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Reliability Evaluation and Improvement Based on Operational Failure Rate of Power Electronics in Islanded Microgrid

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RELIABILITY EVALUATION AND IMPROVEMENT BASED ONOPERATIONAL FAILURE RATE OF POWER ELECTRONICS IN ISLANDED MICROGRID

by

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ABSTRACT

RELIABILITY EVALUATION AND IMPROVEMENT BASED ONOPERATIONAL FAILURE RATE OF POWER ELECTRONICS IN ISLANDED MICROGRID

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The University of Wisconsin-Milwaukee, 2018

Under the Supervision of Dr. Lingfeng Wang

With power electronics being widely applied in microgrids, they become a key part in micro-grid and the reliability assessment considering power electronic devices have become a hot research topic, and much work has been done to evaluate the reliability of power electronics in microgrids. However, the impact of operational failure of power electronics on the overall microgrid reliability has not been studied yet.

This thesis has three objectives. The first objective of this thesis is to construct a systematic operational failure rate model of power electronic systems. The power generated from renewable generation units, such as PV arrays or wind turbines, is uncertain and difficult to predict. With the operational impact based on operational conditions taken into consideration, the evaluation of reliability is more accurate and it will make a great contribution to the design process and avoid costly expenses caused by undesired failures in microgrids. The second objective is to apply this model to do reliability assessment of the overall islanded microgrid with high penetration of renewable energy generation systems. In addition, this paper combines several reliability assessment methods. The third objective is to improve the reliability of the microgrid system by replacing the conventional battery storage system to the hybrid energy storage

system. Based on this proposed model, the operational failure models for the power electronic systems in an modified benchmark 0.4 kV test system were built and tested, and then the sensitivity analysis, exploring the influence of various factors, was studied.

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Chapter 1 Introduction

1.1 Background

Nowadays, energy and environmental issues are a primary concern for human existence and development. Not only does conventional energy have limited sources on our planet, but also causes severe environmental pollution. Under the pressure of these problems that we're facing, finding a new type of sustainable energy to replace conventional power is of great importance [1].

The application of renewable energy is a practical solution to these global issues. Based on the 2017 Renewable Global status report shown in Figure 1.2, the Total global capacity of solar PV(Photovoltaic) generation systems from 2006 to 2016 increases and reaches the 303 GW in 2016 [2]. The average annual growth rate of the solar power capacity from 2006 to 2016 is about 33%.

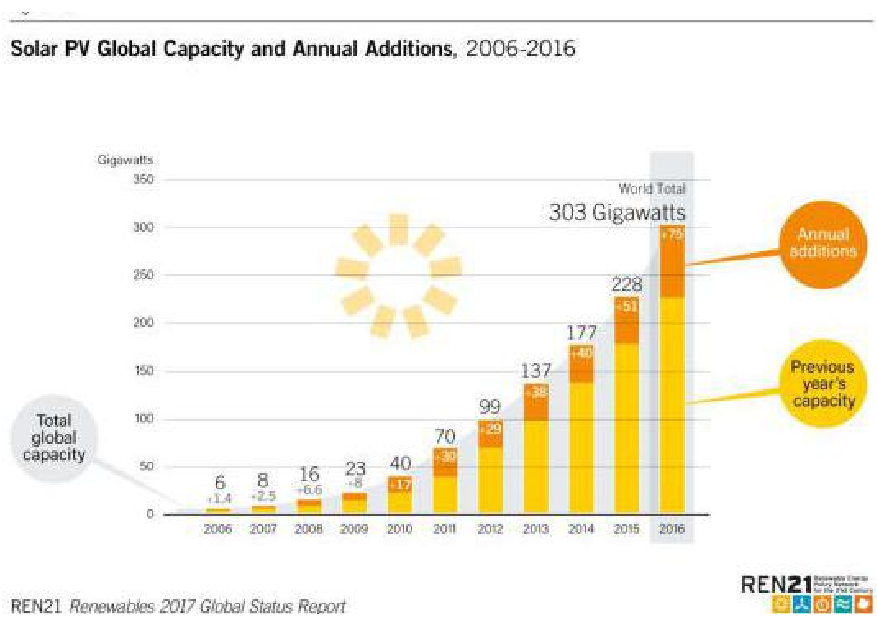

Figure 1-1 PV global capacity during 2006-2016

The total global capacity of the WTG (wind turbine generation) systems from 2006 to 2016 shows an upward trend and reaches the 487 GW in 2016[2]. As shown in figure, the average growth rate of the wind power capacity between 2006 and 2016 is about 13%.

The rapid development of solar and wind energy generation drives the rapid growth of power electronics technology. For renewable energy generation systems, power electronic converters are essential for embedding wind turbines or PV arrays with the power system by converting the natural power to a more stable power that is more compatible with the grid.

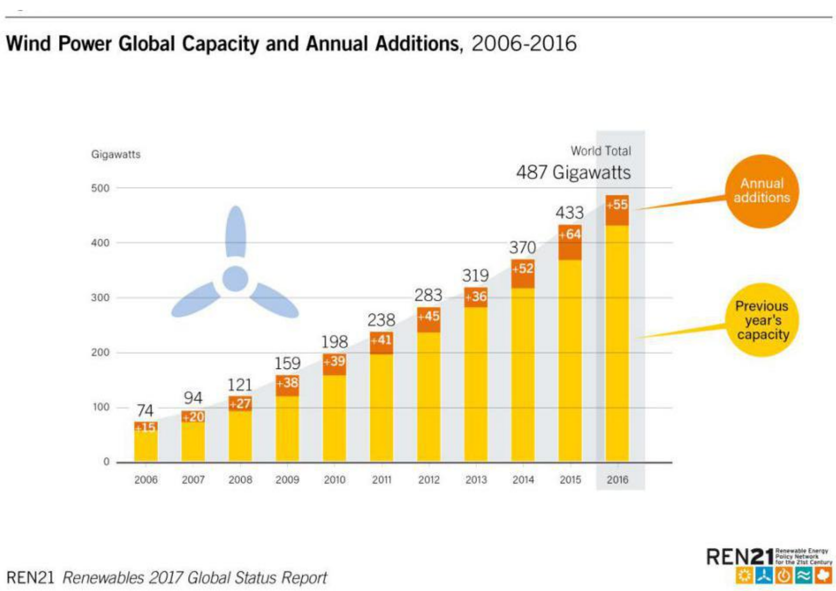

Figure 1-2 power global capacity Wind during 2006-2016

Islanded microgrids with heavy penetration of renewable energy are widely applied in different fields. Especially in countries where they have low transmission capabilities, due to access to electricity being complicated and expensive. However, these places have sufficient renewable energy sources (solar energy, wind energy, and etc), which make it possible to supply the local loads. Compared to building large power plants or transfering electricity from the grid through long-distance power lines, not only do islanded micro-grids reduce global house gases emission, they also solve energy shortage problems as well as avoiding long-distance transmission of electricity and solving the power shortage in some rural and remote places. In addition, when a grid has a failure, micro-grid also has to work in islanded mode, thus the reliability issues of islanded microgrid is of great importance.

1.2 The research of reliability assessment for islanded micro-grid

The reliability engineering firstly emerged to address the reliability issues in military applications [3,4,5]. There are two methods that are widely adopted. The first one is the empirical reliability model, and it is based on previous operating data and several handbooks [6,7]. They mainly use constant values to evaluate the reliability indices. This method has been widely applied to power systems to analyze average reliability indices[8]. However, the empirical approach is independent of operational condition and does not take the physical cause of electronics' failure into consideration.

The second model is the physics-based reliability model, which was first proposed in 1962 [9]. It focuses on identifying the root-cause mechanism of component failures and is based on the specific operational conditions. Since the increased application of integrated circuits (ICs) after the 1990s, it was evident that the constant failure rate of the empirical reliability model is inadequate [10], compared with the former method, a physical-based reliability model is more reasonable and practical [11,12,13]. The physical-based reliability model has played a more critical role in reliability engineering. In previous studies of the physical-based reliability model, two types of failures were widely studied like failures caused by thermal over-temperature and thermal cycling [14].

