Power Grid De-icing Optimal Plan Based on Fractional Sieve Method

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Abstract. Aiming at the problem that the reliability of system was reduced and the security risk was increased during the DC de-icing period, a decision-making model based on the fractional sieve method was proposed. This model introduced risk assessment theory, and took into account the comprehensive failure probability model of protection action and ice cover. Considering the de-icing condition, a DC de-icing strategy model, which was with the objective function of minimizing the load of shedding and minimizing the operating risk, was proposed. The objective function was optimized by particle swarm optimization algorithm and fractional sieve method. The simulative results of IEEE30-bus system indicated that the load loss caused by de-icing and the operational risk of the system could be effectively reduced by the proposed model. It provided a reference for power department to make a de-icing plan.

1 Introduction

Affected by the global climate change, extreme weather disasters occur more frequently, the power system is facing a severe test. In 2008, the area of South China suffered a large area of freezing rain and snow disaster. Power transmission lines and transformation facilities were heavily covered with ice\textsuperscript{[1]}. It is very important to take measures to restore the system state in time, in order to effectively avoid the occurrence of such ice disaster.

In recent years, experts and scholars have conducted a lot of research on line icing mechanism\textsuperscript{[2]}, icing monitoring\textsuperscript{[3]}, prevention and control strategies\textsuperscript{[4]}, and have achieved some results. But there are few literatures about de-icing plan on the security of system.

From the view of reliability and security of the grid, this paper proposes a method of melting ice planning decisions based on fractional sieve method. In this paper, the security risk assessment theory is introduced to establish the integrated failure probability model of the outage of protective action by the increase of the load and power flow. Based on the goal of minimum security risk and minimum load shedding, the ice melting condition is the constraint and a decision-making of de-icing plan is proposed. Then, the objective function is optimized by particle swarm optimization algorithm, and allowable error is given by the operation requirements to get the satisfactory solution set. The optimal de-icing decision plan considering the load loss and security risk is obtained by the fractional sieve method. Finally, taking the IEEE30 bus system as an example, the proposed method is simulated and compared with the traditional method, which verifies the effectiveness and feasibility of the method in this paper.
2 The failure probability model of icing lines

2.1 The failure probability caused by external factors

This paper takes meteorological and topographic factors into account, and predicts after $\Delta t$ hours, the ice thickness of the line is:

$$E(t + \Delta t) = E_t + \frac{1}{\rho_i \pi} \sqrt{(\rho_i S)^2 (3600VW_d^2)} \cdot \Delta t$$

(1)

where $E_t$ is the ice thickness of line at the time of $t$; $W = 0.067S^{0.846}$ is the liquid water content in air; $\rho_i$, the density of ice; $\rho_s$, the density of sleet; $S$, the precipitation intensity; $V$, the speed of wind; and $\alpha_d$, the coefficient affected by the topography.

In this paper, the icing rate is used to describe the icing severity of lines, so as to compare the icing condition of different lines:

$$\delta = \frac{E}{E_{\text{lim}}}$$

(2)

where $E$ is the ice thickness of the line and $E_{\text{lim}}$ is the design ice thickness of the line.

Combined with the failure probability of the growth rate is proportional to the rate of icing, this paper uses exponential function to describe the failure probability[5] caused by external factors as follow:

$$P_m = \begin{cases} 
1 & \delta > 1.4 \\
Ae^{\lambda} & 0 \leq \delta \leq 1.4 
\end{cases}$$

(3)

where $A$ is attenuation coefficient and $\lambda$ is damping coefficient.

2.2 The failure probability caused by internal factors

When the power flow of line is in the rated transmission range, the protection movement is almost no effect by the tidal current, the failure probability is $P_0$. When the power flow of line is greater than the limit value, the protection must act, and the failure probability is 1. When the power flow of line is between the normal and the limit value, the protection action probability is proportional to the tidal current [6].The failure probability caused by internal factors is defined as follow:

$$P_f = \begin{cases} 
P_0, & F_{\text{min}} < F \leq F_{\text{max}} \\
\frac{F - F_{\text{max}}}{F_{\text{lim}} - F_{\text{max}}} \times (1 - P_0) + P_0, & F_{\text{max}} < F \leq F_{\text{lim}} \\
1, & F > F_{\text{lim}} 
\end{cases}$$

(4)

where $F_{\text{min}}$ and $F_{\text{max}}$ respectively are the lower and upper limits of the normal values of the line power flow.

