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Short-Term Reliability Assessment for Islanded Microgrid Based on Time-Varying Probability Ordered Tree Screening Algorithm

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ABSTRACT As the penetration rate of intermittent renewable energy continues to increase in a microgrid, the operational model of interconnected microgrid changes faster and more frequently. To maintain the stability and security of the microgrid, short-term reliability assessment is necessary and must be adapted to the time-varying characteristics of the islanded microgrid. In view of this, this paper proposes a new short-term reliability assessment method based on the time-varying probability ordered tree screening algorithm. First, a screening algorithm based on the time-varying probability ordered tree is proposed, and the number of system states is reduced by screening the system state with high probability at each time. Then, according to the different impact ranges, two event types of load point power supply interruption is defined, and the formulas are given for calculating the time-varying probability. On this basis, the loss of load probability (LOLP) index and the expected demand not supplied (EDNS) index are defined to assess the short-term reliability of the islanded microgrid. Finally, the proposed method is modeled by MATLAB, and a case study is performed on the European low-voltage microgrid system to verify its correctness and effectiveness.

INDEX TERMS Analytic method, islanded microgrid, probabilistic sequence, master-slave control strategy, short-term reliability assessment, time-varying probability ordered tree.

I. INTRODUCTION

In recent years, microgrid has been rapidly developed under the background of energy shortage and environmental degradation [1]–[2]. The microgrid includes interconnected microgrid and independent microgrid, the former has grid-connected mode and islanded mode, while the independent microgrid only has islanded mode. As usual, the interconnected microgrid is connected to the main grid, and its reliability is mainly determined by the main grid. Once the main grid faults occurred, the interconnected microgrid often converts into the unplanned islanded mode and continues to supply power to the load. Under the islanded mode, the operation time of the microgrid becomes shorter, and the short-term factors such as distributed generation (DG) faults, DG output power, load fluctuation, line faults, and communication system faults and etc., have more influence on the stability and security of the islanded microgrid. With more and more short-term factors emerging in the microgrid, the 2004 IEEE PES conference re-emphasized the importance of short-term reliability assessment of power systems [3].

In addition, microgrid usually adopts the layered control strategy which is composed of a three-layer control system [4]–[6]. The bottom layer is the local controller layer, which includes DG controller, load controller and other automatic device controller. The coordination control strategy among these controllers can be divided into master-slave control and peer-to-peer control. Until now, the master-slave control strategy is widely applied in the practical microgrid demonstration project, and the microgrid system under peer-to-peer control strategy is still in the laboratory research stage [7]. Moreover, under the master-slave control strategy,

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once the fault of the main control unit (MCU) or the communication system occurred, the microgrid may collapse [7]. Therefore, this paper focuses on the short-term reliability assessment of the islanded microgrid under master-slave control strategy.

There are two main characteristics of short-term reliability assessment for islanded microgrid. Firstly, the fault probability of component is low and time-varying. Secondly, the combination of random output of DG and system states makes the sampling space very large. Up to now, many reliability assessment methods for power system have been proposed, which can be divided into Monte Carlo simulation (MCS) method and analytical method. The MCS method uses the random sampling to obtain the random output of DG and the system states [8]–[11], in which, MCS method can set the size of the sampling space to be very large to consider most operation scenarios, so it is widely used in the long-term reliability assessment for islanded microgrid. However, the traditional MCS method is insensitive to low-probability events which must be considered in the short-term reliability assessment, so it is not suitable for the short-term reliability assessment for islanded microgrid. The analytic method has clear physical concepts and precise mathematical models by enumerating the various states of the system and performing consequence analysis and probability calculation [12], [13]. But the sampling space of the islanded microgrid is usually very large, so the traditional analytic method cannot enumerate all states. Therefore, [12] proposes a fault tree model with important load to assess the short-term reliability of the islanded microgrid, but the impact of uncertain factors such as wind and illumination on system reliability are not taken into account. In [13], a short-term reliability assessment method for islanded microgrid with time-varying universal generating function (TVUGF) is proposed, but it only considers the single-fault state of the system. Moreover, the control strategy will bring a certain impact on the operational state of the islanded microgrid, but [12] and [13] did not take this into account. In [14], a short-term reliability assessment method for the islanded microgrid under the master-slave control strategy based on time-varying dynamic fault tree (TVDFT) is proposed. But it belongs to the MCS method in essence, and the problem of low probability events has not completely been solved.

In this context, this paper uses the probability ordered tree (POT) proposed in [15] as the basic idea of the screening algorithm. On basis of that, this paper proposes a new short-term reliability assessment method. The main contributions of this paper can be summarized as follows:

1) A time-varying probability ordered tree (TVPOT) screening algorithm is proposed to obtain the state of the system with high time-varying probability at each moment, which improves the efficiency of the short-term reliability assessment.
2) The load point power supply interruption is taken as the target event, and it is defined into the Global Type and the Local Type according to different impact ranges, which provide a new idea for power system reliability assessment.
3) The impact of the control strategy is considered in the short-term reliability assessment, which can truly reflect the short-term reliability level of the islanded microgrid.

The rest of this paper is organized as follows. Section II proposes TVPOT screening algorithm. In section III, Two event types of load point power supply interruption are defined and the formula for calculating the time-varying probability is given. In Section IV, the short-term reliability indexes are defined and the short-term reliability assessment process is given. In Section V, the short-term reliability assessment method is modeled by MATLAB, and a case study is performed on the European low-voltage microgrid system to verify its correctness and effectiveness. Section VI summaries the main conclusions of this paper.

