Research on optimization of power grid range and pre-control strategy of power flow in key areas under typhoon weather

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Abstract. Typhoons are extremely destructive and the route trajectory is extremely uncertain. The power grids in coastal areas are frequently attacked by typhoons, resulting in large-scale power outages. When a typhoon strikes, it is difficult to determine the trajectory, which may cause simultaneous failures of multiple contact lines at the same time and the location of the failure is difficult to predict in advance. Based on the above background, this paper proposes a strategy for optimizing the power supply range of the power grid in key areas and pre-controlling the power flow under typhoon weather. First of all, this article will optimize the scope of key areas. The minimum overhead cable ratio, the optimal generator load capacity ratio and the minimum connection section power flow between the key area power grid and the external power grid are used as the optimization objective function, and the cuckoo search algorithm is used to provide power. Scope is optimized. Based on the above optimization results of the power supply range, a power flow pre-control strategy is proposed to ensure that the power flow of the connection section between the power grid in key areas and external power grids is zero by optimizing the output of generators, energy storage equipment, and load shedding, and finally ensure that the key areas under typhoon mode the grid can transition and operate stably.

1. Introduction

A typhoon is an extremely natural disaster. Due to the uncertain path and extremely destructive nature, a large number of towers will fall when the typhoon passes, which will cause cascading failures of the power grid and cause large-scale blackouts. Because it is difficult to predict the location of the fault and the number of lines in advance, it is difficult to effectively deal with the invasion of typhoons by using traditional power flow pre-control methods.

Literature [1] studied the typhoon wind field model of Guangdong Power Grid. The wind field model can analyze the impact on the power grid through the temporal and spatial distribution characteristics of the typhoon. Typhoons can have a greater impact on the power grid, and in severe cases, the power grid will be discontinued. Literature [2] studied the multi-dimensional identification of important lines in the regional power system under typhoon conditions. This study can give the importance of each line in the power grid under typhoon conditions. The above research focuses on the characteristics of the typhoon in the power grid itself, and has certain reference value and significance for the study of the path of the typhoon and the impact on the important lines of the power grid. However, under typhoon conditions, due to the typhoon, the important lines of the power grid will be disconnected at the same time, which will cause a cascading failure due to tripping, which may eventually lead to the disassembly...
of the regional power grid. In this field, the literature [3] proposes an adaptive third line of defense configuration method for the local isolated network after de-columnization. This scheme forms the isolated network by combining the low-frequency load shedding of the local isolated network and the low-frequency cut-off scheme. The third line of defense control strategy under the network mode. The literature [4] studies the mechanism of the influence of the column time on the transient stability of the isolated network after the separation, and in order to ensure the stability of the isolated network, the calculation method of the optimal separation time is given. Literature [5] proposes a disaster prevention dispatching control strategy that considers the grid load balance and N-1 security constraints under extreme disaster weather. This strategy can improve the power outage dis-tribution of the power system under severe weather conditions and improve the safety of system operation. The literature [6] mentioned that cascading failures are the main cause of blackouts in large power grids. The literature proposes an improved random power flow calculation method that takes into account the un-certainty of wind power and the effect of system frequency modulation. Risk assessment, and effective low-frequency load shedding stability control measures are given. Literature [7] proposes a power grid planning method for urban key areas that can be partially self-balanced. This method plans and builds a grid operation plan against typhoon with grid source load storage, and has the capability of black start and isolated grid operation. Literature [8] studied the impact of low-frequency oscillation caused by an off-region unit on the Guangdong power grid, and adopted reasonable and effective voltage control measures in the weakly damped area to meet the requirements of safe and stable operation of the power grid. Literature [9] proposed an active optimization load shedding defense strategy for key regional power grids in response to typhoons. This strategy optimizes active defense sections before cascading failures, and pre-controls the power flow of key sections to ensure that the power grids in key regions will be impacted when failures occur. The smallest, and ultimately ensure the stable operation of the power grid in key areas under typhoon conditions.

The above-mentioned documents have carried out research on the safe and stable operation of the power grid under extreme climatic conditions such as typhoons, and have achieved certain results. In order to prevent the major impact of cascading failures on the power grid and prevent major power outages in key areas, it is necessary to conduct research from the perspective of more detailed operational control. At present, there are few domestic and foreign research re-sults. Therefore, this article proposes a typhoon. Optimization of power supply range and pre-control strategies of power flow in key regional power grids. First, optimize the scope of the key area. The minimum overhead cable ratio, the optimal generator load capacity ratio, and the minimum connection section power flow as the objective function has been estab-lished. Range optimization model.

