Construction of the core backbone grid based on the maximum profit-to-risk ratio

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Abstract. The construction of the core backbone grid affects the ability of the power system to resist disasters and failures. However, traditional construction methods favor stable water and thermal power sources, which are no longer in line with the development trend of modern power systems. After new energy is connected to the core backbone grid, how to balance the system risk and the economic benefits it brings needs to be solved urgently. This paper takes the maximum profit-to-risk ratio as the objective function, and constructs the core backbone grid by a step-by-step method. The results of the improved IEEE188 node calculation example show that the method proposed in this paper can effectively distinguish the key branch and nodes of the system. The core backbone grid structure constructed can ensure the stability of the system and improve the economy of the disaster-resistant system through the access of new energy units.

Keywords. core backbone grid; new energy; income-risk ratio; Steiner tree; improved binary teaching and learning algorithm

1. Introduction

The core backbone grid of the power system refers to the collection of the smallest branches and nodes that guarantee the safe and stable power supply to important loads in the event of extreme natural disasters or serious failures. The construction of the core backbone grid is of great significance to the safe and stable operation of the power grid and the protection of power supply. At present, many documents have used artificial intelligence algorithms to search the core backbone grid. Dong \textit{et al}. [1] constructs a grid search model from the goal of resistance, recoverability, and maximum connectivity, and uses an improved BBO algorithm to optimize it; Wang \textit{et al}. [2] targets load, power supply, and grid requirements respectively, and obtains a core backbone grid with differentiated requirements by improving the quantum particle swarm algorithm; Zhao \textit{et al}. [3] proposed a two-stage step-by-step construction method to obtain a core backbone grid in a high-proportion new energy system, but his search results may not include new energy units, and they do not fully reflect the role of new energy units in the core backbone grid. It can be seen from the above-mentioned literature that the current research on core backbone grids focuses on the selection of traditional power sources, which runs

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counter to the development trend of a high proportion of new energy sources connected to the power system.

In general understanding, the randomness of new energy power output prevents it from being included in the core backbone grid. However, existing studies have shown that the power structure will affect the stable operation level of the power system and the ability of disaster recovery [4]. Some scholars have also proposed that the participation of wind and photovoltaic units in the power system restoration process will not only have a huge impact on system stability, but will be beneficial to the system’s black start process [5]. In this context, the method of constructing the core backbone grid of the power system with a high proportion of new energy is still worthy of further investigation.

In view of the basic characteristics of the core backbone grid, after considering the new energy access, the following new problems will appear in the construction process:
1) After the new energy access brings great uncertainty to the system, how to use effective methods to accurately identify the branches and nodes that play a key role in the safe and stable operation of the system.
2) Whether the new energy can maintain a certain penetration rate during the construction of the core backbone grid, and improve the economy of the disaster-resistant system while taking into account the stability of the system.

Based on the above analysis, the search ideas for the core backbone grid of the power system after a high proportion of new energy sources can be summarized as follows: accurately identify the risk of system uncertainty and reasonably configure the power supply structure, so that the built core backbone grid can not only operate stably, ensure uninterrupted power supply to important loads, but also make reasonable use of the output of new energy units to improve the economics of the disaster-resistant grid.

This paper adopts a step-by-step construction method, takes the maximum system profit-to-risk ratio as the objective function, and uses an improved binary teaching and learning algorithm to optimize the unit portfolio, and completes the construction of the core backbone grid that takes both risk and economy into consideration.

2. Node and branch importance evaluation and important load grid construction

2.1. Evaluation of the importance of nodes and branches
The core backbone grid requires the strengthening of important nodes and branches to resist failures and disasters. In the context of a high proportion of new energy sources, the importance of nodes and branches should be evaluated more comprehensively. The importance evaluation indicators used in this paper are shown in Table 1, and the probability power flow is used to deal with the randomness of wind power and photovoltaic power. Among them, the branch importance is comprehensively evaluated by the system’s operating conditions on each index after the branch \( b_i \) is returned, and the branch importance is used as the weight to improve the node degree calculation, so that the node importance evaluation result takes into account both topological and electrical characteristics. In this paper, the entropy weight-TOPSIS method is used in the decision-making process of the weight of each indicator. And carry out follow-up work based on the evaluation result.

