Reliability calculation of AC/DC hybrid distribution network with a solid-state transformer

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Abstract: With extensive access of distributed energy resources and DC loads, the traditional 10 kV AC distribution network has greatly increased the number of converters and reduced the reliability of power supply. A solid-state transformer (SST) containing AC and DC terminals to build AC/DC hybrid distribution networks has become the focus of the current research. This study presents an AC/DC hybrid distribution network structure with 10 kV AC, 10 kV DC, ±375 V DC, and 380 V AC four voltage levels. In this network, the load is data centre, which needs high security for power supply reliability. According to the characteristics of this network, this study takes the reliability evaluation by using the minimum path set method and the state enumeration method, and the reliability of this new structure with SST is calculated. Through the study of a numerical example, the results show that after adding the multi-terminal SST, the reliability of the AC/DC hybrid distribution network is suitable for data centre load, and the quantity of the converters can decrease.

1 Introduction

With the development of our society and economy structure adjustment, the current distributed renewable energy has become an important way of energy transformation, in the dense regions of load in our country, especially in southeast coastal having a huge development potential. At the same time, the generalised DC energy-using equipment represented by IT load, frequency consumption and the economic use of DC load, it is imperative to study the reliability of power supply reliability. This paper integrates network and state enumeration methods, and establishes the reliability evaluation analytical method. The typical simulation method is the Monte Carlo simulation method; this method can calculate the influence of related events on the system. In addition, the system size has less effect on the computational complexity. This method is suitable for solving the reliability of complex systems. The analytical method can be divided into a state-space method, a network method and a system state enumeration method [14–17]. There are a few studies on the reliability evaluation of AC/DC hybrid distribution network with multi-terminal SST. At the same time, it is considered that the data centre load occupies a high proportion in the distribution network of DC load and needs high power supply reliability. This paper integrates network and state enumeration methods, and establishes the reliability evaluation method for the AC/DC hybrid distribution network containing data centre load and multi-terminal SST. The reliability analysis model of the multi-terminal SST is also established.

In the first section of this article, we introduce the minimal path set algorithm and build the topology of 10 kV AC/DC hybrid distribution network with two multi-terminal SST and the data centre load. In Section 2, the reliability modelling of SST sub-modules is carried out to calculate the reliability of each terminal of SST. In Section 3, the power supply reliability of data center load is analysed based on the network topology mentioned in Section 2.

2 Establishment of the AC/DC hybrid network

In order to study the influence of multi-terminal SST on the reliability of power distribution network, an AC/DC hybrid power distribution system containing a distributed renewable energy source, multi-terminal SST and data center load is established. In the structure, the SST contains 10 kV AC, 380 V AC, 10 kV DC, ±375 V DC four ports; the data centre load: 3 MW (DC: 1 MW, AC: 2 MW); PV: 1 MW; photovoltaic power generator: 100 kW.
kW. The diagram of the AC/DC hybrid system with multi-terminal SST is shown in Fig. 1.

As the data centre requires high reliability of power supply, the AC/DC hybrid power system introduces two multi-terminal SST. Dual circuit of 10 kV is adopted to connect to the power grid. In order to calculate the reliability of network topology, the schematic diagram of electrical key one-line diagram of the AC/DC hybrid system is given in Fig. 2.

3 Key equipment reliability analysis method and modeling

3.1 Minimum path set algorithm

For the reliability analysis method, the simulation method is suitable for a complex system, and the method of network and state enumeration is applicable to the reliability calculation of small power network. In this article, by integrating the method of the minimum path set and state enumeration method, the reliability of multi-terminal SST AC/DC hybrid network is calculated. Based on the reliability parameters and network topology, the main path in the distribution network is found: starting from the source and ending with the point of load.

As an example of the network shown in Fig. 3, the search method is used to find the minimum path set: from the N1 to N4; the specific process is shown in Fig. 4. In this paper, the state of the first- and two-order faults is enumerated, using the minimum path set algorithm to analyse the effect of fault on the load and calculate the fault rate. The probability of the third-order fault and above is rare; hence, it is ignored.