2. Ideas for optimizing power supply key areas

2.1. Scope objective function of key regional power grids

When a typhoon strikes, in the process of ensuring power, first of all, it is neces-sary to determine the key protection scope, which is called the key regional pow-er grid. The focus of this paper is to formulate distributed and coordinated con-trol strategies to ensure that the power grids in key areas do not have a full shut-down risk under typhoon conditions [10].

Considering comprehensively the reliability, stability, economy and opera-tional safety of the power grids in key areas, a key area power grid with the min-imum overhead cable line ratio, the optimal generator load capacity ratio, and the minimum cross-section power flow as the objective function has been estab-lished. Range optimization model.
Key regional power grids

Fig. 1. Scope of key power supply areas

1) Minimum number of overhead cables

$$\min f_1 = \frac{M}{N-M}$$  

In the formula: $N$ is the number of connecting lines between the key regional power grid and the external power grid; $M$ is the number of overhead lines, then there are $N-M$ cables. The minimum guarantee range is expanded to the outer power grid based on the coverage of key power supply areas. The principle of expansion is to select grounding cables as the tie line as much as possible to minimize the probability and number of circuit trips caused by typhoons[11].

2) Optimal generator load capacity ratio

$$f_2 = \sum_{i=1}^{n} \frac{S_G}{S_L} = b$$  

In the formula: $i$ is the node number; $n$ is the total number of nodes; $S_G$ and $S_L$ respectively represent the total generator set capacity and load capacity at the $i$-th node; $b$ is the value of the function $f_2$ and the range is between 1.1-1.5. The generator capacity in the key area power grid is greater than the load capacity level and the active power flows from the key area power grid to the Zhuhai power grid. This is for when one or more generators fail due to a typhoon or the load naturally fluctuates according to the daily load curve. The power grid has a power regulation margin to ensure that the power grids in key areas have the ability to regulate active power.

3) Minimum contact section current

$$\min f_3 = \sum_{i=1}^{M} P_{\text{line} \_ i} + \sum_{j=M+1}^{N} P_{\text{line} \_ j}$$  

In the formula: $N$ is the number of connection lines between the key regional power grid and the external power grid; $M$ is the number of overhead lines, then $N-M$ is the number of cable lines; $P_{\text{line} \_ i}$ is the active power of the overhead line tie lines between the key regional power grid and the external power grid; $P_{\text{line} \_ j}$ is the key area, the active power of the cable line tie line between the power grid and the external power grid. In order to ensure that the impact is minimized after the connection line fault trips, the power flow of the connection section between the key area power grid and the external power grid should be controlled to the minimum, preferably zero[12].

4) Multi-objective function normalization processing

$$F = \alpha_1 \frac{F_1}{f_1} + \alpha_2 \frac{F_2}{f_2} + \alpha_3 \frac{F_3}{f_3}$$
Where: $\alpha_1$, $\alpha_2$, $\alpha_3$ are the random weights of the three objective functions, which need to be determined according to the actual situation and their own requirements, and the sum of these three values is 1; $F_1$, $F_2$, $F_3$ are three respectively the optimal value of each iteration of the function[13].

2.2. Restrictions

1) Power flow equation constraints

$$
\begin{align*}
    & P_i = P_i + \sum_{k \in C_i} P_{ik} + \Delta P_i \\
    & Q_i = Q_i + \sum_{k \in C_i} Q_{ik} + \Delta Q_i \\
    & \Delta P_i = \left( P_i + \sum_{k \in C_i} P_{ik} \right)^2 + \left( Q_i + \sum_{k \in C_i} Q_{ik} \right)^2 \\
    & \Delta Q_i = \left( P_i + \sum_{k \in C_i} P_{ik} \right)^2 + \left( Q_i + \sum_{k \in C_i} Q_{ik} \right)^2 \\
    & j_{\text{sum}}(P_{ik} + Q_{ik}) + \sum_{k \in C_i} \left( P_{ik} + Q_{ik} \right) \\
    & X_{ij} \\
\end{align*}
$$

Where: $P_i$ and $Q_i$ are the active and reactive power of the branch corresponding to node $ij$, respectively; $\Delta P_i$ and $\Delta Q_i$ are the active and reactive power losses of the branch corresponding to node $ij$, respectively; $\sum P_{ik}$ and $\sum Q_{ik}$ are the sum of power of all branches connected to node $j$ except for branch $ij$; $R_{ij}$ and $X_{ij}$ are the resistance and reactance of the branch corresponding to node $ij$; $C_i$ is the set of all nodes connected to node $j$ except for node $i$.

