IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 19, 2019, accepted October 4, 2019, date of publication October 16, 2019, date of current version October 31, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2947707

Reliability Assessment for AC/DC Hybrid Distribution Network With High Penetration of Renewable Energy

WEI WEI[1], (Member, IEEE), YITONG ZHOU[1], JIE ZHU[2], KAI HOU[1], (Member, IEEE), HE ZHAO[2], ZIJIN LI[2], AND TAO XU[1]

[1]Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China
[2]State Grid Beijing Electric Power, Research Institute Beijing, Beijing 100031, China

Corresponding author: Kai Hou (khou@tju.edu.cn)

This work was supported by the National Key R&D Program of China under Grant 2016YFB0900500 and Grant 2016YFB0900503, and by the National Natural Science Foundation of China under Grant 51707129.

ABSTRACT Recently, the AC/DC hybrid distribution network has become a general trend in energy research. To accommodate the addition of renewable energy, this paper proposes a reliability assessment approach for AC/DC hybrid distribution network considering the new features introduced by the DC distribution technique. First, the probability models of renewable generations and loads are established. Second, the control modes of the voltage source converter (VSC) yielding to different fault scenarios are modeled based on its operating characteristics. Thereafter, an optimal load shedding model that considers the control modes of the VSC is developed, and it can be solved using a second-order cone algorithm. Finally, a reliability assessment method for the AC/DC hybrid distribution network is proposed that is based on the nonsequential Monte Carlo method. Case studies based on a modified AC/DC distribution network are applied to verify the effectiveness of the proposed method. The operational characteristics and reliability performance of the AC/DC distribution network with high integration of renewable energy are demonstrated by comparing it to a corresponding AC distribution network.

INDEX TERMS AC/DC distribution network, reliability assessment, renewable energy, voltage source converter, optimal load shedding model.

I. INTRODUCTION

With the demand for clean energy in modern society, renewable energy is being widely integrated into the distribution network in the form of distributed power, which introduces new challenges for the reliable planning and operation of the distribution network [1]–[3]. The uncertainty of the output of renewable energy affects the reliability of the distribution network. With the development of DC transmission technology and power electronics technology, the flexible DC power distribution technology based on voltage source converters (VSCs) has begun to be applied in distribution networks. The traditional AC distribution network is gradually transformed into the AC/DC hybrid distribution network in places [4], [5]. Comparing with the traditional AC distribution network, the AC/DC hybrid distribution network has strong power flow adjustment capability, high controllability and low network operation loss. In the case of high integration of renewable energy, the AC/DC distribution network has some advantages over the AC distribution network in terms of reliability. As the core of AC/DC hybrid distribution network, VSC and DC network can flexibly perform bidirectional regulation, reduce the power outage range after failure and shorten the switching time of the operating state. On the other hand, it also brings certain challenges to reliability assessment. In order to evaluate the reliability enhancement of the AC/DC network, the differences in the control characteristics and failure modes between VSC and traditional AC switch devices must be handled. In addition, the operation mode the AC/DC hybrid network and the interaction between subsystems are more complex than traditional AC system. Therefore, the traditional reliability assessment

The associate editor coordinating the review of this manuscript and approving it for publication was F. R. Islam.

methods designed for AC distribution network cannot be directly utilized to the AC/DC hybrid distribution network. Therefore, it is important to evaluate the reliability of the AC/DC hybrid distribution network.

The reliability assessment methods for distribution networks mainly include analytical methods and simulation methods. Considering the uncertainty of the output of renewable energy, the Monte Carlo method is generally used for the reliability evaluation [6], [7]. For distribution network, the existing literature generally focus on the traditional AC distribution networks. In [8], [9], a reliability evaluation algorithm for distribution networks with microgrids based on the sequential Monte Carlo method is proposed. However, the sequential Monte Carlo method is complicated and inefficient. In [10], a generalized capacity outage table method is proposed for the active distribution network to characterize the fluctuation of renewable energy. Based on this method, the reliability evaluation of the distribution network is performed using the nonsequential Monte Carlo method. Reference [11] considers the access of wind turbines (WT), photovoltaic (PV) and energy storage. By establishing a Markov model of the distributed power, a reliability evaluation method for the AC distribution network with high integration of renewable energy is proposed. However, these methods are only applicable to the traditional AC distribution network, and DC networks are not involved.

The reliability model of the multiterminal flexible DC interconnection is established in [12], [13]. The Sequential Monte Carlo method is used in [14], [15] for the reliability evaluation of DC distribution networks. A minimum load shedding method is proposed in [16] for the reliability evaluation method of DC distribution networks. However, the research objects are limited to the DC distribution network. The effects between AC and DC distribution networks is not considered.

There are many studies on the reliability of AC/DC hybrid transmission networks. In [17], [18], a reliability model is developed for the AC/DC hybrid transmission networks, which is different from distribution networks. Many studies have been done for the reliability assessment of VSC-HVDC systems [19]–[21], and the technology of reliability assessment for AC/DC hybrid transmission networks is relatively mature. Reference [22] achieves rapid reliability assessment of large-scale AC/DC hybrid transmission networks based on an optimal load shedding model and Monte Carlo method. The above methods are only for the transmission networks, which have some reference values for the reliability assessment of AC/DC distribution networks. But the operation mode of the transmission networks is relatively fixed due to the long distance, and the operation mode of the distribution networks is relatively more flexible. Therefore, the reliability assessment of distribution networks has different characteristics from transmission networks, and the lack of reliability evaluation method for AC/DC hybrid distribution networks persists.

Considering new features of the DC distribution technique, this paper proposes a reliability evaluation method for the AC/DC hybrid distribution network based on the nonsequential Monte Carlo simulation. Compared to the reliability evaluation method for the traditional AC distribution network, the proposed method can analyze the effect of the DC network and VSC in detail. The remainder of the paper is organized as follows: Section II establishes the failure probability models of the AC and DC components and the probability models of renewable generations and loads. In Section III, the control modes of the VSC yielding to different fault scenarios are modeled based on its operating characteristics, and an optimal load shedding model considering the control modes of the VSC is developed, which can be solved by a second-order cone algorithm. Case studies are performed in Section IV, and the conclusions are drawn in Section V.