3.2 Reliability model of critical components

The reliability parameters of components are the basis of reliability evaluation of AC and DC distribution networks, including the annual fault rate (times/a) and average fault repair time (h). The reliability parameters of the components that are not or for a short time put into the engineering application or at the stage of R&D are difficult to acquire. The reliability statistical data of similar components with similar functions or structures can be reasonably predicted or calculated according to the components and topological structure.

In this paper, the analysis of multi-terminal power electronic transformer equipment was still in the stage of prototype. So, calculation of reliability can take reference on VSC converter station statistics, and take advantage of the method of combining structure and components reliability data.

The key equipment of the AC/DC hybrid distribution network is a multi-terminal SST. Its structure, as depicted in Fig. 5, has four ports of 10 kV AC, 10 kV DC, ±375 V DC and 380 V AC. The device can convert the medium-voltage AC or DC power into low-voltage DC and AC power. First, the fault rate is analysed from the 10 kV AC to 10 kV DC port, and the power reliability of other ports is calculated similarly.

3.2.1 Calculation of reliability of terminal 10 kV AC<->10 kV DC

The structure of terminal 10 kV AC<->10 kV DC is shown in Fig. 6. It is composed of five segments:

i. Single-phase bridge full control rectifier and inverter circuit (AC/DC, DC/AC).
ii. Transformer primary-side series inductance L.
iii. High-frequency transformer (T).
iv. Filter capacitor C.
v. Control protection (C&P).

The model for reliability calculation of these five parts is shown in Fig. 7.

The single-phase bridge inverter circuit (DC/AC) is made up of four commutation valves, and each converter valve can be connected by multiple high-reliability crimping converter modules in series.

According to [18], the module of the crimping converter valve is made up of 48 IGBT chips, and the average time to fault of each IGBT chip is 1 year. By referring to flexible HVDC converter valve system, the reliability function of pressure valve connection module is calculated as follows:

\[ R(t) = e^{-\int_{0}^{t} \lambda_{mod} \, dt} \]  
(1)

\[ \lambda_{neut} = \frac{1}{T_{neut}} = \frac{1}{\int_{0}^{\infty} R(t) \, dt} = 0.02083 \text{(times/a)} \]  
(2)

The bus voltage is 10 kV, so the terminal of 10 kV is composed of at least two converter valve modules with rated voltage of 5 kV, which are connected in series. The redundancy is usually designed to be 50%, then the converter valve becomes a two redundant voting system, so the converter valve modules should be 4; the fault rate is shown as follows:

\[ \lambda_{value} = \lambda_{neut} \sum_{i=1}^{4} \frac{1}{i} = 0.019228 \text{(times/a)} \]  
(3)

So, the fault rate of single-phase bridge full control inverter circuit (DC/AC) is as follows:

\[ \lambda_{DC/AC} = \lambda_{DC/AC} = 4 \cdot \lambda_{value} = 0.076911 \text{(times/a)} \]  
(4)

According to \( \lambda_{eq} = \sum_{i=1}^{n} N_{i} \cdot \lambda_{eq} \), \( \lambda_{eq} \) is the equivalent annual fault rate of the equipment. \( N_{i} \) is the quantity of \( i \) equipment, \( \lambda_{eq} \) is the general fault rate of \( i \) equipment, and referring to the formula of reliability calculation of series model, the annual fault rate of SST terminal (10 kV AC<--->10 kV DC) can be obtained as

\[ \lambda_{10kVAC-10kVDC} = \sum_{i=1}^{5} N_{i} \cdot \lambda_{eq} = 0.518951 \text{(times/a)} \]  
(5)

The fault rate, quantity and fault probability of the SST terminal (10 kV AC<--->10 kV DC) are presented in Table 1.

Similarly, the fault rate and annual fault probability of each of the two terminals of SST are calculated, as presented in Table 2. Furthermore, the fault rate and annual fault probability of each terminal of SST are presented in Table 3.

