Reliability assessment method of DC protection system based on hierarchical modeling

Taoyao1*, GuoshengYang1, KaiXu2, SiyeRuan2, XueweiDou1, ZhongqingLi1 and XiangtaoXiao3

1 China Electric Power Research Institute, Beijing, 100192, China
2 State Grid Corporation of China. Beijing 100192, China
3 School of Electrical Engineering Beijing JiaoTong University Beijing 100044 China

*Corresponding author’s e-mail: 19117028@bjtu.edu.cn.

Abstract. The structure of DC transmission system is complexity, and the characteristics differ from components to components. It is difficult to adopt a single reliability assessment method for HVDC transmission protection system to be comprehensive, rapid and accurate. A reliability assessment method based on hierarchical modeling is proposed. At first the structure of DC transmission protection system is analyzed. It is divided into system layer, module layer and component layer. Then according to the characteristics of each layer, appropriate assessment methods are selected to assess each layer of the protection system. And corresponding reliability index is set the to realize the connection between each layer. Taking a DC transmission project as an example, the comprehensive reliability assessment of the protection system is carried out. Thereby the correctness and effectiveness of the proposed method is validated.

1. Introduction
The protection system of DC transmission project is an important barrier and a necessary condition for the safe and stable operation of DC project. In order to improve the reliability of DC protection system, it is urgent to evaluate the reliability of DC transmission protection system.

At present, the reliability research of DC transmission system mainly focuses on the reliability analysis of primary system [1-4]. In [5], the DC transmission system is divided into multiple subsystems for each connection mode of the hybrid multi-terminal UHVDC transmission system, and the reliability evaluation model of each subsystem is combined based on the state enumeration method. The literature [6] proposed a Frequency and Duration (FD) method based on parameter matrix, which matrixed the relevant parameters of all subsystems and realized the reliability assessment of the flexible DC transmission system. The reliability of DC transmission system has been studied comprehensively in the above literature, but the reliability analysis of DC protection system is rarely reported.

Experts combined various mathematical methods to evaluate the reliability of DC protection system. In [7], combined with the concept of source point and sink point in graph theory, the go diagram was decomposed and the reliability evaluation of protection system was carried out by using GO (goal oriented) method. In [8], FD method and minimum cut set method are used to evaluate the reliability of the whole hybrid system.
However, the complete DC protection function is performed by all devices involved in measuring device, protection device, pole control and protection action sequence. The characteristics of different components in DC transmission protection system vary greatly. Therefore, it is difficult to evaluate the protection system comprehensively and accurately by using a single evaluation method to analyze the reliability of the whole system. Based on the above questions, in this paper, the DC protection system is divided into component layer, module layer and system layer according to its structure and characteristics. And reliability evaluation models are established for each layer. The relationship between each layer is established, and the corresponding evaluation method is used to evaluate the reliability.

2. Structure and layering of DC transmission protection system
The complete DC protection system is complex in structure. When evaluating its reliability, it is necessary to take each component of the protection system into full consideration, and the model should be easy to solve. Therefore, the dc protection system is stratified, and then the reliability evaluation of each layer is carried out separately. Then the reliability indexes are used to connect the different levels to realize the overall evaluation of DC protection system.

Protection zones are divided according to the protection objects, mainly including converter transformer protection zone, converter protection zone, neutral bus protection zone, DC bus protection zone, DC filter protection zone, DC line protection zone, grounding lead and grounding protection zone.

According to the hardware structure of dc protection system, the system is stratified according to functions and characteristics. The equipment which performs the specific functions is divided into component layer. A group of components with similar functions are divided into module layer. Finally, different modules are integrated into the traditional DC protection system through information transmission, as the system layer.

3. Reliability model of DC protection system at all levels

3.1. Bayes-Monte Carlo method based on Weibull distribution
In order to evaluate the reliability of component layer, the life distribution of components should be determined first. During the service life of the protection device of the protection system, the failure rate is related to the service time. It can be divided into three stages: early failure zone, accidental failure zone and loss failure zone. Weibull distribution is often used to describe the three stages of protection device in reliability assessment.

It is difficult to obtain enough failure data or even no failure data for the protection system components in the component layer in a limited time. As a special method of small sample data processing, Bayesian method can effectively combine multiple sources and various forms of prior information under small samples. Then a more complete posterior information is obtained, and better probability estimates can be acquired without large subsamples.