In recent years, high reliability is often regarded as one of the main technical advantages of microgrids [15-21]. Most of the previous works explore reliability by considering microgrids penetrated with the conventional or renewable power system. However, their approaches don't consider variable failure and repair rates, or even including any power electronic interfaces [15–19]. Reference [15] proposed an approach evaluating reliability from an operational perspective based on matching generations and loads, which consider components to be completely reliable. Reference [16] focuses on the isolated system, only considering constant power output of generation units, and it cannot be applied to any violently fluctuating renewable generator. Reference [19] is based on variable loads to schedule the optimal structure of the system and find the impact on interruption caused by transmission system failure. To evaluate the reliability more accurately, reference [20] considers the protection issues to evaluate reliability indices of islanded microgrids by using a short-term outage model. Based on this, reference [21] considers the impact of incorrect responses of the protection system and employs the short-term outage model to evaluate the fuzzy reliability indices.

There are few works exploring the effect of the power electronics and the influences of different meteorological factors at the same time on reliability evaluation of islanded microgrids, not to mention presenting systematical reliability models and methods for microgrids. References [22] [23] introduce the basic indices, reliability assessment methods and reliability improvement methods. For component level reliability assessment, the failure rate model proposed by [24] is commonly used in the reliability evaluation of power electronic devices. Based on these, reference [25] provides a real time model of converters based on the multi-level converters in WTG system. However, this method cannot adequately show the hourly failure rate of components.

Previous work did not take the variable failure rates of power electronics which are dependent on different factors into consideration. Since volatile renewable generation has been highly embedded in microgrids, the failure of power interfaces, which is affected by different operational states of the components in the microgrid, have the negative impact on the overall microgrid. Thus, operational reliability has become a hot issue for microgrids. To deal with this problem, this paper proposes a systematical operational reliability model for power electronic devices in the microgrid. The failure rates of power electronic devices in this model are calculated according to operational states, and then microgrid reliability is evaluated considering the failure rates of power electronics. This method will be verified by a case study. Then, the simulation results will be analyzed.

1.3 Reliability metrics

1.3.1 Basic Reliability metrics

To predict the reliability of the system, the reliability metrics which could show the system's performance, should be determined as first. The primary metrics are adopted for the power electronic systems and explained as below.

A. Reliability

The reliability is defined as the ability of an item to perform a required function under stated conditions for period [26,27].

B. Failure Rate

A bathtub curve illustrates that the lifetime of an item which is composed of three periods[26] as shown in Fig.1.5. λ(t) has a close relationship with reliability R(t) and can be expressed:

$$R(t) = e^{-\int_0^t \lambda(\tau) d(\tau)} \tag{1.1}$$

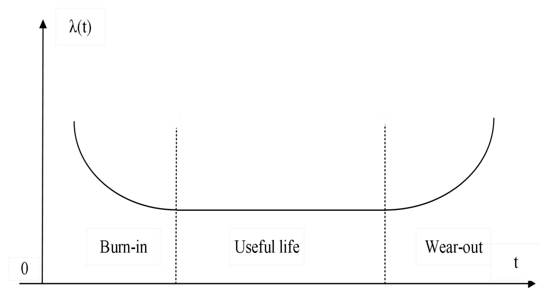

Figure 1-3 A typical failure rate curve as a function of time.

Based on the empirical reliability model, the failure rates of items (components, subsystems) are independent on operational conditions. Although this assumption has limitations [22], the reliability can be expressed by:

$$R(t) = e^{-\lambda t} \tag{1.2}$$

C. Outage Time

Outage Time (U) is defined as the duration time expected to be failure state of an element when it has failure, and can be described as:

$$U_i = \lambda_i \times r_i \tag{1.3}$$

Where "i" means that it is the ith element of the system, and "r" refers to the repair time of this element, the repair time of components can be determined by its maintenance and is dependent on the level of the protection scheme of the microgrid.

1.2.1 Power supply reliability index for customers

(i) System average interruption frequency index (SAIFI)

$$SAIFI = \frac{customer\ interruptions}{customer served} = \frac{\sum \lambda_i N_i}{\sum N_i} [interruptions / customer] \tag{1.4}$$

(ii) System average interruption duration index (SAIDI)

$$SAIDI = \frac{total \quad interruption \quad duration}{customer \quad served} = \frac{\sum U_i N_i}{\sum N_i} [hours / customer] \tag{1.5}$$

(iii) Energy not supplied index (ENS)

$$ENS = total energy not supplied by the system = \sum L_i U_i [kW.h] \tag{1.6}$$

1.4 Reliability Evaluation Method

Based on the definition of reliability basic metrics mentioned above, the effective method should be proposed to evaluate the reliability of islanded microgrid. This section focuses on the summary of the existed method and comparison, then proposes the reliability evaluation method applied in chapter 4. The reliability evaluation method for electric power systems can be mainly classified into a simulation and analytical method.

1.4.1 Simulation Method

The simulation method commonly refers to the Monte Carlo simulation(MCS), which analyzes the reliability indices by simulating different processes of the system. It can be divided into two methods, which are the time sequential MC method and the non-sequential MC method.

On the other hand, sequential MCS can take the sequential operating conditions of the system into consideration and could also address events and states that are dependent on time sequence [28], while the non-sequential Monte Carlo simulation does not.

1.4.2 Analytical Method

The analytical method, which focuses on evaluating the reliability index using the direct numerical method is mainly composed of the FTA, the Markov model, and some other methods.

A. Network Reduction method[29]

The basic idea of the the network reduction method is to describe the structure of the conversion system as serial-parallel networks based on the reliability point of view, so the converter model can also be expressed as a series-parallel combination model in each subsystem. By grouping the components in a series or parallel connection, this method reduces the number of components effectively. As shown in figure 1-6, assuming two components in each system are independent. The equivalent failure rate and repair rate of the two components system is expressed in (1.8). Then we get the repair rate for a parallel system, which consists of n components in function (1.9). A series system that consists of n components failure rate can be calculated in function (1.10)[29].

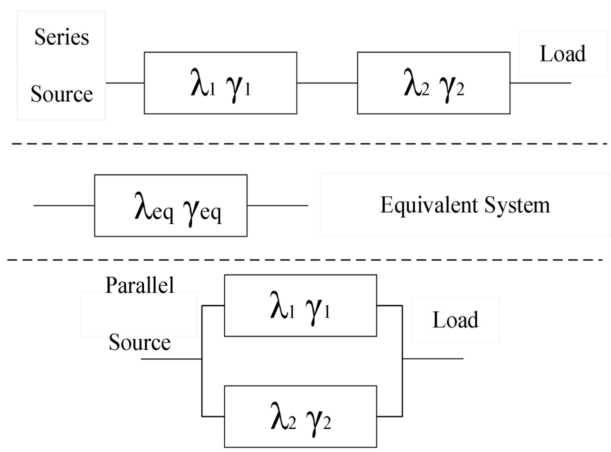

Figure 1-4 The equivalent network for series and parallel components

$$\lambda_{eq} = \lambda_1 + \lambda_2 \qquad r_{eq} = \frac{\lambda_{eq} \cdot r_1 \cdot r_2}{\lambda_1 \cdot \lambda_2 + \lambda_1 \cdot r_2 + \lambda_2 \cdot r_1} \quad \lambda_{eq} = \frac{\lambda_1 \cdot \lambda_2 (r_1 + r_2)}{r_1 \cdot r_2 + \lambda_1 \cdot r_1 + \lambda_2 \cdot r_2} \quad r_{eq} = r_1 + r_2 \tag{1.7}$$

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \tag{1.8}$$

$$r_s = \sum_{i=1}^{n} r_i \tag{1.9}$$

B. Minimum Cut Set

The minimum cut set is a group of components, if anyone of these components has a failure, the entire system will have a failure. Based on the figure 1-5, the minimum cut set of the system is (1,3), (2,4), (1,5,4, (3,5,2) and can be simplified to the figure 1-6.

