Reliability assessment of offshore oil platform power system based on state enumeration method

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Abstract. Based on the state enumeration method, a reliability evaluation method for offshore platform power system is proposed in this paper. Firstly, the reliability model of land-based components and the modelling method of the system are introduced. In reliability evaluation, all fault states are generated based on state enumeration method, power supply circuit sets are identified based on depth-first algorithm. The effects and losses of multiple faults are calculated based on platform maintenance capability, and fault time and load-loss time are separated and counted. Finally, taking an offshore oil platform as an example, the outage table of the system is generated, and the reliability index of the system is obtained, which verifies the effectiveness and accuracy of the method proposed in this paper.

1. Introduction
Reliability refers to the ability of a component, a device, or a system to perform its prescribed functions in predetermined time and under specified conditions [1]. The reliability of power system is the application of the reliability principle in the power system. The purpose is to obtain the probability of the power system's ability to provide power to the user without interruption [2].

Offshore platform power system, also known as offshore electrical system (OES), refers to the power system designed specifically for offshore engineering, which can meet the special marine environment and is not powered by onshore power supply [3]. It is mainly composed of three parts: power supply, distribution network and load [4], [5]. They are connected in a certain way to form a complete power system which includes generation [6], transmission [7], [8], distribution [9] and used system.

At present, the reliability research of offshore platform power system is relatively scarce. It is necessary for the development of offshore power system to study the reliability of offshore platform power system, which is of great significance to the implementation of China's strategy of ocean power and the safe and stable operation of ocean engineering [10].

To solve the above problems, a method based on state enumeration method is proposed to evaluate the reliability of offshore oil platform power system. Firstly, according to the characteristics of the electrical components at sea, the reliability model of the components on land is introduced. In the state selection, the state enumeration method is used to enumerate all possible fault states. Before state assessment, all the circuit sets of components are identified based on depth-first algorithm. In the condition assessment, according to the actual platform's saturation maintenance capability, the influence and loss of the distribution network under multiple conditions are calculated, and the fault time and load curtailment time are separately counted to facilitate the planning personnel to compare and optimize different structures. Finally, taking an offshore oil platform of a company as an example,
the outage table of the platform is generated, and the reliability indexes are obtained, which verifies the validity and accuracy of the proposed method.

2. Component and system modelling

2.1. Component model

The offshore oil platform power system is mainly composed of power generation equipment, distribution network and load. The main equipment includes generator, transformer set, distribution line, circuit breaker and various loads. The gas turbine is often used in the generator group, and the system has at least one standby to ensure that the standby generator can be used for continuous power supply under some fault conditions. The transformer is a dry type transformer. Distribution lines are all cables not exceeding tens of meters. The main loads include various medium-voltage or low-voltage motors, electric heating systems, lighting systems, etc. They are connected to medium-voltage buses and 400V distribution panels according to load size and voltage level. The above components are basically closed devices, and the factors leading to failure are basically the same as those on land power grids. Therefore, the reliability models and parameters of land models are also applicable to offshore power systems. Therefore, transformers, circuit breakers, generators and buses use the three-state model, which corresponds to the normal, maintenance and fault repair state on land. The cable length inside the platform is too short, so the cable components are ignored. For the reliability parameters of each component, the generator can be summed up according to the fault log and maintenance plan, and the reliability parameters of the other components can be used based on the reliability parameters of the corresponding components of the land distribution network.

2.2. System model

The power system structure of the offshore oil platform is different from that of the onshore distribution network. Its main electrical wiring has a large number of outgoing lines. Some outgoing lines directly supply power to the medium-voltage load, while the others supply power to low-voltage distribution equipment through transformers. For such a system, the traditional bus-branch model is not applicable, and the main disadvantage is to ignore the influence of circuit breaker and bus, so the reliability of the system cannot be accurately calculated. The node-component model is used in this paper. Section 1.1 establishes the reliability model of each component according to the actual electrical topological relationship. Circuit breakers, transformers and submarine cables are considered as branch components, while buses, generators, load points and virtual nodes are considered as node components. The two ends of the branch element must be connected with the node element. When all components are connected according to the above requirements, the whole system is modelled.

3. Reliability evaluation based on state enumeration method

3.1. Evaluation process

The evaluation process figure is shown in the figure 1. The reliability evaluation process of this paper is as follows:

1) All road sets are obtained by using depth-first algorithm;
2) The state enumeration method is used in the state selection to obtain the desired state and corresponding probability.
3) Determine the impact and loss of the fault according to the current state $s$ and the system road set.
4) Record the probability of state $s$, failure time, load curtailment time, $EENS$ and other information to the outage table;
5) $s = s + 1$, judging whether all states are computed, if so, turn 6), if not, turn 2);
6) Calculate the overall index of offshore platform according to the outage table.
3.2. State enumeration method

The state enumeration method [11], also known as the Boolean truth table method, is the most intuitive method for calculating system reliability. The Principle of State Enumeration Method can be seen in equation (1).

\[
(P_i + Q_i)(P_2 + Q_2) \cdots (P_N + Q_N)
\]

where, \(P_i\) and \(Q_i\) are the probability of the component \(i\) working and failing respectively; \(N\) is the number of components in the system.