2.3 The comprehensive failure probability

During the DC ice-melting, the failure probability of lines is decided by both external factor and internal factor. The failure probability of line $i$ is defined as follow:

$$P(i) = 1 - (1 - P_m)(1 - P_f)$$

(5)
3. Risk assessment model of power system
The power grid structure will be destroyed in a certain extent by DC ice-melting, and the security of system will be reduced, which will make second failure more likely to occur.

3.1 Severity evaluation index

3.1.1 The severity of low voltage. The severity of the node’s low voltage is expressed as follow:

\[
Sev(V_i) = \begin{cases} 
0 & V_i \geq V_N \\
\frac{V_N - V_i}{V_N - V_{lim}} & V_i < V_N 
\end{cases}
\]

(6)

where \(V_i\) is the operating voltage of node \(i\) and \(V_{lim}\) is the low voltage limit of node, which is generally set to 90% of the rated voltage.

The severity of low voltage in the system is expressed as follow:

\[
S(V_a) = \sum_{i=1}^{N} Sev(V_i) / N
\]

(7)

where \(S(V_a)\) is the severity of voltage in the accident and \(N\) is the total number of bus in system.

3.1.2 The severity of circuit overload. The severity of the circuit overload is expressed as follow:

\[
Sev(F_i) = \begin{cases} 
0 & F_i \leq F_d \\
\frac{F_i - F_{d}}{F_{lim} - F_d} & F_i > F_d 
\end{cases}
\]

(8)

where \(F_i\) is the active power of transmission line \(i\); \(F_{lim}\), the limit power of transmission line; and \(F_d\), the power risk threshold of line, which is generally set to 90% of \(F_{lim}\).

The severity of circuit overload in the system is expressed as follow:

\[
S(F_a) = \sum_{i=1}^{M} Sev(F_i) / M
\]

(9)

where \(S(F_a)\) is the overload severity of preconceived accident \(a\) and \(M\) is the total number of circuit in system.

3.1.3 The severity of land loss. The load loss ratio is expressed as follow:

\[
\eta = \frac{\sum_{i \in I} L_i}{L_0}
\]

(10)

where \(I\) is the loss of load node set; \(L_i\), load loss for the load loss node ; and \(L_0\), total load of the system before the accident.

Under the expected accident \(a\), the load loss severity of the system is expressed as follow:

\[
S(L_a) = \begin{cases} 
\eta & \eta < \eta_{lim} \\
1 & \eta \geq \eta_{lim}
\end{cases}
\]

(11)

where \(\eta\) is system load loss ratio of the maximum threshold, which is taken as 30% of the total load in this paper.
3.2 Comprehensive risk index

In the case of ice disaster, the expected accident is mainly considered as the exit operation of ice covered lines. The risk of system should be the sum of the product of failure probability and system severity. The comprehensive risk index \( P(a) \) is defined as follow:

\[
R = \sum_{a \in M} \left[ S(V_a) + S(F_a) + S(L_a) \right] \times P(a)
\]

(12)

4 Fractional sieve method model

The fractional sieve method is an effective method to solve the multi-objective decision problem, which is mainly used to solve the problem of the form of formula (13):

\[
\min F(x) = \left\{ f_1(x), f_2(x), \ldots, f_m(x) \right\}^T, x \in X
\]

(13)

where \( m \) is the number of objective function to be optimized; \( x \), the decision variables; and \( X \), the constraint set.