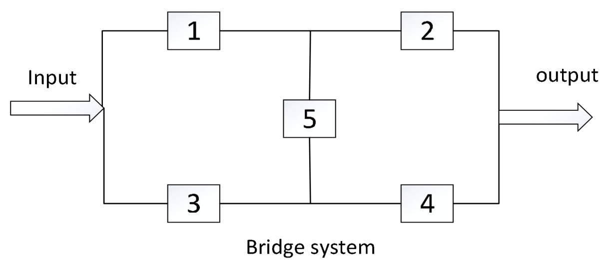

Figure 1-5 Model of network

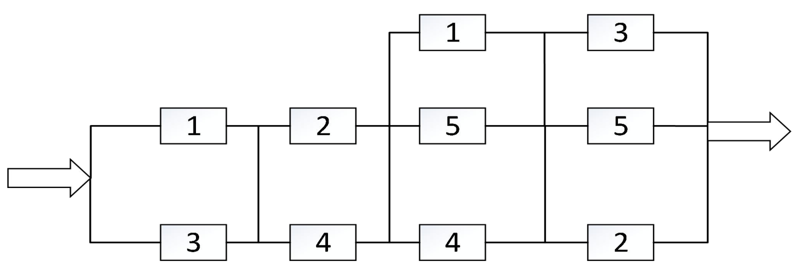

Figure 1-6 Network after minimum set simplification

C. Markov model

The Markov process is an analytical technique giving all possible states of the system, mainly applied in repairable systems. This method assumes the time spent at each state belongs to an exponentially distributed function. A number of possible events are defined as the transitions between different states, and these transitions can be expressed in a transition matrix [30]. By adding the states of components to illustrate the transitions among different combinations of the components' operational condition, this model might be extended to a comprehensive state transition model for the overall system and obtains the system level reliability indices. However, this state-based model is complicated (e.g. maximum 2^n states with n components) , and will increase the difficulty of calculation. In addition, it is mainly based on a constant failure rate and a constant repair rate and can't reflect the influence of different operational factors.

D. Fault Tree Analysis method

The FTA method combines the system failure with component failure and is expressed in a graphic logical reasoning aspect. At first, the FTA method identifies all the causing events for the system's undesired failure, then constructs the failure paths which connect the causing events and related failure. Secondly, when obtaining the failure rates of the causing events and combining it with the network conduction method, which gives it access to calculating the overall failure rate of the top failure event [31,32]. Fault trees are mainly composed of static logical gates, such as "AND" and "OR" gates, and causing events. The FTA method has several advantages, such as taking all factors into account, identifying causes of failure effectively, and identifying the critical components in the system based on the component's physical location in the system [33].

In addition, when obtaining failure rates of components, this model can evaluate the overall system reliability by logical calculation directly, which reduces the complexity of the reliability assessment. However, the previous works using the FTA method are mainly based on a constant failure rate which does not take the dependencies among the components into consideration.

To overcome this limitation, this paper proposes the operational failure rate model to obtain the real time failure rate considering the operational factors (the dependencies among the components, thermal factor, electrical factor, processing factor). This method combines the FTA method with the Network reduction method based on the concept of the minimum cut set, providing the island microgrid with the systematical model to evaluate the reliability performance.

1.4.3 Proposed reliability model

After obtaining failure rates of power electronics from the analysis above, operational reliability indices considering the time-varying failure rates of power electronics in islanded micro-grid can be evaluated. The characteristic effect of renewable energy contributes to the volatile variation of temperature for power electronic systems on the supply of islanded micro-grids can be evaluated through the short term outage model adopted in this paper. Since the operational failure rate model for each subsystem takes the meteorological and environmental factors into consideration, the failure rates of them are dependent on time. Utilizing the short-term outage model [20,21], the operational reliability indices like outage time and repair rate of each load can be obtained. Based on indices and power indices from customer's perspective analyzed above, the influence of different micro-sources on different loads in islanded microgrids can be reflected effectively through the time-varying power reliability indices like SAIFI, SAIDI and ENS introduced in section 1.3, for the overall islanded micro-grid showed as below.

$$\begin{bmatrix} U_1 \\ U_2 \\ \dots \\ U_N \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1M} \\ r_{21} & \gamma_{22} & \dots & r_{2M} \\ \dots & \dots & \dots & \dots \\ r_{N1} & r_{N1} & \dots & r_{NM} \end{bmatrix} \cdot \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \dots \\ \lambda_M \end{bmatrix} \tag{1.10}$$

$$h(i,j) = \begin{cases} 0, & r_{ij} = 0 \\ 1, & r_{ij} > 0 \end{cases} \tag{1.11}$$

$$\lambda_{LP,i} = h(i,:) \cdot \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \dots \\ \lambda_M \end{bmatrix}, \qquad i = 1,2,\dots,N \tag{1.12}$$

$$r_{LP,i} = \frac{U_i}{\lambda_{LP,i}}, \qquad i = 1,2,\dots,N \tag{1.13}$$

where $U_1, U_2, \dots, U_N$ are the outage time for each load point, the r matrix represents the repair rate, $h(i,:)$ is equal to 1 when its related repair rate has variation, otherwise, it is equal to 0. $\lambda_1, \lambda_2, \dots, \lambda_M$ are the operational failure rate of each micro-source sysytem, considering the influence of operational failure rate of power electronics system applied in each micro-source generation system and the failure rate of each source. λ_{LP} and r_{LP} are the failure rate and repair time of each load point, respectively.

1.5 Reliability improvement methods of Power Electronic Systems

A systematical operational reliability model of power electronic systems in subsystems of islanded microgrids will be presented in Section 2.1. As mentioned in chapter 1, the reliability is one criterion in the designing stage. In order to improve the items' reliability, several methods are presented.

Based on the failure rate model of components, it can be observed that the failure rate is a product of several factors such as the aging quality factor, manufacturing factor, thermal factor and the over stress ability factor. Among these factors, the manufacturing factor is the property of components and could be improved in designing stage by replacing the low level quality devices to high level quality devices. In addition, the manufacturing factor accounts for a large part of the whole factors effecting the failure rate of components. Thus the first direct method is to improve the component quality level by improving the quality of components.

Followed by is the electrical and thermal factors(processing factor), especially for semiconductors like IGBT, MOSFET. These two factors have significant influence on the performance of components. Therefore, the second method refining thermal management is an effective method to power electronics [34].

The third method is to add redundancy on the system based on the hardware and software perspective. For the redundancy in the system-level, it improves the reliability of power electronic systems greatly. However, this method will at least double the cost and will also bring new challenges to the reliability issue of the system. Then comes the redundancy in the subsystem-level to overcome this disadvantage, improving the reliability of the system greatly with a lower cost and increasing the system's flexibility [35]. Thus, in this paper, the third method will be utilized and the simulation will verify the proposed method in the followed part.

1.6 Research Objective and Thesis Layout

The Objective of this thesis is to present a systematical operational reliability model to evaluate the reliability of the islanded micro-grid considering the impact of power electronics systems in the real-time operational and environmental factors. In addition, to enhance the reliability of system in a subsystem-level, the hybrid energy storage system replaces the conventional battery energy storage system. Based on this goal, a lot of work has been done and has verified the proposed application of the hybrid energy storage system.

The first chapter is about the research for the reliability assessment of islanded microgrids, the application of hybrid energy storage system, and reliability methods commonly used recently. The first part of the second chapter has an overall introduction of the topology and main components of subsystems in the islanded microgrid, then a framework for a reliability analysis of the power electronics system is proposed and the associated details of the framework are illustrated, and it also has a brief introduction about the reliability improvement. The third chapter covers the operational failure modelling process for converters, considering the operating environments' meteorological factors in each subsystem, and is therefore tested.