II. PROBABILITY MODEL OF THE AC/DC HYBRID DISTRIBUTION NETWORK

A. FAILURE PROBABILITY MODEL OF THE AC AND DC COMPONENTS

In this paper, when analyzing the reliability of an AC/DC hybrid distribution network, the main components that may have fault states are the AC transformer, VSC, AC/DC line and AC/DC bus. Apart from the VSC, the reliability models of the basic components can be expressed as determined reliability parameters, which can be obtained from historical data.

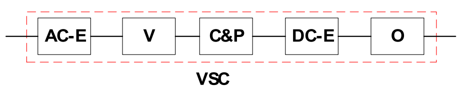

FIGURE 1. Structure of VSC.

As shown in Fig. 1, the VSC consists of five parts: 1) AC equipment (AC-E); 2) Converter valve (V); 3) Control and protection system (C&P); 4) DC equipment (DC-E); 5) Others (O). These five parts are in a series structure.

At present, the reliability parameters of these five parts in the VSC in the distribution network do not have a mature conclusion, which can be derived from the reliability parameters of the high-voltage converter station in the transmission grid. For these five parts, the reliability parameter of the converter valve (V) can be expressed as (1).

$$\lambda_{\text{V-M}} = \lambda_{\text{V-H}} V_{\text{DC-M}} / V_{\text{DC-H}} \tag{1}$$

where λ_{V-M} / λ_{V-H} is the reliability parameter of the converter valve in medium-/high-voltage converters. V_{DC-M} / V_{DC-H} is the DC voltage in the medium-/high-voltage DC system.

The reliability parameters of the other four parts are equivalent to those in high-voltage converter stations in the transmission grid, which can be obtained from historical data [23]. Therefore, the reliability parameter of the VSC can be obtained by a series model, as shown in (2).

$$R_{VSC} = \prod_{i=1}^{N_c} R_{comp,i} \tag{2}$$

where R_{VSC} is the availability of VSC, and $R_{comp,i}$ is the availability of the component i in VSC.

B. PROBABILITY MODEL OF RENEWABLE GENERATION AND LOAD

The high integration of renewable energy in distribution networks effectively improves the economics of the distribution networks, reduces the pollution caused by fossil energy, and introduces a strong uncertainty to the network. To consider these uncertainties, common processing methods include scene clustering, establishing a general outage table, etc. However, these methods do not consider the relative relationship among the output of PV, WT and the load level, which may affect the control characteristics of the AC and DC equipment and the accuracy of the calculation results. To solve this problem, this paper uses the time series sampling method to establish a multistate probability model of renewable energy and load. The specific method is as follows:

1) According to historical data, form the annual output power curve of renewable energy and annual load curve as shown in (3-5).

$$P_{wt} = [P_{wt}^1, P_{wt}^2, P_{wt}^3, \cdots, P_{wt}^T, \cdots, P_{wt}^{8760}] \tag{3}$$

$$P_v = [P_v^1, P_v^2, P_v^3, \cdots, P_v^T, \cdots, P_v^{8760}] \tag{4}$$

$$P_d = [P_d^1, P_d^2, P_d^3, \cdots, P_d^T, \cdots, P_d^{8760}] \tag{5}$$

where P_{wt} is the annual output power curve of WT, P_{v} is the annual output power curve of PV, P_{d} is the annual load curve, and T is the selected time of each simulation.

2) Assume that the total duration of the simulation is N years and 8760 hours a year. Then, extract a random integer T between 0-8760*N as the selected time of simulation scenario i.

3) Determine the output of renewable energy and load level in simulation scenario i, as shown in (6-8).

$$P_{wt}^i = P_{wt}^T \tag{6}$$

$$P_v^i = P_v^T \tag{7}$$

$$P_d^i = P_d^T \tag{8}$$

where p_{wt}^i and p_v^i are the output of WT and PV in simulation scenario i; p_d^i is the load level in simulation scenario i.

The time series sampling method is used to characterize the uncertainties of the renewable energy and load, and it can reflect the relative relationship among the output of PV, WT and load level. When the WT, PV and load fluctuation are considered, the actual situation can be more closely characterized, and the application range is wider. This method can be conveniently combined with the nonsequential Monte Carlo method for a reliability analysis of AC/DC distribution networks with high integration of renewable energy.

III. RELIABILITY ASSESSMENT APPROACH FOR THE AC/DC HYBRID DISTRIBUTION NETWORK

The reliability analysis of the distribution system mainly includes two types of methods: analytical methods and simulation methods. Due to the access of renewable energy, the analytical methods cannot easily solve the fluctuation problem. Therefore, for the AC/DC hybrid distribution network with high integration of renewable energy, this paper uses the nonsequential Monte Carlo method to analyze its reliability.

In the simulation process, the state of the system is obtained by sampling the state of the component (normal operation/fault state) according to the failure rate of the components in the AC/DC distribution network. For each simulation, the renewable energy output and load level are obtained by the failure probability model of the AC and DC components and the probability model of renewable generation and load.

After sampling according to the above model and obtaining the state of the system, we must perform a series of analysis of the system to obtain the reliability index. First, according to the fault state, the control mode of the VSC must be adjusted. Then, after performing the AC/ DC power flow calculation, we conduct the optimal load shedding calculation to obtain the reliability index when the operational constraints of the system is violated.

A. VSC MODEL UNDER MULTIPLE CONTROL MODES

When there is a fault state of the system, a part of distribution network may lose power support. At this time, the control mode of the VSC must be changed to provide power support to the system.

The VSC has two controllable operating parameters. According to different control parameters, the VSC can operate under multiple control modes. The three most typical control modes are:

1) PQ control mode. The two control parameters are the active and reactive powers on the AC side of the VSC.

2) $U_{dc}Q$ control mode. The two control parameters are the voltage amplitude on the DC side of the VSC and reactive power on the AC side of the VSC.

3) $U_{ac}\theta$ control mode. The two control parameters are the voltage amplitude and phase angle on the AC side of the VSC.

