Research on Load Recovery Optimization Strategy Based on Power Grid Partition

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Abstract. Aiming at the problem of fast load recovery after power system blackout, an intelligent optimization strategy of load recovery based on grid partition is proposed. An optimal regionalization strategy for system recovery after major blackouts is proposed. In the optimization model, factors such as charging reactive power of overhead lines for generator recovery and closing times of lines for load recovery are taken into account. After optimizing the large-scale system partition, a unified load recovery optimization model considering network reconfiguration factors is established for each partition to realize the parallel load recovery of each partition. Aiming at the optimization model proposed above, the load recovery optimization problem based on power grid partition is solved by combining traditional graph theory and genetic algorithm. In the solution, the genetic algorithm is improved, and aiming at a large number of infeasible problems arising from the application of genetic algorithm, a method of random load rejection and shortest path repair strategy is proposed, which further improves the optimization efficiency and global optimization ability of the algorithm. The correctness and effectiveness of the proposed model and method are verified by simulation analysis of IEEE30-bus system.

1. Introduction
Load recovery is the ultimate goal of power system restoration control, and how to accelerate the recovery of important loads after accidents is the core issue of load recovery. In recent years, domestic and foreign scholars have carried out systematic research in this area [1-7]. In reference [1], a partitioned recovery scheme with minimal recovery cost is proposed, but the problem of shortest recovery time for important loads is not considered. Literature [2] introduced the constraints of unit start-up time into the goal of power system zonal restoration, without considering the factors of fast or slow recovery of important loads. Reference [3] expresses the network reconfiguration problem as a non-linear optimization problem aiming at maximizing the proportion of important load recovery to the total recovered load. DPSO algorithm is used to give the recovery scheme, but the frequency constraints of the system are not considered, and the stability of the algorithm is not verified. In reference [4], the restoration problem is relaxed to a 0-1 programming problem which only considers the steady frequency
constraints of the system. The approximate algorithm is used to solve the problem, but no specific restoration scheme is given. In reference [5], the extended power flow equation is used to consider the primary frequency modulation effect of power plants and the load recovery plan is given. However, this method must be based on the network reconfiguration. In actual restoration, the network reconfiguration and load recovery need to be coordinated, and the recovery time will be prolonged if the network reconfiguration and load recovery are separated. Document [6] by introducing expert system and considering the characteristics of industrial load in restoration, the recovery steps in black start are given by combining expert system with analysis tools. Literature [7] gives the calculation of the maximum load that can be started at a time during black start. This method not only considers the factor of frequency drop, but also takes voltage drop and time into account. At present, the domestic and foreign research in this area is mostly focused on the relay-type load serial recovery power supply based on the whole system, and seldom consider the overall network reconfiguration and important load recovery of intelligent coordinated optimization recovery control strategy.

2. Algorithmic Implementation of Optimal Partition Load

Aiming at the complex model mentioned above, this paper uses genetic algorithm [1-3] to solve it. In the process of solving, the crossover operation, crossover, mutation probability and selection method of genetic algorithm are improved, which further improves the robustness and global convergence of the algorithm.

2.1. Genetic Algorithms Model for Optimal Partition Recovery

2.1.1. Construction of gene chain. Integer coding is adopted. The coding range is determined according to the number of black-start units in the system, and all nodes of the system are coded. The coding number of each node represents the partition number of the node, and the chromosome length is the total number of nodes in the system. Taking IEEE30 nodes as an example, if the system is divided into three partitions, the coding structure is shown in Figure 1.

![Figure 1. Construction of chromosome](image)

2.1.2. Determination of fitness function. The augmented objective function as shown in equation (1) is introduced.

\[
F_k = \begin{cases} 
C \left( \sum_{i=1}^{m} \sum_{j=1}^{n} Q_i^j \right) + \left(1-c\right) \left( \sum_{i=1}^{m} \sum_{j=1}^{n} \omega_i^j d_i^j \right) & \text{Satisfying Connectivity Constraints} \\
+ \lambda \left( \sum_{i=1}^{m} \sum_{j=1}^{n} p_i^j \right) - \sum_{g \in N_{H_i}} S_g & \text{Not satisfying connectivity constraints}
\end{cases}
\]

(1) Formula: S is a very large positive number, indicating penalties for violation of connectivity constraints; lambda is a penalty factor for power balance. Then the fitness function \(f\) can be taken as:
The function is solved as follows:

(a) For black-start power supply constraints, through the above genetic coding, each gene chain identifies all loads and generators in the partition, so that the generators and loads contained in each partition can be obtained. Since the units with self-startup capability are coded and assigned to different partitions, the recursive search algorithm of graph theory is used to find out whether there is a path from a load or generator to a self-startup generator in each partition. If it is not connected, the number of disconnected loads and generators is counted, and these inappropriate individuals are eliminated by introducing penalty factors.