II. TVPOT SCREENING ALGORITHM

The purpose of the screening algorithm is to screen out the events with high probability. This section introduces the concept of time-varying probability distance at first, and then a TVPOT screening algorithm is proposed.

A. COMPONENT TIME-VARYING PROBABILITY

Most of the components in power system are repairable components, so only the reliability of repairable components is considered. Regardless of the planned outage of the component, a two state reliability model is adopted, and the state space is {0, 1}, in which 0 represents the working state and 1 represents the fault state. Then, for a system with n components, its system state S can be expressed as:

$$S=[x_1, x_2, \ldots, x_n] \tag{1}$$

where x_1-x_n are the state of all components.

Assuming that the λ (fault rate) and the μ (repair rate) of the two state components are constant, and then the working time and fault repairing time of the components are exponentially distributed [16], [17]. Assuming that the component is in the working state at the initial moment ($t = 0$), the component probability of each state at time t is:

$$\begin{aligned} \boldsymbol{p}(t) &= [1 - p(t), p(t)] \\ &= \left[\frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu}e^{-(\lambda+\mu)t}, \frac{\lambda}{\lambda+\mu}\left(1 - e^{-(\lambda+\mu)t}\right)\right] \end{aligned} \tag{2}$$

where 1-$p(t)$ is the working condition probability of the component at t; $p(t)$ is the probability of fault state of the component at t.

Refer to (2), since the state probability of the component changes with time, $\boldsymbol{p}(t)$ is called the time-varying probability of the component.

B. TIME-VARYING PROBABILITY DISTANCE

Assuming that the system state S consists of the states of n components, the time-varying probability of n component fault states are expressed as $p_1(t)$,$p_2(t)$, ..., $p_n(t)$ respectively, and the time-varying probability of the S is:

$$P_S(t) = \prod_{i\in\delta_f} p_i(t) \prod_{i\in\delta-\delta_f} 1 - p_i(t) \tag{3}$$

where δ is the set of all components in the system; δ_f is the set of fault state components in the system.

From the deformation of (3), we can obtain:

$$P_s(t) = \prod_{i\in\delta} 1 - p_i(t) \prod_{i\in\delta_f} \frac{p_i(t)}{1 - p_i(t)} \tag{4}$$

According to the definition of the probability distance in [15], the reciprocal of (4) is taken as the logarithm of the base 10, which can be obtained by:

$$\lg \frac{1}{P_s(t)} = \lg \frac{1}{\prod_{i\in\delta} 1 - p_i(t)} + \sum_{i\in\delta_f} \lg \frac{1 - p_i(t)}{p_i(t)} \tag{5}$$

Refer to (5), assuming that the normal system state is S_1, the time-varying probability distance of S_1 is:

$$L_{S_1}(t) = \lg \frac{1}{\prod_{i\in\delta} 1 - p_i(t)} \tag{6}$$

The time-varying probability distance of ith component is obtained by:

$$L_i(t) = \lg \frac{1 - p_i(t)}{p_i(t)} \tag{7}$$

where 0< $p_i(t)$ <1-$p_i(t)$ <1 and $L_i(t)$ >0. If $p_i(t)$ is greater than 0.5, the normal and fault states are interchanged in the calculation and are interchanged in the result.

Equation (5) can be expressed as time-varying probability distance, which is available:

$$L_S(t) = \lg \frac{1}{P_S(t)} = L_{S_1}(t) + \sum_{i\in\delta_f} L_i(t) \tag{8}$$

Refer to (8), it can be concluded that the larger $P_S(t)$, the smaller $L_S(t)$.

C. TIME-VARYING PROBABILITY ORDERED TREE

According to (7), the probability distance of all components at t are calculated and arranged in order from small to large. For certain t, suppose that the system has n components, numbered 1, 2 ..., n. The TVPOT is generated according to the following rules:

1) The root-node represents the normal system state (S_1).
2) Each child-node represents a fault component.
3) Supposing that the node number is b, then this node has n-b child-nodes, and the numbers from left to right are $b+1, b+2, \ldots, n$.
4) The distance from each child-node to its parent is the time-varying probability distance of the component.

Taking the 3 components system as an example, in this system, the 0-node is a root-node. The time-varying probability distance of each component at t are $L_1(t)$, $L_2(t)$ and $L_3(t)$ ($L_1(t) > L_2(t) > L_3(t)$). According to the above rules, the generated TVPOT is shown in Figure 1.

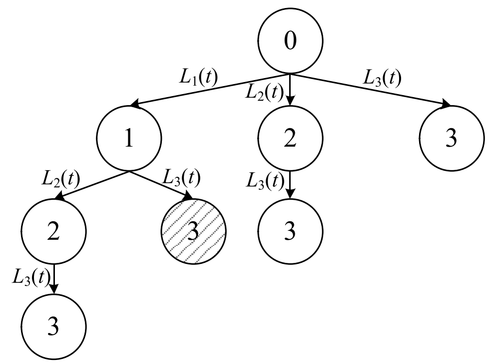

FIGURE 1. The TVPOT of 3 components system.

The following rules can be draught from the generation rules of time-varying probability distance and TVPOT:

1) Each node to the root-node path constitutes a fault system state, the time-varying probability distance of the fault system state is the path length, and the path is unique.
2) Each node may represent a system state or be a component that forms the system state of its child-node. In Figure 1, the shadow node represents the fault of 1st and 3rd component. Refer to (8), the time-varying probability distance of the fault system state is $L_{S_1}(t) + L_1(t) + L_3(t)$.
3) For a system with n components, the system has 2^n states, and each node in the TVPOT represents a system state.
4) The time-varying probability distance of the parent-node is smaller than its child-nodes; under the same parent-node, the time-varying probability distance of the left-child-node is smaller than its right-child-node.