When the control mode of the VSC is $U_{dc}Q$, the DC side of the VSC can provide power support to the DC distribution network. When the control mode of the VSC is $U_{ac}\theta$, the AC side of the VSC can provide power support to the AC distribution network.

In normal operation, the upper-level power supply acts as a balanced node of the AC distribution network, while at least one VSC should be set in the $U_{dc}Q$ control mode to provide voltage support in the DC distribution network. When a fault occurs, if the AC distribution network loses the balance node due to the fault, the control mode of the connected VSC should be set to $U_{ac}\theta$. If the DC distribution network loses the balance node due to the fault, the control mode of the connected VSC should be set to $U_{dc}Q$. All control modes of the remaining VSCs should be set to PQ.

Fig. 2 is an AC/DC distribution network, which shows three typical faults that may occur in the network. The changes of the control mode of VSCs in different scenarios are shown in Table 1.

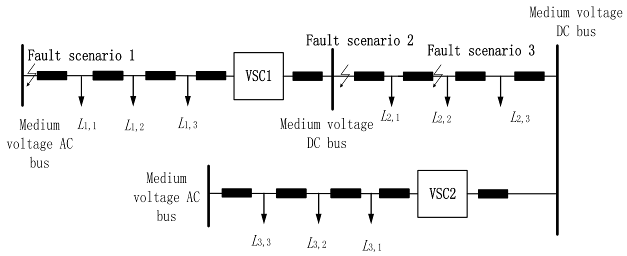

FIGURE 2. Fault states of the AC/DC distribution network.

TABLE 1. Change of the control mode of VSCs in different fault scenarios.

Control mode	Normal state	Fault scenario 1	Fault scenario 2	Fault scenario 3
VSC1	$U_{dc}Q$	$U_{ac}\theta$	PQ	$U_{dc}Q$
VSC2	PQ	$U_{dc}Q$	$U_{dc}Q$	$U_{dc}Q$

B. OPTIMAL LOAD SHEDDING MODEL

If there is line overload or voltage violation in AC/DC hybrid distribution networks after the fault occurs, the loads must be shed to maintain the distribution network reliable. Unlike the traditional AC distribution network, in the calculation of the optimal load shedding for the AC/DC hybrid distribution network, it is necessary to consider the effect of the AC/DC converters and other control equipment. In this regard, this paper proposes an optimal load shedding model that considers the optimization of the VSC parameters. The minimum load shedding model can be expressed as follows:

1) Objective function

$$\min f(x) = \sum_{j=1}^{\mathrm{N_L}} P_{shed,j} \tag{9}$$

where $P_{shed,j}$ is the shed active load of node j; N_L is the number of loads in the distribution networks.

2) Operational constraints

- Power flow constraints of the AC network [24]

$$\sum_{ji\in\Omega_{\mathrm{AC}}} \left(P_{ji} - r_{ji}I_{ji}^2\right) + P_i - P_{shed,i} = \sum_{ik\in\Omega_{\mathrm{AC}}} P_{ik} \tag{10}$$

$$\sum_{ji\in\Omega_{\mathrm{AC}}} \left(Q_{ji} - x_{ji}I_{ji}^2\right) + Q_i - Q_{shed,i} = \sum_{ik\in\Omega_{\mathrm{AC}}} Q_{ik} \tag{11}$$

$$U_i^2 - U_j^2 + \left(r_{ij}^2 + x_{ij}^2\right) I_{ij}^2 - 2\left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right) = 0 \tag{12}$$

$$I_{ij}^2 U_i^2 = P_{ij}^2 + Q_{ij}^2 \tag{13}$$

where P_{ij}/Q_{ij} is the active/reactive power flow from node i to node j; P_i/Q_i is the sum of the active/reactive power injected into node i; R_{ij}/X_{ij} is the resist/reactance of branch ij; Ω_{AC} is the set of AC nodes; $Q_{shed,j}$ is the shed reactive load of node j.

- Power flow constraints of the DC network

$$P_{ij} = U_i \sum_{j\in\Omega_{\mathrm{DC}}} U_j/r_{ij} \tag{14}$$

where Ω_{DC} is the set of DC nodes.

- Load shedding constraint

In the load shedding process, the power factor must be contained, which can be expressed as shown in equation (15).

$$P_i/Q_i = P_{\mathrm{shed},i}/Q_{\mathrm{shed},i} \tag{15}$$

- Operational constraints of the VSC

The active power and reactive power of the VSC should satisfy the following constraints.

$$P_{\mathrm{VSC}}^2 + Q_{\mathrm{VSC}}^2 \le S_{\mathrm{VSC}}^2 \tag{16}$$

$$P_{\mathrm{VSC,DC}} = -\left(P_{\mathrm{VSC,AC}} + \alpha\left|P_{\mathrm{VSC,AC}}\right|\right) \tag{17}$$

where P_{VSC}/Q_{VSC} is the active/reactive power through the VSC; S_{VSC} is the capacity of the VSC; $P_{VSC,AC}/P_{VSC,DC}$ is the active power from the AC/DC side of the VSC; α is the loss factor of the VSC.

- Secure operation constraints

$$\left(U^{min}\right)^2 \le U_i^2 \le \left(U^{max}\right)^2 \tag{18}$$

$$I_{ij}^2 \le \left(I^{max}\right)^2 \tag{19}$$

where U^{min}/U^{max} are the lower and upper bounds of the node voltage. I^{max} is the upper bound of the branch current.

Since the optimal load shedding model involves the optimization control of AC/DC converters and AC/DC power flow calculation, it cannot be directly solved by the solver. The artificial intelligence algorithm and heuristic algorithm mainly perform repeated corrections by continuously performing a power flow calculation, so the number of times of solving and time consumption are large. Therefore, this paper adopts the second-order cone optimization algorithm and considers the optimization of the VSC parameter to solve the optimal load-shedding model.

Cone optimization is a kind of mathematical programming using a convex cone in a linear space, which has strict requirements on the mathematical model of the optimization problem. The objective function of the cone optimization must be a linear function of the decision variable. The constraints are composed of linear equations or inequalities and nonlinear second-order cones or rotating cones [25]. Therefore, to use the second-order cone optimization to solve the optimal load-shedding model, the above model must be transformed.