### Table 1: Data of reliability calculation for terminal 10 kV AC<--->10 kV DC [7]

| Equipment       | Equivalent annual fault rate | Quantity | General fault rate \( \lambda_{i} \) | Annual fault probability |
|-----------------|-------------------------------|----------|-------------------------------------|--------------------------|
| DC/AC or AC/DC  | 0.076911                      | 30       | 2.30733                             | --                       |
| L               | 0.000028                      | 10       | 0.00028                             | --                       |
| T               | 0.004643                      | 10       | 0.04643                             | --                       |
| C               | 0.001139                      | 20       | 0.022776                            | --                       |
| C&P             |                                |          | 0.25143                             | --                       |
| SST (10 kV AC<--10 kV DC) | 2.62825                       |          | 0.003                               |                          |

### Table 2: Data of reliability calculation of each of the two terminals

| Equipment                        | General fault rate \( \lambda_{i} \) | Annual fault probability |
|----------------------------------|--------------------------------------|--------------------------|
| SST (10 kV AC<--10 kV DC)        | 2.62825                              | 0.003                    |
| SST (10 kV AC<--380 V AC)        | 1.273029                             | 0.0015                   |
| SST (10 kV AC<--±375 V DC)       | 2.47887                              | 0.00283                  |
| SST (10 kV DC<--380 V AC)        | 3.901279                             | 0.004453                 |
| SST (10 kV DC<--±375 V DC)       | 5.10712                              | 0.005830                 |
| SST (380 V AC<--±375 V DC)       | 3.75189                              | 0.004283                 |

3.2.2 Calculation of the fault rate and annual fault probability of the AC/DC hybrid network: Therefore, the reliability parameters of the key equipment of the AC/DC hybrid distribution network system are calculated, as presented Table 4: the power
supply reliability of the AC source is 99.9358%, which is statistics of 10 kV distribution network of the Dongguan Power Grid Corporation. The fault rate and repair time of distribution line are acquired from top journals in the industry papers.

4 Analysis of reliability

In order to calculate the reliability of AC/DC hybrid distribution network, Fig. 8 is proposed according to Figs. 1–4 and Table 4, and the equivalent diagram of AC/DC hybrid distribution system for reliability calculation is depicted as follows.

4.1 Annual fault probability calculation

In this paper, the state of the first- and two-order faults is enumerated. The probability of the third-order fault and above is rare. So, it is ignored. Table 5 shows the first- and two-order faults and probability.

According to Tables 5 and 6, the sum of annual fault probability of the first- and two-order faults is \( \sum p_i \). Therefore, the power supply reliability for data centre is \( P = 1 - \sum p_i = 0.999718 \).

4.2 Results analysis

The results show that the power supply reliability of the AC/DC hybrid distribution network contained by the multi-terminal SST is 99.97%. Referring to the standard [13], this topology has strong fault-tolerance ability and can satisfy the power supply requirements of TierI and TierII (data centre). Adding energy storage, UPS or one AC source can greatly improve the reliability of power supply and achieve the TierIII and TierIV standards, and the quantity of the converters in the system can decrease.

5 Conclusion

In this paper, an AC and DC hybrid network topology with multi-terminal SST is presented. The reliability model of SST is established according to the sub-module, and the reliability value of the equipment is calculated. The reliability of the hybrid AC and DC network is calculated by using the minimum path set method and the state enumeration method. The results show that the proposed structure can guarantee the reliability of the load of the data centre. If energy storage, UPS or one AC source are properly added, the reliability of this structure can be greatly improved and the system reliability can meet a higher level. The reliability analysis of AC/DC hybrid distribution network containing SST is a new topic. There are still many other topics to be studied further.

### Table 3  Reliability data of each terminal of SST

| Equipment                      | General fault rate \( \lambda_i \) | Annual fault probability |
|--------------------------------|------------------------------------|--------------------------|
| SST1\(10\)kVAC, SST2\(10\)kVAC | 6.380149                           | 0.007283                 |
| SST1\(10\)kVDC, SST2\(10\)kVDC | 11.63665                           | 0.013284                 |
| SST1\(380\)VAC, SST2\(380\)VAC | 5.174308                           | 0.005907                 |
| SST1\( \pm375\)VDC, SST2\( \pm375\)VDC | 11.33788                           | 0.012943                 |