The state probability of the system is given by equation (2).

\[
P(s) = \prod_{i=1}^{N_f} Q_i \prod_{i=1}^{N-N_f} P_i
\]

where, \(N_f\) and \(N - N_f\) are the number of failed and non-failed components in state \(s\), respectively.

In normal condition, when all components are in operation, \(N_f = 0\), the equation (2) can become equation (3).

\[
P(s) = \prod_{i=1}^{N} P_i
\]
All enumerated system states are mutually exclusive, so the cumulative failure probability of the system, which is shown in equation (4), is the direct sum of all failure state probabilities.

\[ P_f = \sum_{s \in G} P(s) \]  

(4)

where, \( G \) is a set of all failure states.

Any other reliability index functions corresponding to each system failure state, such as load reduction \( C(s) \), can be obtained by state assessment, and then the mathematical expectations of the index functions for all system failure states are given by equation (5).

\[ E(C) = \sum_{s \in G} C(s)P(s) \]  

(5)

Compared with Monte Carlo method, state enumeration method is more effective for systems with fewer components and lower failure probability.

This paper uses state enumeration method to get the outage table. Firstly, enumerate all possible states of all components, then analyse the state of the system, and calculate the output power and various losses in the state, combined with the same impact of the fault, and finally get the simplified shutdown table. The reliability index of the system is obtained according to the outage table.

3.3. Depth-first algorithm for power supply circuit set

There is a transfer of part of the load of offshore platform power grid. In practice, there are more than one feasible power supply path, so the traditional minimum path method is not complete. Considering the above situation, this paper uses depth-first algorithm to search all feasible path sets.

The topological structure formed by 2.2-section system modelling is transformed into an association matrix, and the information of components is stored in the form of branches. Then the correlation matrix is input into the depth-first algorithm.

After calculating the circuit set of each component, the remaining circuit set after component failure is determined. Suppose \( L \) is the main connection set.

When the components \( i \) fail or overhaul, the remaining roads in the distribution network are set up.

\[ X = L \cap R(i) = R(i) \]  

(6)

According to the \( X \) at this time, the unreachable nodes are determined, and the influence range of the fault is obtained.

3.4. Multiple fault

There may be multiple faults in state \( s \). The traditional reliability evaluation directly multiplies the maximum fault time by the maximum fault loss load, so the \( EENS \) obtained is too large. Moreover, when there is a part of the load that can be transferred under fault conditions, the fault time is not necessarily equal to the load curtailment time. Therefore, this paper simulates the process of system recovery from multiple faults to normal, and improves the accuracy of reliability evaluation.

Consider that the state \( s \) is the most serious fault condition, which is \( N \)-fault occurs simultaneously. In practice, production workers and maintenance personnel are on duty on offshore platforms. Even if multiple faults occur at the same time, they can be repaired at the same time. Therefore, it is considered that the process of repairing \( N \)-fault should be carried out at the same time.

The simulation process of \( N \)-fault is as follows:

1) When multiple faults occur in the system, the fault is assumed to be \( N \)-fault and the initial time \( t = 0 \);
2) Set the time of fault duration \( time \), and calculate it as follows:

\[ time = \min(time_1, \ldots, time_N) \]  

(7)

where, \( time_i \) denotes the outage time of component \( i \).
If \( \text{time} \) is empty set, then turn 5); otherwise, turn 3);  
3) Check whether the system is load- curtailment in case of failure, record the load curtailment amount as \( EDNS \) and calculate \( EENS \): 

\[
EENS = EDNS \times (\text{time} - t)
\]  

4) Record \( t = \text{time} \). And if \( \text{time}_i = \text{time} \), then \( \text{time}_i = 0 \), delete failure of component \( i \) and turn 2);  
5) The system restores to its normal state and the simulation process ends. 

3.5. Index calculation 

In this paper, the loss and time in each state of the system are directly obtained and recorded in the outage table, which is similar to the outage table of generation system reliability evaluation. The form of outage table is shown in table 1.

| \( s \) | \( P(s) \) | \( EDNS_s \) | \( EENS_s \) | \( EFT_s \) | \( ETLC_s \) |
|-------|---------|-------------|-------------|--------|---------|

where \( P(s), EFT_s, ETLC_s, EDNS_s, EENS_s \),which represent the parameters in state \( s \), can be obtained in the status assessment. The definitions of these parameters can be found in the next paragraph. 