First, the square of the node voltage amplitude is replaced by u_i, and the square of the branch current amplitude is replaced by i_{ij}. Equations (10)-(13) are transformed into (20)-(23):

$$\sum_{ji\in\Omega_{ac}} \left(P_{ji} - r_{ji}i_{ij}\right) + P_i - P_{shed,j} = \sum_{ik\in\Omega_{ac}} P_{ik} \tag{20}$$

$$\sum_{ji\in\Omega_{ac}} \left(Q_{ji} - x_{ji}i_{ij}\right) + Q_i - Q_{ahed,j} = \sum_{ik\in\Omega_{ac}} Q_{ik} \tag{21}$$

$$u_i - u_j + \left(r_{ij}^2 + x_{ij}^2\right) i_{ij} - 2\left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right) = 0 \tag{22}$$

$$i_{ij}u_i = P_{ij}^2 + Q_{ij}^2 \tag{23}$$

Then, the capacity constraint of the VSC (16) is transformed into a rotating cone constraint, as shown in (24):

$$P_{VSC}^2 + Q_{VSC}^2 \leq 2\frac{S_{VSC}}{\sqrt{2}}\frac{S_{VSC}}{\sqrt{2}} \tag{24}$$

Finally, the system power flow constraint (23) is transformed into a second-order cone constraint by relaxation, as shown in (25):

$$\left[2P_{ij} \quad 2Q_{ij} \quad i_{ij} - u_i\right]_2^T \leq i_{ij} + u_i \tag{25}$$

After these steps, the optimal load shedding model is converted from a nonlinear programming model, which is difficult to solve, to a second-order cone programming model, which can be solved by an existing mature algorithm package such as CPLEX. Hence, the requirements for fast convergence and optimal solution can be simultaneously satisfied.

C. RELIABILITY EVALUATION PROCESS

Based on the nonsequential Monte Carlo simulation, the process of reliability evaluation of AC/DC hybrid distribution networks with high integration of renewable energy can be expressed as follows and as shown in Fig. 3.

1) Read in the data and set the maximum number of simulations. Establish the annual output power curve of renewable energy and annual load curve based on historical data.

2) The state of the components in the system is sampled using the nonsequential Monte Carlo method. Simultaneously, the renewable energy output and load level are sampled.

3) Determine whether there is a failure component. If there is, go to step 4; otherwise, return to step 2.

4) Adjust the control mode of the VSCs and set an initial value to the control parameters.

5) Perform power flow calculation for the AC/DC hybrid distribution network to obtain the operation scenarios of distribution networks.

6) Determine whether the operational constraints of the system is violated. If yes, go to step 7; otherwise, return to step 2.

7) Solve the load shedding model with the control parameter optimization of VSCs and obtain the minimum load curtailments.

8) Determine whether the number of simulations has reached the preset value. If yes, the simulation process ends, and the reliability index is calculated and output; otherwise, return to step 2.

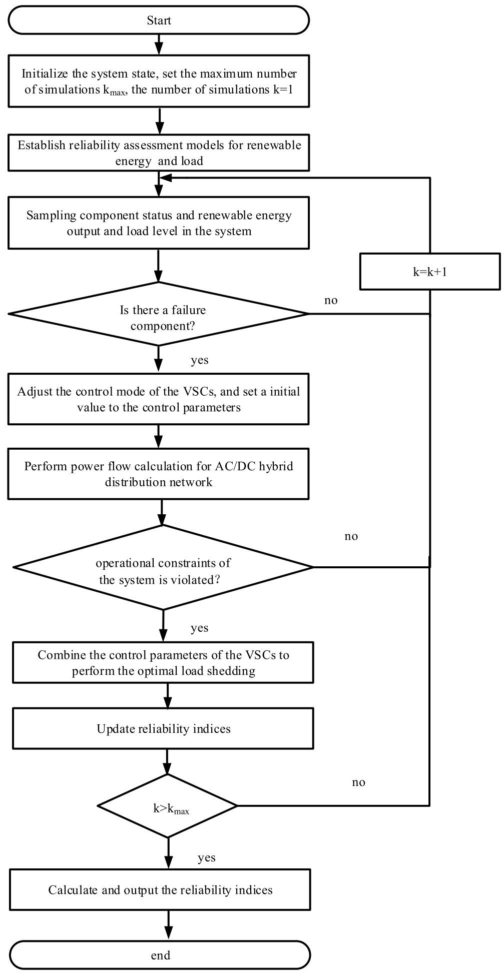

FIGURE 3. Flow chart of the reliability evaluation of AC/DC hybrid distribution networks with high penetration of renewable energy.

IV. CASE STUDY

The proposed method is used to evaluate the reliability of an AC/DC distribution network to verify its effectiveness. The case used is modified based on [26]. The circuit topology after the modification is shown in Fig. 4. The voltage level of the AC grid is 10 kV, and the voltage level of the DC grid is ±10 kV. The annual load curve and annual output power curve of WT and PV are derived from [27]. The reliability parameters of the AC/DC components can be obtained in the IEEE RBTS Reliability Standard Network [28] and IEEE 2007 reliability data [29], as shown in Table 2. The maximum load of the distribution network is 22 MW. Five DGs with the capacities of 2 MW are integrated into the networks. The capacity of each converter is 5 MW. In the normal state, the control mode of VSC1 is $U_{dc}Q$, and the control mode of VSC2 and VSC3 are PQ. The sampling number of the Monte Carlo simulation is 10^6. Three reliability indices are used in this paper: expected energy not supplied (EENS), system average interruption frequency index (SAIFI), and system average interruption duration index (SAIDI). The switching time of the tie switch is 0.5 hours.