Chapter 4 covers a case study, which is based on the modified benchmark 0.4 kV test system and will use the short-term outage model to evaluate the reliability of the system. Then an analysis based on different factors(operational failure rates of electronic power system, types of ESS, types of Micro-sources)is studied to investigate their impact on the reliability of the electronic power system and the overall system's reliability performance. And the sensitivities analysis considering the effect of yearly characteristics, parameters of wind turbine , parameter of PV array and ESS capacity will be done in chapter 5. Finally, Chapter 6 presents conclusions and future works.

Chapter 2 The operational reliability model for power electronic systems

2.1 The subsystem main components and topology of island microgrid

To evaluate the reliability of microgrid, the topology and components are introduced in this section. A micro-grid is composed of generation system, energy storage system, control system and loads. Generation systems in this thesis are composed of renewable and non-renewable generation system, the former one mainly refers to WTG system and PV system which has been mostly utilized in nowadays. Since micro-turbine generation (MTG) has many advantages: high efficiency, lower cost, and higher possibility to meet customers [36], it is chosen as non-renewable energy generation in the studied system. With development of power electronic technology, the fully controlled switches are increasingly applied in conversion system and show good performance. As shown in the Figure 1-3, this converter is composed of 6 diodes and 6 IGBTs, then the generation side connected rectifier is connected to inverter through a DC-link capacitor.

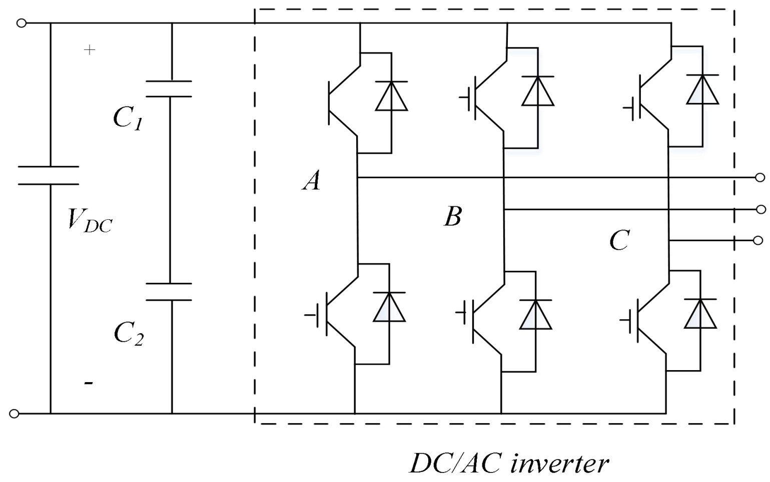

Figure 2-1 Illustration of the two-level converter

A. PV system

Nowadays, the application of PV systems is greatly increasing and have a promising future, since it is environmentally friendly and easy to obtain. Though, PV systems interfaced to microgrids usually employ two stages conversion system [37]– [39]. This paper is based on a single stage inverter topology. Most commonly used topology is the 2L-VSI (two level voltage source inverter) [38].A single stage inverter topology can convert the intermittent solar power into AC power for microgrids effectively and also have several advantages such as higher efficiency, economic and smaller size [39].

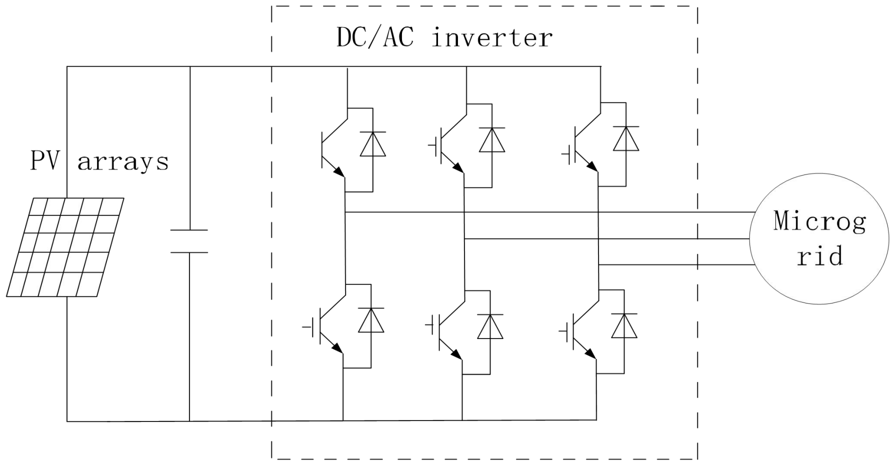

Figure 2-2 A typical grid converter topology of PV modules

C ESS system

For islanded micro-grid, the power generated by DGs (distributed generation system) and ESS(energy storage system) has to meet the demand of loads. Because of the unstable characteristic of renewable energy and the loads demands, a reliable ESS system can improve stability and power quality of system. Therefore, the reliability of components in ESS is considered as a criterion when choosing the topology for system [40,41]. The primary topology of ESS is a single stage inverter that is similar to the topology of the PV system. Power electronic systems interface the storage units to the microgrid should have ability to allow smoothly transition between the different modes, and transfer power bidirectionally and work continuously [42].

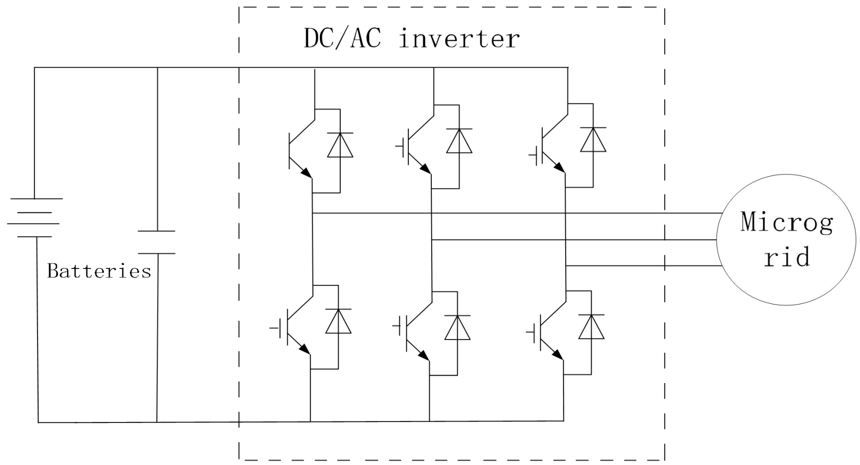

Figure 2-3 The topology of ESS

B. WTG system or MTG system

For WTG system or MTG system, this paper is based on a back-to-back topology (2L-BTB) as shown in Fig. 2-4[43-49]. The desirable characteristics of the 2L-BTB is compact structure and low cost, and the technology available in this field is mature. The commonly adopted uncontrollable rectifier composed of diodes will generate harmonic currents, causing additional losses and increase temperature rise of generator. To overcome this problem, a directional PWM rectifier is analyzed in this paper which is composed of 6 IGBTs and parallel connected diode [46].