D. TVPOT SCREENING ALGORITHM

For a system with n components, if it is necessary to obtain some system states with large time-varying probability, the solution scale will reach 2^n and a combined explosion may occur when using the traditional comparison method. To address this problem, a time-varying probability ordered tree screening algorithm is proposed.

Definition two set:

1) Selected set, represented as Φ_{past}

Φ_{past}: the nodes in the selected set are obtained by TVPOT screening algorithm.

2) Selecting set, represented as Φ_{now}

Φ_{now}: the nodes in the selecting set need to select by TVPOT screening algorithm.

TVPOT screening algorithm is the basic idea of continuously updated elements in Φ_{past} and Φ_{now}, and then gets the system state. Suppose $\delta\%$ is the cutoff accuracy of the screening algorithm, and $k(t)$ is the number of system

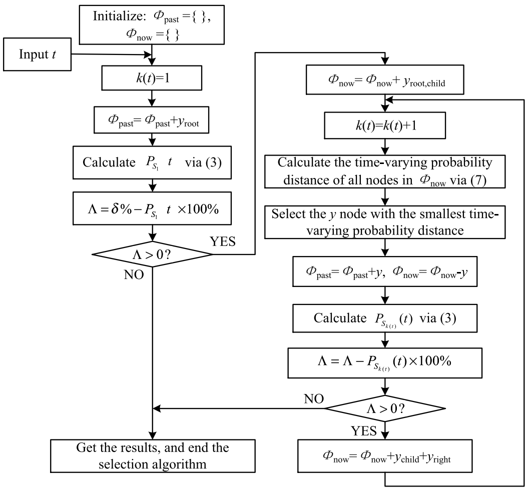

FIGURE 2. Flowchart of TVPOT screening algorithm.

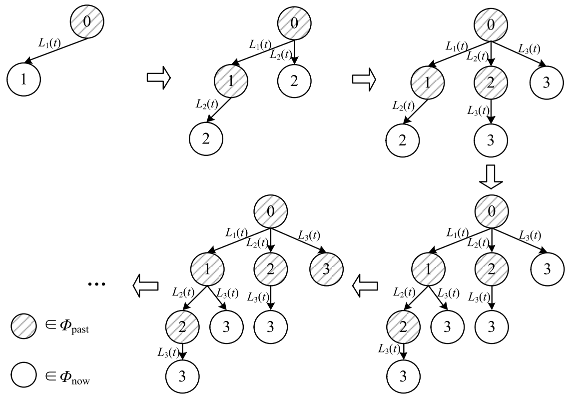

FIGURE 3. Process of screening algorithm.

states obtained by the screening algorithm. The flowchart of TVPOT screening algorithm is shown in Figure 2, and the specific steps are as follows:

1) Initialize: Φ_{past} and Φ_{now} as a null set, $k(t)$ =1.
2) $\Phi_{past} = \Phi_{past} + y_{root}$ (y_{root} is the root-node). Calculate $P_{S_1}(t)$ via (3).
3) Judge $\Lambda = \delta\% - P_{S_1}(t) \times 100\% > 0$? If so, $\Phi_{now} = \Phi_{now} + y_{root,child}$ ($y_{root,child}$ is the left-child-node of the root-node), $k(t) = k(t) + 1$; otherwise, get the results and end the screening algorithm.
4) Calculate the time-varying probability distance of all nodes in Φ_{now} via (7), and select the y node with the smallest time-varying probability distance, $\Phi_{past} = \Phi_{past} + y$, $\Phi_{now} = \Phi_{now} - y$. Calculate the time-varying probability $P_{S_{k(t)}}(t)$ of the node y via (3).
5) Calculate Λ via (9), and judge Λ >0? If so, $\Phi_{now} = \Phi_{now} + y_{child} + y_{right}$ (y_{child} is the left-child-node of the node y; y_{right} is the right-node of the node y), $k(t) = k(t)+1$, then go back to step 4; otherwise, get the results and end the screening algorithm.

$$\Lambda = \Lambda - P_{S_{k(t)}}(t) \times 100\% \tag{9}$$

Taking the TVPOT as shown in Figure 1 as an example, supposing that $L_1(t) > L_2(t) > L_3(t)$, $L_1(t) + L_2(t) > L_3(t)$, $\delta\% = 100\%$, the screening process of 3 components system is shown in Figure 3.

TVPOT screening algorithm only needs to solve the $k(t)$ times local optimal solution, and the calculation efficiency is greatly improved.

III. TIME-VARYING PROBABILITY CALCULATION OF LOAD POINT POWER SUPPLY INTERRUPTION

A. TWO TYPES OF LOAD POINT POWER SUPPLY INTERRUPTION

There are many factors affecting the short-term reliability of the islanded microgrid. The load point power supply interruption is taken as the target event. According to different impact ranges, two event types of load point power supply interruption are defined as:

⇒ Global Type: when this type of event occurs, the power supply of all load points is interrupted. This type includes the faults of the MCU and the communication system.

⇒ Local Type: when this type of event occurs, the power supply of partial load points is interrupted. There are two main reasons for this type. On the one hand, the feeder between the load point and the MCU fails. On the other hand, the DG or the energy storage system (ESS) contained in the island cannot meet the load required.

For convenience of presentation, the load point to be assessed is denoted by LPj.

