The preventive measure of power system blackout considering the thermal stability and voltage stability

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Abstract. In order to ensure the reliable transmission of electric energy, some preventive measures are adopted to improve the stability of the power system. The thermal stability of the system can be improved by increasing the transmission capacity. And the voltage stability of the system can be improved by installing reactive power compensation device. In this paper, the above two methods are integrated. Firstly, the objective functions of thermal stability, voltage stability and economy of the system are established. Then the multi-objective particle swarm optimization (MOPSO) algorithm is used to solve the optimal configuration scheme of the thyristor controlled series capacitor (TCSC) and the static var compensator (SVC). Finally, according to the simulation results of the classical power failure model, the effectiveness of the proposed method is verified.

1. Introduction
In recent years, a number of major power failures have occurred worldwide, causing serious consequences. These blackouts are often accompanied by large-scale power flow transfer, line overload, and local voltage instability. Eventually these factors caused the accident to expand in scope. Therefore, how to improve the power flow distribution in the evolution process of blackout to improve the thermal stability of the line and the reactive power configuration of the grid to improve the voltage stability is of great significance for the prevention and control of power system blackout.

At present, in order to reduce the risk of power failure, scholars put forward a variety of prevention and control measures from different perspectives. In literature [1], the risk of power failure is calculated based on Bayesian network. And this method takes the minimum risk of power failure as the objective function and adopts the interior point method to give the optimal load cutting strategy. In literature [2], transmission line vulnerability is evaluated based on the fault chain theory. Moreover, this method takes the transmission line vulnerability as the objective function and uses the optimization power flow and interior point method to optimize the system control variables. In literature [3], based on the fault chain theory, indicators of power failure risk and control measure are given. This method takes the power failure risk and control cost as the objective function to optimize the system coordination control. In the literature [4], the fault shutdown model of the line is also established based on the fault chain theory. In addition, the model takes into account the factors such as the line itself, power flow transfer, hidden fault and weather. In the above study of preventive and control measures based on the risk assessment of fault chain, the power flow diversion caused by the chain break in the process of power failure is paid attention to, but the voltage instability in the chain fault is ignored.
The configuration of Facts device is an important means to improve the security of power grid. TCSC and SVC belong to Facts device. Installing TCSC on the line and SVC on the node can improve the thermal stability and voltage stability of the system respectively. At present, scholars around the world have done a lot of work on addressing and parameter configuration of SVC and TCSC, and a variety of algorithms have been used to solve related problems. In the literature [5-6], the static voltage stability of the system was analysed based on modal identification, and further, the configuration location and parameters of the SVC device were determined. In reference [7], the sensitivity method was used to select the appropriate location for SVC configuration. In literature [8], a new method to determine the installation position of SVC is proposed based on the normal form theory of vector field. In literature [9], a site selection method based on particle swarm optimization (PSO) algorithm is proposed for a fixed number of SVC devices. In literature [10], an optimal configuration method of SVC based on hybrid genetic algorithm was proposed. The objective function of this method is minimum network loss, maximum reactive capacity and minimum cost. The limitation of the above method lies in that it does not consider the change of topology structure in the process of power failure and does not configure SVC from the perspective of reducing the risk of power failure.

In this paper, the objective function is established from three aspects of power grid voltage stability, thermal stability and economy to provide the optimal configuration of TCSC and SVC for the system to prevent the occurrence of power failure. On the one hand, based on the theory of accident chain, the risk index of voltage instability is introduced into the objective function. On the other hand, MOPSO, a multi-objective particle swarm optimization algorithm, was selected to solve the multi-objective optimization problem. Finally, Soc-Power Failure model [11] was adopted to verify the results of the proposed algorithm.

2. The evaluation method of the state of power state

2.1. The evaluation method of thermal stability of power grid

Thermal stability refers to the ability of electrical equipment to withstand the thermal action of short-circuit current without causing damage to the equipment. In the progress of power failure, power flow transferring in a large range often leads to exceeding the limit of thermal stability of the line and continuous breaking of the line. In order to measure the thermal stability of power grid under disturbance, a comprehensive evaluation index considering power flow transferring and line thermal stability is introduced.

