A method for determining equipment to be maintained based on comprehensive risk assessment of power system

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Abstract. With the development of on-line monitoring and condition-based maintenance, the optimization research of condition-based maintenance scheduling is getting more and more important. A reasonable maintenance strategy can save a lot of energy and reduce costs. This paper proposes a method to determine the equipment to be maintained, which is based on the comprehensive risk assessment of power system. First we build a mathematical model of maintenance based on comprehensive risk index. Then non-sequential Monte Carlo simulation and DC power flow optimization model are used to minimize the sum of failure risks and maintenance risks. Finally, the feasibility and validity of the proposed model is analyzed on the IEEE-RTS79 system.

1. Introduction

As a new maintenance mode, condition-based maintenance has drawn an increasing attention due to its reliability and efficiency [1-2]. Researchers have proposed many maintenance optimization strategies based on condition-based maintenance in recent years, which focus on optimization of maintenance time [3] and maintenance level [4], while the determination of the equipment to be maintained is often in a default condition. The purpose of this paper is to determine the equipment to be maintained.

In the background of condition-based maintenance, the maintenance decision-making of single equipment is relatively easy, but in the process of making a maintenance plan, we have to consider not only the single performance of the equipment but also the influence on the whole power system [5]. Sometimes there would have contradiction and conflict between the single equipment and power system [6], it is very important to solve these contradictions.

This paper aims to minimize the overall cost of power systems and proposes a method for determining equipment to be maintained based on non-sequential Monte Carlo [7] simulation and DC power flow optimization. In this paper, the maintenance is divided into two levels: complete maintenance and incomplete maintenance [8]. By analyzing the importance index [9] of equipment and the failure probability of equipment, we can filter out the equipment that brings greater risk to the system and determine the maintenance level which can minimize the overall risk of the power system. In order to solve the problem of equipment maintenance decision, we start from the definition and quantitative expression of the failure risk and maintenance risk. Then, risk index of equipment, failure risk and maintenance risk is calculated based on non-sequential Monte Carlo simulation and DC power flow optimization. Finally, a comprehensive risk maintenance model is set up and case study is given to prove the practicability of this method.

2. Prediction of equipment failure rate
The prediction of equipment failure rate is mainly based on online monitoring technology. In 2008, State Grid Corporation of China enacted Test rules for condition-based maintenance of transmission and transformation equipment and draw up the standard of deduction for the status of the equipment. We use this standard as a basis to score equipment in the system. Health Index \textsuperscript{10} is used to calculate the failure rate of the equipment. The formula is as follows:

$$\lambda = Ke^{HI \cdot C}$$  \hspace{1cm} (1)

In equation (1), \(\lambda\) is the current failure rate of equipment, \(K\) is the ratio coefficient, \(HI\) is the Health Index, \(C\) is the curvature coefficient. As long as there are more than 2 years of equipment Health Index and equipment failure rate, we can use the following formulas to calculate \(K\) and \(C\)

$$P = \frac{n}{N} \times 100\% = \sum_{i=1}^{m} \frac{N_i \cdot Ke^{C \cdot HI_i}}{N} \times 100\%$$  \hspace{1cm} (2)

In equation (2), \(P\) is the annual failure probability, \(n\) is the number of failure equipment, \(N\) is the total number of equipment, \(i\) is the classification of equipment, \(m\) is the number of classifications, \(N_i\) is the number of a class of equipment, \(HI_i\) is the average value of the corresponding \(HI\) under the classification of \(i\).

3. Sequencing of equipment risk index
Risk assessment is based on risk index. Risk index is the product of probability and consequences, for the equipment in the system, it has its importance, and this importance is reflected in its impact on the system. In this paper, we use EENS (Expected Energy not Supplied) to show the consequences, and the importance degree of equipment is described by the risk index of equipment. We use non-sequential Monte Carlo Simulation to calculate this risk data, the non-sequential Monte Carlo is widely used in power system risk assessment which is also called the state sampling method.

The risk index of equipment in reliability economics can be interpreted as that the value of equipment depends on the loss caused when it is lost from the system. So the equipment with high investment amount is not necessarily more valuable than the low investment equipment in the reliability of the system. We can use a risk index which combined by fault probability and fault loss to describe this ‘value’ or this ‘influence’. The calculation steps of the equipment risk index are as follows:

STEP 0. Establishing a system risk assessment model

STEP 1. Assessing the basic risk of the system, this moment, all equipment in the system is in operation, but they may be random failure.

STEP 2. Calculating system risk index when equipment is out of operation, this moment, the rest of the equipments are still in operation but may fail at any random time.