| Table 1. The evaluation index of the importance of branches and nodes |
|-------------------------|--------------------------|
| Category    | Index                      |
| Node voltage limit \( b_{11} \)  |
| Branch \( b_i \)  | Active power limit of branch \( b_{12} \)  |
|                     | Load shedding \( b_{13} \)  |
|                     | Wind and photovoltaic abandonment \( b_{14} \)  |
|                     | Improve node degree \( d_{j1} \)  |
2.2. Construction of important load grid

In this paper, the important load grid is defined as a sub-grid $G'$, which containing all important load nodes, and the branches and nodes have the largest importance but the smallest grid size. The construction of the important load grid belongs to the Steiner tree problem [6]. The spanning tree that connects all the points (Steiner points) in the specified point set and has the smallest sum of edge weights is called the Minimal Steiner Tree. Important load nodes are selected according to actual political and economic needs, while the selection of other nodes and branches in the important load grid is based on the evaluation results in 1.1.

The Steiner tree problem can be accurately solved by the idea of dynamic programming (DP). In this paper, the node-branch-node minimum transmission unit importance is negatively converted as the Steiner tree edge weight to solve the important load grid. In this way, the node importance can be included in the construction of the Steiner tree.

The transformation of the importance of the minimum transmission unit is shown in formula (1), and the negative direction of formula (2) is used as the edge weight of the tree.

\[
C_{ij} = d_i/n_i + b_{ij}/n_j
\]

\[
C_{ij} = 2 - C_{ij}
\]

Where: $d_i, d_j$ is the importance of the node $i, j$; $b_{ij}$ is the importance of the branch $ij$, and all the importance indicators are normalized; $n_i, n_j$ is the number of branches connected to the node $i, j$.

The main process of Steiner tree DP algorithm is as follows:
1) Express the connected state of $n$ Steiner nodes with a binary number $b$, then $dp[i][b]$ represents the minimum weight of the subgraph connected to the node with the corresponding state $b$ with $i$ as the root;
2) The state is transferred in the way of state relaxation according to the side, then:
   \[
   dp[i][b] = \min (dp[i][b], dp[i'][b] + w[i][i'])
   \]

Formula (3) is similar to the shortest path constraint, and the dijkstra algorithm can be directly used for state transition.

3. Principles of power supply selection and mathematical model of grid construction

After obtaining the important load grid $G'$, finally only need to configure the power supply selection reasonably to complete the construction of the core backbone grid frame.

The core backbone grid based on the maximum profit-to-risk ratio combines the safe and stable operating conditions of the traditional core backbone grid with a certain amount of new energy units. In the case of new energy units outputting a certain power, a reasonable arrangement of thermal power units to reduce output can obtain certain benefits from the perspective of coal burning and environmental costs. But endless access to new energy will increase the risk level of the system. The trade-off between benefits and risks is an economic issue. The profit-to-risk ratio [7] in economics is selected as the objective function. The profit-to-risk ratio is the possible profit-to-possible loss, and the system risk is regarded as the possible loss after the new energy is connected to the backbone grid. Therefore, the objective function of the core backbone grid framework is as follows:
Where: $R$ is the operational risk of the core backbone grid, the core backbone grid will only consider the grid voltage deviation after the line is strengthened as the operational risk, measured by the average value of the probability flow of $N$; $B$ is the revenue of new energy power generation, taking $N$ times average value of the probability power flow, where $C_1$ is the cost of thermal power generation, $B_e$ is the environmental benefit; $L_T$ is the traditional power generation capacity, $\Delta L = L_{imp} - L_T$; $a$, $b$, $c$ is the thermal power fuel cost coefficient; $d$ is the environmental cost coefficient; $\alpha$ is the adjustment coefficient, used to balance the order of magnitude.

In order to ensure stable power supply to important loads, the maximum power of the selected traditional unit should meet the following formula:

$$\sum P_{max,T} \geq L_{imp}$$

Where: $P_{max,T}$ is the reserved maximum power of the traditional power supply; $L_{imp}$ is the size of the important load.