2.1.1. The entropy of power flow

Entropy can describe the degree of chaos of the system, and power flow transferring entropy [12] can measure the degree of unbalanced power flow distribution of the system after disturbance. It is defined that after line i exits from operation, the power flow impact on a line k is defined as follows:

$$\Delta F_{k,i} = |P_{ki} - P_{k0}|$$  \hspace{1cm} (1)

The impact on the whole system caused by the exit of line I is defined as follows, that is, the sum of the power flow impact on all lines in the system:

$$\Delta F_{sum,i} = \sum_{k=1}^{N} |P_{ki} - P_{k0}|$$  \hspace{1cm} (2)

The power flow transferring entropy when exits is defined as follows:

$$H_{i} = -\sum_{k=1}^{N} \frac{\Delta F_{k,i}}{\Delta F_{sum,i}} \ln \eta_{k,i}$$  \hspace{1cm} (3)
2.1.2. The load rate of power system

Power flow transfer entropy only considers the unbalanced power flow distribution of the system after disturbance, not the power flow limit of each line. In literature [13], the line load rate is considered and the load rate of power system is given.

The load rate of the line is defined as follows:

\[ L_{li} = \frac{F_{li}}{F_{li,max}} \]  

(4)

The load rate of all lines is arranged in descending order. After taking the logarithm, the least square method is used for linear regression calculation to obtain the slope of the fitting curve:

\[ W_i = |k_i| \]  

(5)

And the higher the slope value, the worse the thermal stability of the power grid.

Based on the above two indicators, the comprehensive evaluation index of thermal stability of line i is defined as follows:

\[ S_{i,\text{Thermal}} = aH_i + bW_i \]  

(6)

2.2. The evaluation method of thermal stability of power grid

PV curve method is a classical method of static voltage stability analysis. On the one hand, it can be used to determine whether the system is in voltage instability and on the other hand, it can be used to judge the voltage stability margin.

The PV curve is shown in figure 1. When the operating point is on the upper half of the PV curve, the system is in a stable state. When the operating point is at the lower half of the PV curve, the system is in the state of voltage instability. When the operating point is at the nose point, the system is in the critical instability state. Based on PV curve, the voltage stability margin of node i is defined as follows:

\[ \mu_i = \frac{|Z_{eq}| - |Z_i|}{|Z_{eq}|} \times 100\% \]  

(7)

Where, \( Z_{eq} \) is the Thevenin equivalent impedance of node i, and \( Z_i \) is the load equivalent impedance of node i.

2.3. Risk assessment of blackout considering voltage stability and thermal stability

2.3.1. Risk assessment of blackout based on accident chain

According to the fault chain theory, the power grid contains multiple accident chains, and the expression for a certain accident chain is as follows:

\[ L_i = \{T_{i1}, T_{i2}, ..., T_{in}\} \]  

(8)

Where, \( T_{ij} \) is the jth intermediate link of fault chain i.

According to the definition of accident chain, the calculation formula of power failure risk is as follows:

\[ R_i = P_i \times S_i \]  

(9)
Where, $R_i$ is the risk value of the fault chain $L_i$, $P_i$ is the probability value of the accident chain $L_i$, and $S_i$ is the severity value of the accident chain $L_i$.

The probability calculation formula of fault chain can be obtained based on conditional probability:

$$P_i = P(T_0)P(T_1 | T_0)...P(T_n | T_{n-1}...T_{i-1})$$

(10)

### 2.3.2. The severity function of power failure risk

From the point of view of power grid security, the function of power failure severity is given by considering the risk of voltage instability and load loss.