STEP 3. Repeat STEP 2 for the equipments which need to be calculated the risk index.

STEP 4. Calculating the difference between the basic risk of the system and the system risk when an equipment is out of operation, and take the product of this difference and the probability of the equipment's out of operation as a risk index.

STEP 5. Sorting the various equipments by according to the risk index obtained in STEP 5.

4. Comprehensive risk assessment model of power system
In this assessment model, we take the sum of failure risks and maintenance risks as comprehensive risk of power system. For power system, maintenance and failure are unified and contradictory contradictions, inadequate maintenance will lead to larger failure risks, excessive maintenances will bring a waste of maintenance resources and lead to larger maintenance risks. We need to find a balance to coordinate the contradiction between maintenance and failure.

4.1 Failure risks
Power system failure risks $R_F$ can be expressed in the following equation:

\[
\begin{align*}
R_F &= R_{F1} + R_{F2} \\
R_{F1} &= \sum_{i=1}^{m} C_{Fi} \cdot P_{Fi} \\
R_{F2} &= \sum_{i=1}^{m} P_i \cdot \Delta T_F \cdot C_F \cdot P_{Fi}
\end{align*}
\]  

(3)

In the equation (3), $R_{F1}$ is the risk of the equipment after its own failure, such as the cost of maintenance or replacement. $R_{F2}$ is the loss of load risk of power system caused by equipment failure. $m$ is the number of non maintained equipment, $C_{Fi}$ is the cost of equipment $i$ maintenance or replacement, $P_{Fi}$ is the probability of equipment $i$ failure, $P_i$ is the power loss risk of power system caused by equipment $i$ failure, $\Delta T_F$ is the duration of the loss of load, $C_F$ is the cost of unit load loss.

4.2 Maintenance risks

Power system maintenance risks $R_M$ can be expressed in the following equation:

\[
\begin{align*}
R_M &= R_{M1} + R_{M2} + R_{M3} + R_{M4} \\
R_{M1} &= \sum_{j=1}^{n} C_{Mj} \\
R_{M2} &= \sum_{j=1}^{n} P_{Mj} \cdot T_{Mj} \cdot C_M \\
R_{M3} &= \sum_{j=1}^{n} P_j \cdot \Delta T_{Mj} \cdot C_F \\
R_{M4} &= \sum_{j=1}^{n} \omega \cdot R_F
\end{align*}
\]  

(4)

In the equation (4), $R_{M1}$ is the cost of equipment maintenance, $R_{M2}$ is the planned loss of load caused by equipment maintenance, $R_{M3}$ is the unplanned loss of load caused by equipment maintenance, $R_{M4}$ is the failure risk of equipment after maintenance. $n$ is the number of equipment required to be maintained, $C_{Mj}$ is the maintenance cost of equipment $j$, $P_{Mj}$ is the load loss caused by maintain equipment $j$, $T_{Mj}$ is the duration of the planned load loss caused by maintaining equipment $j$, $P_j$ is the unplanned load loss caused by maintaining equipment $j$, $\Delta T_{Mj}$ is the duration of unplanned load loss caused by maintaining equipment $j$, $\omega$ is the age reduction factor.[11]

4.3 Objective function

\[
\min \left( R_F + R_M \right)
\]  

(5)
5. DC power flow optimization model

Objective function:

\[
\min \sum_{i \in N_d} P_{d,i}
\]

\[s.t.
\]

\[
\sum_{i \in N_g} P_{g,i} + \sum_{i \in N_d} P_{d,i} = \sum_{i \in N_d} P_{c,i}
\]

\[
T = A \left( P_g - P_c + P_d \right)
\]

\[
-T_{\max} \leq T \leq T_{\max}
\]

\[
P_{g,\min} \leq P_g \leq P_{g,\max}
\]

\[
0 \leq P_d \leq P_c
\]

\[P_g, P_c \text{ and } P_d \text{ are generator active output, node load and load loss vector, respectively. } N_g, N_d \text{ correspond to generator sets and load sets, respectively. } T, T_{\max} \text{ are the active power transmission and the maximum allowable active power transmission of the transmission equipment, respectively. } A \text{ is the correlation matrix between transmission equipment’s active power and active power of node. } P_{g,\max}, P_{g,\min} \text{ is the upper and lower limit vectors of active power output of generators.}
\]

We can use this DC power flow optimization model to calculate EENS. So as to calculate power system failure risks and maintenance risks.

