Research on Probability Model of Non-independent Fault of Nuclear Power Units Based on Power Grid Operating Parameters

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Abstract. Nuclear power plants have the characteristics of high safety and reliability requirements, unlike the conventional thermal power plants adopting an independent fault probability model, the probability of its fault is closely related to the operation status of the power grid. To solve this problem, a non-independent fault probability model of nuclear power plants considering power grid operation parameters is proposed in this paper. This research firstly simulates N-1 fault scenarios of each power component in the grid, then the influences of the fault scenarios on the voltage and frequency of nuclear power plants access point are simulated through the power system analysis software tools (PSD-BPA), the possibility of its outage is determined according to the corresponding protection thresholds of nuclear power plants, and then the occurrence probabilities of these fault scenarios are taken into account, finally the non-independent fault probability of nuclear power plants which is relevant with power grid operation parameters will be obtained. The model lays the foundation for the evaluation of the operational reliability and risk of power grid with nuclear power plants accessed to.

1. Introduction

With the rapid growth of power demand, the large-scale renewable energy is accessed and the global energy internet is constructed, the scale of China's power grid is expanding, so the safe and reliable operation of power system is becoming increasingly prominent. How to evaluate the reliability and risk of power system quickly and accurately is a difficult problem that power systems all over the world need to solve urgently.

The power equipment failure or outage is the fundamental cause of power system failure. The probability of equipment failure depends on its own health level, external environmental conditions and system operation status. Establishing the probability model of equipment failure is the core issue of system reliability and risk assessment[1].

In recent decades, there have been abundant related studies on the failure probability model of power equipment. The traditional equipment failure probability model is mainly used in routine reliability analysis such as power grid planning and maintenance. It mainly reflects the long-term stability of equipment operation, ignoring the impact of short-term operating conditions on the failure probability. In traditional reliability evaluation, the failure probability of equipment is generally taken as the average value of long-term statistics, which has some problems such as low reliability and application lag[2-6].
Generator is the core equipment in power system. Its failure or outage state will affect the safe and stable operation of power grid. It is of great significance to study the fault probability model of generator. In traditional research, some of the measures of unit failure probability under operating conditions are expressed directly by Forced Outage Rate (FOR)[7], and others are described by Outage Replacement Rate (ORR)[8]. In order to simplify the calculation, several sets of generator stochastic outage events and their probability of state occurrence are specified[9].

Nuclear power unit has the characteristics of large capacity and high safety requirement, and its failure or outage easily has a significant impact on the power grid[10]. At present, there are few studies on the calculation and calculation of failure probability of nuclear power units. The conventional method is to treat nuclear power units as traditional thermal power units. However, nuclear power units are very sensitive to power grid disturbances. In traditional reliability analysis, independent failure probability models are usually used for generating units, without considering the impact of the frequency and voltage fluctuation of the access points of nuclear power units on the failure probability of generating units. Therefore, the traditional failure probability models of generating units can not reasonably characterize the characteristics of nuclear power units.

In order to solve this problem, a non-independent failure probability model of nuclear power unit considering the operation parameters of power grid is proposed. After obtaining the fault probability parameters of the equipment in power grid, the N-1 fault scenarios of each equipment are simulated in turn. The impact of the fault scenario on the voltage and frequency of the access point of nuclear power unit is simulated by PSD-BPA, and according to the operation threshold of voltage and frequency protection, it estimates the possibility of outage, takes into account all external faults of nuclear power units and their occurrence probability, and then obtains the probability of non-independent faults associated with the operation parameters of the power grid. The model effectively considers the operation and protection characteristics of nuclear power units, and lays a foundation for the operation reliability and risk assessment of nuclear power network.

2. Classical Failure Probability Model

The classical equipment reliability model is shown in Figure 1. The equipment in the running state enters the outage state due to go wrong (the planned outage state of the equipment is not considered here), and the outage state equipment returns to the running state after repairing.

Figure 1. State space graph of repairable component

\[ \lambda \] is the failure rate (number of failures per year), \( \mu \) is the repair rate (number of repairs per year), they are defined as:

\[
\lambda = \frac{\text{Number of failures in operation time}}{\text{Operation time}} \quad (1)
\]

\[
\mu = \frac{\text{Number of repairs during outage}}{\text{Outage time of equipment}} \quad (2)
\]

The model does not consider the influence of external environment and operating conditions.

Given the failure rate and repair rate of the equipment, the failure probability of the equipment can be evaluated. Conceptually, Poisson distribution with constant failure rate parameters can be used to simulate the probability of failure occurrence.

According to Poisson distribution formula, the probability of equipment failure within a given time \( t \) is in the form:

\[
P_o = 1 - P_{mo} = 1 - \frac{e^{-\lambda t} (\lambda t)^0}{0!} = 1 - e^{-\lambda t}
\]

(3)
Where $P_0$ is probability of equipment failure, $P_{n0}$ is probability of no failure, $\lambda_0$ is average failure rate, $t$ is time interval.