1. The severity function of voltage instability risk

   In order to reflect the risk of voltage instability during the evolution of interlocking faults, based on the voltage stability margin, the risk severity function of voltage instability is given as follows (Figure. 2):

   $$S_{stability}(\mu) = \begin{cases}
   1, & (\mu \leq 0) \\
   \frac{\mu_N - \mu}{\mu_N}, & (0 < \mu \leq \mu_N) \\
   0, & (\mu_N < \mu \leq 1)
   \end{cases}$$

(11)

Where, $\mu_N$ is the voltage stability margin of the system in the initial state. The smaller the margin, the greater the risk of instability of the system.

2. The severity function of load loss

   Typically, load losses are counted in cascading Failure models that only consider the thermal stability of components (e.g., OPA model, soc-power Failure model). Define the relative value of load loss caused by thermal stability:

   $$L_i = \frac{P_{loss}^{i,0}}{\sum_{i=1}^{N}P_{li}}$$

(12)

Where, $P_{loss}^{i,0}$ is the actual load loss of power failure when only thermal stability factors are considered. $P_{li}$ is the active power of load nodes, and $N$ is the number of load nodes. Further, under the condition that only thermal stability factors are considered, the severity function of load loss in power failure is defined as follows:

$$S_{loss} = L_i$$

(13)

### 2.4. Economic evaluation of power failure prevention and control measures

In this paper, Facts device (TCSC and SVC) is adopted to prevent and control power failure. In order to analyse the operation economy of the device, the calculation formula of configuration cost of different Facts devices is given as follows:

$$C_{FACTS} = \alpha S^2 + \beta S + \gamma$$

(14)

Where, $C_{FACTS}$ is the cost of a single Facts device ($\text{\$}$), $S$ is the reactive power adjustment range (MVAR) of Facts device, $\alpha$, $\beta$ and $\gamma$ are the formula parameters, which depend on the type of Facts device (Table 1).

| Facts | $\alpha$ | $\beta$ | $\gamma$ |
|-------|---------|---------|---------|
| TCSC  | 0.0015  | -0.7130 | 153.75  |
| SVC   | 0.0003  | -0.3051 | 127.38  |

Therefore, the total cost of the configured Facts device is as follows:

$$C_{TOTAL} = \sum_{i=1}^{N_{TCSC}} C_{i,TCSC} + \sum_{j=1}^{N_{SVC}} C_{j,SVC}$$

(15)
Where, $N_{\text{TCSC}}$ and $N_{\text{SVC}}$ are the number of TCSC and SVC configurations respectively.

3. Optimal configuration of TCSC and SVC based on multi-objective particle swarm optimization

As shown in Figure 3, this paper presents the objective function from three aspects of grid thermal stability, voltage stability and economy of preventive measures, as well as two levels of process evaluation and result evaluation. Furthermore, based on the multi-objective particle swarm optimization algorithm, the optimal TCSC and SVC configurations are given.

3.1. The objective function

(1) The objective function of thermal stability

The objective function of thermal stability is defined as follows:

$$\text{min. } S_{\text{Thermal}} + \sum_{i=1}^{N} R_{\text{loss}}(L_i)$$  \hspace{1cm} (16)

where, $S_{\text{Thermal}}$ is the progress evaluation part, and $R_{\text{loss}}(L_i)$ is the result evaluation part.

(2) take into account the objective function of power grid voltage stability

The objective function of voltage stability is defined as follows:

$$\text{min. } \frac{1}{\mu} + \sum_{i=1}^{N} R_{\text{stability}}(L_i)$$  \hspace{1cm} (17)

where, $\frac{1}{\mu}$ is the progress evaluation part, and $R_{\text{stability}}(L_i)$ is the result evaluation part.

(3) economic cost of preventive control measures

The objective function of economic cost of preventive control measures is defined as follows:

$$\text{min. } C_{\text{TOTAL}}$$  \hspace{1cm} (18)

3.2. The constraint condition

In power flow calculation, TCSC can be regarded as the capacitance or reactance of the series circuit, and its steady-state reactance can be expressed as:

$$X_{\text{TCSC}} = \beta X_{\text{Line}}$$  \hspace{1cm} (19)

Where, $X_{\text{Line}}$ is the reactance value of the compensated circuit, $X_{\text{TCSC}}$ is the TCSC reactance value. $\beta$ is the compensation degree, and its value range is -0.8~0.2.