2) Node voltage constraints

$$U_{i_{\text{min}}} < U_i < U_{i_{\text{max}}}
$$

In the formula: $U_{i_{\text{max}}}$ and $U_{i_{\text{min}}}$ are the upper and lower limits of bus voltage at any node within the power grid of the key area, respectively[14].

3) Node capacity constraints

$$S_{i_{\text{min}}} < S_i < S_{i_{\text{max}}}
$$

In the formula: $S_{i_{\text{max}}}$ and $S_{i_{\text{min}}}$ are the upper and lower limits of the capacity of any node in the key area power grid, respectively.

4) Grounding cable active power constraint

$$P_{\text{line},i} < P_{\text{line},i_{\text{max}}}
$$

In the formula: $P_{\text{line},i}$ is the active power of any grounding cable after any overhead tie line fails in the power grid of the key area; and $P_{\text{line},i_{\text{max}}}$ is the thermal stability limit value of the aforementioned grounding cable.

5) Overhead line active power constraint

$$P_{\text{line},i} < P_{\text{line},i_{\text{max}}}
$$
In the formula: $P_{\text{line, j}}$ is the active power of any overhead line after any grounding cable fails in the power grid of the key area; and $P_{\text{line, j max}}$ is the thermal stability limit value of the overhead line mentioned above[15].

3. Solution based on cuckoo search algorithm

3.1. Cuckoo search algorithm

The step size factor $\varphi$ of the CS algorithm and the probability $P$ of the bird's nest being discovered by the owner are generally fixed, so it has the problem of premature maturity and slow convergence. Therefore, the learning factor of particle swarm is introduced, and the adaptive step factor $\varphi$ and the discovery probability $P$ are used to improve the CS algorithm. The adaptive formula is:

$$\varphi^+_i = c_1(p_i - x_i) + c_2(p_g - x_i)$$  \hspace{1cm} (10)

$$p_a^+ = p_{a\min} + (p_{a\max} - p_{a\min})(1 - \frac{p_g^+}{p_g})$$  \hspace{1cm} (11)

Where: $c_1$ and $c_2$ are learning factors; $p_i^+$ is the probability that the i-th bird's egg is found in the kth iteration; $p_{a\max}$, $p_{a\min}$ are its upper and lower limits respectively; $p_i$ is the best location in the history of the Bird's Nest; $p_g$ is the historical best position of all bird's nests. In the CS algorithm, the position of each bird’s nest can be regarded as a solution generated randomly during the initialization process, and each random initialization is:

$$x_i = \text{round}[SW_{\min,d} + \text{rand} \times (SW_{\max,d} - SW_{\min,d})]$$  \hspace{1cm} (12)

For each initialized bird's nest, use the radial topology check algorithm to check, and then use the objective function to calculate its fitness, the formula is as follows:

$$x_i^{\text{new}} = \text{round}[x_{\text{best}} + \varphi \times r \times \Delta x_i^{\text{new}}]$$  \hspace{1cm} (13)

$$\Delta x_i^{\text{new}} = \frac{\text{rand}_s}{\text{rand}_y} \times \frac{\sigma_s(\beta)}{\sigma_y(\beta)} \times (x_{\text{best}} - g_{\text{best}})$$  \hspace{1cm} (14)

In the formula: $g_{\text{best}}$ is the bird’s nest position corresponding to the optimal fitness; $\text{rand}_s$ and $\text{rand}_y$ are two normally distributed random variables, and the standard deviation $\sigma_s(\beta)$ is calculated by formula (13), $\sigma_{y}(\beta)=1$; $\beta$ is the distribution factor ($0.3 \leq \beta \leq 1.99$), so:

$$u = \text{randn(size(x))} \cdot \sigma_s(\beta)$$

$$v = \text{randn(size(x))} \cdot \sigma_y(\beta)$$  \hspace{1cm} (15)

Where: $\text{randn}$ is the random step size. Then the real-time position and step length of the bird’s nest satisfy:

$$x_i^{\text{new}} = \text{round}(x_{\text{best}} + p_a \times \Delta x_i^{\text{new}})$$  \hspace{1cm} (16)

(1) Obtain the topology information and related data of the power grid, such as the capacity of all generators and loads, the number of cables and overhead lines in all tie lines, the power size and direction of each tie line in the power grid, etc., and enter the objective function $F$ And according to formula (12) the number of initial iterations;
6

(2) Calculate the objective function of each solution, find the corresponding fitness and record the current optimal solution and fitness value;

(3) Set the number of iterations \( t=1 \), then determine the adaptive step factor and update the previous solution, and form a new solution through testing, comparison, etc.

