Considering that bus restoration will shorten the distance between the surrounding bus and the electrified system, so bus restoration benefits include the restoration benefits of the load to be restored on the bus and the potential restoration benefits that can be brought to the surrounding bus by restoring the bus. Based on the unit restoration value of the load to be restored, the capacity of the load to be restored, the evaluation time, the electrical distance between the bus to be restored and the power supply system, and the adequacy of the system's power supply capacity, this paper defines the restoration income of the bus to be restored, that is, the recovery profit $I_l(t)$ of the $l$-th load bus to be recovered at time $t$ can be defined as in equation (7):
\[
\eta_{\text{adv}}(t) = \frac{\Delta P_{\text{gl-max}}(t)}{P_{L-\text{to-rec}}(t)} \times 100\%
\]

(7)

Where \( \hat{b}_{l-0,i} \) and \( P_{l-0,i} \) are the unit restoration value and load capacity of the \( i \)-th load to be restored on the \( l \)-th bus to be restored at \( t \) time; \( \hat{b}_{l-j,k,i} \) and \( P_{l-j,k,i} \) are the unit restoration value and load capacity of the \( i \)-th load to be restored on the \( k \)-th load bus on the \( j \)-th layer at \( t \) time, respectively, obtained by traversing the width first outward from the \( l \)-th bus; \( i \) is the load serial number; \( M_{l-0} \) is the number of all loads to be restored on the \( l \)-th bus at time \( t \); \( M_{l-j,k} \) is the number of all the loads to be restored on the \( k \)-th bus of the \( j \)-th layer obtained by width-first traversing outward from the \( l \)-th bus at \( t \) time; \( k \) is the serial number of the bus; \( K_{l-j} \) is the total number of buses on layer \( j \), which is obtained by width-first traversal from the \( l \)-th bus outward; \( j \) is the serial number of layers when the width first traversal is made outward from the \( l \)-th bus; \( J_l \) is the total number of layers set for width-first traversal outward from the \( l \)-th bus; \( \Delta t_l \) is the time consumption from the initial power outage time to the estimated recovery time of the \( l \)-th bus; \( \Delta t \) is the average time taken to restore one bus; \( r_{l-j,k} \) is the number of line segments of the shortest path between the \( l \)-th bus and the \( k \)-th bus on the \( j \)-th floor; \( \eta_{\text{adv}}(t) \) is the adequacy of the system power supply capacity of the proposed power supply partition to which the \( l \)-th bus belongs at \( t \) time, reflecting the shortage of system power supply (that is, the supply capacity of system standby power to load demand); \( \Delta P_{\text{gl-max}}(t) \) and \( P_{L-\text{to-rec}}(t) \) are the sum of the rotating standby capacity of the (quasi-) electrified system in the partition to which the \( l \)-th bus belongs at time \( t \) and the rated capacity of the unit in normal recovery and the remaining capacity to be recovered in the partition. When there are multiple (quasi-) electrified systems in the system, the recovery object is divided into a certain (quasi-) electrified system according to certain principles to form their own independent recovery partitions; the electrified system is a system in stable operation; quasi-electrified system is a power supply with self-starting capability or a bus with power supply capability in power failure state.

The recovery cost \( C_l(t) \) of article \( l \)-th bus mainly includes two aspects: on the one hand, it is the sum of all switching operation costs on the shortest path between the power supply and the bus; on the other hand, it is the cost of voltage control (reactive power compensation) to ensure the safety of power supply.

\[
C_l(t) = C_{l-\varepsilon}(t) + C_{l-\text{ctrl}}(t)
\]

(9)

Where \( C_{l-\varepsilon}(t) \) and \( C_{l-\text{ctrl}}(t) \) are the energy consumption cost and control cost of restoring the \( l \)-th bus at time \( t \), respectively.
The recovery risk of the \( l \)-th bus bar mainly refers to the operational risk \( R_l(t) \) during the recovery process, as in equation (10):

\[
R_l(t) = p_l(t)L_{sl}(t)
\]  

(10)

Where \( p_l(t) \) and \( L_{sl}(t) \) are the probability and loss of unsuccessful recovery of the \( l \)-th bus at time \( t \), respectively, and the recovery risk of the recovered bus is 0.