For SVC, the maximum reactive power compensation range is -100~100MVar, so the capacity constraints of TCSC and SVC are as follows:
\[-0.8 \leq \beta \leq 0.2\]  \hfill (20)
\[-100 \leq Q_{\text{SVC}} \leq 100(\text{MVar})\]  \hfill (21)

3.3. **TCSC and SVC configuration algorithm based on MOPSO**

In this paper, the thermal stability and voltage stability evaluation indexes are used to find the lines and voltage stability weak nodes with large power flow impact, and the installation location of Facts device is preliminarily determined to improve the optimization efficiency. The optimization algorithm flow chart is shown in figure 5.

4. **Verification method of TCSC and SVC configuration scheme based on linkage fault model**

Calculation flow of Soc-Power Failure model considering voltage instability factor is shown in figure 6. And this model can be used to compare the advantages and disadvantages of different schemes.

5. **Simulation and verification**

5.1. **TCSC and SVC configuration scheme based on MOPSO**

IEEE39 node system is selected as the simulation object in this paper (as shown in figure 4), and the optimization method proposed in this paper is adopted for simulation analysis.

In order to select the installation location of TCSC, calculate the thermal stability function\( S_{\text{thermal}} \) value of the lines in the IEEE39 node system, and sort the results to get the top 5 key lines (see table 2).

| Line   | Value |
|--------|-------|
| 16-19  | 4.21  |
| 10-11  | 3.90  |
| 6-11   | 3.87  |
| 26-27  | 3.86  |
| 15-16  | 3.81  |

According to the table, the weak line of the system is located near the hub node 16 and the balance node 32. During the development of power failure, the power flow on relevant lines may fluctuate greatly due to power flow transfer and generator power increase.

In order to determine the installation location of SVC, the voltage stability margin of each load node in the initial state of the system was calculated, and the results were sorted to obtain the first 5 load nodes with small voltage stability margin (Table 3).
Table 3. The key node

| Node | Value     |
|------|-----------|
| 8    | 0.554     |
| 4    | 0.567     |
| 20   | 0.684     |
| 15   | 0.705     |
| 3    | 0.723     |

As can be seen from table 3, the node with a small voltage stability margin is in the receiving end region, which may take the lead in the voltage instability accident in the major power failure.

Furthermore, according to the pre-installed positions of TCSC and SVC, MOPSO algorithm was used to coordinate the thermal stability, voltage stability and economy to solve the optimal configuration.

In the simulation, the number of particle swarm is set as 200, update algebra 200, and the maximum number of Pareto solution is 200. Simulation results based on the above Settings are as follows.

Fig. 7 Pareto optimal frontier

45 Pareto solutions are obtained through simulation, and the optimal objective vector corresponding to the Pareto solution is given the optimal allocation scheme of TCSC and SVC. As shown in figure 7, the black point in the figure represents the non-dominant solution set, Pareto solution set constitutes the Pareto front end face, and the optimal solution set is the result of comprehensive consideration of voltage stability, thermal stability and economy.

5.2. Verification of TCSC and SVC configuration scheme

Scheme 1: in order to verify the optimization results of TCSC and SVC and their preventive and control effects on blackout, an optimal solution from Pareto’s optimal set (Table 4 and Table 5) was extracted for simulation.

Table 4. TCSC configuration parameters based on MOPSO

| Line   | 6-11 | 10-11 | 15-16 | 16-19 | 26-27 |
|--------|------|-------|-------|-------|-------|
| \( \beta \) | 0.2  | 0.2   | 0.35  | 0.2   | 0.15  |

Table 5. SVC configuration parameters based on MOPSO

| Node | 3     | 4     | 8     | 15    | 20    |
|------|-------|-------|-------|-------|-------|
| Capacity | 8.61   | 33.26 | 68.15 | 4.79  | 100   |

In the system, the cost of configured TCSC is \( 7.15 \times 10^5 \)$, and the cost of configured SVC is \( 6.98 \times 10^5 \)$.