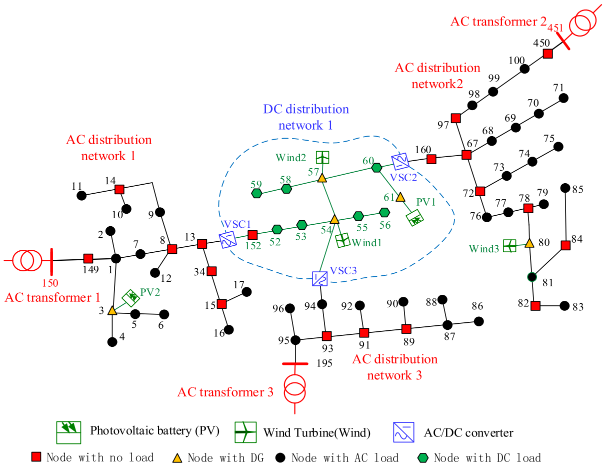

FIGURE 4. Structure of the modified AC/DC distribution network.

TABLE 2. Reliability parameters of AC/DC components.

Component	Fault rate (occ./year)	Repair time (h)	Replacement time (h)
Transformer	0.015	200	10
VSC	2.6828	4.7193	/
Line	0.04 /km	30	/
Buses	0.001	2	/

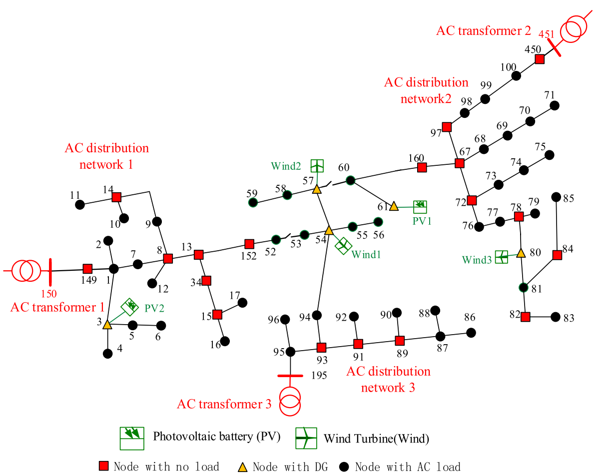

FIGURE 5. Structure of the comparison AC distribution network.

To analyze the effect of the DC components on the reliability, an AC distribution network is set up as a comparison case based on the above AC/DC distribution network. The DC lines are replaced by AC lines while the VSCs are replaced by tie switches, as shown in Fig. 5.

Three scenarios are set to study the characteristics of the AC/DC distribution network.

Scenario I: The load curves of all buses are identical. The renewable energy penetration is constant.

Scenario II: The load curves in the AC distribution network 2 are resident; other load curves are general industrial and commercial. The renewable energy penetration is constant.

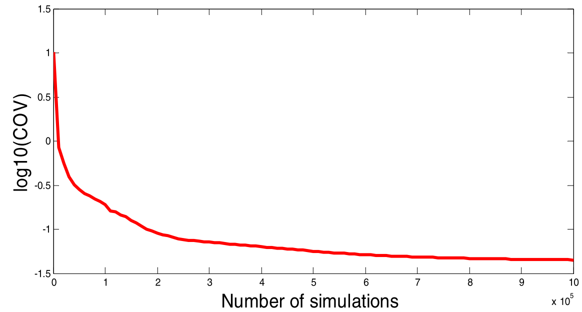

FIGURE 6. Convergence curve of the Monte Carlo simulation.

TABLE 3. Reliability indices in scenario I.

	EENS MWh/Year	SAIFI Times/Year	SAIDI Hours/Year
AC network	9.2131	0.0816	4.0802
AC/DC network	7.8075	0.0978	2.9398

Scenario III: The load curves of all buses are identical. The penetration of renewable energy is 30-90%.

Scenario I: The Monte Carlo convergence standard is according to the coefficient of variation (COV) of the EENS. When the value of COV is less than 0.05, the simulation process is considered to be convergent. The curve of $log_{10}(COV)$ throughout the calculation process is shown in Fig. 6.

The results are shown in Table 3. The EENS and SAIDI of the AC/DC hybrid distribution network are lower than those of the AC distribution network, so it is more reliable than traditional AC distribution network.

Due to the higher fault rate of the VSC, the AC/DC network has a slightly higher SAIFI than the AC network. In contrast, the AC/DC network has a lower SAIDI than the AC network. The main reason is that it takes more time to operate the tie switches in the AC network, while VSCs have faster adjustment speeds in the AC/DC network. With the improvement of the DC power electronics technology, the reliability of the AC/DC network will be even higher than the existing results.

To explain the lower EENS of the AC/DC distribution network compared to the AC distribution network, the N-1 analysis is used to analyze the reliability improvement by the VSCs, as shown in Fig. 7. The load sheddings of failure 16-71 of the two networks are identical. Thus, the reliability improvement of the hybrid network is a result of Fault 1-15.

Detailed analysis shows that those 15 fault states consist of three failure types that lead to load shedding only in the traditional AC distribution network, as shown in Table 4.

In summary, the lower EENS of the AC/DC distribution network compared to the AC distribution network because of two reasons:

1) VSCs can provide voltage support to the distribution network under extreme failure scenarios. When the failure occurs in the traditional AC network, the voltage drop may result in load shedding. However, in the AC/DC hybrid

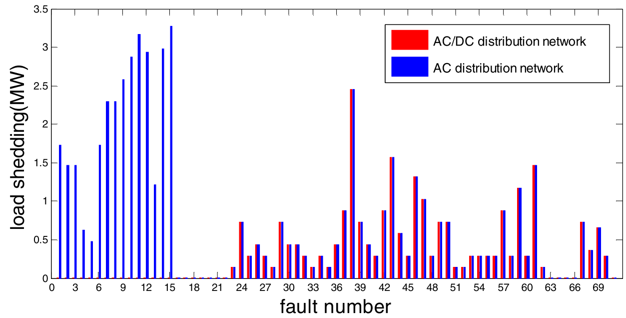

FIGURE 7. Comparison of load shedding in all N-1 faults.

TABLE 4. Fault scenario for the first 15 faults.