In addition, the core backbone grid should also satisfy the equality and inequality constraints of a small power system. Uniformly expressed as:

$$g(x) = 0$$

$$h(x) \leq 0$$

4. Backbone grid search based on improved binary teaching and learning algorithm

4.1. Construction of important load grid

The Teaching and Learning Algorithm (TLBO) was proposed by Rao et al. in 2011 [8,9]. It is a heuristic optimization algorithm that simulates class learning. It improves the overall level of the class through the "teaching" of teachers, and improves personal performance through "learning from each other" between different students, so as to achieve the purpose of optimization. Among them, teachers and students are equivalent to individuals in the evolutionary algorithm, and the number of subjects each student learns is the number of control variables, that is, the dimensionality of the variables. There are three main steps:

1) Initialize the class, each student $X^i = (x^i_1, x^i_2, \ldots, x^i_d)$ $(i = 1, 2, \ldots, NP)$ in the class is randomly generated in the search space.

2) In the "teaching" stage, in the "teaching" stage of the TLBO algorithm, each student $X^i$ in the class learns according to the difference between $X_{teacher}$ and the average student. The following formula can be used to realize the "teaching" process:

$$X_{new}^i = X_{old}^i + \text{diff}.$$  
$$\text{diff}_i = r_i (X_{teacher} - TF_i M)$$

Where: $X_{new}^i \wedge X_{old}^i$ represents the value before and after learning of the student $i$ respectively; $M$ is the average of all the students' performance; learning factor is $TF_i = \text{round} [1 + \text{rand}(0, 1)]$; $r_i = \text{rand}(0, 1)$ means learning step length.
3) In the "learning" stage, each student $X^i$ randomly selects a learning object in the class to compare differences and learn to adjust. The following formula can be adopted to realize the process of "learning":

$$X'^i = \begin{cases} 
X_{\text{old}} + \tau_i(X^i - X') & f(X') < f(X^i) \\
X_{\text{old}} + \tau_i(X^i - X') & f(X') < f(X^i) 
\end{cases}$$

(9)

After each "teaching" and "learning", students need to be updated, and each student chooses whether to update or not according to the results before and after learning.

4.2. Binary teaching and learning algorithm and its improvement strategy

Since the TLBO algorithm is mainly used for searching for continuous functions, it is not suitable for the 0-1 non-linear problem of unit selection. To this end, the introduction of Sigmoid function to find parameters $s$:

$$s = \text{Sigmoid} = \frac{1}{1 + \exp(-X(i+1))}$$

(10)

According to this function, a mapping is formed to modify the components generated by the basic TLBO each time the students learn, in the following form:

$$X(i+1) = \begin{cases} 
1 & \text{rand} < s \\
0 & \text{else} 
\end{cases}$$

(11)

Where: $\text{rand}$ is the random number in (0,1). In this way, the Binary Teaching and Learning Algorithm (BTLBO) [10] for solving 01 problem can be applied.

In the BTLBO algorithm, after each iteration of "teaching" and "learning" is completed, the poor performance of individual students will affect the convergence ability of the entire class, resulting in low algorithm efficiency. At the same time, in the "learning" stage, mutual learning between students will absorb bad information and easily cause local convergence. To this end, an improved BTLBO algorithm (EBTLBO) [11] is proposed, which retains the best elite individuals, and replaces the worst individuals in each iteration to enhance the convergence ability of the algorithm, thereby improving the stability of the algorithm and the overall search ability. The overall flow of the algorithm is shown in Figure 1.

![Figure 1. EBTLBO algorithm flow](image)
5. Example analysis
In order to verify the effectiveness of the construction method proposed in this paper, the core backbone grid frame of the improved IEEE118-node system is constructed. This system includes 118 nodes, 186 branches and 54 generators. Assuming that there are 20 important load nodes, which are 11,15,27,40,42,49,54,56,60,62,70,74,76,78,80,90,92,112,116. The important load is 70% of the original load. At the same time, some generator nodes were changed to wind power and photovoltaic power sources to verify the effectiveness of this method. The modified power node rated power is the same as the original power. Generators 19,25,26,34,46,54,74,111 were changed to wind power sources, and the wind speed obeys the two-parameter Weibull distribution; generators 24,31,55,62,90,116 were changed to photovoltaic power sources, with light intensity obey the two-parameter beta distribution.