(4) According to formula (13), update the algorithm to optimize the search position, and obtain the new \( x_{best} \) and \( g_{best} \) by comparing the fitness function values;

(5) Take a random number \( r (r \in [0, 1]) \) and compare it with the discovery probability \( P \). If \( r > P \), update \( x_{best} \) and \( g_{best} \) according to formula (14) and find the optimal planning plan, otherwise return to the second step of step (1) to re-initialize;

(6) Judge whether the number of iteration converges, if it is satisfied, terminate the calculation and output the power grid planning plan for key areas, otherwise re-turn to step (2) to continue iteration;

The corresponding flow chart is shown below:

Fig. 2. Flow chart of cuckoo algorithm

4. Research on Pre-control Strategy of Power Flow in Key Regional Power Grid

Under the condition of a typhoon, the power grid will have severe Nm faults at any time. The power grids in key areas are interconnected external power grids through the L-circuit connection line. In order to prevent the cascading failures caused by the typhoon from causing the L-circuit line to jump completely, the sum of the L-circuit connection cross-sectional power needs to be calculated Zero cut control[16].

Power balance should be maintained at all times between generating sets, energy storage devices, and the transmission power of tie lines in key areas and the load level of the grid itself. The specific formula is as follows:

\[
P_\text{S} + P_\text{Store} + P_\text{power} = P_\text{L}
\]

(17)
Fig. 3. Generator output AGC + energy storage + new energy joint control diagram

$P_i$ is the active power of the connection section between the key regional power grid and the external power grid; $P_{\text{Store}}$ is the active power of the energy storage device; $P_{\text{Power}}$ is the active power of the generator[17];

$P_{\text{line-}\min}$ Control the active power of the connection section $S$ to be $P_i$, and the principle is that the section power flow $P_S \leq W$. Among them, $P_e$ are divided into positive and negative directions, which define the positive direction of active power flowing out of the grid in key areas and the negative direction of flowing into it. According to the adjustable capacity of generators, the adjustable capacity of energy storage devices, and the load-shedding capacity of the power grids in the key regions, the maximum value of active power of the power grid in key regions $P_i$ and the maximum value of active power flowing into the power grid of key regions $P_j$ are determined. Assuming that the minimum limit of thermal power in any loop of the connecting section is $P_{\text{line-}\min}$ and during a typhoon, if there are multiple connecting line failures (Nm), the sum of the power flow after all the connecting lines fails is still $P_i$, but in order to ensure that the remaining lines are not It must be ensured that $P_i$ cannot exceed the minimum thermal power limit of any loop in the contact section $S$, $P_{\text{line-}\min}$.

\[
|P_i| \leq P_{\text{line-}\min}
\]

The maximum value $P_i$ of the grid active power flowing out of key areas depends on the negative regulation capacity of the energy storage device. The output level of the energy storage station is read in real time. $P_{\text{Se}}, P_{\text{SC-N}}$ is the total charging capacity of the energy storage station, and $P_{\text{SK-Tn}}$ is the current negative adjustable capacity of the energy storage station. Considering the delay of the energy storage power station in the negative power adjustment (loading) process, set $K_{\lambda_1}$ as the energy storage loading proportional coefficient, which is less than 1.

\[
P_{\text{SK-Tn}} = P_{\text{SC-N}} \cdot P_{\text{SF}}
\]

\[
P_i = P_{\text{SK-Tn}} \cdot K_{\lambda_1}
\]

The maximum value of active power flowing into the grid in key areas $P_j$ depends on the forward regulation capacity of the energy storage device and the capacity of load shedding. The output level of the energy storage power station is read in real time $P_{\text{Se}}, P_{\text{RN}}$ is the total discharge capacity of the energy storage power station, $P_{\text{SK-TP}}$ is the energy storage power station the current positive adjustable capacity. Considering the time delay of the energy storage power station in the forward power adjustment process, set $K_{\lambda_2}$ as the energy storage discharge proportional coefficient, which is less than 1.

