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A Fast Method for Reliability Evaluation of Ultra High Voltage AC/DC System Based on Hybrid Simulation

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ABSTRACT The construction and operation of the ultrahigh voltage power grid has solved the problem of optimal allocation of energy resources and played a key role in promoting social development. However, concerns about its safety have kept growing in recent years. In order to analyze the reliability of ultrahigh voltage AC/DC system combined with the quasi-Monte Carlo method and PSD-BPA simulation, the reliability model of various components and system is established, and the simulation speed is improved with accuracy ensured. In order to ensure the compatibility and efficiency of the software, we design the BPA-Matpower data interface, and the data translation from BPA to Matpower is realized by fourth conversion. Then, we propose an index system for reliability evaluation, concise and easy to compute, to reflect the reliability of the UHV grids and the characteristics of AC and DC systems. Based on actual regional powergrid, we compare the model in this paper with the traditional sequential Monte Carlo method, and carry out the analysis of the component sensitivity to study the multi-fault characteristics and the weakness of the system, and verify the scientific and effective result of this paper.

INDEX TERMS Ultra high voltage, reliability evaluation, data interface, hybrid simulation, index system.

I. INTRODUCTION

As China's energy supply and demand distribution is geographically uneven, it is important to establish efficient energy transport platform with advanced technology to achieve a wide range of energy resources allocation [1], [2]. Ultra high voltage (UHV) AC/DC transmission can achieve large-scale, long-distance, large-capacity energy transport and cross-regional asynchronous networking. With the increase of the proportion of UHV AC/DC power grid in the whole power system, it is very important to study the influence of DC power grid on the whole transmission system and realize the quick assessment of the reliability of the whole AC / DC hybrid transmission system [3], [4].

In recent years, some scholars have been focusing on the reliability evaluation of UHV power grids. Reference [5] studies the reliability evaluation model of double 12-pulse ultra HVDC transmission systems, but does not consider the impact of the AC system; In [6] and [7], The reliability and economy of UHVAC and UHVDC are contrasted, which provides a reference for planning; Reference [8] studies the evaluation of the EHV grid reliability at full voltage level, but its evaluation index is not comprehensive enough for UHV system. So far, no typical research has been conducted to evaluate the reliability of UHV AC/DC systems.

The reliability evaluation of transmission system is mainly composed of two parts: state selection and selected system state evaluation. In the state selection step, the methods mainly include analysis method (AM) and Monte Carlo simulation methods (MCSM) [9]. AM is usually applied to systems in small scale with simple structure and strong links. When the size of the system increases, its computational complexity increases exponentially. MCSM is independent of the size of the grid, and the control strategy of the actual operation of the system can be considered. MCSM is more suitable for the reliability evaluation of large-scale power grid. MCSM contains Sequential Monte Carlo (SMC) and Non-Sequential Monte Carlo (NSMC). The sampling method of NSMC is simple and computationally fast, but its accuracy cannot be guaranteed for simulations of multiple lengths of time. SMC can reflect the time characteristics of the system, which is more suitable for long-scale reliability assessment. The disadvantage is that if the evaluation results require a higher calculation accuracy, the corresponding calculation time will be significantly increased. One of the important reasons is that due to the low probability of component failure, the search for abnormal state of the system often takes a lot of time, and uneven characteristics [6] exists in the sampling pseudo-random number sequence. In the selected system state evaluation step, the calculation mainly includes the power flow calculation and the load adjustment calculation. In the complex system, the calculation is still very large.

For the AM and MCSM, some scholars have achieved to improve the calculation speed and simplify the model. Reference [11] applies Markov chain simulation element state, thus improving the SMC to improve the accuracy, but the defects of sampling method have not been fundamentally resolved. In [12], the state space segmentation method is proposed to speed up the calculation by merging the system fault type, but is not suitable for the reliability of the ''N-K'' traversal assessment. Reference [13] combines SMC and NSMC to simulate, that is, the pseudo-sequential Monte Carlo (PSMC) method. The paper carries on the sequential simulation to the power supply elementand the non-sequential simulation to the non-power element, which improves the calculation speed. However, the method still does not improve the sampling strategy. When the system is large, there are still computational problems. In [10], a quasi-Monte Carlo (QMC) method is proposed to improve the generation of random numbers and solve the problem of slow sampling speed. In terms of system status assessment, PSD-BPA program has speed and accuracy advantages compared with Matlab [14] in response to large-scale complex systems. However, most of the current reliability assessment is based on Matlab. In terms of evaluation index, Reference [15] proposed for AC and DC system reliability index based on the complex network theory, but did not reflect the role of UHV. Reference [3] established risk assessment indicators for UHV, but is not suitable for the reliability assessment.

To sum up, the common problem facing current reliability assessment methods is how to realize the comprehensive balance of calculation precision and calculation efficiency for a given large power grid and calculation accuracy index. This problem involves the selection of the sample of the system state assessment and the reliability state assessment algorithm. Generally speaking, the application of Matlab software is mostly applied in the reliability calculation, meanwhile, the stable computation simulation needs to conduct in the Matpower to obtain system state. From the perspective of power system stability simulation, BPA is superior to Matpower in computing speed and accuracy when the network is relatively large (closer to the actual grid). However, it is more convenient to program the QMC algorithm and calculate reliability metrics in Matlab, and BPA does not provide this type of calculation. Therefore, this paper considers the combination of Matlab and BPA for reliability simulation and calculation to maximize the advantages of both.