(b) For the reactive power part during the black start of the generator, it can be calculated according to Formula (3).

\[ Q_e = 2\pi fCU^2 \]  

In the formula: \( f \) is the system frequency; \( C \) is the charging capacitance of the line; \( U \) is the system voltage amplitude. Therefore, the problem of recharging reactive power can be transformed into solving the shortest path problem of all generators connected in the area. The classical Dijkstra (Dijkstra) algorithm [4-5] is used to start with the generator with black-start capability. As the initial vertex, when the recovery path of a generator is found, the length of the path is set to a number close to zero. In this way, the path obtained by this algorithm is the shortest line connecting all generators in this area.

(c) After connecting all generators in the area, it is necessary to find the path from load to power supply. Since the recovery time of load is mainly related to the number of switching operations, it can be considered that it is determined by the number of lines to be put in from the generator to the load. Therefore, the weight of all lines in the process of load recovery can be set to 1. Dijkstra (Dijkstra) algorithm is still used to solve the minimum number of input lines \( d_i \) from all loads to the nearest power supply terminal in this area, which determines the time of load recovery.

(d) In a partition, it is necessary to ensure that all nodes in each partition have path connections, while satisfying the basic power balance relationship. Therefore, individuals who do not satisfy connectivity constraints or whose total load is greater than the total generating capacity should be eliminated.

2.1.3.  Crossover and mutation operations. Heterotopic crossover [6] was used to improve population diversity. In order to ensure the stability of the algorithm, in the early stage of evolution, it is necessary to search globally with a larger crossover probability and a smaller mutation rate. At the end of evolution, the global search probability decreases gradually, while the local search ability increases by adjusting the mutation probability. Linear method is used to adjust the probability of crossover and mutation the formula is as follows:

\[ P_c = P_{c_{\text{max}}} - (P_{c_{\text{max}}} - P_{c_{\text{min}}}) \times \frac{n}{N} \]  

\[ P_m = P_{m_{\text{max}}} - (P_{m_{\text{max}}} - P_{m_{\text{min}}}) \times \frac{n}{N} \]  

In the formula, \( P_{c_{\text{max}}} \) and \( P_{c_{\text{min}}} \) are the maximum and minimum crossover probability, \( P_{m_{\text{max}}} \) and \( P_{m_{\text{min}}} \) are the maximum and minimum mutation probability, \( n \) is the current evolutionary algebra, and \( N \) is the total evolutionary algebra.

The flow chart of the algorithm is shown in Figure 2.
2.2. Genetic Algorithms for Load Recovery

For model (4), genetic algorithm is still used to solve the problem. In the process of solving, aiming at the problem of the generation of infeasible solutions, a solution is proposed, which further improves the optimization performance and efficiency of the algorithm.
2.2.1. Construction Gene Chain. Code in line state, 0 means disconnection, 1 means commissioning. Chromosome length is the number of lines in the subsystem.

2.2.2. Fitness Function and Constraints Processing. Since line power flow can only be calculated when the network is connected, it is necessary to judge the connectivity of the current grid structure before calculating the fitness function. According to the results of power flow calculation, a formula is constructed.

(6) Fitness function.

\[ F = \sum_{i=1}^{n} \omega_i PX_i - \mu \]  

In the formula, Mu is the penalty factor. For individuals violating active power balance and line capacity constraints, reactive power balance and node voltage constraints, over-voltage constraints and frequency constraints, corresponding penalty coefficients are introduced to modify their fitness functions.

2.2.3. Crossover and mutation operations. Crossover, mutation and optimal partition.

2.2.4. Unfeasible Solution Processing and Algorithmic Optimization. In view of the above problems, this paper puts forward some improvement measures. After the crossover and mutation of the parent population to produce the offspring, the following measures are taken:

(a) For the problem of non-convergence of power flow, a stochastic load removal method is proposed. In order not to destroy the randomness of genetic algorithm as far as possible, the stochastic weight is assigned to each load, and multiplied by the weight of the load itself as the final load weight. The load with the smallest total weight is removed each time until the total load is less than the generating capacity. In this way, not only the randomness of search is not destroyed, but also the important load is not removed, which improves the search efficiency.

(b) To solve the problem of violation of network connectivity among generations, a repair strategy is proposed. Firstly, according to the line state, depth-first search is used to traverse all lines, and the number of islands generated by the corresponding line state of the current chromosome is counted. Starting from the isolated islands that have been restored to power supply, Dijkstra (Dijkstra) algorithm is used to solve the shortest path from the power supply area to a single island until all the islands are connected. At this time, the line weight is no longer the length of the line, but the magnitude of the new load introduced after connecting the line. In this way, not only can the randomness of genetic algorithm be guaranteed, but also unnecessary loads can be introduced to minimize, so that the whole grid becomes a connected network. The flow chart of applying genetic algorithm to solve load recovery problem is shown in Figure 3.