\[
P_{\text{SK-TP}} = P_{\text{RN}} \cdot P_{\text{SF}}
\]
Read the current load level $P_L$ in the power grid in the key area, and the load shedding changes in real time with the current load level proportionally. The number of load shedding stations is $C$, and the current real-time load level of each station is $P_{li}$, then:

$$P_L = \sum_{j=1}^{C} P_{li-j}$$

The proportion of the load shedding of each station to the load of the station is $K_{cut}$, and $K_{cut}$ is the proportional coefficient, which is less than 1, which is obtained according to the simulation of the grid operation mode. Define the internal load shedding capacity of the power grid in key areas as $P_{Li,Cb}$, and the margin coefficient in load shedding as $K_{\lambda_3}$, and $K_{\lambda_3}$ is less than, then there is:

$$P_{Li,Cb} = K_{cut} \ast P_{Li}$$

$P_j$ depends on the sum of the adjustable capacity of the forward power of the energy storage site and the load that can be cut, then there is:

$$P_j = P_{f,TP} \ast K_{\lambda_2} + P_{Li,Cb} \ast K_{\lambda_3}$$

In this way, the positive limit $P_j$ and the negative limit $P_j$ of the control target $P_j$ of the connection section $S$ between the key regional power grid and the external power grid are determined[18].

5. Simulation analysis

The case selects a coastal power grid to conduct research. Key regional power grids are interconnected with external power grids through tie lines. The total installed capacity of the main power sources of external large power grids is 4580MW. After the optimization in Chapter 3 of this article, the scope of the key regional power grids can be obtained. This article selects three different operation modes to optimize the scope of key areas and perform power flow pre-control for the power grids of key areas. The scope of the key areas optimized under the three operating modes is as follows:

Operation mode I: The load of the external large power grid is limited to 60%, the load of key areas is limited to 87%, the output of the unit is increased by 486MW, and the flow of the connected section is 5MW;

Operation mode II: The load of the external large power grid is limited to 60%, the load of key areas is limited to 60%, the output of the unit is increased by 523MW, and the flow of the connected section is 13MW;

Operation mode III: The load of the external large power grid is limited to 50%, the load of key areas is limited to 60%, the output of the unit is increased by 535MW, and the contact section is 22MW.

The contact section can be cut to zero by controlling the output of the generator set, limiting the load, etc.

According to the three key regional power grid schemes, a variety of fault types are set up, including N-1, N-2,...N-N and other fault modes to simulate transient stability characteristics, and the simulation results are observed in key regional power grids. Generator power angle curve, 220kV bus voltage curve and system frequency curve.
Table 1. Three key area plan failure settings

| Key area | Active power of contact section | Fault type            | Number of failures |
|----------|---------------------------------|-----------------------|--------------------|
| I        | 5MW                             | Three-phase disconnection | N loop is all disconnected |
| II       | 13MW                            | Three-phase disconnection | N loop is all disconnected |
| III      | 22MW                            | Three-phase disconnection | N loop is all disconnected |

The simulation curve is as follows:

![Fig. 4. Bus voltage curve diagram of three key area Schemes](image1)

![Fig. 5. System frequency curve diagram of three key area schemes](image2)

![Fig. 6. Generator power angle curve diagram of three key area schemes](image3)

Simulation verification shows that the bus voltage curve, system frequency curve and generator power angle curve of the power grid under the three key area schemes can maintain stability.

6. Conclusion

Under typhoon conditions, typhoons can cause cascading failures. In order to avoid cascading failures caused by typhoons, this article focuses on the research on the stability control strategy of key regional power grids under typhoon conditions, a kind of optimization of power supply range and power flow prediction of key regional power grids under typhoon weather. Control strategy, first to optimize the scope of the key area, the minimum overhead cable line ratio, the optimal generator load capacity ratio and the minimum connection section power flow between the key area power grid and the external power grid are used as the optimization objective function, and the cuckoo search algorithm is used. To optimize the power supply range, and through the BPA simulation, verification of an actual power grid, the simulation results show that the power grid can maintain stable operation by optimizing the grid range in key areas and pre-controlling the power flow in advance. Therefore, the strategy proposed in...
this paper can effectively ensure the key points in the typhoon mode. Stability of the regional power grid.

Acknowledgments
Technology Project of Guangdong Power Grid Co., Ltd. (GDKJXM20185859(030400KK52180049))

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