The Bayesian-Monte Carlo method steps of component layer are as follows.
1) First of all, judge whether the component has failure data. If so, Weibull distribution parameters are obtained by least-square method and average rank method according to failure data. If there is no failure data, the Bayesian estimation value of component failure rate is obtained by historical information and expert estimation, which is directly used as Bayesian prior distribution.
2) The k-S goodness of fit of weibull distribution model is verified to verify whether the life distribution of the component conforms to Weibull distribution.
3) The parameters m and η of Weibull distribution are taken as known values, which are substituted into the sampling formula to generate multiple groups of regenerated samples. Then Weibull fitting is performed on the regenerated samples to get the corresponding parameters.
4) The Bayesian prior distribution is generated from the parameters of the regenerated samples.
5) The Bayesian posterior distribution is obtained by Bayesian formula, and then the reliability index of component layer is calculated.

3.2. Event tree - Monte Carlo method based on event tree matrix
Event tree method can fully reflect the functional and logical relationship between modules and components. It combines the advantages of clear physical concept of dynamic event tree, high precision of model. Monte Carlo simulation process could reflect the essence of system development and change, so as to improve the calculation accuracy and reduce the computational complexity.

When establishing the event tree, components with the same function are composed into each module. Taking the failure of each module as the top event and the output information of the component layer as the basic data of the module layer, so the event tree model of each module is constructed.

The complete evaluation process of the module layer is shown as follows.
1) Determine the corresponding relationship between components and modules. That is, the components corresponding to a module.
2) Taking the failure of each module as the top event of event tree. The event tree model is established from top to bottom according to the logical relationship between modules and components.
3) The event tree model is normalized to a event tree matrix, which is easy to solve
4) By using Monte Carlo method, the state of components at the bottom of event tree is sampled. And according to the event tree matrix, the state of top event of event tree in a certain simulation time is obtained, that is, the state of module.
5) The reliability index of module layer is calculated.

3.3. Goal oriented method
GO method is used to analyze the system layer. It is a success-oriented reliability analysis method. Which can directly establish the reliability model according to the system schematic diagram and flow chart, so it is more convenient and practical.

GO method translates the system schematic diagram directly into GO flow chart. Starting from the input events of the system, it is calculated according to the relevant principles of GO process until the final success probability value of the system is obtained. The key elements of go graph and go operation are operator and signal.

The GO model is determined according to the redundancy configuration of the protection system. The output information of module layer is taken as the basic data of system layer and combining with the direction of information transmission. The data of go model operator can be directly calculated according to the direction of information flow. Therefore, the GO model can be solved quantitatively if the operator, signal flow and the operator data are all determined.

3.4. Protect system reliability index
The hierarchical evaluation method is adopted in the protection system to keep the relative independence among the levels. While, the ultimate goal is to realize the overall evaluation of the protection system. So the whole system is integrated by the transmission of reliability index between different levels.

Component layer reliability index is component failure rate. Its common unit is (1/10^6h).

\[
\lambda(t) = \Delta N_i(t) / \Delta t \]  \hspace{1cm} (1)

The reliability index of module layer includes mean time between failures, mean time to repair, mean time between failures, average working time or times between two failures, and steady-state availability. Among them, the mean time between failures (MTTF) is as follows.

\[
MTTF = \int_0^\infty f(t) dt = \int_0^\infty R(t) dt = \frac{1}{N} \sum_{i=1}^{N} t_i \]  \hspace{1cm} (2)
Where \( f(t) \) is the failure density of the element; \( R(t) \) is the reliability of the element; \( t_i \) is the duration of each operation; and \( N \) is the number of continuous failures free operation.

Mean time to repair MTTR:

\[
MTTR = \int_0^\infty g(t) dt = \int_0^\infty t dG(t) = \frac{1}{N_r} \sum_{i=1}^{\infty} t_i
\]

Where \( g(t) \) represents the repair density of the element; \( G(t) \) represents the repair distribution function of the component; and \( N_r \) represents the repair times.