For the equipment in operation state, considering its failure probability in a short time (several hours), the condition $\lambda_0 t \ll 1$ is satisfied, then the formula (3) can be approximately expressed as:

$$P_0 = \lambda_0 t$$

(4)

Because the duration of the fault is usually short, the average failure rate can be approximated by the average failure frequency. And then the average fault frequency can be obtained from historical data.

The fault probability obtained by formula (3) and (4) is related to the time interval considered, and is a time-varying fault probability model. However, in traditional reliability analysis, a constant probability value is usually used to represent the probability of equipment failure at any time. The value can be obtained from the average value of historical failure data after long-term statistics.

3. Characteristics and Model Analysis of Nuclear Power Units

Nuclear power units have the characteristics of large single-unit capacity, high requirements for nuclear safety, sensitive nuclear island to power grid disturbance, and long shutdown and fuel change time. Nuclear power units will have a more serious impact on each other after they are connected to the power grid. Nuclear power units have different characteristics from conventional generators. It takes longer time for nuclear power units to restore operation than general power plants. Therefore, the frequency of failure should be reduced to the greatest extent. Voltage and frequency are the main parameters of power grid affecting nuclear power units. The particularity of large-capacity nuclear power units also requires high voltage and frequency of the whole power grid.

Faults or disturbances in the power grid will cause fluctuations in the frequency and voltage of the access points of nuclear power units, which will have an impact on the safe and stable operation of nuclear power units. When the fluctuations exceed the allowable range, they may cause the shutdown or emergency shutdown of nuclear power units and further deteriorate the power grid fault.

3.1 Characteristics of Nuclear Power Unit Protection

Nuclear power units must operate in a certain range of voltage and frequency. If they exceed the range, the protection measures in nuclear power plants will start automatically, which will lead to the separation of the power grid and nuclear power units, and make the power grid lose important power sources and suffer greater impact.

By simulating the influence of voltage and frequency disturbance on nuclear power unit under power grid fault, the response characteristics of nuclear power unit are analyzed, and the frequency and voltage disturbance tolerance threshold which can ensure the safe and stable operation of nuclear power unit are obtained. Based on the actual operation standards and experience of nuclear power plants, the standard requirements of partial frequency, voltage allowable range and duration of nuclear power units when connected to power grid are shown in Table 1.

| Frequency/Hz | Duration/s | Terminal voltage/p.u. | Duration/s |
|--------------|------------|------------------------|------------|
| Above 53.5   | 0.1        | Above 1.25             | 0.5        |
| 51.0–52.0    | 5          | 0.8–1.05               | Normal operation |
| 49.5–50.5    | Normal operation | 0.7–0.75             | 0.8        |
| 47.0–47.5    | 6          | Below 0.7              | 0.3        |
| Below 47.0   | 0.5        |                        |            |

It can be seen that when the frequency range of access point is 49.5–50.5Hz and the voltage range is 0.8–1.05p.u., the nuclear power unit can operate normally. When the frequency of access point is
higher than 53.5 Hz or lower than 47.0 Hz and the terminal voltage is higher than 1.25 p.u. or lower than 0.7 p.u., the frequency or voltage protection of nuclear power units should be operated quickly to separate the units from the power grid to prevent serious accidents in nuclear power plants.

3.2 Fault State Model of Nuclear Power Units Associated with Power Grid Operating Parameters

When the voltage and frequency of the access point of the nuclear power unit increase or decrease to the protection fixed value, the protection device of the nuclear power unit operates, and the action time limit of the protection decreases with the deepening of the frequency and voltage exceeding limit, and the probability of the nuclear power unit’s shutdown is increased. In order to facilitate research and analysis, the following assumptions and simplifications are made in this paper:

1) When the frequency of the nuclear power unit is within the normal range, the failure probability of the nuclear power unit is taken as its reference value, as shown in equation (5). The reference value represents the average failure probability of nuclear power units, which is mainly reflected in the failure caused by the aging of units and other factors. It can be given by the long-term operation experience and statistical data of nuclear power plants at home and abroad.

\[ P(F_{normal}) = P_{ref} \quad (F_{NG, min} \leq F_{NG} \leq F_{NG, max}) \]  

Where \( F_{NG} \) is the frequency of the nuclear power unit, \( F_{normal}^{NG, min} \) is the lower limit of normal frequency value for nuclear power units, and \( F_{normal}^{NG, max} \) is the upper limit of normal frequency value for nuclear power units.

2) When the frequency of the nuclear power unit exceeds the allowable limit value, the frequency protection action causes the nuclear power unit to shut down, and its failure probability is 1, as shown in equation (6):

\[
\begin{align*}
P(F_{NG}) &= 1 \quad \left( F_{NG} \geq F_{NG, max} \right) \\
P(F_{NG}) &= 1 \quad \left( F_{NG} \leq F_{NG, min} \right)
\end{align*}
\]  

Where \( F_{NG, max} \) is the upper limit of allowable frequencies for nuclear power units, and \( F_{NG, min} \) is the lower limit of allowable frequencies for nuclear power units.