Fault type	Fault component	Overlimit node or line
A (Failure 1-5)	AC transformer 1, AC line 150-149, 147-1, 1-7, 7-8	The voltage of node 4/5/6/11/10 is too low
B (Failure 6-12)	AC transformer 2, AC line 450-451, 450-100, 99-100, 98-99, 98-97, 97-67	The voltage of node 76 to 85 is too low; the line current of AC line 95-195 is too high
C (Failure 13-15)	AC transformer 3, AC line 95-195, 95-93	The voltage of node 86/87/88/89 is too low; the line current of AC line 450-451 is too high

network, the voltage drop can be relieved due to the voltage support ability of VSC and improve the system reliability.

2) In the AC/DC network, each AC network may have multiple backup sources because of the connection of the DC network. Due to the flexibility of the operation mode of the VSC, the network can have continuous power control capability, which effectively reduces the load shedding. In contrast, it is difficult for the AC system to transfer all loads through the switching operation, and it takes a certain amount of time. Therefore, the AC/DC network has a stronger transfer capability and higher reliability.

To verify the results of this paper, a state enumeration method in literature [30] is used to perform on the exactly same AC/DC distribution network. In the state enumeration method, the fluctuation of renewable energy and load are processed by the clustering method. The results of the state enumeration method are related to the maximum number of failures considered, which is shown in the TABLE 5.

Based on the result, several conclusions can be drawn:

1) As the number of failures considered by the state enumeration method increases, the result of the state enumeration method is gradually approaching the results of the proposed method, which illustrates the accuracy of the proposed method.

2) With N-1 failure considered, the calculation time of the state enumeration method is much less than the proposed method, but the error of the result is very large. With N-2 failure considered, the accuracy is better than the case while considering N-1 failure, but the calculation time of the state enumeration method exceeds the proposed method. This

TABLE 5. Reliability indices of AC/DC network using different method.

AC/DC network	EENS MWh/Year	SAIFI Times/Year	SAIDI Hours/Year	Calculation time/Second
The method we proposed	7.8075	0.0978	2.9398	44367
state enumeration method(N-1 failure considered)	7.2056	0.0917	2.7507	713
state enumeration method(N-2 failure considered)	7.4526	0.0934	2.8018	66327

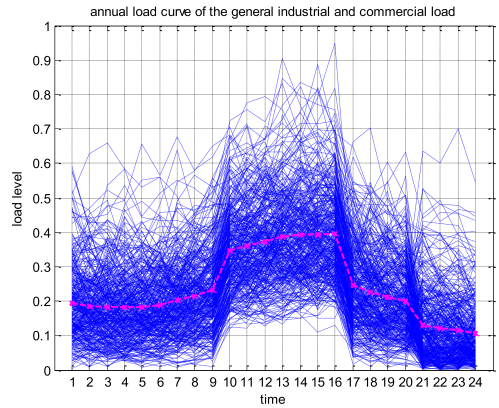

FIGURE 8. Annual load curve of the residential load.

TABLE 6. Reliability indices in scenario II.

	EENS MWh/Year	SAIFI Times/Year	SAIDI Hours/Year
AC network	10.5114	0.0944	4.7217
AC/DC network	7.9096	0.0978	2.9398

result indicates that the proposed method is more efficient and precise in the case while considering multiple failures which is closer to the actual operation case.

Scenario II: For the resident loads, the peaks of loads exist at night. In contrast, the peaks of industrial and commercial loads exist in the daytime, which leads to changes in the system operation mode. The annual load curve of the residential load is shown in Fig. 8, and the annual load curve of the general industrial and commercial load is shown in Fig. 9. The abscissa in the figure represents a 24 hour day, and there are 8760 data points in total for 365 days. The red dotted line in the figure indicates the trend of the load level, which is represented by the standard value.

The results are shown in Table 6.

Compared with scenario I, the changes of the reliability indices of the two systems are shown in Fig. 10. For the AC/DC network, the reliability indices are nearly identical in the two scenarios. However, for the AC network, the

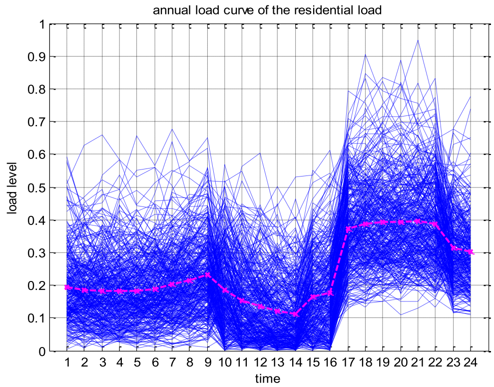

FIGURE 9. Annual load curve of the general industrial and commercial loads.

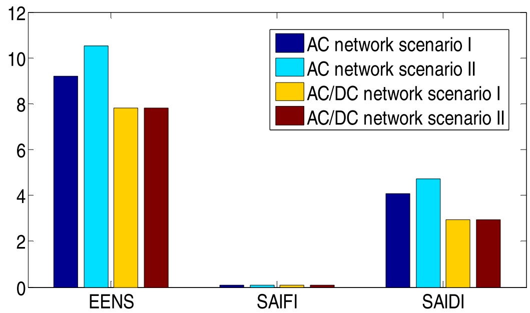

FIGURE 10. Changes of the reliability indices in different scenarios.

reliability indices in scenario II are higher than those in scenario I.

In scenario II, the EENS and SAIDI of the AC distribution network are even greater than the AC/DC hybrid distribution network compared to scenario I. In addition to the three failure types in scenario I, one more type of failure state that may cause power loss only in the AC distribution network: when the sampling time is at night, the load level of the AC distribution network 2 is relatively high. At the same time, if the output of renewable generation is low, there may be a voltage drop at the end node of the line, which results in load shedding. In this situation, for the AC/DC distribution network, due to the flexible and controllable capability of VSC and DC link, when AC distribution network 2 is overloaded, AC distribution networks 1 and 3 can transfer power to AC distribution network 2 to avoid voltage or current violations.

From the above results, two others characteristics of the AC-DC distribution network can be drawn: flexibility and controllability. When an AC distribution network cannot provide sufficient power due to excessive load, the DC link and VSC can flexibly perform power transmission to provide the required power; otherwise, when the load is relatively low, a reverse power transmission can be performed to provide power support for other distribution networks. However, in the traditional AC distribution network, such power transmission cannot occur, so the aforementioned fault scenario may occur and cause a load shedding process.

