Reliability Analysis of Flexible Multiple State Switch Based on Bayesian Network Method

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Abstract. In order to accurately establish the reliability model of flexible multiple state(FMSS) switch and excavate the weaknesses of component reliability, a method of reliability modeling of FMSS based on Bayesian network is proposed in this paper. Firstly, a multi-state reliability model is established by Markov process. Then, the Bayesian network of MMC is established. The correctness of the model is verified by examples. The reliability of SM, MMC and FMSS is calculated. The influence of submodule redundancy on FMSS is analyzed. The weak link of FMSS is analyzed. The research results in this paper can provide support for the application of FMSS in distribution network.

1 Introduction

Flexible multi-state switch(FMSS) is a new device based on power electronic technology, which can replace the traditional tie switch. The device is regarded as the key equipment to improve the flexibility and reliability of system. However, due to the immature development of power electronic devices, the reliability of distribution network may be affected by the reliability of the electronic devices. It is of great significance to study and evaluate the reliability of FMSS[1].

In the traditional power system reliability study, two-state model is adopted in component reliability[2]. However, FMSS has multi states in the actual operation due to its topology and operation control mode. Thus, multi-state reliability model is more practical. There are a number of methods for analyzing the reliability of the system such as reliability block diagram[3], fault tree analysis[4] and Markov process model[5]. With the increase of system complexity, these methods is usually limited to some extent. In recent years, Bayesian networks (BN) has been successfully applied in fields of fault diagnoses and data mining. It can be used to evaluate the reliability of the network and the weak link of the components.

This paper proposed a reliability analysis method of three-terminal FMSS based on BN technology. Firstly, the structure of FMSS and MMC are analyzed. FMSS is divided into several subsystems. Then, the reliability model of FMSS is established. Next, the multi-layer Bayesian network model is established based on MMC bridge arm and submodule(SM). Finally, the Bayesian network of each layer is integrated and the reliability
index of the FMSS is calculated. The research realizes the calculation of FMSS reliability and the identification of weak links of FMSS. The results can provide reference data for the reliability calculation of distribution network.

2 The structure and operation of FMSS and MMC

2.1 The structure of FMSS and MMC

The topology of FMSS in distribution network is shown in Fig. 1. The FMSS includes three MMCs, which are connected in parallel via DC link, and the AC sides of these three MMCs are respectively connected to three different feeders.

![Figure 1. The topology of FMSS in distribution network.](image1)

The physical structure of MMC is shown in Fig. 2. Each bridge arm in MMC is composed of n submodules (SM) and a reactor in series. The structure of SM is shown as Fig.3. The SM consists of two IGBT modules, a capacitor (C), a thyristor (thy), a bypass switch (SW) and a SM controller (SMC).
2.3 The control system of FMSS

The reliable operation of FMSS is closely related to valve control equipment and hierarchical control and protection (C&P) system, which consists of four levels. The highest level is the device level control and protection system (DLCAPS), which is designed for the entire device. A third-level C&P system is designed for MMC, which includes converter-level C&P system, valve base controller (VBC) and submodule controller (SMC). In addition to the DLCAPS, the analysis of MMC reliability should also consider the fault of valve cooling system.

3 The reliability model of FMSS

FMSS includes three MMCs and a DLCAPS. Each of the subsystem can be normal or failure, so the FMSS has a total of 16 operating states. Among the 16 states, through state merging, considering four operation modes of FMSS, an eight-state model of FMSS can be obtained, as shown in Tab.1.

| States                  | MMC1 | MMC2 | MMC3 | DLCAPS |
|-------------------------|------|------|------|--------|
| Normal operation        | N    | N    | N    | N      |
| Two-terminals operation | F    | N    | N    | N      |
|                         | N    | F    | N    | N      |
|                         | N    | N    | F    | N      |
| STATCOM mode            | F    | F    | N    | N      |
|                         | F    | N    | F    | N      |
|                         | N    | F    | F    | N      |
| FMSS outage             | /    | /    | /    | /      |