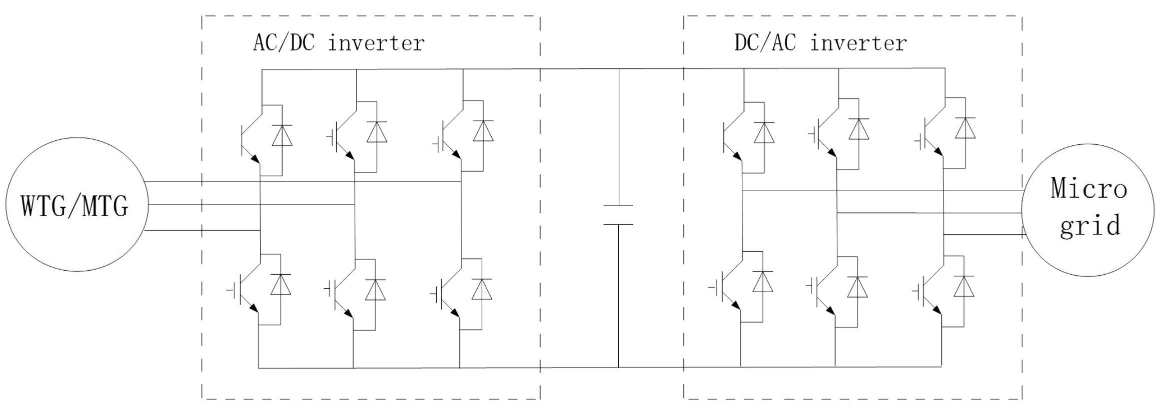

Figure 2-4 A typical grid converter topology of MTG or WTG system

2.2 Reliability Evaluation of Power Electronic Systems

In this part, a systematical failure rate model of power electronic is demonstrated. The model is composed of several procedures which assess the reliability performance of power electronic systems based on specific operational condition. The proposed model is demonstrated in Fig. 2.1[50]. This model works for power electronic systems in islanded microgrid. The operational condition (meteorological factors, physical configuration parameters, ect) that determines the operational conditions of the power electronic systems is the input to the general model, and the various reliability metrics including failure rate, reliability, availability can be obtained from the model.

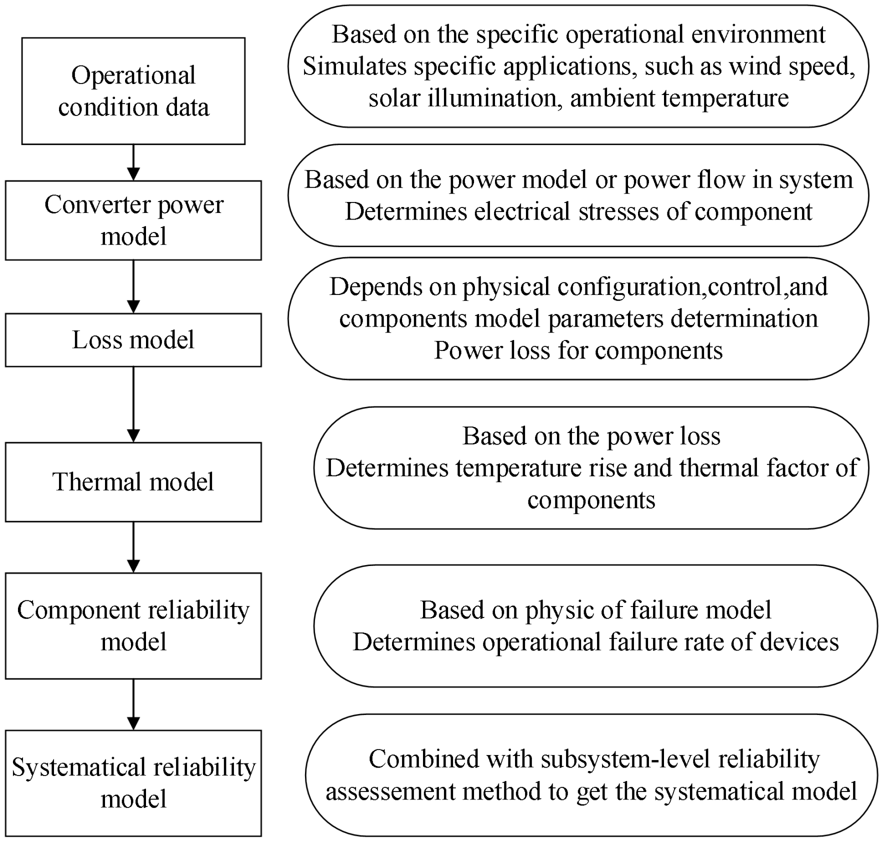

Figure 2-5 A systematical failure model of reliability assessment

2.2.1 Operational conditions

For power electronics, the operational condition represents variable loads, the real time meteorological statistics and the output of power generation systems, and these factors will determine different stresses of the power electronics. Among those factors, the electrical and thermal factors of components have close relationship with the output requirement of the converters and the real time meteorological statistics.

2.2.2 Power model

To obtain the output of DGs and ESS within a specific interval, variable power models based on real time meteorological statistics are illustrated in this part.

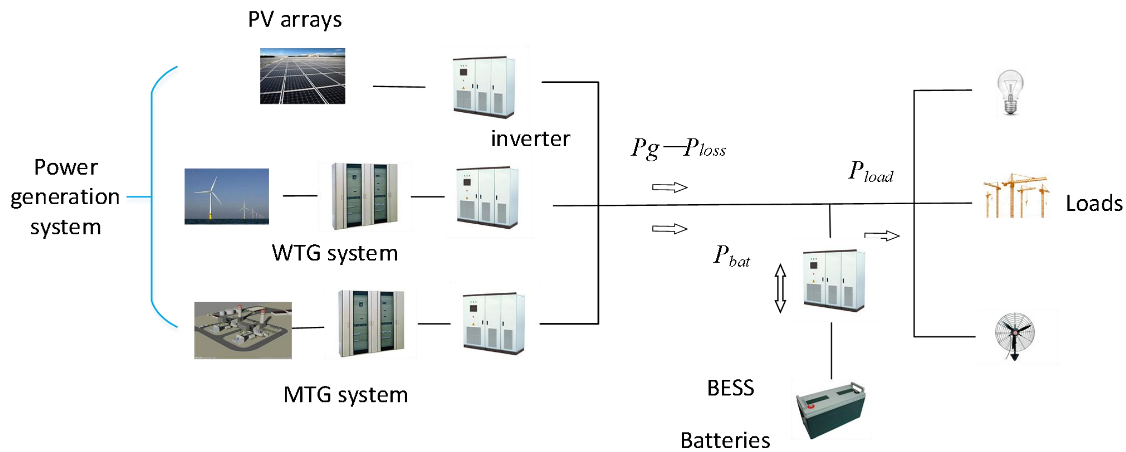

Figure 2-6 A systematical power flow of microgrid

A. Calculating Output Power for WTG

After obtaining the meteorological statistics for wind turbines, take it as input to the power model, then the output of WTG systems are presents as below. As the expression shows, the output power of wind turbine has closely relationship with wind speed [49]. As shown in the representation, P_{WTG} is output of the WTG system, v_{ci} is the cut in wind speed, v_{co} is cut out wind speed .

$$P_{WTG}=\begin{cases} P_{wr} & v_r \le v < v_{co} \\ P_{wr}\times\frac{v-v_{ci}}{v_r-v_{ci}} & v_{ci} \le v < v_r \\ 0 & others \end{cases} \quad (2.1)$$

B Calculating Output Power for PV system

After obtaining the meteorological statistics for solar panels, take it as input to the power model. Then the output power of PV systems are presents as below. As the expression shows, the output power of PV models has closely relationship with meteorological factors [49]. As shown in the representation, P_{PV} is output of the PV modules, T_a is the ambient temperature, Is is the solar illumination, P_{sr} is the rated output of PV modules, T_r is the reference temperature and I_r is the reference solar illumination.

$$P_{PV} = P_{sr}\left[1 - 0.0045\left(T_a - T_r\right)\right]\frac{I}{I_r} \tag{2.2}$$

C Calculating Output Power for MTG system

Since MTG systems is controllable energy generation system, in the case study in the 4 chapter, with the peer-to-peer control energy management strategy, MTG system and renewable generation systems both supply the power to loads, when there is mismatch between the power supplied by distribution systems and loads requirement, then ESS will fill the gap. The variable output power of micro-turbine can be expressed as below. When it can fully fill the gap between the load required and power of other generation subsystems, the output can be expressed as:

$$\begin{aligned} P_{MTG} &= P_{PV} + P_{WTG} + P_{ESS} - P_{loss} \\ P_g &= P_{PV} + P_{WTG} \end{aligned} \tag{2.3}$$

Otherwise, the output of micro-turbines can be expressed as:

$$P_{MTG} = P_{MTrated} \tag{2.4}$$

D Calculating Power flow of ESS

The overall power flow of the islanded microgrid system [51] is shown in Figure 2-6. Considering the switching losses in electronic power systems in microgrid, the relationship between the power flow in the micro-grid system can be expressed as below:

$$P_{load} + P_{loss} = P_{ESS} + P_g + P_{MTG} \tag{2.5}$$

Where P_g is the sum of the output of the WTG and PV systems, Pload is the requirement of loads, P_{ESS} is power flow in or out of ESS.