The time-varying probability of occurrence of Global Type events is:

$$f_{Global}(S, \mathrm{LP}j, t) = P_S(t)\,(1 - \varphi(S)) \tag{10}$$

where $\varphi(\bullet)$ is a indicating function of Global Type, and the function is as shown in (11).

$$\varphi(S) = (1 - x_{MCU})(1 - x_{CS}) \tag{11}$$

where x_{MCU} is the MCU state; x_{CS} is the communication system state.

It can be known from (10) and (11) that $\varphi(\bullet)$ is only related to system state. If x_{MCU} and x_{CS} are all 0, then $\varphi(S,\mathrm{LP}j)$ =1, $f_{pa}(S,\mathrm{LP}j,t)$ =0, LPj power supply is normal; conversely, LPj power supply is interrupted due to the Global Type.

The time-varying probability of the Local Type is related to the system state, the output of each DG and ESS, and the load level. Therefore, the time-varying probability of occurrence of Local Type events is:

$$f_{Local}(S, \mathrm{LP}j, t) = P_S(t)\phi(S, \mathrm{LP}j, t) \tag{12}$$

where $\phi(\bullet)$ is a indicating function of Local Type.

Different from $\varphi(\bullet)$, $\phi(\bullet)$ is a time-varying probability to be solved, and its time-varying probability is related to the system state, the output of each DG and ESS, and the load level. Therefore, it is necessary to establish a reasonable time-varying model of microgrid.

B. TIME-VARYING MODEL OF MICROGRID

DG and ESS have two states of working and fault, and the DG or the ESS state is judged by:

$$\gamma_{\text{DG or ESS}}(S) = (1 - x_{\text{DG or ESS}}) \prod_{i \in \omega(\text{DG or ESS})} (1 - x_i) \quad (13)$$

where x_{DGorESS} is the state of DG or ESS; $\gamma(\bullet)$ is the output indication function; $\omega(\bullet)$ is a path search set, and the set element is composed of the feeder contained between the component and the MCU. When $\gamma(\bullet)$=1, the output of DG or ESS is normal. Otherwise, the output of DG or ESS is 0.

The types of DG considered in this paper are mainly micro turbine (MT), wind turbine (WT) and photovoltaic (PV).

MT is a non-intermittent DG, and the output of it is rated power.

The random output of the WT changes with the wind speed under working state, which can be expressed as:

$$G_{\text{WT}} = \begin{cases} 0, & 0 \le v < v_{\text{ci}}, v > v_{\text{co}} \\ \frac{v - v_{\text{ci}}}{v_{\text{r}} - v_{\text{ci}}} G_{\text{WTr}}, & v_{\text{ci}} \le v \le v_{\text{r}} \\ G_{\text{WTr}}, & v_{\text{r}} < v \le v_{\text{co}} \end{cases} \quad (14)$$

where G_{WT} is the output of the WT;G_{WTr} is the rated power of the WT; v is actual wind speed; v_{r}, v_{ci}, v_{co} are rated wind speed, cut-in wind speed and cut-out wind speed of WT respectively.

At present, relevant research shows that the Weibull distribution can be well fitted to the actual wind speed, and its probability density function is:

$$f_{\text{v}}(v) = \frac{c_1}{c_2} \cdot \left(\frac{v}{c_2}\right)^{c_1 - 1} \cdot \exp\left(-\left(\frac{v}{c_2}\right)^{c_1}\right) \quad (15)$$

where c_1 is shape parameter and c_2 is scale parameter. c_1 and c_2 can be approximated by the mean and standard deviation of wind speed over a period of time.

According to (14) and (15), the output probability density function of WT is derived, we can get:

$$f_{\text{WT}}(G_{\text{WT}}) = \begin{cases} 1 + F_{\text{v}}(v_{\text{ci}}) - F_{\text{v}}(v_{\text{co}}), \quad G_{\text{WT}} = 0 \\ \left(\frac{v_{\text{r}} - v_{\text{ci}}}{G_{\text{WT}}}\right)\left(\frac{c_1}{c_2^{c_1}}\right)\left(v_{\text{ci}} + (v_{\text{r}} - v_{\text{ci}})\frac{G_{\text{WT}}}{G_{\text{WTr}}}\right)^{c_1 - 1} \\ \times \exp\left(-\left(\frac{v_{\text{ci}} + (v_{\text{r}} - v_{\text{ci}}) \cdot \frac{G_{\text{WT}}}{G_{\text{WTr}}}}{c_2}\right)^{c_1}\right), \\ \qquad 0 < G_{\text{WT}} < G_{\text{WTr}} \\ F_{\text{v}}(v_{\text{co}}) - F_{\text{v}}(v_{\text{r}}), \quad G_{\text{WT}} = G_{\text{WTr}} \end{cases} \quad (16)$$

where $F_{\text{v}}(\bullet)$ is the probability cumulative function of (15).

The random output of PV is related to the intensity of the illumination. In a period of time, the intensity of the illumination obeys the Beta distribution. Therefore, the random output of PV can be approximated as obeying the Beta distribution. Under working state, the output probability density function of PV is:

$$f_{\text{PV}}(G_{\text{PV}}, t) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) + \Gamma(\beta)} \left(\frac{G_{\text{PV}}}{G_{\text{PVr}}(t)}\right)^{\alpha - 1} \left(1 - \frac{G_{\text{PV}}}{G_{\text{PVr}}(t)}\right)^{\beta - 1} \quad (17)$$

where $\Gamma(\bullet)$ is Gamma function; G_{PV} is the output of the PV; $G_{\text{PVr}}(t)$ is the maximum output of PV at t; α and β are shape parameters obeying the Beta distribution, which can be approximated by the mean and standard deviation of the PV output over a period of time.