4 Reliability model of MMC based on Bayesian network

4.1 Reliability model of MMC bridge arm based on Bayesian network

This paper assumes that each bridge arm consists of n SMs, n-k is the number of redundant submodules in each arm. The load sharing mode of redundant SM is considered to calculate the reliability of the bridge arm in this paper. The reliability of series valve system in an arm is shown as follows:

\[
R_{s-SM}(t) = \sum_{i=1}^{n} C_n^i [R_{SM}(t)]^i \cdot [1 - R_{SM}(t)]^{n-i} \quad (1)
\]

The reliability of a single arm can be expressed as:

\[
R_{arm}(t) = R_{s-SM}(t) \times R_{vcl}(t) \quad (2)
\]

where \(R_{vcl}(t)\) is the reliability function of the arm reactor.

The reliability function of MMC can be obtained by the series-parallel principle:

\[
R_{MMC}(t) = [(R_{arm}(t))^2 \times R_{VBC}(t)]^3 \times R_{cp}(t) \times R_{cl}(t) \quad (3)
\]

where \(R_{VBC}(t)\), \(R_{cp}(t)\), \(R_{cl}(t)\) are the reliability functions of VBC, converter-level C&P system and valve cooling system.

The Bayesian network can be established as shown in Fig.3. G1 represents the top event, i.e. MMC fails. F1, F2 and F3 respectively represent the fault of DLCAPS, converter unit and valve cooling system. E1, E2 and E3 respectively indicate the fault of converter unit of each phase. D1, D2 and D3 respectively indicate fault of upper bridge arm of phase.
B, VBC and lower bridge arm of phase B. C1 and C2 represent the fault of series valve system and reactor of upper bridge arm of phase B respectively.

4.2 Reliability model of SM based on Bayesian network

The reliability function of SM is shown in Equation (4).

\[ R(t) = e^{-\lambda t} \]  

(4)

According to the structure of SM, its fault tree can be converted into Bayesian network, as shown in Fig. 4. A1, A2, A3 and A4 are the basic events, which respectively represent the fault of each component, B1 is the status of the SM, and 0 for failure, 1 for normal.

Based on the series reliability method, the SM reliability can be calculated as following:

\[ R_{SM}(t) = \left[ R_{IGBT}(t) \right]^2 \times R_C(t) \times R_{THY}(t) \times R_{SMC}(t) = e^{-\lambda_{net}} \]  

(5)

where \( R_{IGBT}(t), R_C(t), R_{THY}(t), R_{SMC}(t) \) respectively indicate the reliability function of IGBT, capacitor, thyristor and SM controller.

The SM failure rate is expressed as

\[ \lambda_{SM} = 2 \times \lambda_{IGBT} + \lambda_C + \lambda_{THY} + \lambda_{SMC} \]  

(6)

where \( \lambda_{IGBT}, \lambda_C, \lambda_{THY}, \lambda_{SMC} \) are the fault rate of IGBT, capacitor, thyristor and SM controller.
5 Case study

In order to verify the effectiveness of the method proposed in this paper, Bayesian toolbox based on MATLAB is adopted for simulation calculation.

5.1 Basic parameters

The original reliability data of the components in FMSS is shown in Tab.2.

| Component                  | Failure rate (occ/year) |
|----------------------------|-------------------------|
| IGBT module                | 0.04                    |
| Capacitor                  | 0.04                    |
| Thyristor                  | 0.01                    |
| SM controller              | 0.001                   |
| Arm reactor                | 0.004                   |
| Valve base controller      | 0.02                    |
| Converter-level C&P system| 0.015                   |
| Device-level C&P system    | 0.015                   |
| Valve cooling system       | 0.03                    |

5.2 Calculation results of reliability

The reliability function of the curve can be obtained to be \( R_{SM}(t) = e^{-0.14t} \). Therefore, the fault rate of the SMs is 0.14 times per year. Using the same method, the fault rate of the bridge arm is 0.32 times per year. The fault probability of the bridge arm can be calculated to be \( 2.6377 \times 10^{-3} \) times per year. The reliability of MMC is also calculated with redundancy configuration of \( n = 7, k = 6 \), and the fault rate of MMC is 0.0204 times per year. The fault probability of the bridge arm is calculated to be \( 1.6857 \times 10^{-4} \). The fault rate of MMC under different redundancy conditions can be obtained by changing the redundancy of the SMs, as shown in Tab.3.