### Table 4  Fault probability of equipment in the AC/DC hybrid network [19–21]

| Equipment Code | Length | General fault rate \( \lambda_i \) | Recovery time \( \gamma_i \) | Annual fault probability |
|----------------|--------|------------------------------------|-----------------------------|--------------------------|
| source         |        |                                    |                             |                          |
| SST1\(10\)kVAC, SST2\(10\)kVAC |         | SST1\(10\)A, SST2\(10\)A | 6.380149 | 10 | 0.007283 |
| SST1\(10\)kVDC, SST2\(10\)kVDC |         | SST1\(10\)D, SST2\(10\)D | 11.63665 | 10 | 0.013284 |
| SST1\(380\)VAC, SST2\(380\)VAC |         | SST1\(380\), SST2\(380\) | 5.174308 | 10 | 0.005907 |
| SST1\( \pm375\)VDC, SST2\( \pm375\)VDC |         | SST1\( \pm375\), SST2\( \pm375\) | 11.33788 | 10 | 0.012943 |
| 10 kV AC bus   | L₁, L₂ | 0.58                               | 0.01096                     | 13.65                    | 0.000099 |
| 10 kV DC bus   | L₃     | 0.36                               | 0.01096                     | 13.65                    | 0.000062 |
| ±375 V DC bus  | L₄, L₅ | 0.03                               | 0.01096                     | 13.65                    | 0.000005 |
| 380 V AC bus   | L₆, L₇ | 0.03                               | 0.01096                     | 13.65                    | 0.000005 |

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Table 5  Probability of first order fault

| Equipment | Fault affects reliability or not | Probability ($p_i$) |
|-----------|---------------------------------|---------------------|
| $S_1$     | ×                               |                     |
| $S_2$     | ×                               |                     |
| SST10A    | ×                               |                     |
| SST15D    | ×                               |                     |
| SST0.38   | ×                               |                     |
| SST10.375 | ×                               |                     |
| SST20A    | ×                               |                     |
| SST20D    | ×                               |                     |
| SST20.375 | ×                               |                     |
| SST20.38  | ×                               |                     |
| $L_1$     | ×                               |                     |
| $L_2$     | ×                               |                     |
| $L_3$     | ×                               |                     |
| $L_4$     | ×                               |                     |
| $L_5$     | ×                               |                     |
| $L_6$     | ×                               |                     |
| $L_7$     | ×                               |                     |

Table 6  Probability of two-order faults

| Equipment | Fault affects reliability or not | Probability $p_i$ |
|-----------|---------------------------------|-------------------|
| $S_1, L_2$| √                               | $5.51 \times 10^{-8}$ |
| $S_1, S_2$| √                               |                     |
| $S_1, L_3$| √                               |                     |
| $S_1, SST20A$ | √       |                     |
| $L_1, S_2$ | √       | $7.86 \times 10^{-8}$ |
| $L_1, L_2$ | √       |                     |
| $L_1, L_3$ | √       |                     |
| $L_2, SST20A$ | √       |                     |
| $L_3, S_2$ | √       | $4.92 \times 10^{-8}$ |
| $L_3, L_2$ | √       |                     |
| $L_3, SST20A$ | √       |                     |
| $L_4, S_5$ | √       | $6.47 \times 10^{-9}$ |
| $L_4, SST20.375$ | √       |                     |
| $L_6, S_2$ | √       | $6.92 \times 10^{-9}$ |
| $L_6, L_2$ | √       |                     |
| $L_6, L_7$ | √       |                     |
| $L_6, SST20A$ | √       |                     |
| $L_6, SST20.38$ | √      |                     |
| SST10A, $S_2$ | √       | $10.09 \times 10^{-5}$ |
| SST10A, $L_2$ | √       |                     |
| SST15D, $L_2$ | √       |                     |
| SST10A, $L_7$ | √       |                     |
| SST15D, SST20A | √      |                     |
| SST10A, SST20.38 | √      |                     |
| SST10.375, SST20A | √     |                     |
| SST10.375, SST20.38 | √   |                     |
| SST10.375, $S_2$ | √       | $1.76 \times 10^{-4}$ |
| SST10.375, $L_5$ | √       |                     |
| SST10.375, SST20.375 | √ |                     |

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