ESS is an indispensable component in the microgrid. When the interconnected microgrid enters the island mode, the state of charge (SOC) of ESS is full. Since short-term reliability assessment is considered in this paper, when there is a power deficiency in the islanded microgrid, ESS can be processed as a power supply with rated output [13], [14].

Traditional power system reliability assessment often uses a constant load model. However, due to the islanded microgrid contains DG with intermittent output, if using the constant load model, there must be a large error. So, using a time-varying load curve, the load model is obtained as:

$$G_{\text{LP}j}(S, t) = \begin{cases} 0, & \prod_{i \in \omega(\text{LP}j)} (1 - x_i) = 0 \\ G_{\text{LP}j,\text{r}} G_{\text{rate}}(t), & \prod_{i \in \omega(\text{LP}j)} (1 - x_i) = 1 \end{cases} \quad (18)$$

where $G_{\text{LP}_j}(\bullet)$ is load power of the LPj; $G_{\text{LP}j,\text{r}}$ is the peak load power of the LPj; $G_{\text{rate}}(t)$ is the load rate value.

Assuming that there are m load points in the system, the minimum load shedding strategy is adopted to reduce the load points that cannot meet the power supply requirements. The load power threshold $E(S,\text{LP}j,t)$ of LPj is calculated according to the flowchart shown in Figure 4. If the sum of the output of all DG and ESS in the system is greater than $E(S,\text{LP}j,t)$, the LPj is powered normally. Otherwise, the power supply of LPj is interrupted.

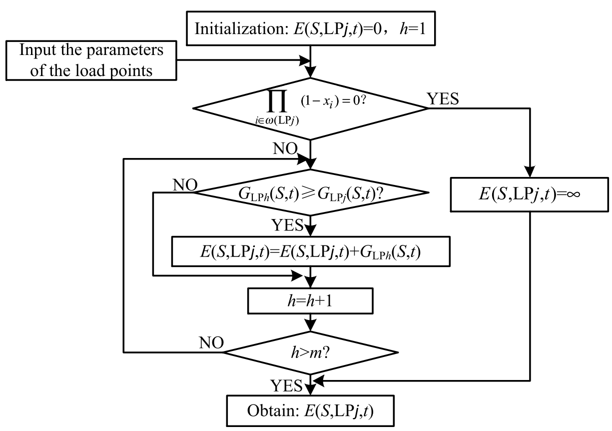

FIGURE 4. Flowchart of load power threshold calculation.

C. TIME-VARYING PROBABILITY CALCULATION OF $\phi(\bullet)$

From the established microgrid model, the MT and ESS output are rated power, while the WT and PV random output are subject to different probability distributions. Therefore, solving $\phi(\bullet)$ requires constructing a function of the combined output of WT and PV.

The sequence operation theory expresses the probability distribution of random variables through probabilistic sequences [18], and uses the operations between sequences to obtain new probability distributions.

Taking the same step size q for WT and PV output, supposing the probability sequence of WT output is $a(i_a)$, considering the discrete probability when $G_{WT} = 0$ and $G_{WT} = G_{WTr}$, $a(i_a)$ is:

$$a(i_a) = \begin{cases} \int_0^{q/2} A + f_{WT}(0), & i_a = 0 \\ \int_{i_a q - q/2}^{i_a q + q/2} A, & 0 < i_a < N_{WT} \\ \int_{i_a q - q/2}^{i_a q} A + f_{WT}(G_{WT\max}), & i_a = N_{WT} \end{cases} \tag{19}$$

where N_{WT} is the sequence size of WT output; $i_a = 0, 1, \ldots, N_{WT}$; $N_{WT} = G_{WTr}/q$; $A = f_{WT}(G_{WT})dG_{WT}$.

Supposing the probability sequence of PV output at t is $b(i_b, t)$, $b(i_b, t)$ is:

$$b(i_b) = \begin{cases} \int_0^{q/2} f_{PV}(G_{PV})dG_{PV}, & i_b = 0 \\ \int_{i_b q - q/2}^{i_b q + q/2} f_{PV}(G_{PV})dG_{PV}, & 0 < i_b < N_{PV}(t) \\ \int_{i_b q - q/2}^{i_b q} f_{PV}(G_{PV})dG_{PV}, & i_b = N_{PV}(t) \end{cases} \tag{20}$$

where $N_{PV}(t)$ is the sequence size of PV output at t; $i_a = 0, 1, \ldots, N_{PV}(t)$; $N_{PV}(t) = G_{PVr}(t)/q$.

The sequence of the combined output of WT and PV is represented by $c(i_c, t)$, which is defined as:

$$c(i_c) = a(i_a) \oplus b(i_b, t) = \sum_{i_c = i_a + i_b} a(i_a)b(i_b) \tag{21}$$

where $i_c = 0, 1, \ldots, N_c(t)$; $N_c(t) = N_{WT} + N_{PV}(t)$.

$c(i_c, t)$ is a sequence in which q and $N_c(t)$ are step size and sequence size, respectively. Each output value corresponds to a probability, as shown in Table 1.

TABLE 1. Probabilistic sequence of intermittent DG combined output.