6. Case study

In this paper, we choose the IEEE-RTS79 test system, there are 33 lines and 5 transformers in the system. The performance indicators and other detailed data of equipment can be seen in document [12]. In this case, the maintenance grade is divided into two categories: complete and incomplete. Set 20000 times of the non-sequential Monte Carlo simulation. We specify that the failure and maintenance data are as follows:

Table 1. Failure and maintenance data of line and transformer

| category                  | Failure cost | Maintenance cost | Time for maintenance | \(\omega\) |
|---------------------------|--------------|------------------|----------------------|-----------|
| Transformer               | 80000000 ¥   |                  |                      |           |
| Line                      | 70000 ¥ / km |                  |                      |           |
| Transformer complete      | 5000000 ¥    | 36 h             | 0.2                  |           |
| maintenance               |              |                  |                      |           |
| Transformer incomplete    | 250000 ¥     | 18 h             | 0.5                  |           |
| maintenance               |              |                  |                      |           |
| Line complete             | 5000 ¥ / km  | 36 h             | 0.2                  |           |
| maintenance               |              |                  |                      |           |
| Line incomplete           | 2500 ¥ / km  | 18 h             | 0.5                  |           |
| maintenance               |              |                  |                      |           |

At first, we use non-sequential Monte Carlo simulation and DC power flow optimization model to calculate the risk index of 33 lines and 5 transformers, then, select the first 15 of them and sort out. These 15 equipment is listed as a set of equipment to be maintained, detailed data in Table 2.

Table 2. Sequencing of equipment risk index

| index (MW) | Equipment index |
|------------|-----------------|
| 1.99465    | 11              |
| 1.61666    | 23              |
| 1.24023    | 7               |
| 1.23356    | 5               |
Next, we shall separately evaluate the failure risk and maintenance risk of these 15 equipments. Because the probability of equipment out of operation is random, we simulate the risk of failure under the state of maximum load model. The actual maintenance generally chooses low load state, therefore, we use the average load state (81.86%) when carrying out maintenance risk assessment. This approximation does not affect the final result.

| Equipment index | Complete maintenance cost (Million Yuan) | Incomplete maintenance cost (Million Yuan) | Non maintenance loss (Million Yuan) | Equipment index |
|-----------------|------------------------------------------|-------------------------------------------|------------------------------------|----------------|
| 11              | 83.1677                                  | 91.9740                                   | 125.833                            | 11             |
| 23              | 92.7496                                  | 67.5553                                   | 72.9513                            | 23             |
| 17              | 34.2517                                  | 38.6984                                   | 53.9313                            | 7              |
| 15              | 122.853                                  | 86.5903                                   | 62.9091                            | 5              |
| 19              | 86.3621                                  | 91.8848                                   | 121.759                            | 17             |
| 10              | 59.2174                                  | 47.8301                                   | 45.5535                            | 10             |
| 18              | 89.2204                                  | 61.0509                                   | 41.1018                            | 19             |
| 5              | 79.9212                                  | 86.5611                                   | 116.501                            | 16             |
| 16              | 45.9057                                  | 41.6367                                   | 46.7096                            | 27             |
| 19              | 82.9065                                  | 87.4451                                   | 114.979                            | 15             |
| 8              | 73.0401                                  | 67.1392                                   | 76.5478                            | 21             |
| 14              | 40.9513                                  | 35.1653                                   | 36.7241                            | 18             |
| 29              | 22.8691                                  | 19.9270                                   | 21.2311                            | 29             |
| 8              | 48.1346                                  | 35.6326                                   | 28.9133                            | 8              |
| 14             | 16.6944                                  | 15.8154                                   | 18.6706                            | 14             |

From Table 3 we can know the equipment that required complete maintenance is 11, 7, 17, 16, 15; the equipment that required incomplete maintenance is 23, 27, 21, 18, 29, 14; the equipment that does not required maintenance is 5, 10, 19, 8. This is a relatively reasonable maintenance plan based on comprehensive risk of power system.

7. Conclusion
In order to find a reasonable maintenance strategy to save energy and cost, the power system failure risk and maintenance risk is defined in this paper. Then we use non-sequential Monte Carlo simulation and DC power flow optimization model to simulate the operation of the system. In the case study, we calculate the risk index of equipment, the failure risk, the maintenance risk and give a set of reasonable maintenance plan. But one of the disadvantages of this method is that it is conservative, because we use the maximum load model when evaluating the risk of failure, and we use the average load model when making maintenance risk assessment. This problem will lead to a pessimistic result of the calculation. We could consider time load information to solve this problem, but it will take a long time to calculate. So using an intelligent algorithm may be a good choice. In summary, this
method could help maintainer to determine the set of equipment to be maintained and lay the foundation for further optimization of maintenance decision.

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