Such research faces the issue of incompatible BPA data with Matpower. When the power grid is relatively small, the data can be manually converted, but when the power grid is large, manual conversion of data is inefficient and time-consuming. Therefore, in order to improve the efficiency of power system analysis in Matlab platform, it is necessary to develop BPA-Matpower data interface. In this paper, the data interface is developed based on JAVA language, and the data translation from BPA to Matpower is realized by fourth data conversion. The accuracy and efficiency are guaranteed by comparing the calculation results.

Meanwhile, For UHV power grid, the current reliability index lacks correlation and effectiveness. Therefore, it is necessary to establish a more comprehensive index system, which can reflect the reliability of the system and the characteristics of AC and DC systems, and the index system should be concise and easy to calculate.

In this paper, combined with the QMC and PSD-BPA simulation, the reliability model of various components and systems is established, and the simulation speed is improved while ensuring the simulation accuracy by improving the sampling and simulation method. In order to facilitate the simulation, the data interface of BPA-Matpower is designed. meanwhile, the reliability evaluation index system suitable for UHV power grid is put forward. Finally, in the case study, the reliability and sensitivity analysis of the actual power grid verify the effectiveness of the method in this paper, and the weak link of the system is analyzed and solved.

II. RELIABILITY MODEL OF UHV TRANSMISSION SYSTEM

A. UHV AC LINE

For the AC line, we only consider two states: the normal operation and fault outage. It is possible to randomly generate a number that is uniformly distributed over the interval [0,1], and compare this random number with the forced outage rate of the component to determine its status: normal operation or failure outage. The operating state of the AC transmission line can be obtained by the following.

$$X_{a,m} = \begin{cases} 1, & x \geq \lambda_{a,m}, \text{ normal operation} \\ 0, & x < \lambda_{a,m}, \text{ failure outage} \end{cases} \tag{1}$$

where $X_{a,m}$ represents the operating status of AC line m, $\lambda_{a,m}$ indicates forced outage of AC line m, x is a random number that is uniformly distributed over the interval [0,1].

B. GENERATOR

Generators are similar to AC lines and we still consider two-state models. The operating state of the generator can be obtained by the following.

$$X_{g,m} = \begin{cases} 1, & x \geq \lambda_{g,m}, \text{ normal operation} \\ 0, & x < \lambda_{g,m}, \text{ failure outage} \end{cases} \tag{2}$$

where $X_{g,m}$ represents the operating status of generator m, $\lambda_{g,m}$ indicates forced outage. For generator sets, if G_m is the actual capacity of the n-th generator, the sum of the generating capacity of all generators in the system can be expressed as

$$G = \sum_{m \in M} G_m X_{g,m} \tag{3}$$

where M is the set of all generators.

C. UHV DC SYSTEM

For the DC system, the model is more complex because of its multiple running state. It can be divided into single twelve pulse system (STPS) and double twelve pulse system (DTPS) according to the wiring mode. Also, the derating operating status of DC system should be considered.

1) SINGLE TWELVE PULSE SYSTEM (STPS)

UHV DC transmission system is equivalent to a multi-state component to participate in system sampling. For a STPS, the simplified schematic diagram is shown in Figure 1.

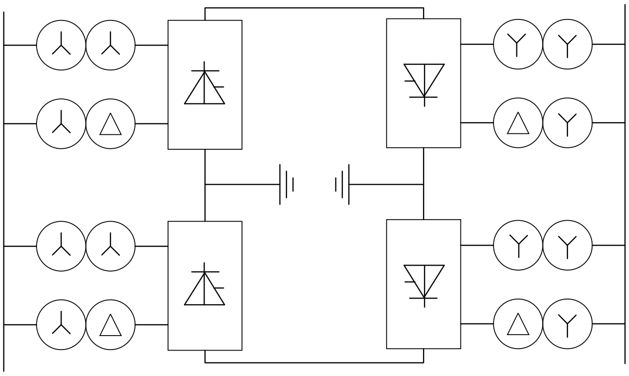


FIGURE 1. Simplified schematic diagram of STPS.

STPS has a total of three kinds of capacity status, respectively: 0,50% and 100% rated capacity. Assuming that the probability of 0% rated delivery capacity is a_1, the probability of 50% rated delivery capacity is b_1, the probability of 100% rated delivery capacity is $1 - a_1 - b_1$, the random number x and the probability a_1, b_1 and $1 - a_1 - b_1$ are compared with each other to determine the capacity state of the STPS under the sampling system, as shown below:

$$P_d = \begin{cases} 0 & 0 \le x \le a_1 \\ 0.5P_{dn} & a_1 < x \le a_1 + b_1 \\ P_{dn} & a_1 + b_1 < x \le 1 \end{cases} \tag{4}$$

where P_d indicates the injected power of the DC system, P_{dn} indicates the rated delivery capacity.

2) DOUBLE TWELVE PULSE SYSTEM (DTPS)

DTPS is equivalent to two single STPS in series, as shown in Figure 2. The DTPS has five basic rated capacity states, namely, 0, 25%, 50%, 75%, and 100% rated capacity.