	Value				
	0	1	2	…	$N_c(t)$
Output/kW	0	q	$2q$	…	$N_c(t)q$
Probability	$c(0)$	$c(1)$	$c(2)$	…	$c(N_c(t))$

Then, the time-varying probability of $\phi(\bullet)$ is obtained by:

$$\phi(S, \mathrm{LP}j, t) = \sum_{i_c=1}^{N_c(t)} c_t(i_c)\, |E(S, \mathrm{LP}j, t) - G_{MTr} - G_{ESSr} > i_c q \tag{22}$$

IV. SHORT-TERM RELIABILITY INDEX AND ASSESSMENT PROCESS

A. DEFINITION OF SHORT-TERM RELIABILITY INDEX

The short-term reliability level of islanded microgrid is measured by short-term reliability indexes. Define two short-term reliability indexes, the LOLP index and the ENDS index, which are calculated as follows:

$$L_{OLP}(\mathrm{LP}j, t) = \sum_{g=1}^{k(t)} \left(f_{Global}(S_g, \mathrm{LP}j, t) + f_{Local}(S_g, \mathrm{LP}j, t)\right) \tag{23}$$

where $L_{OLP}(\mathrm{LP}j, t)$ is the LOLP index of LPj at t.

$$E_{DNS}(t) = \sum_{j=1}^{m} L_{OLP}(\mathrm{LP}j, t) G_{\mathrm{LP}j,r} G_{rate}(t) \tag{24}$$

where $E_{DNS}(t)$ is the EDNS index of system at t.

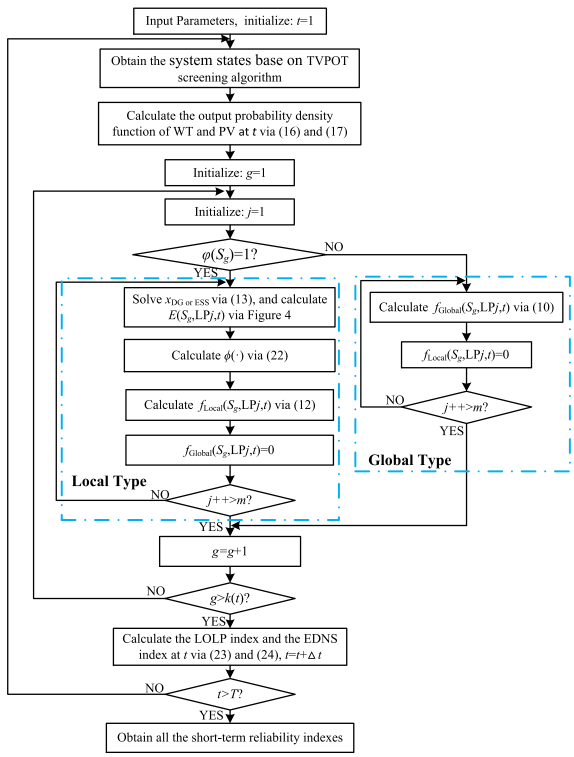

FIGURE 5. Flowchart of short-term reliability assessment.

B. CALCULATION PROCEDURE OF SHORT-TERM RELIABILITY ASSESSMENT

As shown in Figure 5, the main steps for the proposed short-term reliability assessment are summarized as follows:

1) Input the short-term reliability assessment parameters and initialize $t = 1$.
2) Some system states with high time-varying probability are obtained base on TVPOT screening algorithm. Calculate the output probability density function of WT

and PV at t via (16) and (17) respectively. Initialize $g = 1$.

3) Initialize $j = 1$.
4) Judge if $\varphi(S_g) = 1$. If so, then go to the step 5. Otherwise, go to the step 7.
5) Solve the state of each DG and ESS via (13), and calculate $E(S_g,\text{LP}j,t)$, $\phi(\cdot)$ and $f_{\text{Local}}(S_g,\text{LP}j,t)$ via Figure 4, (22) and (12) respectively, and let $f_{\text{Global}}(S_g,\text{LP}j,t) = 0$.
6) Let $j = j + 1$, judge if j is more than m, then go to the step 9. Otherwise, go back to the step 5.
7) Calculate $f_{\text{Global}}(S_g,\text{LP}j,t)$ via (10), and let $f_{\text{Local}}(S_g,\text{LP}j,t) = 0$.
8) Let $j = j + 1$, if j is more than m, then go to the step 9. Otherwise, go back to the step 7.
9) Let $g = g + 1$. Judge if $g > k(t)$. If so, then go to the step 10. Otherwise, go back to the step 3.
10) Calculate the LOLP index and EDNS index at t via (23) and (24) respectively. Let $t = t + t$ (t is the time interval duration).
11) Judge if $t > T$ (T is the total assessment time). If so, all the reliability indexes are obtained, and end the simulation. Otherwise, go back to the step 2.

V. CASE STUDY

A. EXAMPLE SYSTEM

In this section, the example system uses the European Union low-voltage microgrid structure [19], as shown in Figure 6.

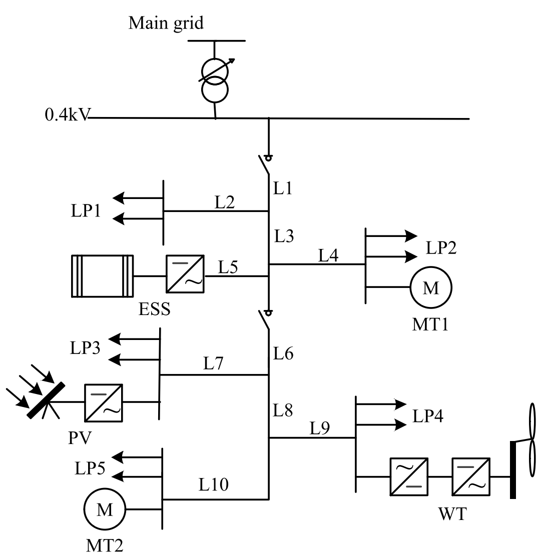

FIGURE 6. European union low-voltage microgrid structure.