In the calculation of index, the reliability indicators of the system, including Probability of system Failure \( P_f \), probability of system load curtailments \( P_{LC} \), probability of system normal \( P_N \), expected time of load curtailments \( ET \), expected fault time \( EFT \), expected demand not supplied \( EDNS \), expected energy not supplied \( EENS \). These index are obtained directly by using the information contained in the outage table. The calculation methods of the indicators are as follows:

\[
P_{LC} = \sum_{i \in \text{C}} P_i
\]

\[
P_N = 1 - P_f
\]

\[
ETLC = \sum_{s=1}^{s_{\text{max}}} ETLC_s \times P(s)
\]

\[
EFT = \sum_{s=1}^{s_{\text{max}}} EFT_s \times P(s)
\]

\[
EDNS = \sum_{s=1}^{s_{\text{max}}} EDNS_s \times P(s)
\]

\[
EENS = \sum_{s=1}^{s_{\text{max}}} EENS_s \times P(s)
\]

where \( \text{C} \) is a set of all failure states include load curtailments; \( s_{\text{max}} \) is a the number of state.

4. Example analysis 

Taking an offshore oil platform as an example, the main electrical wiring of the platform is shown in figure 2. There are two generators in the platform, One in normal use and one in reserve. The main equipment is shown in the table 2.

Table 1. Outage table.
Table 2. Equipment list.

| Device name                  | Number | Power or load per unit |
|------------------------------|--------|------------------------|
| Turbine generator            | 2      | 5.947MW                |
| Gas compressor               | 3      | 0.22MW                 |
| Associated gas compressor    | 4      | 0.415MW                |

All load information has been labelled in the figure 2.

![Figure 2. Main electrical wiring diagram of an offshore oil platform.](image)

The system outage table is shown in table 3.

Table 3. System outage table.

| s   | P(s)     | EDNS<sub>s</sub> | EENS<sub>s</sub> | EFT<sub>s</sub> | ETLC<sub>s</sub> |
|-----|----------|------------------|------------------|-----------------|------------------|
| 1   | 0.819508255 | 0                | 0                | 0               | 0                |
| 2   | 0.046926294  | 0                | 0                | 24              | 0                |
| 3   | 0.030955239  | 0                | 0                | 48              | 0                |
| 4   | 0.030519582  | 0                | 0                | 120             | 0                |
| 5   | 0.02167196   | 4.875            | 117              | 24              | 24               |
| 6   | 0.006087754  | 0                | 0                | 15              | 0                |
| 7   | 0.005855351  | 0                | 0                | 72              | 0                |
| 8   | 0.005103631  | 4.875            | 351              | 72              | 72               |
| 9   | 0.003063345  | 0.415            | 19.64            | 24              | 24               |
| 10  | 0.003063345  | 0.415            | 25.8             | 24              | 24               |
| 11  | 0.003063257  | 0.415            | 17.22            | 24              | 24               |
| 12  | 0.003063257  | 0.415            | 21.84            | 24              | 24               |
| 13  | 0.002042223  | 0.22             | 14.96            | 24              | 24               |
| 14  | 0.002042223  | 0.22             | 21.12            | 24              | 24               |
| 15  | 0.002042171  | 0.22             | 12.54            | 24              | 24               |
| 16  | 0.002042171  | 0.22             | 17.16            | 24              | 24               |
The system reliability index is shown in table 4.

| Index | $P_N$ | $P_f$ | $P_{LC}$ | $EFT$ | $ETLC$ | $EDNS$ | $EENS$ |
|-------|-------|-------|----------|-------|--------|--------|-------|
| 17    | 0.001988194 | 0.22 | 5.28 | 24 | 24 |
| 18    | 0.000802153 | 4.875 | 117 | 144 | 24 |
| 19    | 0.000797904 | 4.875 | 117 | 72 | 24 |
| 20    | 0.000781993 | 0 | 0 | 144 | 0 |
| 21    | 0.000682257 | 4.875 | 117 | 48 | 24 |

5. Conclusions

Based on the state enumeration method, this paper presents a reliability evaluation method for offshore oil platform power system, and obtains the system outage table and system reliability index. The proposed method is not only applicable to offshore platforms, but also to independent small power grids with the same characteristics. It has certain practical significance.

6. References

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Acknowledgments

This work is supported by The National Key Research and Development Program of China (2018YFB0904800). The author sincerely thanks the anonymous reviewers and editors for their suggestions on improving the quality of the paper.