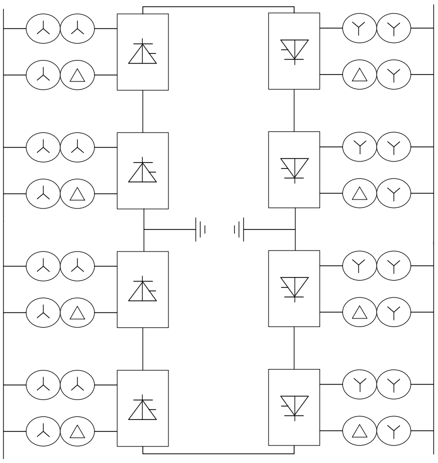


FIGURE 2. Simplified schematic diagram of DTPS.

Assuming that the five states correspond to the probability of a_2, b_2, c_2, d_2 and $1 - a_2 - b_2 - c_2 - d_2$, the capacity state of DTPS can be obtained according to the STPS, as shown in (5).

$$P_d = \begin{cases} 0 & 0 \le x \le a_2 \\ 0.25P_{dn} & a_2 < x \le a_2 + b_2 \\ 0.5P_{dn} & a_2 + b_2 < x \le a_2 + b_2 + c_2 \\ 0.75P_{dn} & a_2 + b_2 + c_2 < x \le a_2 + b_2 + c_2 + d_2 \\ P_{dn} & a_2 + b_2 + c_2 + d_2 < x \le 1 \end{cases} \tag{5}$$

3) DERIVED OPERATING STATE OF DC

For the derating operating state of the DC transmission system, it is assumed that the injected power is evenly distributed between the minimum permissible value and the rated value. In this paper, the STPS is taken as an example to illustrate its derating operating state in Monte Carlo simulation.

The injection power can be calculated by the following (6) when the system is on derating operating state [16].

$$P_{do} = \mu(P_d - P_{low}) + P_{low} \tag{6}$$

where P_{do} is the injection power, μ is a random number that is uniformly distributed over the interval [0,1], P_{low} is the minimum permissible value when it is on derating operating state.

Assuming that the probability of derating operating state is c_1. When the rated injection power is between 0% and 50% of the rated power, the DC system injection power is shown in (7). When the rated injection power is between 50% and 100% of the rated power, the DC system injection power is shown in (8).

$$P_d = \begin{cases} 0 & 0 \le x \le a_1 \\ P_{do} & a_1 < x \le a_1 + c_1 \\ 0.5P_{dn} & a_1 + c_1 < x \le a_1 + c_1 + b_1 \\ P_{dn} & a_1 + c_1 + b_1 < x \le 1 \end{cases} \tag{7}$$

$$P_d = \begin{cases} 0 & 0 \le x \le a_1 \\ 0.5P_{dn} & a_1 < x \le a_1 + b_1 \\ P_{do} & a_1 + b_1 < x \le a_1 + b_1 + c_1 \\ P_{dn} & a_1 + b_1 + c_1 < x \le 1 \end{cases} \tag{8}$$

The derating operation of the DTPS, not described here in detail, is similar to STPS.

D. RELIABILITY MODEL OF UHV AC / DC TRANSMISSION SYSTEM

that the AC / DC transmission system can be divided into q series subsystems, and each subsystem consists of $k_1 \sim k_q$ parallel components. The universal series and parallel system reliability model are shown in Figure 3.

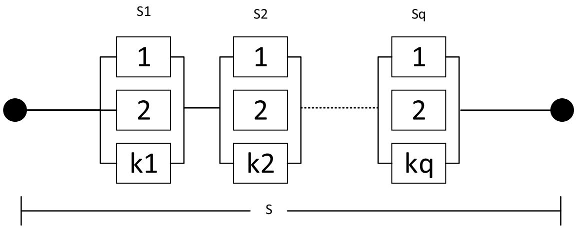


FIGURE 3. Series - Parallel System Reliability Model.

S is the system reliability, and S1, S2, S_q is the parallel subsystem, as shown in Figure 3.

The failure rate of the transmission system λ_S is equal to the sum of the failure rates of the parallel subsystems $\lambda_{S_i}^{k_i}$, as shown in (9).

$$\lambda_S = \sum_{i=1}^{q} \lambda_{S_i}^{k_i} \tag{9}$$

Parallel subsystem failure outage rate $\lambda_{S_i}^{k_i}$ is shown in (10).

$$\lambda_{S_i}^{k_i} = [\prod_{j=1}^{k_j} \lambda_{ij}] \cdot \sum_{j=1}^{k_j} \tau_{ij} \tag{10}$$

The calculation of the forced outage time the transmission system τ_S is shown in (11).

$$\tau_S = \sum_{i=1}^{q} \lambda_{S_i}^{k_i} \tau_{S_i}^{k_i} / \lambda_S \tag{11}$$

The calculation of the failure time of the parallel subsystem is shown in (12).

$$\tau_{S_i}^{k_i} = \frac{\tau_{S_i}^{k_{i-1}} \cdot \tau_{k_i}}{\tau_{S_i}^{k_{i-1}} + \tau_{k_i}}. \tag{12}$$

III. RELIABILITY EVALUATION OF UHV AC / DC SYSTEM BASED ON HYBRID SIMULATION

A. QUASI-MONTE CARLO METHOD

1) HALTON SEQUENCE GENERATION

The traditional Monte Carlo method is based on the random variable variance, and the confidence degree is constant. Its probability error is proportional to the number of samples $N^{-1/2}$. In order to improve the accuracy, it may take hundreds of times to simulate, the error convergence rate is relatively slow. QMC is a method of replacing pseudo-random number sequences in traditional Monte Carlo by introducing a low-deviation set of units on a hypercube.Its integral error is proportional to $N^{-1} \lg^n N$ [17], where n is the number of basic random variables. The convergence rate is obviously much faster and the error is deterministic.