2.2.3 Loss Model

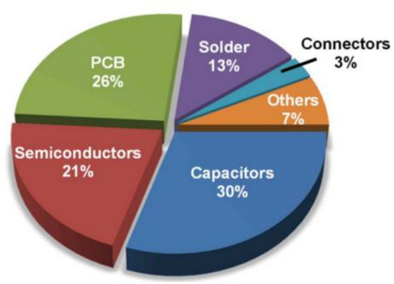

Figure 2-7 Survey of different fragile components responsible for converter failure [48]

As shown in the pie chart above, the least reliable components in electronic power systems are semiconductors and capacitors, especially in islanded micro-grid, their performance will have influence the quality of power supplied to customers directly. When obtaining the current, voltage and power of the devices provided by the power model, then a loss model is used to calculate the power loss of the components. The power loss of the VSC is the sum of power loss of diodes and IGBTs. The loss of each component (IGBT or diode) could be calculated based on the output power, voltage, current, frequency of switch of the wind turbine, PV modules or energy storage system, micro-turbine generator [52]. The power loss of each component in VSC can be expressed as follows respectively [52], [53]:

$$P = V_{diode} I(\frac{1}{2\pi} -/+ \frac{M}{8}\cos\theta) + R_{diode} I^2 \left(\frac{1}{8} -/+ \frac{M}{3\pi}\cos\theta\right) + \frac{f}{\pi} \cdot \frac{V_{DC} I}{V_{ref,diode} I_{ref,diode}} E_{diode} \qquad (2.6)$$

$$P = V_{IGBT} (\frac{1}{2\pi} \pm \frac{M}{8}\cos\theta) + R_{IGBT} I^2 \left(\frac{1}{8} \pm \frac{M}{3\pi}\cos\theta\right) + \frac{f}{\pi} \cdot \frac{V_{DC}}{V_{ref,IGBT} I_{ref,IGBT}} E_{on} + E_{off} \qquad (2.7)$$

As shown in the loss model of each component, V_{DC} represents DC link voltage;M is the modulation index; and θ is the angle between the current and voltage, I is the peak phase current. For each diode, R_{diode} is the conduction resistance and E_{diode} is the rated switching loss; the V_{diode} is the voltage drops across the diode; $V_{ref,diode}$ and $I_{ref,diode}$ are the reference commutation current and voltage respectively. For each IGBT, R_{IGBT} is the conduction resistance and R_{IGBT} are the conduction resistance; V_{IGBT} is the voltage drops across IGBT; $V_{ref,diode}$ and $I_{ref,diode}$ are the reference commutation voltage and current of diode respectively; E_{on} and E_{off} are the power losses of IGBT during the switching operation. I can be expressed by[49]:

$$I \approx \frac{\sqrt{2}P_t}{\sqrt{3}U_l} \tag{2.8}$$

Where Pt is the power output of the generation systems or energy storage systems and Ul is the line-to-line voltage for each subsystem on the AC side. The total power loss of the converters can be expressed as below:

$$P_{loss} = \sum_{i=1}^{N1} P_{IGBT,i} + \sum_{j=1}^{N2} P_{diode,j} \tag{2.9}$$

N1 and N2 represents the number of IGBTs and diodes in the converter.

2.2.4 Thermal Model

The power losses of devices could be utilized as input for the thermal model to obtain thermal factors of devices. This model is to predict thermal factors like junction temperature and temperature variation and detect thermal cycling of devices. Two factors like junction temperature and temperature variation are critical factors to semiconductor devices [52]. The temperature rise in the converter (inverter and rectifiers) can be calculated as below [49]:

$$T_{module} = T_{ambient} + R_{ha} P_{loss} \tag{2.10}$$

where ambient temperature is represented by $T_{ambient}$ and thermal resistance from ambient temperature to heatsink is represented by R_{ha}.

2.2.5 Component Reliability Model

Using the component reliability model, several reliability metrics, like failure rate, reliability, mean time to repair and availability can be calculated. Take the different factors obtained from the models analyzed in above sections. Based on these basic metrics, other reliability indicators can also be obtained. In the failure rate model of this paper, the hourly failure rate is regarded as unit. The failure rate model of each component in electronic power systems could be expressed as below, different basic factors can be referenced in [54].

$$\lambda = \prod_{PM} \prod_{process} \prod_{induced} \left(\gamma_{TH} \prod TH + \gamma_{TC} \prod TC + \gamma_{M} \prod M + \gamma_{RH} \prod RH\right) \tag{2.11}$$

In which γ_{TH}, γ_{TC}, γ_{M}, γ_{RH} are the basic failure rate influenced by temperature, thermal cycling, mechanical and humidity respectively. In addition, the Π_{PM} is manufacturing factor and $\Pi_{process}$ can represent the aging quality of the component during its lifetime, and $\Pi_{induced}$ is the factor reflecting its overstress ability. Π_{TH} and Π_{TC} are the thermal factor and thermal cycling factors, respectively, and they can be expressed as

$$\prod_{TH} = \exp\left(11604 \times 0.44 \times \left[\frac{1}{293} - \frac{1}{T_{ambient} + \Delta T + 273}\right]\right) \tag{2.12}$$

$$\prod_{TC} = 12 \times \sqrt[3]{0.5} \times \left(\frac{\Delta T_{cycling}}{20}\right)^{2.5} \times \exp\left(1414 \times \left[\frac{1}{313} - \frac{1}{T_{\max} + 273}\right]\right) \tag{2.13}$$

in which $\Delta T = 10℃$, $\Delta T_{cycling}$ is the temperature variation in a phase and T_{max} is the maximum temperature in a phase.

2.2.6 System Reliability Model

After the analysis above, the reliability metrics of components are obtained. Based on component-level reliability metrics of devices and using the system-level reliability method which considers the interaction among components and subsystems to give a systematical model for microgrid.

2.3 Conclusion

In the first section of this chapter, the topology which is selected as one stage conversion system for DC sources (PV modules and Battery banks) and the topology which is selected as AC/AC conversion system composed of bidirectional PWM rectifier for AC sources (wind generators and micro-turbine generators) and one VSC (Voltage Source Converter) inverter are illustrated.

In section 2.2, an outline of systematical operational failure rate model, which is composed of operational conditions, power output model, converter model, loss model and thermal model, is presented. In this systematical model, operational condition is to determine different stresses of power electronics. The loss model is to calculate the power loss of power converters based on the operational conditions of power electronics. Based on the operational factors, the operational reliability models of components can be built. Finally, combined with proposed system level reliability assessment method, the reliability models of each subsystem and overall system can be constructed. Since the reliability evaluation results is a criterion in design stage and provides a guidance on reliability improvement. Then the three commonly-used methods to improve reliability of power electronic systems are introduced in section 2.3. Last part is the conclusion of this chapter.

Chapter 3 An operational reliability model and improvement of islanded micro-grid

3.1 Introduction

This chapter is organized in the following way. Based on systematical failure model of power electronics systems proposed in section 2.2. In this chapter, the reliability of the power electronics systems in islanded microgrid are evaluated. The reliability models of PV system, WTG system, MTG system and ESS system are introduced in section 3.2. In section 3.3, some tests have been done to verify the model. The introduction of HESS (hybrid energy storage system) and to enhance the reliability performance of microgrid by replacing the conventional BESS (battery storage system) with HESS, then theoretically analysis will be introduced in section 3.4. The conclusion is given in section 3.5.