In summary: the restoration value \( V_l(t) \) of the \( l \)-th bus is shown in equation (11):

\[
V_l(t) = I_l(t) - C_l(t) - R_l(t)
\]

(11)

4. Power supply restoration optimization model of distribution network based on dynamic evaluation of bus restoration value

In the recovery process, there will be control costs due to energy consumption, switching operation, etc. In addition, the equipment operation is uncertain, and the uncertainty of recovery operation after power failure is greater, which cannot be ignored. Therefore, recovery control decision is a multi-process and multi-objective optimization problem. The recovery income, recovery cost and recovery risk are unified as monetary dimensions, and their algebra sum is defined as the recovery net income[8-9].

4.1. Objective function

In this paper, the optimization model of distribution network restoration decision-making is established with the goal of maximizing the overall restoration net income of all restoration processes as in equation (12):

\[
\max F(t) = \sum_{m=1}^{M} \left( F_{m}^u(t) - F_{m}^c(t) - F_{m}^r(t) \right)
\]

(12)

Where \( F(t) \) is the cumulative net recovery income available in all recovery processes executed by the recovery plan at time \( t \); \( M \) is the total number of recovery processes; \( m \) is the serial number of the recovery process; \( F_{m}^u(t) \), \( F_{m}^c(t) \), and \( F_{m}^r(t) \) are the recovery benefit, recovery cost, and recovery risk of the \( m \)-th recovery process at time \( t \), respectively, which can be calculated by equations (13)-(15).

\[
F_{m}^u(t) = \sum_{x=1}^{N_{m,u}} b_{m,x}(t) P_{m,x} T_{m,x}
\]

(13)

\[
F_{m}^c(t) = C_{m,d}(t) + C_{m,ctrl}(t)
\]

(14)

\[
F_{m}^r(t) = \sum_{z=1}^{N_{m,z}} p_{m,z}(t)L_{m,z}(t)
\]

(15)

Where \( N_{m,u} \) and \( N_{m,d} \) are the total number of objects to be recovered and the total number of recovery paths in the \( m \)-th process; \( b_{m,x}(t) \), \( P_{m,x} \), \( T_{m,x} \) are the unit restoration value, required power supply capacity, and power supply time in advance of the \( x \)-th object to be restored in the \( m \)-th process at time \( t \); \( C_{m,e}(t) \) and \( C_{m,ctrl}(t) \) are the energy consumption cost and control cost of the object to be restored in the \( m \)-th process at time \( t \); \( z \) is the serial number of the recovery path in the \( m \)-th process; \( p_{m,z}(t) \) and \( L_{m,z}(t) \) are respectively the probability and loss of unsuccessful operation of the \( z \)-th path in the \( m \)-th process at time \( t \).
4.2. Constraint condition
In order to ensure the stable and safe operation of the distribution network in the restoration process, the optimization solution should meet the following requirements: (1) node voltage constraints; (2) Branch current constraint; (3) Transmission line capacity constraints; (4) Power balance constraint; (5) Radial network constraints.

\[ U_{i,\text{min}} \leq U_i \leq U_{i,\text{max}} \]  
\[ I_{i,\text{min}} \leq I_i \leq I_{i,\text{max}} \]  
\[ S_i \leq S_{i,\text{max}} \]  
\[ \sum_{i=1}^{N_L} P_i < \sum_{s=1}^{N_G} P_s \]  
\[ g_i \in G \]

Where \( U_i \) is the actual voltage of node \( i \), \( U_{i,\text{max}} \) and \( U_{i,\text{min}} \) are the upper and lower limits of the voltage of node \( i \), \( I_i \) is the actual current of the line, and \( I_{i,\text{max}} \) and \( I_{i,\text{min}} \) are the upper and lower limits of the current of the \( i \)-th branch respectively. \( S_i \) is the current running capacity of transformer or line represented by branch, and \( S_{i,\text{max}} \) is the maximum rated capacity of line or transformer represented by branch; \( N_L \) is the restored load set, \( P_i \) is the restored capacity of the \( i \)-th load, \( N_G \) is the power supply set, and \( P_s \) is the output power of the \( s \)-th power supply; \( g_i \) is the \( i \)-th network topology in the recovery process, and \( G \) is the set of all radial network topologies.

4.3. Solution steps of distribution network restoration scheme based on dynamic evaluation of restoration value
Optimization steps of distribution network restoration scheme are as follows.

Step 1: Establish the topology of distribution network based on graph theory, and identify the (quasi-) electrified system and bus to be restored in distribution network.

Step 2: Partition according to the (quasi-) electrified system. When there is a communication path between the bus to be restored and more than one (quasi-) electrified system, consider the power transmission path, standby capacity, original power transmission mode before power failure and other factors to determine the recovery partition to be partitioned.