Different sets of low-deviation points represent different quasi-Monte Carlo methods, and statisticians have proposed many such kinds of point sets, such as Faure sequences, Halton sequences, Sobol sequences [18] etc. Although the methods of constructing the set of points are different, these sequence sets are more evenly distributed in the unit hypercube than the pseudo-random sequence. Halton sequence is used in this paper.

Let r be any prime number, then any natural number c has a unique r basis:

$$c = c_0 + c_1 r + c_2 r^2 + \ldots + c_R r^R \tag{13}$$

where $R = [\ln c / \ln r]$, [] represents rounding calculation. $c_i \in \{0, 1, \ldots, r-1\}(i = 0, 1, 2, \ldots, R)$, the root inverse of c is defined as follows:

$$\varphi_r(c) = c_0 r^{-1} + c_1 r^{-2} + \ldots + c_R r^{-R-1} \tag{14}$$

for any integer $c > 0$, $\varphi_r(c) \in [0, 1]$.

The point set $\{\varphi_{r1}(c), \varphi_{r2}(c), \ldots, \varphi_{rn}(c)\}$ is a Halton sequence, and n is the dimension.

2) POINT SET UNIFORMITY TEST

Whether the low deviation point set can meet the required uniformity, it is needed to carry on the uniformity test. One of the more common methods of inspection is the Kermo Glover fitting test [19], which is briefly described below.

Let $F(c)$ be the cumulative distribution function of random variable c, and $F_N(c)$ is the sample distribution function obtained by sampling N times on c. For any c, there are (15) holds:

$$P\{\lim_{N \to \infty} \sup_{-\infty < c < +\infty} |F_N(c) - F(c)| = 0\} = 1 \tag{15}$$

$$F_N(c) = \begin{cases} 0, \ c < c(1) \\ \frac{i}{N}, c(i) \le c < c(i+1), i = 1, \ldots, N-1 \\ 1, \ c > c(N) \end{cases} \tag{16}$$

The Kermo Glover statistic D_N is used to fit the goodness test

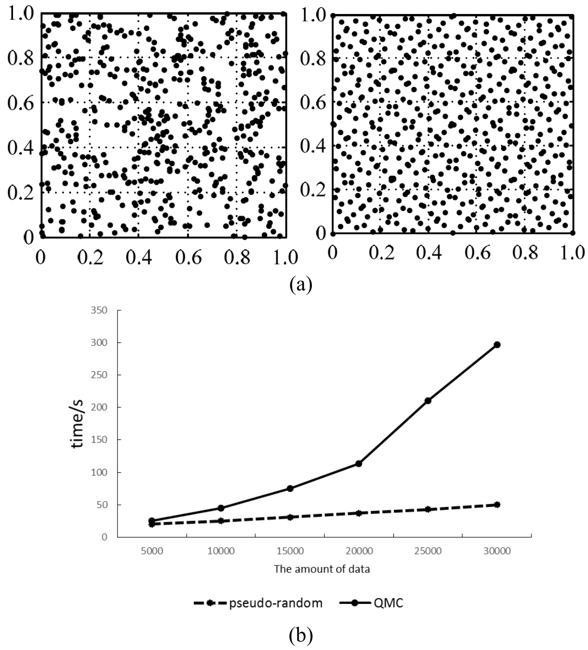
$$D_N = \sup_{-\infty < x < +\infty} |F_N(c) - F(c)| \tag{17}$$

3) CONVERGENCE CRITERION

After multiple simulations, the value of the expected value E (F) and the variance V (F) of the reliability index areestablished. Whether reliable system indicators are smooth is evaluated by:

$$\beta = \sqrt{V(E(F))} / E(F) \tag{18}$$

The following figure shows the distribution of the pseudo-random number sequence and QMC sampling point over the unit area. It can be seen that from Figure 4(a) the distribution of the sampling points of the Halton sequence is more uniform, and the distribution of the pseudo-random numbers is obviously dense and large in the blank area. In Figure 4(b), The horizontal axis represents the number of data(the actual number of lines) needs to be simulated; the vertical axis represents the calculation time. It can be seen that QMC is more efficient as the amount of computation increases. Therefore, it is necessary to extract a large number of sample points and reduce the computational efficiency.



(a)

(b)

FIGURE 4. Comparison of pseudo-random number sequence and QMC. (a) Distribution comparison of QMC(left) and pseudo-random number sequence(right). (b) Simulation speed comparison.

The reliability of the QMC method is verified by an example of the power generation part of the standard RTS79 system, which is commonly used in reliability calculation. The system has 32 generators with an installed capacity of 3 405 MW and a load of 2 580 MW. The values of EDNS and LOLP are solved by two methods. Figure 5 shows the convergence β of the pseudo-random number sequence and QMC.