3.2 Operational failure model of subsystems in island microgrid

3.2.1 Operational failure model of renewable generation system

For the model illustrated in figure 3-1, first the hourly WTG/PV output is calculated based on the meteorological statistics. Then the electrical stresses for power electronics in subsystem can be obtained, combining them with the physical configuration and parameters. Then the total power loss of the power electronics is calculated based on loss model and the temperature rise over the converter can also be obtained based on thermal model. Based on operational factors, combined with system level reliability assessment method, the converter operational failure rate can be obtained. In one words, if we input the hourly meteorological statistics into this model we can calculate the real-time failure rate of power electronic system.

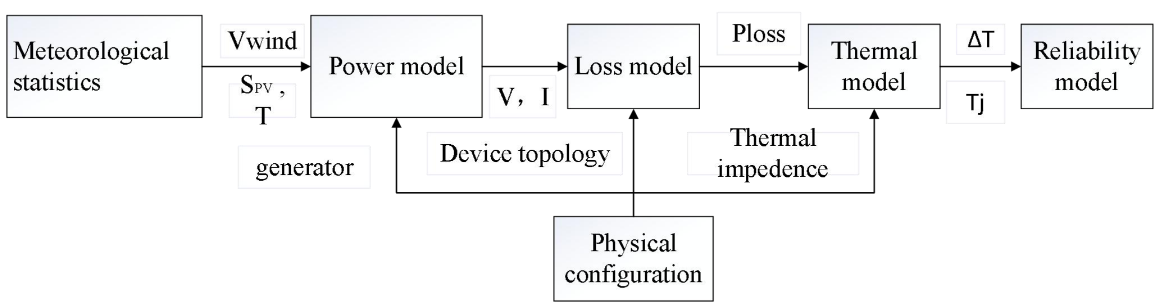

Figure 3- 1 Operational converter outage model for WTG/PV system

3.2.2 Operational failure model of MTG system or ESS system

For the model illustrated in figure 3-2, when there is mismatch between the power supplied by renewable generation systems, energy storage system and loads requirement, the hourly power flow of MTG and ESS is calculated. Then the total power loss of the power electronics is calculated and the real-time temperature over the converter is also calculated based on thermal model [52]. Finally, the converter operational failure rate can be calculated.

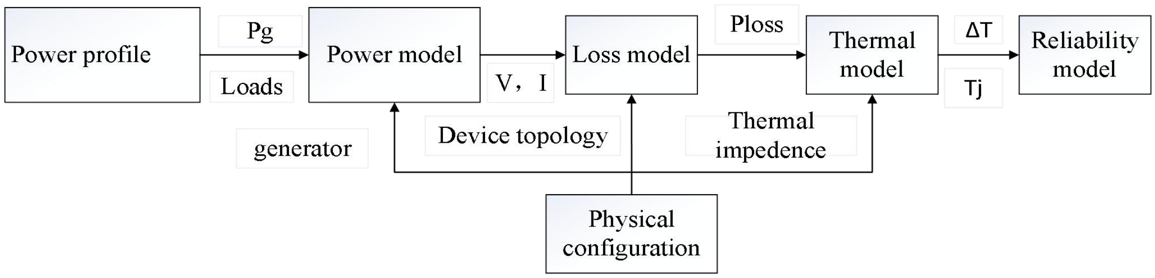

Figure 3- 2 Operational converter outage model of ESS or MTG

3.3 Model Test

After constructing the time-varying operational failure model of subsystems in island microgrid, in order to verify the models. Some tests have been done in this section.

3.3.1 Model Test of Wind turbine generation system

The rated output of this wind turbine is 1000 kw, when increasing the wind speed linearly, the output of wind turbines can be observed in figure 3-3. In the first period, before the V (wind speed) reaches the V_{ci} (cut-in speed), the output of wind turbines is 0. In the second period, when V ranges from the V_{ci} to V_r (rated speed) , the output shows an upward trend. In the third period, when V exceeds V_r , the output power of wind turbines remains at rated power.

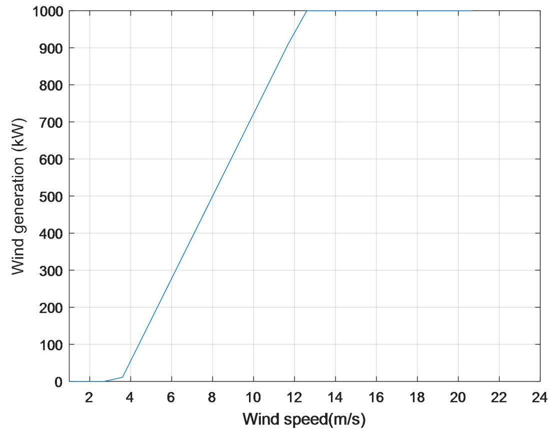

Figure 3- 3 Relationship between wind speed and output

Taking hourly temperature and wind speed for one day in 2010 summer in Milwaukee as inputs and meteorological statistics are shown as below:

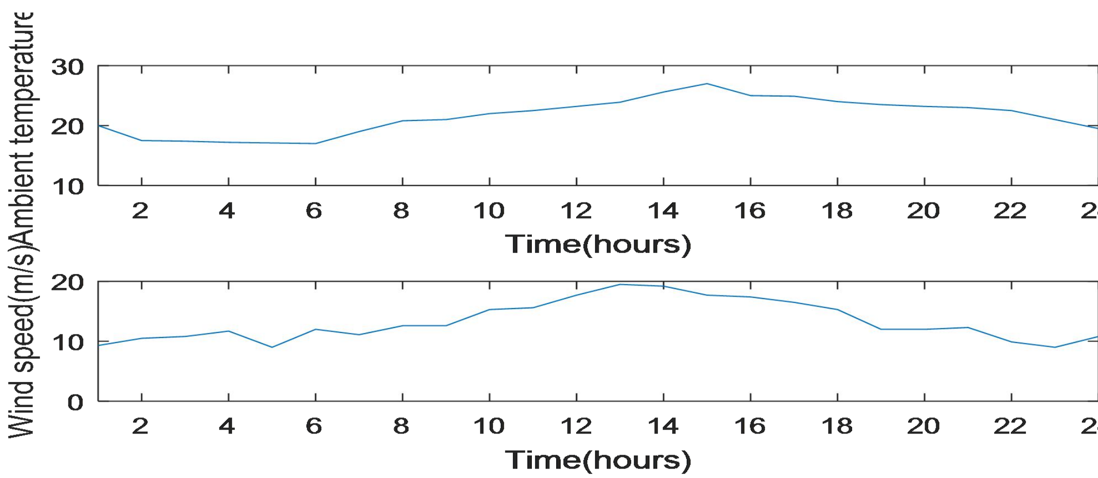

Figure 3-4 Meteorological factors during the day

As we can see in the Figure 3-4, the wind speed reaches its peak point around 13:00 and the ambient temperature reaches its peak point around 15:00. It is obvious that the wind speed is fluctuates more frequently than the ambient temperature.