The optimal coefficient \( a_j \) is defined as the sum of the results obtained by the feasible solutions \( x^l \) and \( x^i \) for all objective functions. The expression is as follows:

\[
a_j = \sum_l a_{ij}
\]

(14)

where \( l \) is the number of objective function.

\[
a_{ij} = \begin{cases} 
1.00 & F_i(x^0) > 0.75 \\
0.75 & F_i(x^0) > 0.50 \\
0.50 & F_i(x^0) > 0.25 \\
0.25 & F_i(x^0) > 0.00 \\
0.00 & F_i(x^0) \leq 0.00 
\end{cases}
\]

(15)

where \( F_i(x^0) = \left[ f_i(x^0) - f_i(x^l) \right] \cdot \frac{1}{f_i(x^l)} \).

The sum optimal coefficient \( a_i \) is defined as the sum of optimal coefficient that \( x^l \) compared with all other feasible solutions. The expression is as follows:

\[
a_i = \sum_j a_{ij}
\]

(16)

It is assumed that the satisfactory solution set of the decision maker is \( S \), and the satisfactory solution number is \( k \), recorded as \( \Omega = \{1, 2, \ldots, k\} \). The principle of optimal coefficient is as follows:

1. Suppose \( x^l, x^i \) are the feasible solutions correspond with \( a_i, a_j \). If \( a_i > a_j \), then \( x^i > x^l \).

2. If \( a_i > a_j, j \neq i \), then \( x^i \) which is corresponding to \( a_i \) is the optimum solution of this Multi-objective decision-making problem.

5 Optimal decision-making model of de-icing plan

5.1 The objective function

In this paper, we should make the strategy of de-icing under the premise of ensuring the security of system, and consider the following two points:

1. Should try to reduce the security hazards and economic loss caused by de-icing.
2. Should make the risk of second failure in system to a minimum as far as possible during de-icing period. Therefore, this paper considers load loss and security risk of the system and makes it a multi-objective optimization problem. The objective function is as follows:

\[
\min E_{ELC} = \sum_{t=1}^{T} C_t \tag{17}
\]

where \( E_{ELC} \) is the load shedding during de-icing period; \( C_t \), the load shedding at the period \( t \); and \( T \), the number of de-icing period.

\[
\min R_{risk} = \sum_{t=1}^{T} \sum_{i=1}^{M_t} \left( [S(V_i) + S(F_i) + S(L_i)] \times P(i) \right) \tag{18}
\]

where \( R_{risk} \) is the security risk of system during de-icing period and \( M_t \) is the line set that don’t participate in de-icing work at the period \( t \).

5.2 The constraints
The constraints are as follows:

\[
\delta_i' \geq \delta_{alarm} \tag{19}
\]

where \( \delta_i' \) is the icing rate of line \( i \) at the period \( t \) and \( \delta_{alarm} \) is the warning value of icing rate.

\[
\delta_i' \geq \delta_{emer}, k_i' = 1 \tag{20}
\]

where \( \delta_{emer} \) is the emergency value of icing rate and \( k_i' \) represents the de-icing state variable of line \( i \) at the period \( t \).

\[
\sum_{i \in M_0} k_i' s_i \leq S_t \tag{21}
\]

where \( M_0 \) is the branch set of system; \( s_i \) is the resources that line \( i \) needed to melt ice; and \( S_t \) is the upper limit of resources at the period \( t \).

5.3 The process of de-icing plan
In this paper, a multi-objective optimization model is built with the objective of minimizing the load loss and maximizing the security risk of the system during the de-icing period. Using the particle swarm optimization algorithm to optimize the objective function based on the principle of the fractional sieve method. According to the optimal value of the objective function and the actual operation requirements of the system, the allowable errors of the target function are given.

Calculating the sum optimal coefficient of each element in preference solution set according to the principle of optimal coefficient. And the maximal element is the optimal de-icing plan.