| Redundancy | 6/7       | 6/8       | 6/9       | 6/10      | 6/11      | 6/12      |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Fault rate | 0.0204    | 0.0197    | 0.0194    | 0.0191    | 0.0190    | 0.0189    |

It can be concluded that with the increase of redundancy of SMs, the fault rate of MMC will decrease, and the decreasing speed will slow down gradually.

The fault probability of FMSS in eight states under different SM redundancy conditions can be calculated by the frequency and duration method, the results are shown in Tab. 4.

| States       | redun dancy | 6/7       | 6/8       | 6/9       | 6/10      | 6/11      | 6/12      |
|--------------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Normal       | 1           | 0.9994    | 0.9994    | 0.9994    | 0.9994    | 0.9994    | 0.9994    |
| operation    | 2           | \( 1.68 \times 10^{-4} \) | \( 1.63 \times 10^{-4} \) | \( 1.60 \times 10^{-4} \) | \( 1.58 \times 10^{-4} \) | \( 1.57 \times 10^{-4} \) | \( 1.56 \times 10^{-4} \) |
| Two-         | 3           | \( 1.68 \times 10^{-4} \) | \( 1.63 \times 10^{-4} \) | \( 1.60 \times 10^{-4} \) | \( 1.58 \times 10^{-4} \) | \( 1.57 \times 10^{-4} \) | \( 1.56 \times 10^{-4} \) |
| terminals    | 4           | \( 1.68 \times 10^{-4} \) | \( 1.63 \times 10^{-4} \) | \( 1.60 \times 10^{-4} \) | \( 1.58 \times 10^{-4} \) | \( 1.57 \times 10^{-4} \) | \( 1.56 \times 10^{-4} \) |
| operation    | 5           | \( 2.84 \times 10^{-8} \) | \( 2.65 \times 10^{-8} \) | \( 2.57 \times 10^{-8} \) | \( 2.49 \times 10^{-8} \) | \( 2.46 \times 10^{-8} \) | \( 2.44 \times 10^{-8} \) |
5.3 Weak link analysis of FMSS based on Bayesian network

Based on the Bayesian network model of FMSS, the conditional failure probability of each component under the condition of FMSS failure is calculated to analyze the importance of each component. The conditional fault probability of each component is shown in Tab. 5.

Table 5. The conditional fault probability of each component.

| Components                  | Number | The conditional fault probability |
|-----------------------------|--------|-----------------------------------|
| IGBT                        | 1      | 0.0132                            |
| Capacitor                   | 2      | 0.0132                            |
| Thyristor                   | 3      | 0.0033                            |
| SM controller               | 4      | 0.0003                            |
| Arm reactor                 | 5      | 0.0161                            |
| MMC C&P system              | 6      | $1.2327 \times 10^{-4}$          |
| Valve base controller       | 7      | 0.0080                            |
| Valve cooling system        | 8      | $2.4651 \times 10^{-4}$          |

According to Tab.5, the conditional failure probability of MMC C&P system and valve cooling system is smaller than that of other components, which is more likely to cause the FMSS failure. MMC C&P system and valve cooling system are closer to the top event in the fault tree, but the number is less than other components, so the conditional failure probability is relatively low. Increasing the redundancy of SM can improve the reliability of FMSS.

6 Conclusion

In this paper, the state space theory and Bayesian network method are used to model the reliability of FMSS. Based on the established model, the reliability indexes of the FMSS are calculated quantitatively by simulation, and the effectiveness of the method is verified. Then, the conditional fault probability of each component is calculated, which shows that SM is the weak link of FMSS. It can effectively improve the reliability of the switch to configure some redundant SMs in the system. In the following research of redundancy configuration, based on the relationship of redundancy and fault rate obtained in this paper, considering the economy and reliability, redundancy can be selected reasonably.

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