Step 3: Independent optimization within the partition, and dynamic evaluation of the restoration value of the bus in the partition by the method proposed in Section 2.

Step 4: Determine the top \( n \) buses with the highest recovery value in the current partition, and set the recovery capacity of single process as \( n*a \) MW (\( n=3 \), \( a=3 \) in this article), and take the load with the highest unit recovery value at the current moment as the recovery scheme of the current recovery process.

Step 5: Update the load with restored power supply and corresponding power supply in the partition, repeat steps 3-4, and enter the next recovery process until no new recovery scheme can be generated in the partition, that is, the recovery operation in the partition ends.

Step 6: Repeat steps 3-5 until all partitions cannot generate a new recovery plan, thus obtaining the final power supply recovery plan of the distribution network.

5. Results & Discussion
In order to verify the effectiveness of the method proposed in this paper, a decision-making system of distribution network restoration control based on dynamic evaluation of restoration value is developed based on C++ language, and relevant simulation calculations are carried out. All the simulations are completed on a computer configured with Intel Core i5-3337 CPU@1.80 GHz and 8 GB RAM. In this paper, taking one of several parallel partitions in the process of power supply restoration in a distribution
network as an example, the influence of dynamic evaluation of restoration value on power supply restoration decision is illustrated. The topology of the partition is shown in Figure 2, and the load information of each bus is shown in Table A1 of Appendix A. The total load is 275 MW, and all loads are assumed to be controllable loads. In this paper, the maximum unit power loss of load is divided into 1-5 levels, which are respectively 100,40,30,200,10 ten thousand yuan/(MW·h). The loads in Figure 2 all represent the aggregation of the load carried by the bus, and in the following table "bus serial number-the bus with load serial number" indicates the name of the unaggregated load, taking B1-1 as an example, it means number 1 on the B1 bus load. There are two distributed power sources DG1 and DG2 in the sub-zone, none of which can start automatically. The evaluation time of restoration value is $T=12$ h.

![Figure 2. Local system topology of grading distribution network in a certain place.]

The regional full stop time is recorded as 00:00, the gas turbine DG1 (rated power is 50 MW, starting power is 0.5 MW, starting time takes 5 min) is in a shutdown state, and the photovoltaic unit DG2 has a permanent fault. At 02:00, 100 MW was transmitted from bus AP1, and at 03:30, the transmission capacity of transmission network was restored to the level before power failure. The loads B3-4, B3-8, B5-4, B8-4 and B12-1 are temperature-controlled loads. The change of their unit recovery value with outage time after considering the modification of CLPU is shown in Figure 3. It can be seen from Figure 3 that the unit recovery value of each temperature control load is not large at the beginning of power failure, but with the extension of power failure time, the unit recovery value gradually increases and eventually approaches their maximum unit power loss. See Table A2 of Appendix A for loads with functional coupling relationship. Taking loads B2-3, B5-1 and B3-2 as examples, the influence factors of loads B2-3 and B5-1 on the function of load B3-2 are 0.2 and 0.1 respectively, and the influence factor of load B2-3 on the function of load B5-1 is 0.3. In this paper, the function completion degree of the load is defined as the multiple of the maximum running capacity of the load. According to the function coupling relationship between loads in the system of the example, the function completion degree between loads is set as follows: only load B3-2 restores power supply, and its function completion degree is 0.7; both loads B3-2 and B5-1 resume power supply, with the function completion degree of load B3-2 being 0.8 and the function completion degree of load B5-1 being 0.7; loads B2-3, B5-1 and B3-2 all resume power supply, and their functional completion degree is 1.
At 02:00, the power transmission network will send electricity, and the restoration value of each bus in this district will be evaluated according to the method proposed in Section 2. The evaluation results are shown in Table 1. It can be seen from Table 1 that the three buses with the largest recovery value at 02:00 are DG1, B3, and B4, respectively. Because the recovery capacity in the partition is insufficient, the calculated DG1 has the largest recovery value, and the loads connected by buses B3 and B4 have a large proportion of important loads, so they also have great recovery value. Using the recovery decision optimization method proposed in this paper, the recovery objects of process 1 are DG1, load B3, and load B4. After the process 1 is executed, refresh the recovery value of the bus, and optimize the recovery object of the next recovery process until the power supply of the partition is restored. During the whole restoration process, the dynamic change of restoration value of some buses is shown in Figure 4. It can be seen from the figure that DG1 started and resumed power supply in recovery process 1(02:00), and the transmission network added capacity to the distribution network in recovery process 19(03:30), all of which increased the power supply capacity of the district. Therefore, the restoration value of all load buses increased greatly in the following process. In other periods, with the advancement of the recovery process, the reserve capacity in the partition decreases continuously, so the recovery value of each load bus in the partition decreases gradually.