Therefore, when there are different types of loads in several areas of the system, the AC/DC distribution network can greatly adapt to the changes of the load distribution due to the flexibility and controllability of its operating mode, which improves the reliability of the system.

Scenario III: The renewable energy penetration in this paper is defined as the ratio of the maximum power output of renewable energy to the maximum load level of the system. The EENS and abandoned wind and light (AWAL) of the two systems under different renewable energy penetration levels are shown in Table 7.

TABLE 7. EENS and AWAL of two systems under different renewable energy penetration levels.

	renewable energy penetration						
(MWh/Year)	30%	40%	50%	60%	70%	80%	90%
EENS of AC system	9.9831	9.5372	9.0134	8.0732	7.5254	7.2318	7.0834
EENS of AC/DC system	7.8075	7.4939	7.0897	6.9543	6.8298	6.8136	6.8192
AWAL of AC system	0	0	0	0.6726	1.2561	4.4106	9.1624
AWAL of AC/DC system	0	0	0	0	0.4234	2.0006	5.8304

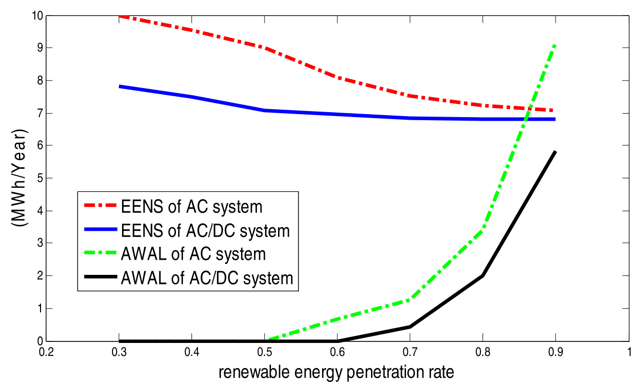

FIGURE 11. EENS and AWAL of two systems under different renewable energy penetration levels.

The trend is shown in Fig. 11.

Fig. 11 shows that when the renewable energy penetration is low, if the power generation level is low, the traditional AC distribution network may not be able to provide sufficient power, which violates the lower limit of the node voltage. In the AC/DC distribution network, since the DC link and VSC can be flexibly controlled to provide the required power, the violation of the lower limit of the node voltage is prevented, and the system reliability is improved.

When renewable energy penetration is high, the AC distribution network may not completely eliminate the electricity generated by renewable energy, which violates the upper limit of the node voltage and the system operational constraints, resulting in the abandonment of wind and light. The AC/DC distribution network can flexibly adjust the power imbalance in the system, reduce the violation of the upper limit of the node voltage, and improve the consumption capacity of renewable energy.

In short, the AC/DC distribution network can greatly exploit the power supply ability of renewable energy due to its flexible and controllable characteristics. It can reduce the occurrence of the situation where the system operational constraints are violated when the renewable energy penetration is low or high, which improves the reliability of the system.

V. CONCLUSION

The high penetration of renewable energy and application of the AC/DC hybrid distribution technique make the traditional reliability assessment method no longer applicable. In this paper, the probability models of renewable energy and load are established. Then, multiple control modes of VSC are modeled considering different fault scenarios. Thereafter, an optimal load shedding model for the AC/DC hybrid distribution network is proposed. Based on this model, a reliability assessment approach is developed for AC/DC hybrid distribution networks. Case studies are conducted, and the following conclusions are drawn:

1) The proposed approach considers regulation ability of the VSC. It fully simulates the control characteristics and failure modes of VSC, establishes power flow and optimization algorithm which are suitable for AC/DC distribution network. Therefore, this method can effectively evaluate the reliability of AC/DC hybrid distribution network.

2) Compared with the state enumeration method, the result of the proposed method is more accurate. It is more efficient and precise in the case while considering multiple failures which is closer to the actual operation case. In addition, the proposed method can better handle the fluctuation of renewable energy and load.

3) Due to the flexible and controllable characteristics of VSC, the AC/DC distribution network is generally more reliable than the traditional AC distribution network. The AC/DC distribution network can well adapt to the changes of the load distribution, better exploit the integration capability of renewable energy, and consequently improve the reliability. Thus, this paper clarifies the improvement of reliability brought by AC/DC distribution network, and indicates the occasions that are more suitable for establishing AC/DC distribution network.

REFERENCES

[1] E. Hajipour, M. Bozorg, and M. Fotuhi-Firuzabad, “Stochastic capacity expansion planning of remote microgrids with wind farms and energy storage,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 491–498, Apr. 2015.

[2] L. Che, X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, “Optimal interconnection planning of community microgrids with renewable energy sources,” *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1054–1063, May 2017.

[3] A. Ehsan and Q. Yang, “State-of-the-art techniques for modelling of uncertainties in active distribution network planning: A review,” *Appl. Energy*, vol. 239, pp. 1509–1523, Apr. 2019.

[4] A. Kwasinski, “Quantitative evaluation of DC microgrids availability: Effects of system architecture and converter topology design choices,” *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 835–851, Mar. 2011.

[5] P. Zhang and W. Li, “Boundary analysis of distribution reliability and economic assessment,” *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 714–721, May 2010.

[6] C. L. T. Borges, “An overview of reliability models and methods for distribution systems with renewable energy distributed generation,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 4008–4015, Aug. 2012.

[7] R. Billinton and Y. Gao, “Multistate wind energy conversion system models for adequacy assessment of generating systems incorporating wind energy,” *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 163–170, Mar. 2008.

[8] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, “Role of outage management strategy in reliability performance of multi-microgrid distribution systems,” *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2359–2369, May 2018.

[9] G. Li, Z. Bie, H. Xie, and Y. Lin, “Customer satisfaction based reliability evaluation of active distribution networks,” *Appl. Energy*, vol. 162, pp. 1571–1578, Jan. 2016.