3) When the frequency of the nuclear power unit is between the normal value and the limit value, the probability of the protection device operation increases with the increase of the frequency exceeding limit. Here, the line fitting method is used to fit the failure probability of the nuclear power unit, as shown in equation (7):

\[
P(F_{NG}) = \left( 1 - P_{ref} \right) \times F_{NG} + P_{ref} \times F_{NG, max} - F_{NG, max} \times F_{NG, max} \
\quad \left( F_{NG, min} < F_{NG} < F_{NG, max} \right)
\]  

Similarly, the relationship between the random terminal voltage variation and the failure probability of nuclear power units can be obtained, as shown in equation (8) – (10):

\[
P(U_{NG}) = P_{ref} \quad \left( U_{normal}^{NG, min} \leq U_{NG} \leq U_{NG, normal} \right)
\]

\[
P(U_{NG}) = 1 \quad \left( U_{NG} \geq U_{NG, max} \right)
\]

\[
P(U_{NG}) = 1 \quad \left( U_{NG} \leq U_{NG, min} \right)
\]
(10)
\[
P(U_{NG}) = \begin{cases} 
(1 - P_{ng}) \times U_{NG} \times U_{NG,\text{max}} - U_{NG,\text{normal}} \times U_{NG,\text{max}} \\
\frac{P_{ng} \times U_{NG,\text{max}} - U_{NG,\text{normal}} \times U_{NG,\text{max}}}{U_{NG,\text{normal}} < U_{NG} < U_{NG,\text{max}}} 
\end{cases}
\]

(11)
\[
P(F_{NG}, U_{NG}) = \max \{ P(F_{NG}), P(U_{NG}) \}
\]

4. Non-independent failure probability calculation process for nuclear power unit

In order to obtain the non-independent failure probability of nuclear power units, all external faults leading to the disaggregation of nuclear power units must be obtained by accident simulation method. Assuming that there are M devices in the power grid except for nuclear power units, the probability of each device failure (simple single failure) is \( P(A_i) \), \( i = 1, \ldots, M \).

On this basis, the non-independent failure probability of nuclear power unit can be calculated according to the following procedure.

(1) Firstly we should confirm the failure probability of all equipment except nuclear power units in power grid, that is \( P(A_i) \). These probabilistic values can generally be given by historical statistical data of long-term operation of equipment.

(2) The initial power flow of the power grid is calculated, and the normal operation status of the nuclear power unit is judged according to the voltage and frequency of the access point.

(3) N-1 fault scenario simulation of equipment in power grid is carried out successively by PSD-BPA. In the process of fault simulation, the principle that the electrical distance between the simulated equipment and the nuclear power unit is from near to far is adopted, that is, the N-1 fault of the equipment near the nuclear power unit is simulated first. The types of failures that can be set include:

1) "N-1" Fault of Nuclear Power Output Line.
2) "N-1" Fault of Power Transmission Line.
3) Excision of a large capacity generating set.
4) Three-phase Short Circuit Fault of Transmission Line and Bus.
5) Transformer Fault and Outage.

(4) The fault simulation of the i equipment in the power grid is carried out to check the voltage and frequency level of the access point of the nuclear power unit after the fault. The failure probability of the nuclear power unit in this fault scenario is obtained by combining the formula (5)~ (11), that is \( P_i(F_{NG}, U_{NG}) \).

(5) The product of the probability \( P(A_i) \) of the failure and the probability \( P_i(F_{NG}, U_{NG}) \) of the failure of the nuclear power unit is obtained. The probabilistic product of all N-1 fault scenarios is summed, and the influence of the aging of nuclear power units and other factors on the probability of
failure is superimposed to obtain the non-independent failure probability of nuclear power units taking into account the operation parameters of power grid.

\[ P = \sum_{i=1}^{M} \left[ P(A_i) \cdot P(F_{NG}, U_{NG}) \right] + P_{ng} \]  

(12)

The process of calculating the non-independent failure probability of nuclear power units associated with grid operation parameters is shown in Figure 2.

After completing the simulation of N-1 fault scenario, the relationship between the failure probability of nuclear power unit and the failure of power grid equipment is analyzed, and the set of external equipment failures that can cause the outage or failure of nuclear power unit is found. In this way, the power grid can take corresponding preventive measures to improve the operation safety level of nuclear power units.

Because the probability of simultaneous faults of multiple devices in the power grid is very low, this study only analyses the N-1 fault scenarios of devices in the power grid, without considering the N-2, N-3 and above fault scenarios.

5. Conclusion

In view of the fact that nuclear power units are sensitive to power grid disturbances and the probability of failure is closely related to the operation status of the power grid, a non-independent failure probability model of nuclear power units considering the operation parameters of the power grid is proposed in this paper. Firstly, the classical failure probability model is given, and then the characteristics of nuclear power unit protection are explained, and the failure probability model of nuclear power unit is analyzed scientifically. Then, using PSD-BPA to simulate N-1 faults, the variation of voltage and frequency at the access point of nuclear power is analyzed, and the probability of failure of power grid equipment and the probability of failure of nuclear power unit are considered comprehensively, and the probability of non-independent failure of nuclear power unit taking into account the operation parameters of power grid is obtained. The model effectively considers the characteristics of nuclear power units, and lays a foundation for operational reliability and risk assessment of nuclear power network.
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