Mean time between failure (MTBF) is the average working time or working times between two adjacent failures of repairable components.

\[
MTBF = MTTF + MTTR
\]

Reliability index of system layer is the steady-state availability \( A \) and steady-state unavailability \( Q \).

\[
A = \lim_{t \to \infty} \frac{\text{working time}}{\text{calendar time}}
\]

\[
Q = \lim_{t \to \infty} \frac{\text{calendar time-working time}}{\text{calendar time}}
\]

4. Reliability analysis and result

According to the proposed reliability evaluation scheme, combined with the data of a DC transmission protection system, a complete reliability calculation is carried out for the traditional DC protection system. The following is a hierarchical reliability calculation example. The contents of complete traditional DC protection system are shown in Table 1.

4.1. component layer numerical examples

There are many components in the component layer, so a large amount of data is needed to solve in this layer. The measurement interface (I/O chassis) module is taken as an example to illustrate the calculation in this level, and the other four modules are the same.

The measurement interface module consists of I/O processing board, switching I/O board, analog I/O board, communication board, power module and chassis backplane. Under the same operation level and working conditions, their respective operation time, failure time and fault components are recorded, and the data are processed.

Two-parameter Weibull distribution fitting was carried out for each component of the module. And the shape parameters and scale parameters of the Weibull distribution are obtained. The Weibull distribution line fitting diagram of each component is shown in Figure 1.
The Weibull parameters of each component of the module can be obtained, and the fault probability density can be earned through the Weibull calculation formula.

\[ f(t) = \frac{mt^{m-1}}{\eta^m} \exp\left[-\left(\frac{t}{\eta}\right)^m\right] \]  \hspace{1cm} (7)

Cumulative distribution function failure distribution function:

\[ F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^m\right] \]  \hspace{1cm} (8)

Reliability function:

\[ R(t) = 1 - F(t) = \exp\left[-\left(\frac{t}{\eta}\right)^m\right] \]  \hspace{1cm} (9)

Failure rate function:

\[ \lambda(t) = \frac{mt^{m-1}}{\eta^m} \]  \hspace{1cm} (10)

Where, \( t \) is the time, \( m \) is the shape parameter, and \( \eta \) is the calibration parameter.

The failure rate and repair rate of each component can be calculated, as shown in Table 1.

| Component              | Failure rate | Repair rate | Component              | Failure rate | Repair rate |
|------------------------|--------------|-------------|------------------------|--------------|-------------|
| I/O processor board    | 33.24e-6     | 1/8         | Communication board    | 6.58e-6      | 1/8         |
| Digital I/O            | 12.64e-6     | 1/8         | Power supply module    | 11.86e-6     | 1/6         |
| Analog I/O             | 20.18e-6     | 1/8         | Chassis backplane      | 5.32e-6      | 1/6         |

4.2. Module layer numerical examples

There are five modules in the module layer, and each module establishes the corresponding event tree model. This paper takes the measurement interface module as an example to calculate the reliability of the module layer.

Event tree matrix transformation steps are shown as follow:

1) The dynamic event tree is stratified and searched from top to bottom.

2) After stratifying, the logical units and basic events are numbered according to the principles from bottom to top and from left to right.

3) Writing barrier matrix with logic gate as main line, the method is as follows: a) the number of logical units is listed in the first column; b) the category of logical units is listed in the second column; c) the corresponding levels of logical units are listed in the third column; d) the events contained in the logical unit are listed in the fourth and later columns.

If the event is a LOGICAL unit, the logical unit number plus the number of basic events is taken as the event number in the fault matrix. The number of events with the largest number of events in a logical unit is taken as the number of base events. While the number of events in other logical units is not enough, it shall be treated as supplement 0. The event tree matrix is shown in equation 11.
According to the processing mode of the measurement interface module, the corresponding event tree matrix is established for the remaining four modules, and then solved by the program. There is no need to repeat it here.

The established event tree is solved by Monte Carlo method, combined with the failure rate, repair rate and the event tree matrix of each component under the module. The reliability index of the module layer is shown in Table 2.

| tMTTF (h) | tMTTR (h) | tMTBF (h) | steady-state availability A |
|----------|----------|----------|-----------------------------|
| 1.098e+04 | 7.5128   | 1.0987e+04 | 0.999316241 |

4.3. System layer numerical examples

GO model of DC protection system is composed of modules according to signal flow direction, as shown in Figure 2. According to the data of each module calculated at the module level, the steady state is available, expressed by 1; and steady state unavailability, expressed by 0. The go method operator data is shown in Table 3.