Table 1. A slightly more complex table with a narrow caption.

| Bus | Restored value/10,000 yuan | Bus | Restored value/10,000 yuan |
|-----|---------------------------|-----|---------------------------|
| DG1 | 27350                     | B7  | 7719                      |
| B1  | 7044                      | B8  | 7215                      |
| B2  | 6911                      | B9  | 7719                      |
| B3  | 9171                      | B10 | 7304                      |
| B4  | 8731                      | B11 | 7597                      |
| B5  | 7326                      | B12 | 7085                      |
| B6  | 7008                      | **  | **                        |

A variety of bus recovery value evaluation methods are used to verify the rationality of the proposed method, which are as follows: Method 1 is the bus recovery value evaluation method proposed in this paper; method 2 only ignores the CLPU in Method 1; method 3 only ignores the coupling effect of load function in method 1; method 4 is to use only the importance of load itself to statically evaluate the bus restoration value, that is, to ignore the influence of CLPU, load function coupling relationship and potential restoration value around the bus.

When methods 1 and 3 are used to make recovery decisions respectively, the trend of function completion degree of loads B2, B5, and B3 with time is shown in Figure B1 of Appendix B, and the
results obtained by methods 1 and 3 are represented by solid lines and dashed lines respectively. It can be seen that taking full account of the influence of functional coupling between loads to make recovery decisions can make the related loads recover synchronously and quickly as much as possible, so that important loads can recover and improve their functions as soon as possible.

Figure 5. Curves of zone net income.

The actual net income curves obtained by making recovery decisions based on the above four bus recovery value evaluation methods are shown in Figure 5. It can be seen from Figure 5 that the net income obtained by adopting method 1 is the largest; since the power supply can be started and restored only at 02:00 in this area, the unit restoration value of most temperature-controlled loads is very close to its maximum unit power loss after 2 hours of power failure. Therefore, the net income obtained by using method 2 is only slightly smaller than that obtained by method 1 and greater than that obtained by method 3. The net income of method 4 is obviously less than that of the other three methods. The analysis of an example fully shows that the influence of CLPU, load function coupling relationship and potential restoration value around the bus should be fully considered in the evaluation of bus restoration value, which is of great help to improve the net income of restoration and make the restoration capacity obtain greater economic benefits.

6. Conclusions
In this paper, the CLPU and the coupling relationship between load functions are fully considered to modify the unit recovery value of load. Combined with the potential recovery value of bus recovery and the shortage of system power supply, a dynamic evaluation method of power supply or load bus recovery value is established, which integrates the recovery benefits, costs and risks. Furthermore, the optimization decision-making method of power supply restoration in distribution network based on dynamic evaluation of restoration value is proposed. The example shows that the proposed method can fully reflect the dynamic change of restoration value of the object to be restored with the duration of power outage and restoration process, which is of great help to effectively improve the utilization rate of restoration resources and improve the restoration efficiency to obtain greater economic benefits.

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Appendices

Appendix A

| Load name | Load capacity | Load level | Belonging bus |
|-----------|---------------|------------|---------------|
| Name 1    | Capacity 1    | Level 1    | Bus 1         |
| Name 2    | Capacity 2    | Level 2    | Bus 2         |