This system consists of 10 segments of feeders, 5 load points, 4 DGs and 1 ESS. The LP1-LP5 loads are 20 kW, 72 kW, 50 kW, 15 kW and 47 kW, respectively. The rated power of MT1 and MT2 are 65 kW and 60 kW respectively. The rated power of WT is 70 kW, and the rated power of ESS is 30 kW. The components reliability parameters refer the parameters in [20], and the communication system reliability parameters refer the parameters in [21].

Setting WT parameters: v_r, v_{ci}, and v_{co} are 10.5 m/s, 3 m/s, and 22.5 m/s, respectively, and the measured data from April 6, 2011 to April 12, 2011 in Hunan Province, China is used as historical data. Historical data of PV output is generated by HOMER software.

The microgrid example system enters the island operation mode when $t = 0$, and adopts the master-slave control strategy. MT1 is the MCU and adopts V/F control; the remaining DGs and ESS adopt PQ control.

B. TIME-VARYING OF TVPOT SCREENING ALGORITHM

In order to verify the time-varying of the TVPOT screening algorithm, setting $\delta\% = 99.92\%$ and changing the value of t, the TVPOT screening algorithm is used to obtain the system states with a high time-varying probability. We get $k(1)$, $k(10)$ and $k(24)$, which listed in Table 2.

TABLE 2. Number of system states at different moment.

	$k(1)$	$k(10)$	$k(24)$
Number of system states	1	4	6

According to Table 2, we find the relationship that $k(t)$ increases as t increases. This is because as t increases, $p(t)$ increases, so more faulty system states are taken into account. It is shown that the TVPOT screening algorithm can truly reflect the time-varying characteristic of the components.

C. SIMULATION PARAMETERS OF THE PROPOSED METHOD

The simulation accuracy of the proposed method is mainly related to two simulation parameters, q and $\delta\%$. Therefore, it is necessary to determine reasonable q and $\delta\%$.

Setting $\delta\% = 99.92\%$, $t = 10$ h and changing the value of q, the proposed method is used to assess the short-term reliability for the example system. Taking $E_{\text{DNS}}(10)$ and simulation time as the comparison objects, the results are shown in Figure 7.

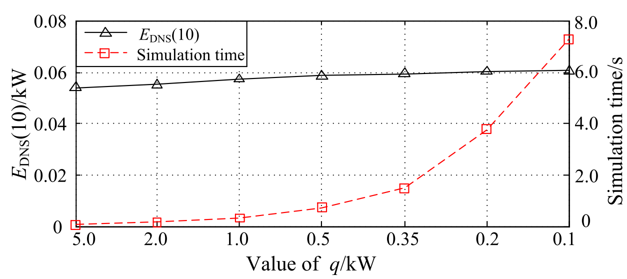

FIGURE 7. Comparison of short-term reliability assessment results by using different step size.

According to Figure 7, as the step size decreases, the calculation accuracy is improved continuously, while the simulation time is also increased correspondingly.

When q <0.35 kW, the variance coefficient of $E_{\mathrm{DNS}}(10)$ is less than 0.1%, indicating that $E_{\mathrm{DNS}}(10)$ tends to converge.

This indicates that the value of q should be reasonable. If it is too large, the error of simulation results will be large. Otherwise, the simulation time will be too long, which is not conducive to online analysis.

Setting $q = 0.35$ kW, $t = 10$ h and changing the value of $\delta\%$, the proposed method is used to assess the short-term reliability for the example system. Taking $E_{\mathrm{DNS}}(10)$, $k(10)$ and simulation time as the comparison objects, the results are shown in Table 3.

TABLE 3. Comparison of short-term reliability assessment results by using different cutoff accuracy.

Value of $\delta\%$	Results		
	$k(10)$	$E_{\mathrm{DNS}}(10)$/kW	Simulation time/s
99.80%	1	0.0583	0.98
99.92%	4	0.0599	1.47
99.99%	8	0.0604	2.17
99.995%	12	0.0604	2.84

It can be seen from Table 3 that:

1) $k(10)$ increases following the increasing of $\delta\%$, indicating that the larger the $\delta\%$, the more system states are considered.
2) Compared with the short-term reliability assessment results at $\delta\% = 99.80\%$ and $\delta\% = 99.92\%$, those two values in $E_{\mathrm{DNS}}(10)$ have a large relative error. This is because the added system states are all fault system states with a high time-varying probability, and these system states contribute to the short-term reliability index.
3) Compared with the short-term reliability assessment results at $\delta\% = 99.99\%$ and $\delta\% = 99.995\%$, those two values in $E_{\mathrm{DNS}}(10)$ have a small relative error. This is because the added system states with a low time-varying probability and these system states have little impact on the reliability index.

This indicates that the value of $\delta\%$ should be reasonable. If it is too small, the error of simulation results will be large. Otherwise, the simulation time will be too long, which is not conducive to online analysis.

Based on the above analysis, the parameters used herein are determined: $q = 0.35$ kW, $\delta\% = 99.99\%$.

D. CONPARISON BETWEEN THE PROPOSED METHOD AND OTHER METHODS

In order to verify the correctness of the proposed method, taking the same reliability parameters and setting $t = 10$, the proposed method and other methods are respectively used to assess the short-term reliability of the example system. Taking $L_{\mathrm{OLP}}(\mathrm{LP1},10)$, $E_{\mathrm{DNS}}(10)$ and simulation time as the comparison objects, the results are shown in Table 4.