5.1. Branch and node importance evaluation
According to the evaluation system proposed in Section 1, the branches and nodes of the improved IEEE118-node system are evaluated, and the results are shown in Figure 2. Among them, branches 8-9, 85-86, and 26-30 have the highest importance. From the system structure diagram, branches 8-9 and 85-86 are at the edge of the system, and isolated nodes 10 and 87 will be directly generated after their return, so their importance is higher; branches 26-30 are at the center of the entire system and are connected to the hub nodes, so their importance is relatively high.

In terms of node evaluation results, nodes 38, 65 and 80 are of higher importance. On the one hand, the node is in the middle of the system and is more important in terms of topology; on the other hand, the node is connected to more branches and the importance of the branches is not low, so its importance is higher, reflecting the electrical characteristics of this node.

![Figure 2. The evaluation results of the importance of branches and nodes](image)

5.2. Solving the important load grid
Using the Steiner tree DP algorithm proposed in Section 2 to solve the important load sub-grid of the improved IEEE118 node grid. The result of the construction is shown in Figure 3. The total importance of the entire important load grid is 37.0852. Among them, "●" means important load nodes; "●" means non-load nodes selected into the important load grid; "——" means branches selected into the important load grid.

![Figure 3. Important load grid](image)
5.3. Results of the construction of the core backbone grid based on the maximum profit-to-risk ratio

This article assumes that all thermal power units have the same consumption characteristics, and the objective function parameters are shown in Table 2. It can completely absorb the output of new energy, and give priority to reducing the output of thermal power units in the dispatch. The core backbone grid runs independently for 48 hours in the event of a major disaster in the system.

The EBTLBO algorithm parameters are set as follows: Population size is 100; The maximum number of iterations \( k = 300 \); Number of elite students \( ES = 3 \). In addition, the EBTLBO algorithm does not need to set other parameters. The core backbone grid structure constructed by this algorithm is shown in Figure 4, and "G" indicates that this generator node is selected.

![Figure 4. Core backbone grid](image)

From the construction results, the method proposed in this paper finally selects a total of 9 generator nodes, including 3 wind and photovoltaic nodes. Within 48 hours of independent operation of the core backbone grid, through the output of new energy units, the cumulative benefit of reduced thermal power generation and environmental costs was 217,240 yuan. At the same time, the system risk level remained low, only 0.0238. According to the calculation method of risk in formula (5), this risk level represents that the average voltage deviation of each node does not exceed 2.5%.

| Table 2. Various parameters in the objective function |
|---------------------------------|---------------------------------|
| parameter | Numerical value | parameter | Numerical value |
| --- | --- | --- | --- |
| \(a\) | 1000 | \(d\) | 0.299 |
| \(b\) | 14.7 | \(N\) | 48 |
| \(c\) | 0.00048 | \(\alpha\) | \(10^{-6}\) |

In order to verify the performance of the EBTLBO algorithm, compared with the traditional GA algorithm and BTLBO algorithm, the population size and the maximum number of iterations are consistent. Figure 5 shows the convergence curve of the average fitness of the three algorithm populations. From Figure 5, we can see that the EBTLBO algorithm used in this paper has fast convergence speed and good convergence accuracy, and has obvious advantages compared with the other two algorithms.
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Figure 5. Algorithm convergence curve

6. Conclusion
This paper proposes a core backbone grid construction method based on the maximum profit-to-risk ratio: First, a set of branch and node importance evaluation system suitable for power systems containing new energy is proposed; Secondly, use Steiner tree DP algorithm to solve the important load grid. This grid contains all important loads, and the branch nodes are the most important, and the grid scale is the smallest. Finally, by improving the binary teaching and learning algorithm, rationally optimizing the power configuration of the core backbone grid and constructing the core backbone grid with the largest profit-to-risk ratio. The effectiveness of the method proposed in this paper is verified by an example of IEEE118 nodes.

7. References
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