Table A1. Load information on buses.
| /MW | /MW |
|-----|-----|
| B1.1 | 2 | 2 | B1 | B6.8 | 4 | 5 | B6 |
| B1.2 | 2 | 2 | B1 | B7.1 | 2 | 2 | B7 |
| B1.3 | 2 | 2 | B1 | B7.2 | 3 | 3 | B7 |
| B1.4 | 2 | 3 | B1 | B7.3 | 4 | 3 | B7 |
| B1.5 | 2 | 3 | B1 | B7.4 | 2 | 3 | B7 |
| B1.6 | 2 | 3 | B1 | B7.5 | 2 | 4 | B7 |
| B1.7 | 3 | 4 | B1 | B7.6 | 4 | 4 | B7 |
| B1.8 | 2 | 4 | B1 | B7.7 | 2 | 4 | B7 |
| B1.9 | 3 | 5 | B1 | B7.8 | 3 | 5 | B7 |
| B1.10 | 2 | 5 | B1 | B8.1 | 3 | 2 | B8 |
| B2.1 | 3 | 2 | B2 | B8.2 | 2 | 3 | B8 |
| B2.2 | 2 | 2 | B2 | B8.3 | 4 | 3 | B8 |
| B2.3 | 6 | 3 | B2 | B8.4 | 3 | 3 | B8 |
| B2.4 | 5 | 4 | B2 | B8.5 | 2 | 4 | B8 |
| B2.5 | 2 | 5 | B2 | B8.6 | 5 | 4 | B8 |
| B2.6 | 3 | 5 | B2 | B8.7 | 2 | 4 | B8 |
| B3.1 | 2 | 1 | B3 | B8.8 | 2 | 5 | B8 |
| B3.2 | 3 | 1 | B3 | B9.1 | 2 | 1 | B9 |
| B3.3 | 3 | 2 | B3 | B9.2 | 3 | 2 | B9 |
| B3.4 | 3 | 2 | B3 | B9.3 | 2 | 3 | B9 |
| B3.5 | 4 | 3 | B3 | B9.4 | 5 | 3 | B9 |
| B3.6 | 3 | 4 | B3 | B9.5 | 2 | 4 | B9 |
| B3.7 | 2 | 4 | B3 | B9.6 | 4 | 4 | B9 |
| B3.8 | 4 | 4 | B3 | B9.7 | 2 | 4 | B9 |
| B3.9 | 3 | 5 | B3 | B9.8 | 3 | 5 | B9 |
| B4.1 | 3 | 1 | B4 | B10.1 | 2 | 2 | B10 |
| B4.2 | 2 | 1 | B4 | B10.2 | 5 | 3 | B10 |
| B4.3 | 3 | 2 | B4 | B10.3 | 2 | 3 | B10 |
| B4.4 | 5 | 3 | B4 | B10.4 | 2 | 3 | B10 |
| B4.5 | 4 | 4 | B4 | B10.5 | 4 | 4 | B10 |
| B4.6 | 5 | 5 | B4 | B10.6 | 3 | 4 | B10 |
| B5.1 | 3 | 2 | B5 | B10.7 | 2 | 4 | B10 |
| B5.2 | 4 | 3 | B5 | B10.8 | 4 | 5 | B10 |
| B5.3 | 3 | 3 | B5 | B11.1 | 2 | 1 | B11 |
| B5.4 | 2 | 3 | B5 | B11.2 | 5 | 2 | B11 |
| B5.5 | 5 | 4 | B5 | B11.3 | 3 | 3 | B11 |
| B5.6 | 2 | 4 | B5 | B11.4 | 2 | 3 | B11 |
| B5.7 | 2 | 4 | B5 | B11.5 | 2 | 3 | B11 |
| B5.8 | 3 | 5 | B5 | B11.6 | 2 | 4 | B11 |
| B6.1 | 3 | 2 | B6 | B11.7 | 3 | 4 | B11 |
| B6.2 | 2 | 3 | B6 | B11.8 | 2 | 4 | B11 |
| B6.3 | 4 | 3 | B6 | B11.9 | 2 | 5 | B11 |
| B6.4 | 2 | 3 | B6 | B12.1 | 3 | 2 | B12 |
| B6.5 | 3 | 4 | B6 | B12.2 | 5 | 3 | B12 |
| B6.6 | 2 | 4 | B6 | B12.3 | 2 | 3 | B12 |
| B6.7 | 2 | 4 | B6 | B12.4 | 5 | 4 | B12 |
| B12.5 | 4 | 4 | B12 | B12.6 | 3 | 5 | B12 |
Table A2. Loads with functional coupling.

| Load | Load associated with functions | Functional correlation factor |
|------|--------------------------------|------------------------------|
| B₂₋₃ | B₁₋₂                           | 0.2                          |
|      | B₅₋₁                           | 0.3                          |
| B₁₋₂ | B₅₋₄                           | 0.3                          |
|      | B₂₋₃                           | 0.2                          |
| B₃₋₂ | B₅₋₁                           | 0.1                          |
| B₅₋₁ | B₂₋₃                           | 0.3                          |
|      | B₃₋₂                           | 0.1                          |
| B₅₋₄ | B₁₋₂                           | 0.3                          |
| B₇₋₁ | B₉₋₁                           | 0.4                          |
| B₉₋₁ | B₇₋₁                           | 0.4                          |
| B₁₁₋₁| B₁₂₋₂                          | 0.3                          |
| B₁₂₋₂| B₁₁₋₁                          | 0.3                          |

Appendix B

Figure B1. Load function completion.

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