Optimization scheme 1 was obtained by MOPSO algorithm. In order to compare the schemes, the configuration schemes of TCSC and SVC were respectively given by using single objective particle swarm optimization (PSO) on the premise of the same or approximately same economic cost.
Scheme 2: the minimum flow transfer entropy was taken as the objective function, and the TCSC economic cost was taken as the constraint condition to obtain the optimal parameters of the TCSC device.

The TCSC device parameters configured in the system are shown in table 6, and the cost is \(7.19 \times 10^5\$\).

| Line   | 6-11 | 10-11 | 15-16 | 16-19 | 26-27 |
|--------|------|-------|-------|-------|-------|
| \(\beta\) | 0.2  | 0.35  | -0.5  | -0.8  | 0.53  |

Scheme 3: The maximum voltage stability margin is taken as the objective function, and the SVC economic cost was taken as the constraint condition to obtain the optimal parameters of the SVC device.

| Node | 3   | 4   | 8   | 15  | 20   |
|------|-----|-----|-----|-----|------|
| Capacity | 27.74 | 53.62 | 25.25 | 30.68 | 26.97 |

According to the optimization scheme 1 obtained by MOPSO, and the optimization scheme 2 and scheme 3 obtained by PSO, based on the above three schemes and based on the Soc-power failure model considering voltage instability, 200 power failure accidents were simulated respectively.

As shown in figure 8, the time series diagram of load loss in power failure accidents corresponds to four situations. The loss load and disturbance times under four simulation conditions were logarithmic and expressed in the log-log coordinate graph (Figure 9).

Through the analysis of the loss-load sequence of power failure and Scale-frequentness log-log graph under the four schemes, it can be seen that, from the perspective of loss of load, the effect of scheme 2 is better. In scheme 2, TCSC device is specifically configured on the line to effectively change the system power flow and significantly reduce the scale of system power failure. In scheme 3, SVC devices are installed at key nodes to reduce the frequency of large-scale system failures. In scheme 1, the optimization effect is between the above two.

By adding load disturbance randomly to the whole network, 2000 power failure accidents were simulated for 3 different schemes respectively, and voltage instability accident parameters under 4 conditions were statistically compared (Table 8).
Table 8. Statistics of parameters related to instability accidents

| Distance (m) | uncompensated | Scheme 1 | Scheme 2 | Scheme 3 |
|-------------|---------------|----------|----------|----------|
| The frequency of instability | 0.0175 | 0.011 | 0.015 | 0.014 |
| Average variation of voltage stability margin | -0.019 | 0.012 | 0.024 | 0.012 |

According to the analysis of table 8, all three schemes can reduce the risk of power grid instability to different degrees. Among them, scheme 1 can effectively reduce the risk of voltage instability, while scheme two has no obvious effect on reducing the risk of voltage instability. By calculating the mean value of variation of power grid voltage stability margin in all accidents, scheme 2 is not conducive to system voltage stability.

By comparing the prevention and control effects of the three schemes on thermal stability and voltage stability accidents, scheme 1 is more suitable. In the optimization process, when only one of the two objective functions of thermal stability or voltage stability is adopted, the optimization of one objective may lead to the deterioration of the other.

6. Conclusion

(1) In order to establish the objective function, thermal stability, voltage stability and economy of power grid are considered. MOPSO multi-objective optimization algorithm was used to solve the optimal configuration of TCSC and SVC devices of the system.

(2) Based on the previous methods, the method proposed in this paper integrates the factor of voltage instability into the objective function, so as to achieve better optimization results.

(3) By using the SOC-Power Failure model that takes into account voltage instability factors, multiple schemes are compared to verify the advantages of the scheme proposed in this paper.

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