[10] Z. Bie, P. Zhang, G. Li, B. Hua, M. Meehan, and X. Wang, “Reliability evaluation of active distribution systems including microgrids,” *IEEE Trans. Power Syst.*, vol. 27, no. 4, pp. 2342–2350, Nov. 2012.

[11] T. Adefarati and R. C. Bansal, “Reliability assessment of distribution system with the integration of renewable distributed generation,” *Appl. Energy*, vol. 185, pp. 158–171, Jan. 2017.

[12] M. Ding, J.-J. Wang, and Q. Song, “Reliability modeling and redundancy analysis of converter valves for VSC-HVDC power transmission system based on k-out-of-n:G model,” *Power Syst. Technol.*, vol. 32, no. 21, pp. 32–41, Nov. 2008.

[13] M. Ding, X. Li, and R. Bi, “Reliability evaluation of AC-DC hybrid transmission system with VSC-HVDC,” *Power Syst. Technol.*, vol. 32, no. 16, pp. 53–58, Aug. 2008.

[14] C. J. Greiner, T. Langeland, J. Solvik, and Ø. A. Rui, “Availability evaluation of multi-terminal DC networks with DC circuit breakers,” in *Proc. IEEE Trondheim PowerTech*, Trondheim, Norway, Jun. 2011, pp. 1–8.

[15] D. Liang, C. Qin, S. Wang, and H. Guo, “Reliability evaluation of DC distribution power network,” in *Proc. China Int. Conf. Electr. Distrib. (CICED)*, Tianjin, China, Sep. 2018, pp. 654–658.

[16] Z. Ling, Y. Shan-shui, C. Lin, and W. Li, “Reliability analysis of DC power distribution network based on minimal cut sets,” in *Proc. 14th Eur. Conf. Power Electron. Appl.*, Birmingham, U.K., Aug./Sep. 2011, pp. 1–7.

[17] S. Xie and X. Wang, “Reliability estimation of AC/DC hybrid power system,” *Electr. Power Auto. Equip.*, vol. 31, no. 7, pp. 10–16, Jul. 2011.

[18] L. Wang, G. Wang, and B. Li, “An optimal load shedding model for AC/DC hybrid transmission system adequacy assessment,” *Auto. Electr. Power Syst.*, vol. 35, no. 7, pp. 7–12, Apr. 2011.

[19] C. MacIver, K. R. W. Bell, and D. P. Nedić, “A reliability evaluation of offshore HVDC grid configuration options,” *IEEE Trans. Power Del.*, vol. 31, no. 2, pp. 810–819, Apr. 2016.

[20] B. Wang, X. Wang, X. Wang, C. Shao, and S. Liu, “Reliability evaluation of voltage-source converter-based multi-terminal direct current integrated offshore wind plants,” *IET Renew. Power Gener.*, vol. 10, no. 6, Sep. , Jul. 2016.

[21] Y. Guo, H. Gao, and Q. Wu, “A combined reliability model of VSC-HVDC connected offshore wind farms considering wind speed correlation,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 4, pp. 1637–1646, Oct. 2017.

[22] H. Xie, J. He, and Z. Bie, “Reliability evaluation of large-scale AC.DC hybrid power grid based on second-order conical shear load model,” *Power Syst. Technol.*, vol. 40, no. 12, pp. 3761–3767, Dec. 2016.

[23] J. Zeng, X. Xu, and Y. Zhao, “Reliability comparison of AC and DC distribution network,” *Power Syst. Technol.*, vol. 38, no. 9, pp. 2582–2589, Sep. 2014.

[24] M. E. Baran and F. F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing,” *IEEE Trans. Power Del.*, vol. 4, no. 2, pp. 1401–1407, Apr. 1989.

[25] P. Li, H. Ji, C. Wang, J. Zhao, G. Song, F. Ding, and J. Wu, “Coordinated control method of voltage and reactive power for active distribution networks based on soft open point,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 4, pp. 1430–1442, Oct. 2017.

[26] C. Sun, P. Li, C. Wang, J. Wu, D. Lin, and F. Xing, “A novel power flow algorithm for active distribution system with multiple DC components,” *Auto. Electr. Power Syst.*, vol. 39, no. 21, pp. 59–65, Nov. 2015.

[27] J. Zhao, M. Zhang, H. Yu, H. Ji, G. Song, P. Li, C. Wang, and J. Wu, "An islanding partition method of active distribution networks based on chance-constrained programming," *Appl. Energy*, vol. 242, pp. 78–91, May 2019.
[28] R. N. Allan, R. Billinton, I. Sjarief, L. Goel, and K. S. So, "A reliability test system for educational purposes-basic distribution system data and results," *IEEE Trans. Power Syst.*, vol. 6, no. 2, pp. 813–820, May 1991.
[29] *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*, IEEE Standard 493, Jun. 2007.
[30] K. Zou, A. P. Agalgaonkar, K. M. Muttaqi, and S. Perera, "An analytical approach for reliability evaluation of distribution systems containing dispatchable and nondispatchable renewable DG units," *IEEE Trans. Smart Grid*, vol. 5, no. 6, pp. 2657–2665, Nov. 2014.

WEI WEI (M'15) received the D.S. degree in electrical engineering from Tianjin University, Tianjin, China, in 2004. He is currently an Associate Professor with the School of Electrical and Information Engineering, Tianjin University. His research interests include planning and operation of smart distribution power systems and integrated energy systems.

YITONG ZHOU received the B.S. degree in electrical engineering from Tianjin University, in 2017, where she is currently pursuing the M.S. degree in electrical engineering and its automation. Her current research interests include secure operation of distribution networks, reliability evaluation of ac/dc hybrid distribution networks, and flexible operation of distribution networks based on controllable resources.

JIE ZHU, photograph and biography not available at the time of publication.

KAI HOU (M'16) received the Ph.D. degree in electrical engineering from Tianjin University, Tianjin, China, in 2016. He is currently a Lecturer with the Electrical Engineering Department, Tianjin University. His research interests include reliability and risk assessments of power systems, integrated energy systems, and smart grid.

HE ZHAO, photograph and biography not available at the time of publication.

ZIJIN LI, photograph and biography not available at the time of publication.

TAO XU, photograph and biography not available at the time of publication.