As can be seen from the figure, in the conventional method, the β value is about 0.025 when sample number is over 20000. After QMC is adopted, the rate of β decreases obviously increased. When sample number reaches 20000, the β value is about 0.019. Although the β *value* is roughly the same, the QMC method has a faster convergence rate when calculating the system reliability index.

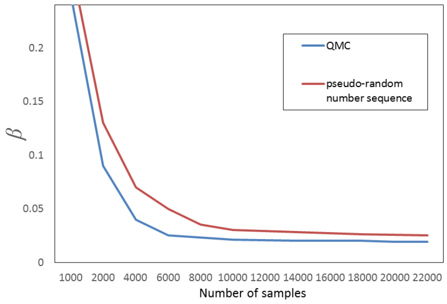


FIGURE 5. Comparison of convergence.

B. PSD-BPA CALCULATES BOUNDARY CONDITIONS

In cases where the initial system failure is known, subsequent failures and load reductions need to be simulated. This paper uses PSD-BPA program to simulate. Simulation conditions are set as follows.

1) CALCULATION TOOLS

The China Electric Power Research Institute "PSD Power System Software Toolkit (PSD Power Tools)" is adopted as the calculation and analysis tools, including:

- PSD-BPA flow calculation program;
- PSD-BPA transient stability calculation program.

2) FAULT SIMULATION

In the calculation, the fault types are:

- 1000kV UHV AC line three - phase permanent fault;
- 1000kV UHV AC line three - phase permanent jump double - loop fault;
- 1-2 1000kV UHV AC transmission channel lost simultaneously;
- 1-2 UHV DC transmission channels lost simultaneously;
- 500 kV AC line three - phase permanent fault;
- 500kV AC line three - phase permanent jump double - loop fault;
- DC single / bipolar latch fault.

3) STABILITY CRITERIA

The system stability criterion is divided into three aspects: power angle stability, voltage stability and frequency stability. The criterion is as follows.

- power angle

There is no relative power out of step in any main unit in the synchronization system.

- voltage aspects

After the fault is removed, the bus voltage of the main hub substation can be restored to the operating allowable range, and the bus voltage can eventually be restored to 0.80p.u.

- frequency aspects

The system does not frequently collapse. it can return to normal range and does not affect the safe operation of large units.

C. BPA-MATPOWER DATA CONVERSION INTERFACE

The grid calculation result needs to be transferred to Matpower to achieve the statistical calculation of the reliability index. Therefore, it is necessary to design an efficient interface data conversion to improve the simulation efficiency.

BPA adopts data card to store data, and each data has a fixed position. Comment lines and invalid data cards begin with (.). Network data is mainly stored in the node data card, line data card and transformer data card. And Matpower stores the data in the form of matrixof three kinds:node matrix, generator matrix and branch matrix. Here is a specific example:

In BPA data, the data card "BQ 4XYDCg2 20. 0 15.8. 600. 500. 360. 1. 05" indicates the generator node, in which the name is 4XYDCg2, the reference voltage is 20 kV, the active load is 15 MW, the reactive load is 8 MW, the maximum active output is 600 MW, the actual active output is 500 MW, the maximum reactive power output is 360 Mvar and the voltage amplitude is 1. 05.

In the Matpower data, "5 1903000110 34511. 10. 9" indicates that the node number is 5, the type is 1 (PQ node), the active load is 90MW, the reactive load is 30 Mvar, the conductance and susceptance are 0, the voltage amplitude value is 1, the voltage angle is 0, the reference voltage is 345 kV and the voltage upper limit is 1. 1, the voltage lower limit is 0. 9.

We can see from the data structure analysis above that there is a huge difference between BPA and Matpower data structure. Matpower attributes lines and transformers tothe line matrix and sets up the generator matrix. BPA places the generator nodes and other nodes in the node data card, and sets the transformer data card separately. Therefore, in the conversion process, we must identify the node name and voltage level, and then number them.

This interface is designed in Java language. The process is to: first read BPA's (. dat) data files, then identify valid data card, determine its type, intercept the data and convert to the corresponding matrix. When intercepting data, substring function is applied, namely the public String substring (int begin Index, int end Index). The interface will read BPA data cyclically in a total of four times.The process is shown below.

After designing the BPA-Matpower data interface, the power flow calculation results of BPA and Matpower are compared to verify the accuracy of the data conversion. The results show that the interface is effective.

D. RELIABILITY INDEX SYSTEM

In addition to the traditional reliability index described in (1)∼(4), we propose a new reliability index which is closely related to UHV, as is described in (5)∼(6).

1) LOSS OF LOAD PROBABILITY(LOLP)

LOLP represents the probability that the system will reduce the load due to insufficient power generation capacity at a certain load level.

$$LOLP = \frac{1}{N}\sum_{i=1}^{N} F_{LOLP}(X_i) \tag{19}$$

The data conversion process is shown in Figure 6.