6. Tests and results
This paper assumes that the ten branches shown in Table 1 will continue to be affected by varying degrees of freezing disaster in the next 24 hours. According to the weather and the line data to calculate the initial ice cover of the branches and ice coating growth rate as shown in Table 1.

| Line number | Initial ice thickness/mm | Initial icing rate | Ice covering growth rate/(mm/h) |
|-------------|--------------------------|--------------------|---------------------------------|
| 3           | 5                        | 0.5                | 0.2449                          |
| 5           | 4                        | 0.4                | 0.1094                          |
| 9           | 2                        | 0.2                | 0.1530                          |
| 12          | 1                        | 0.1                | 0.2723                          |
| 18          | 3                        | 0.3                | 0.1345                          |
| 19          | 4                        | 0.4                | 0.3128                          |
| 23          | 2                        | 0.2                | 0.2445                          |
According to this method, the optimal fitness function value of two objective functions are:
\[ f_1 = 15.58589 \text{MW}, \quad f_2 = 1.0257. \]
It is assumed that the allowable error of the optimal value is:
\[ \delta_1 = 2.5 \text{MW}, \quad \delta_2 = 3.0. \]
To expand the scope of the search to get the preference solution program, as shown in Table 2:

Table 2. Decision maker's preference solution scheme

| Scheme | Line number | \text{Period 1} | \text{Period 2} | \text{Period 3} | \text{Period 4} | \text{Period 5} | \text{Period 6} | \text{Risk} | \text{ELC} |
|--------|-------------|----------------|----------------|----------------|----------------|----------------|----------------|------------|----------|
| 1      | 3,19        | 5,18,28,32     | 9,23,41        | 12,19          | 3              | -              | -              | 17.09322   | 2.5992   |
| 2      | 5,28,41     | -              | 3,9,18,19      | 12,23,32       | 41             | -              | -              | 16.59244   | 2.2177   |
| 3      | 5,19,28,41  | 3,18           | 23,32          | 12             | 9,19           | 28             | 32,41         | 17.88785   | 1.7691   |
| 4      | 5,19,28     | 3,18           | 23,32,41       | 9,12,19        | -              | -              | -              | 16.59676   | 3.6687   |
| 5      | 28          | 5,32,41        | 3,9,18,19,23   | 12             | -              | -              | -              | 15.58589   | 3.9588   |
| 6      | 5,41        | 28,32          | 3,9,18,19,23   | 12,23,32       | -              | -              | 32,41         | 17.41415   | 2.2020   |

To normalize the data in Table 2, and calculate the optimal coefficient and the sum optimal coefficient of each scheme by fractional sieve method, as shown in Table 3:

Table 3. The optimal coefficient and sum optimal coefficient of each scheme

| Scheme | 1   | 2   | 3   | 4   | 5   | 6   | The sum optimal coefficient |
|--------|-----|-----|-----|-----|-----|-----|----------------------------|
| 1      | 0.00| 0.00| 0.75| 1.00| 1.00| 0.25| 3.00                        |
| 2      | 1.50| 0.00| 1.00| 1.25| 1.00| 1.00| 5.75                        |
| 3      | 1.00| 1.00| 0.00| 1.00| 1.00| 1.00| 5.00                        |
| 4      | 0.50| 0.00| 1.00| 0.00| 0.25| 1.00| 2.75                        |
| 5      | 1.00| 1.00| 1.00| 0.00| 1.00| 1.00| 5.00                        |
| 6      | 1.00| 0.25| 0.50| 1.00| 1.00| 0.00| 3.75                        |

The sort of the sum optimal coefficient is: \( a_2 > a_3 = a_6 > a_4 > a_1 > a_5 \), so we choose Scheme 2 as the best de-icing plan.

Set the reference scheme to melt the ice when ice thickness is over warning value. The comparison results of the reference scheme and the scheme of this paper are shown in Figure 1.

Figure 1. Comparison of scheme between reference and this paper

Obviously, in Figure 1, the load shedding index and the security risk index of this paper are better than the reference plan. The reference scheme is of great loss of load, the waste of melting ice resources, and the system security level is reduced. The scheme of this paper is on the basis of ensuring the timeliness of melting ice, considering the load loss and security risk, the arrangement of the de-icing branch in each time period is more reasonable.
7. Conclusion
The optimal scheme is obtained by fractional sieve method, which avoids the trouble of setting weight coefficient of multiple objective optimization. Besides, this paper overcomes the shortcomings of the existing de-icing plans which haven’t considered the safety of system operation.

In summary, the de-icing plan made by this paper which is based on the fractional sieve method is better than traditional scheme in both reliability and security aspects. This method has certain reference value in practical application.

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