3. Example analysis

Taking IEEE30-bus standard system as an example, the system single-line diagram is shown in Figure 4, and the system data are detailed in reference [7]. Suppose the system has two black start units: Unit 1 and Unit 11. For the convenience of research, the capacity of Unit 1 is 150 MW, Unit 2 is 100 MW, Unit 11 is 60 MW, and the load 14, 15, 16, 19, 21, 24 are set as important loads and need to be restored first. The power frequency static characteristic coefficient of generator unit is 25 (standard unitary value), the load regulation effect coefficient is 2 (standard unitary value), and the system power base value is 100 MVA. According to 110 kV voltage level, charging capacitance per kilometer of line

\[ C = 8.7 \times 10^{-9} \text{ F/km}, \quad QC = 2 \pi fCU^2 = 0.033 \text{ Mvar/km} \] 

The above assumptions and parameters

In addition, this paper will discuss the optimization of rapid load recovery after blackouts from two aspects: optimal zoning and load recovery. The simulation analysis is carried out in the Pentium 4 3.0 GHz, 4 GB memory computer, MATLAB7.0 Conducted in the environment.
3.1. Optimal Partition Recovery

As can be seen from Figure 4, nodes 19, 21, 24 are closer to self-starting unit 11. The environmental parameters of genetic algorithm are shown in Table 1.

In order to illustrate the robustness and stability of the algorithm, Fig. 5 shows the distribution of fitness function values obtained by 50 independent runs of the algorithm, which takes about 50 seconds to run once. As can be seen from the graph, the numerical stability of the algorithm is very good.

The final partition results are shown in Figure 6. As can be seen from Figure 6, the number of nodes in Zone 1 is 21, the total power generation is 250.2 MW, and the total load is 245.7 MW. The number of nodes in Zone 2 is 9, the total generation capacity is 60 MW and the total load is 52.7 MW. From the results of the division of units, it can be seen that there are four non-black start units in the Division 1 and no non-black start units in the division 2. This result ensures that the charging reactive power is minimized under the given parameters. From load to load

The results show that 14, 15 and 16 loads with larger weight are in Zone 1 and 19, 21 and 24 are in Zone 2. This result ensures that important loads can be connected to nearby generators more quickly.

![Figure 4. IEEE30-bus test system](image1)

![Figure 5. Fitness results over 50 trials](image2)

![Figure 6. Results of optimal system-partitioning](image3)

![Figure 7. Scheme 2 of load restoration in the 1st partition](image4)

### Table 1. The environmental parameters of Gas

| Population size | Genetic algebra | Selection method | Crossover mode | Crossover rate | Mutation rate |
|-----------------|-----------------|------------------|----------------|----------------|---------------|
| 100             | 30              | championships    | Ectopic cross  | 0.95–0.4 Linear decrease with genetic algebra | 0.01–0.2 Linear increase with genetic algebra |

![Table 1](image5)
3.2. Load Recovery under Optimal Zoning

According to the above partition results, the load of the two partitions is recovered in parallel. The environmental parameters of genetic algorithm execution are the same as Table 1. Suppose that in Zone 1, the black-start unit 1 has been started and the driving unit 2; the units 1 and 2 have recovered 15.5% and 40% of the power supply respectively; in Zone 2, the black-start unit has recovered 42% of the power supply.

In Figure 7, through simulation calculation, the following recovery scheme is obtained in partition 1: 
Under the load recovery scheme, the total power output is 38.866 MW, the total load is 38.338 MW, \( f = 0.487 \) Hz, and the network loss is 0.528 0 MW. This scheme has fewer input lines and less network loss, so it has good power quality and fewer input lines, so it is better to choose this scheme for load recovery.

Similarly, the restoration scheme in Zone 2 under the current generation capacity can be obtained, as shown in Table 2.

Table 2. Load restoration results in the 2nd partition

| Line Recovery Sequence | Input line |
|------------------------|------------|
| 1                      | (11-9)     |
| 2                      | (9-10)     |
| 3                      | (10-20)    |
| 4                      | (20-19)    |
| 5                      | (10-22)    |
| 6                      | (22-24)    |

Among them, the total generating capacity is 26.351 MW, the total load is 26.087 MW, and \( F = 0.108 \) Hz. According to the calculation results, 19 and 24 load nodes with larger weight have been restored, and 21 nodes are also important loads, but because of too much load, they can not be restored under the current power generation regulation capacity. It is necessary to restore enough power generation as soon as possible to ensure that the next important load can be restored. At this time, the frequency decreases by 0.108 Hz, which meets the requirements of power quality.

4. Conclusion

Aiming at the problem of fast load recovery after power system blackout, an intelligent optimization strategy of load recovery based on power grid partition is proposed in this paper. Firstly, partitioning is carried out with the goal of minimizing the recovery cost and priority recovery of important loads. Within each subsystem, how to recover as many important loads as possible quickly as possible when the generator has a certain power generation capacity is studied. In the process of optimization, the power flow equation considering frequency deviation is introduced to check the line power flow, node voltage and system frequency. At the same time, the improved genetic algorithm is used to avoid the generation of infeasible solutions and greatly improve the search efficiency. The simulation results show that the algorithm has good stability and global convergence.

When the proposed method is applied to the load recovery problem of large-scale power grid after blackouts, the calculation scale of the system can be reduced by partitioning reasonably when the system is in normal operation, and then the load recovery calculation can be carried out in parallel for each partition to further reduce the calculation time. In addition, the obtained optimal load recovery schemes can provide more choices for power dispatchers to deal with uncertainties in the process of network restoration.

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