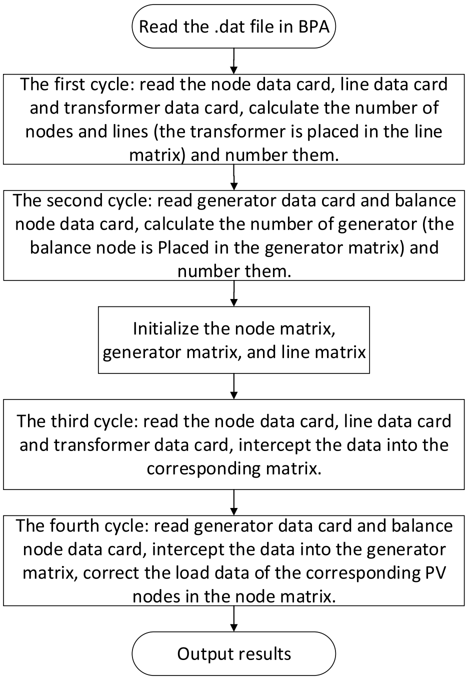


FIGURE 6. **Data conversion process.**

where $F_{LOLP}(X_i)$ indicates the flag that the system reduces the load in the state X_i, which can be obtained from:

$$F_{LOLP}(X_i) = \begin{cases} 1, \text{Load reduction} \\ 0, \text{Noload reduction} \end{cases} \tag{20}$$

2) EXPECTED DEMAND NOT SUPPLIED(EDNS)

EDNS indicates the amount of load reduction caused by insufficient system power generation capacity. The unit is MW and usually takes 1 hour as the period.

$$EDNS = \frac{1}{N}\sum_{i=1}^{N} F_{EDNS}(X_i) \tag{21}$$

where $F_{EDNS}(X_i)$ indicates the load reduction in the state X_i.

3) EXPECTED ENERGY NOT SUPPLIED (EENS)

EENS indicates that the average value of the user's power outage due to the insufficient capacity of the system. The unit is MW · h and usually takes 1a as the period.

$$EENS = EDNS \times T \tag{22}$$

where T is research cycle, this paper take 8760h a year.

4) SEVERITY INDEX(SI)

SI represents the time at which the system loses the full load for a period of peak load. The unit is min.

$$SI = \frac{EENS}{P_{\max}} \times 60 \tag{23}$$

where $P_{\max}$ represents the maximum load value of the system during the period.

5) CONTRIBUTION COEFFICIENT OF UHV TO EENS

It reflects the contribution of UHV to the system reliability level [16]. The larger the value is, the lower the reliability of the system will be.

$$U_{EENS} = \frac{EENS_1 - EENS_0}{C_{UHV}} \tag{24}$$

where $EENS_0$ and $EENS_1$ are the EENS before and after removal of UHV lines respectively. C_{UHV} is the rated capacity of the removal line.

6) CONTRIBUTION COEFFICIENT OF UHV TO LOLP

It reflects the effect of UHV on the system to reduce the load; the higher the value is, the lower the reliability of the system appears.

$$U_{LOLP} = \frac{\sum\limits_{X_i \in F_1} F_{LOLP}(X_i) - \sum\limits_{X_j \in F_0} F_{LOLP}(X_j)}{N} \tag{25}$$

where F_0 and F_1 are the load shedding state sets before and after removal of UHV lines respectively.

E. EVALUATION STEPS

The reliability evaluation steps in this paper are as follows:

(1) First, collect the basic data of grid operation and calculate the operational capacity probability state model.

(2) Set the number of faulty devices, that is, N-K fault form. And then form the initial set of failures.

(3) Based on the initial set of faults, simulations are performed in the PSD-BPA to detect whether load reduction is generated. If so, turn to (4), otherwise perform the next fault simulation.

(4) Make state sampling based on QMC according to the fault situation of PSD-BPA simulation. Then the probability of failure is calculated based on Eq. (9) - (12).

(5) After all the fault simulations are completed, calculate the system reliability index based on Eq.(19)-(25) and draw the relevant conclusions.

The calculation flow of this paper is shown in figure 7.

IV. CASE STUDY

A. CASE INTRODUCTION

In order to verify the correctness of the proposed model in this paper, we adopt a regional power grid which is used in [3]. In [3], the results of the risk assessment were analyzed. In this paper, we evaluated the reliability of the grid and studied the sensitivity of the components.

The area takes 500kV lines as the main grid structure, with the total installed capacity of 10.2589 million kilowatts and transmission load of 7.47 million kilowatts (winter big way). The dotted line represents AC 500 kV, solid line represents AC 1000 kV, chain line represents DC ± 800 kV, S represents source, and B represents node (converter station, substation and load).

Based on the domestic and foreign UHV operation history data, we get the reliability parameters of UHV equipment, as is shown in Table 1, Table 2 and Table 3.

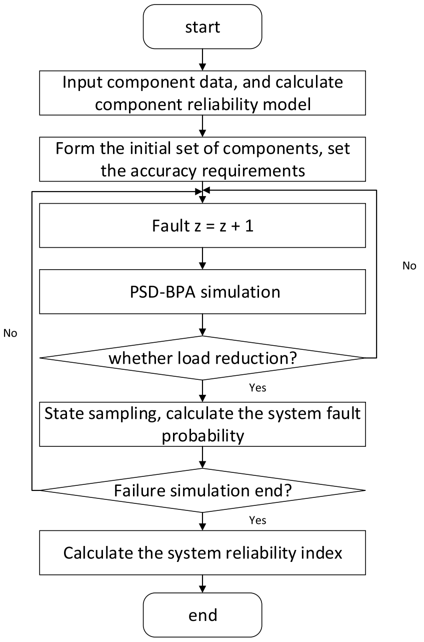


FIGURE 7. Calculation flow of this paper.