It can be seen from Table 4 that:

1) Compared with other methods, the MCS method has a large relative error and a large volatility under different values of N. This shows that the MCS method is not suitable for short-term reliability assessment of islanded microgrid.

TABLE 4. Comparison of short-term reliability assessment results by using different methods.

Method	N (number of samples)	Results		
		$L_{\mathrm{OLP}}(\mathrm{LP1},10)$	$E_{\mathrm{DNS}}(10)$/kW	Simulation time/s
Proposed method	—	0.4387×10^{-3}	0.0604	2.17
TVUGF method	—	0.4376×10^{-3}	0.0601	2.91
MCS method	50 000	0.3514×10^{-3}	0.0498	3.87
	100 000	0.4817×10^{-3}	0.0679	8.17
	200 000	0.4689×10^{-3}	0.0657	17.32
TVDFT method	50 000	0.4409×10^{-3}	0.0612	0.69
	100 000	0.4401×10^{-3}	0.0608	1.48
	200 000	0.4397×10^{-3}	0.0607	3.04

2) The TVDFT method is essentially MCS method, and its calculation error is related to N. With the improvement of the accuracy of the assessment results, the simulation time is continuously increasing, and the calculation efficiency is continuously reducing.
3) The proposed method belongs to analytical method, and its calculation error is independent of N. Compared with the TVUGF method, the relative errors of $L_{\mathrm{OLP}}(\mathrm{LP1},10)$ and $E_{\mathrm{DNS}}(10)$ of the proposed method are 0.2514% and 0.4992% respectively. Compared with the TVDFT method ($N = 200000$), the relative errors of $L_{\mathrm{OLP}}(\mathrm{LP1},10)$ and $E_{\mathrm{DNS}}(10)$ of the proposed method are 0.2729% and 0.4942% respectively. The relative error is within the acceptable range, which indicates the correctness of the proposed method.
4) In terms of simulation time, compared with the TVUGF and the TVDFT ($N = 200000$) method, the simulation time of the proposed method is reduced by 25.43% and 27.71%. It indicates that the proposed method has higher computational efficiency under the premise of ensuring the accuracy of calculation.

E. SHORT-TERM RELIABILITY ASSESSMENT RESULT

Setting the simulation parameters: $T = 24$ h, $t = 1$ h, the short-term reliability assessment for the example system is carried out by using the proposed method. Curve of the LOLP index is shown in Figure 8, and curve of the EDNS index is shown in Figure 9.

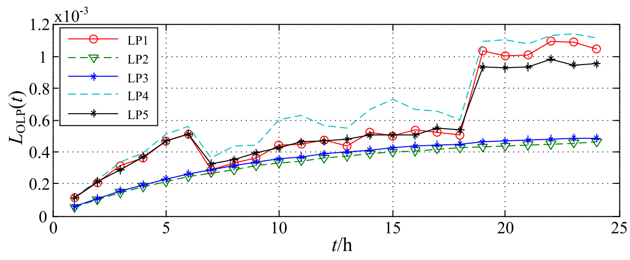

FIGURE 8. Curves of the LOLP index.

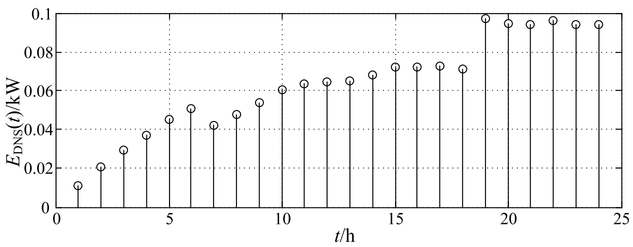

FIGURE 9. Curves of the EDNS index.

It can be seen from Figure 8 and Figure 9 that:

1) The LOLP index and the EDNS index change with time, indicating that the short-term reliability level of the islanded microgrid has time-varying characteristic. This is due to the time-varying characteristics such as the system state, the output of each DG and ESS, and the load level.
2) The reliability levels of LP2 and LP3 are relatively high, monotonously increases with the increase of t, and the fluctuation is small. This is because LP2 and LP3 have high peak loads, which are usually not easy to remove due to the minimum load shedding strategy. Therefore, the main type of load point power supply interruption at LP2 and LP3 is Global Type.
3) The reliability levels of LP1, LP4 and LP5 are relatively low, and generally increase with the increase of t, and the fluctuation is large. This is because LP1, LP4, and LP5 have low peak loads, when the DG or the ESS contained in the island cannot meet the load required, those load points will lose the power supply in priority. Therefore, the types of load point power supply interruption at LP1, LP4 and LP5 are Global Type and Local Type.

VI. CONCLUSION

In this paper, a short-term reliability assessment method based on the TVPOT screening algorithm has been proposed for the characteristics of short-term reliability time-varying and large sampling space of the islanded microgrid. In this method, the TVPOT screening algorithm has been used to obtain system states with high probability at each moment. Then, based on these system states, the time-varying probability of the Global type and Local type of load point power supply interruption has been calculated. In turn, the LOLP index and the EDNS index have been obtained. The simulation results have shown that the TVPOT screening algorithm can have obtained the state of the system with high probability at each moment, which is suitable for the sample acquisition of short-term reliability assessment. Moreover, the proposed reliability assessment method can truly reflect the short-term reliability level of the islanded microgrid, which belongs to the analytical method and has high efficiency. In summary, the proposed method can provide some references for short-term dispatching and operation of islanded micro-grid and has the prospect of online application.

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