The calculation process of GO method is as follows. Among them, Psi represents the state probability of the signal flow and Pci represents the state probability of the operator. Input operator:

\[ P_{s1} = P_{s1}, P_{s2} = P_{s2}, P_{s2} = P_{s2} \]  

(12)

Type 1 two state units:

\[ P_{s4} = P_{s4} \oplus P_{s1}, P_{s5} = P_{s5} \oplus P_{s2}, P_{s6} = P_{s6} \oplus P_{s3} \]  

(13)

\[ P_{s7} = P_{s7} \oplus P_{s4}, P_{s8} = P_{s8} \oplus P_{s5}, P_{s9} = P_{s9} \oplus P_{s6} \]  

(14)

Type 10 two out of:

\[ P_{s10} = \sum_{i=2}^{1} U_j(i) = U_2(i) + U_3(i), i = 0,1 \]  

(15)
\[ U_s(i) = P_{s1} \cancel{P_{s2}} P_{s3} = (P_{c1} \cancel{P_{c2}} P_{c3}) \cancel{(P_{s4} \cancel{P_{s5}} P_{s6})} \cancel{(P_{s7} \cancel{P_{s8}} P_{s9})} \] (16)

\[ U_s(i) = (1-P_{s7}) P_{s8} + P_{s7} (1-P_{s8}) P_{s9} + P_{s8} \cancel{P_{s9}} \cancel{(1-P_{s7})} \] (17)

Type 2 two state units:

\[ P_{e11} = P_{e10} \cancel{P_{e11}}, P_{e12} = P_{e11} \cancel{P_{e12}} \] (18)

According to the above calculation formula of signal flow and substituting the data of each operator into formulas, the steady-state availability and steady-state unavailability of signal stream 12 can be obtained. That is, the reliability calculation of the whole DC protection system is realized.

The results of steady state availability of DC protection system is 0.9657, while steady state unavailability of DC protection system is 0.0343. According to the calculation results in the table above, the steady-state availability of the whole DC protection system high.

5. Conclusion

In order to solve the problem of complex structure and large difference of electrical characteristics of each part of DC transmission system, a reliability evaluation method of DC transmission protection system based on hierarchical modeling is proposed in this paper. The protection system is divided into component layer, module layer and system layer from bottom to top. Each layer selects the corresponding method according to the structure and characteristics. The rationality and accuracy of the method are verified by the evaluation of the model and the analysis of an example.

Acknowledgments

This work was supported by Technology Projects of the State Grid Corporation of China under Project Numbers 5442JB190008-K.

References

[1] Dai H.Y., Li Y.L., Hao J.H., et al. Research on the Reliability Evaluation Method for DC Grid[J]. Advanced Materials Research, 2013, 732-733:762-766.
[2] Li Y., Yuan S., Liu W., et al. A Fast Method for Reliability Evaluation of Ultra High Voltage AC/DC System Based on Hybrid Simulation[J]. IEEE Access, 2018, PP:1-1.
[3] Liu Y., Singh C.. Reliability Evaluation of Composite Power Systems Using Markov Cut-Set Method[J]. IEEE Transactions on Power Systems, 2010, 25(2):777-785.
[4] Wang C., Xie H., Bie Z., et al. Reliability evaluation of AC/DC hybrid power grid considering transient security constraints[C] IEEE Conference on Automation Science & Engineering. IEEE, 2018.
[5] LI L.F., HU B., HUANG Y., et al. Reliability Evaluation of Hybrid Multi-Terminal UHVDC Transmission System[J]. Southern Power System Technology, 2018, 12(11):79-89.(in Chinese).
[6] GUO J., WANG X., HOU Y.S., et al. Reliability assessment of the VSC-HVDC transmission system based on a modified FD method[J]. Power System Protection and Control, 2015, 43(23):8-13.(in Chinese).
[7] MEI N., CHEN D., MA W., et al. Reliability Assessment of Protections for HVDC Transmission System Based on Extended Goal-Oriented Method[J]. Power System Technology, 2013, 37(4): 1069-1073.(in Chinese).
[8] DAI H.Y.. Research on the reliability evaluation method for AC/DC power grid[D]. Beijing: North China Electric Power University, 2014(in Chinese).