TABLE 1. Line reliability parameters(times/(A·hundred km).

Line	failure rate	repair rate
UHV-DC lines	4.708	1101.89
UHV-AC lines	0.156	856.00
units	0.085	1251.64

TABLE 2. Stps reliability parameters.

Capacity	Probability	Occurrence frequency(times/a)	Average duration/a
100%	0.98962	14.2721	607.4181
50%	0.010329	14.3656	6.2985
0%	0.000051	0.0934	4.7832
total outage time(h/a)		45.6876	
Energy availability(%)		99.47	

TABLE 3. Dtps reliability parameters.

Capacity	Probability	Occurrence frequency(times/a)	Average duration/a
100%	0.9849	24.4581	352.8957
75%	0.0059	14.8856	3.3773
50%	0.0091	9.922	7.8614
25%	0.000044	0.1618	2.385
0%	0.00002	0.044	4.0141
total outage time(h/a)		52.035	
Energy availability(%)		99.41	

As can be seen from the table, the bipolar outage probability and duration of STPS are higher than the DTPS's, but its bipolar operation, that is, the probability of rated capacity of running and the duration of the state are slightly higher than the DTPS's. This is mainly because the number of DTPS equipment is greater, the probability of failure is relatively high.

B. RELIABILITY EVALUATION RESULTS

In order to verify the validity of method in this paper(hybrid method), the conventional reliability evaluation method—SMC is used as a contrast. The system of Figure 8 is simulated. The simulation time scale is 100 million hours and the initial maximum number of failures of the system is 2, and then the initial set of failures is formed based on Matlab. In the hybrid method, the chain failure and fault recovery are simulated in BPA. In QMC, based on the Matlab platform, the optimal power flow method is used for fault recovery. The entire simulation runs on the i7 2.6GHz, 16G memory PC computer. The reliability calculation results are shown in Table 4.

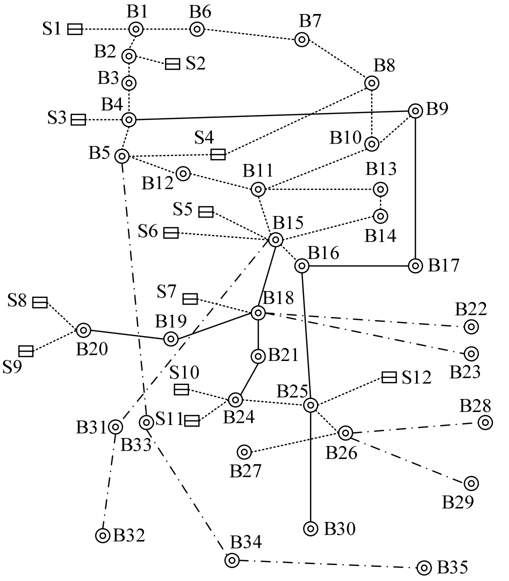


FIGURE 8. Planning scheme for a regional grid.

TABLE 4. Reliability calculation results.

index	hybrid method	SMC
Sampling numbers	42651	67124
Computing time/h	5.54	8.02
LOLP	0.000278	0.000275
EDNS	1.2823	1.2828
EENS	11232.948	11237.328
SI	90.22448	90.25966
U_{EENS}	0.214	0.215
U_{LOLP}	0. 139	0.138

By analyzing Table 4, we can see:

(1) From the calculation results of various reliability indicators, the two methods are basically the same, which shows that the method proposed in this paper is to meet the accuracy requirements. From the calculation of time and sampling numbers, the mixing method is significantly better than SMC. Since the scale of the case system is not very large, when the system is further expanded, the hybrid method mentioned in this paper will have a greater advantage.

(2) Considering three indicators of LOLP, EDNS and EENS, The system basically meets the reliability requirements. However, SI indicator takes nearly 90 minutes, which shows room for improvement in system reliability. From U_{EENS} andU_{LOLP} , we can find that the UHV AC / DC lines contribute greatly to the reliability of the entire system. Meanwhile, we need to analyze the sensitivity of each component, and find the lines or units with high influence on the system reliability.

C. WEAKNESSES ANALYSIS

Component sensitivity analysis is used to find out the weak links in the transmission system which has great influence on the system reliability, and then we can take effective measures to strengthen system reliability.

In this paper, the perturbation method is used to find the weak links of the system. The steps are as follows: Firstly, the reliability evaluation of the system is obtained by routine reliability evaluation. Then, makethe other conditions of variables unchanged and change the reliability parameters of a component only, such as forced outage or rated capacity, and the reliability of the case is re-evaluated. Finally, according to the difference in the reliability of each component reliability parameter to the degree of reliability of the system, we can obtain the components that have a great influence on the system reliability by sorting the sensitivity of all the components, which is relatively the weak link of the system. This paper chooses the system severity index SI as the reliability index of reliability sensitivity analysis. The results of the sensitivity calculation are shown in Table 5.

By analyzing Table 5, we can see:

(1) From the component type, the order of SI sensitivity is: units > AC lines > DC lines. This shows that the reliability of the generator parameters on the reliability of the system is higher than the transmission lines, therefore, reducing the failure rate of the generator can greatly improve the system reliability level. At the same time, it is possible to consider an appropriate increase in the capacity of the generator.

(2) From a single component sensitivity, SI sensitivity of six components in the system are more than 10, namely S7, S10, S11, B15-B18, B16-B25, B15-B31. Among themthe three units(S7, S10, S11) not only have larger capacity (1000MW), but also are located in the key position of the grid structure, which will affect the important balance of power. The SI sensitivity of two AC lines(B15-B18, B16-B25) are almost higher than units, which shows that the two lines are extremely important to system reliability. We can carefully observe to find that these two lines belong to important tie lines of the regional grid and an important support for the southern power grid and the north power grid. Therefore, we can consider the two lines for capacity uprating, or add more tie lines to increase system reliability.

TABLE 5. Sensitivity calculation results.

Sequence	Component	Forced outage rate increment(10%)	SI increment
		Units	
1	S7	0.0085	15.69
2	S10	0.0085	12.86
3	S11	0.0085	12.47
4	S5	0.0085	9.14
5	S6	0.0085	9.08
6	S4	0.0085	5.12
7	S12	0.0085	1.01
…			
		AC lines	
1	B15-B18	0.0156	16.74
2	B16-B25	0.0156	15.89
3	B21-B24	0.0156	3.87
4	B18-B19	0.0156	2.45
5	B15-B16	0.0156	2.08
6	B24-B25	0.0156	1.42
7	B4-B9	0.0156	1.07
8	S6-B15	0.0156	0.71
9	S5-B15	0.0156	0.52
10	S7-B18	0.0156	0.27
…			
		DC lines	
1	B15-B31	0.4708	10.01
2	B5-B33	0.4708	3.24
3	B18-B22	0.4708	1.21
4	B18-B23	0.4708	1.20
5	B26-B28	0.4708	0.46
…			

(3)Some DC lines have a significant impact on system reliability (B15-B31). However, as a whole, the sensitivity of the DC line is lower than the AC line, this is because DC penetration is not high. In fact, the UHVDC systems have a significant impact on voltage stability. As the transmission capacity of DC systems continues to increase, especially in UHV DC transmission systems, the proportion of single-loop DC inrush power received by the terminal AC system will increase, and DC reactive power compensation equipment in converter station has larger capacity, which put forward higher requirements for the system reactive power balance and voltage stability. In addition, DC unipolar or bipolar blocking will cause a significant shift of power to the UHV AC channel, reactive power consumption increased significantly, the voltage stability of UHV AC system will have a greater impact on the system.

(4) The ability of the AC system to withstand high power transfer is closely related to the three factors of the DC fault morphology, the initial power of the AC cross-section, and the voltage support of the AC system. The greater the DC power, the greater the number of commutation failures, the greater the impact on the AC system; The larger the initial power of AC cross section is, the smaller the static stability margin is; The larger the capacity of the AC power-on, the higher the static limit of AC delivery and the greater the ability of power transfer after DC fault.

(5) In summary, the reliability of the system is not only related to component capacity and component reliability, but also closely related to the network structure and AC/DC coupling characteristics. Therefore, a reasonable upgrade to the network topology and AC / DC coordination and control strategy are important means to enhance the reliability of the system.

V. CONCLUSION

This paper is devoted to studying the reliability model of UHV transmission system, and set up a series of indicators which can better evaluate the reliability of the system. Through modeling and case studies, the following conclusions are drawn:

(1) The rationality of AC and DC configuration can improve system reliabilityin the actual power grid planningin order to achieve the reliability improvement. We should give full consideration to the choice of line capacity, coordination of AC and DC.

(2) Reasonable upgrade to the network topology is an important mean to enhance the reliability of the system. In the construction of the line, the rationality of the grid structure should be considered.

(3) The sensitivity of different lines on the system is different, which is due to the different capacity, voltage level and geographical location of the line. Therefore, we need to pay full attention to those high sensitivity lines, to ensure system security.

(4) The research results of this paper are more in line with these applicable scenarios: comparison of the reliability of two schemes with similar investment, or calculation and improvement of the reliability of the actual operation of the power grid.

The reliability evaluation of AC / DC hybrid transmission system is a research topic involving many contents, complicated steps and complicated factors. This paper has done some exploration and research in the aspects of model, calculation method and so on, but there is still a lot of work to be advanced in the research process, as follows:

(1)The system reliability level upgrades usually through the system equipment with the new upgrade to improve the backup and other measures. At this point the cost of the system will become high, the economy will be worse. It is necessary to find the optimal solution in the system's reliability and economy in order to achieve a balance. So it is necessary to take economic considerations into account in the next step.

(2) In this paper, the reliability evaluation of the transmission and distribution system is only the content of the static reliability analysis, that is, we only consider the system's adequacy and do not consider the system's dynamic security. If we need to analyze the dynamic security of the system, we need to add the dynamic differential equation, and then

the factors to be considered become more. This topic can be explored in the future.

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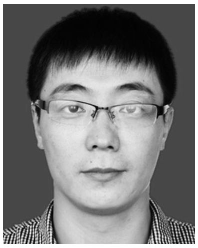

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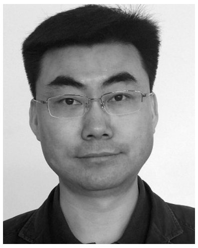

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