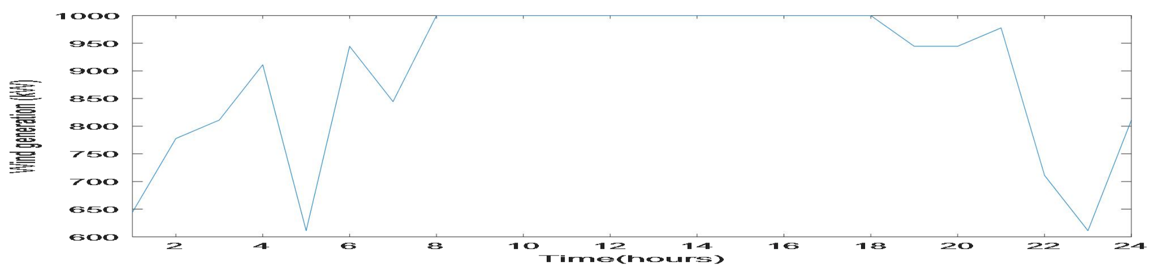

Figure 3-5 Real-time wind power output

As shown in the Figure 3-5, power output of wind turbines reaches the peak value and remains at rated power from 8:00 to 18:00, since the wind speed start to increase from 8:00 at 12m/s and maintain its increasing trend until 13:00, then begin to drop but is still above 12m/s. Based on the real-time meteorological statistics, the operating failure rate can be calculated as below:

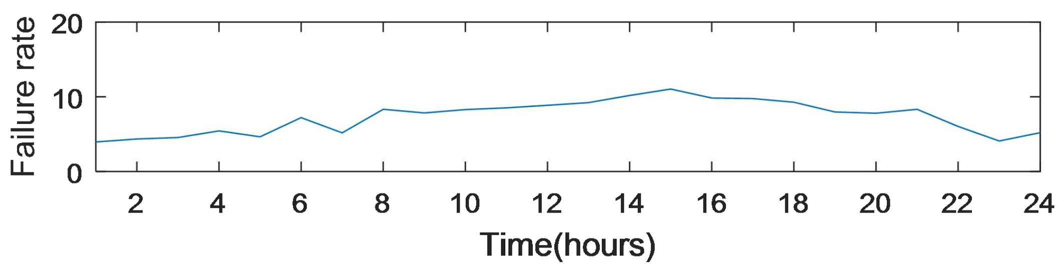

Figure 3-6 Operational converter failure rate of WTG

As is shown in Figure 3-6, the failure rate reached the highest point around 15:00 and reached a minimum point at 23:00. In the meantime, the ambient temperature is almost in lowest level and the wind speed reached its minimum point at 9. It is obvious that the operational failure rate curve varies similarly as the ambient curve. Take the interval from 13:00 to 15:00 as an example, the ambient temperature is increasing, while the wind speed is decreasing. The results show that the operational failure rate of WTG from 13:00 to 15:00 is increasing and reaches highest point at 15:00.

3.3.2 Model Test of Solar power system

Taking the real-time meteorological statistics as inputs, the power of PV arrays can be calculated. The hourly temperature and solar illumination for one day in summer 2010 in Milwaukee is used to verify this model and are shown as below:

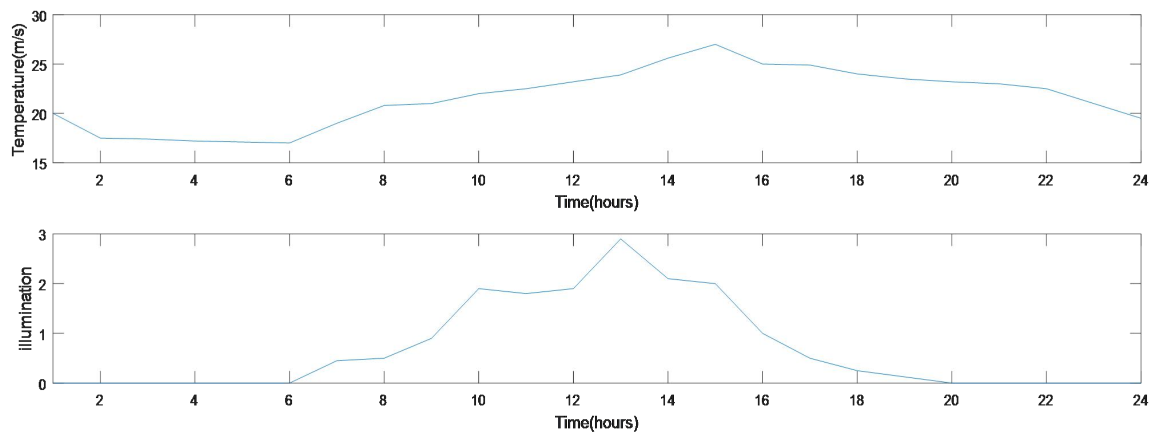

Figure 3- 7 Hourly ambient temperature and solar illumination in Milwaukee

As shown in the figure above, the ambient temperature reached its peak at 13:00 and the solar illumination reached its peak at 15:00. It is obvious that the solar illumination fluctuates more violently than the ambient temperature. Based on the real time meteorological statistics, the hourly output of PV arrays can be obtained. As shown in the Figure 3-8, the solar power output reaches its peak at 13:00, because the solar illumination reaches their peak value in the meantime.

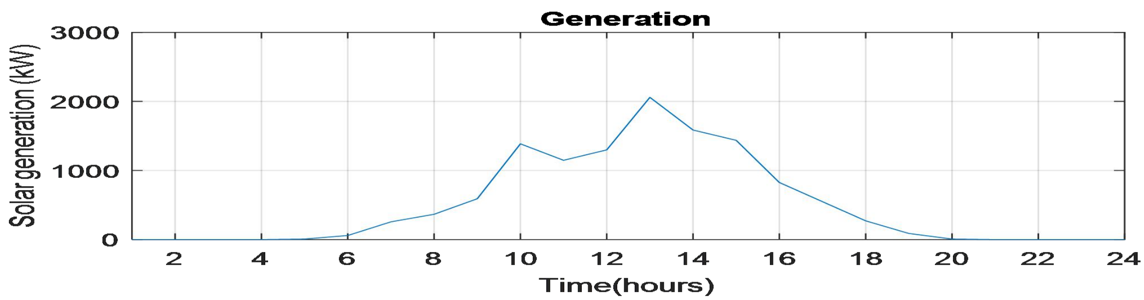

Figure 3- 8 Real-time solar illumination power output

Then the operational failure rate of PV arrays can be calculated as below:

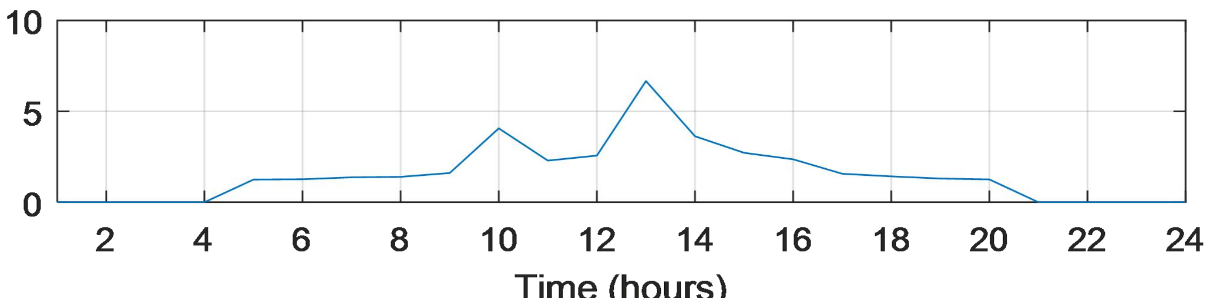

Figure 3-9 Operational converter failure rate in PV generation

As shown above, the failure rate reached a minimum from 0:00 to 4:00 and 23:00 to 24:00, reaching the highest point around 13:00. Also, the solar illumination reached its peak at 13:00. Observing the curves above, it shows that the operational failure rate curve is similar to the solar illumination curve.

3.4 The reliability improvement in sub-system level

For islanded microgrid with high penetration of renewable energy storage systems, because of the intermittent and uncertain characteristics of generation system, the system has unstable supply if without the energy storage systems [55], and it also brings big challenges to reliability issues when islanded microgrid have to supply necessary loads like governmental or residential loads, the energy storage system is critical and have close relationship with reliability performance of system. Combining the reliability improvement methods introduced in section 2.4 with the development of ESSs, the characteristics and configuration of HESS to improve reliability performance in subsystem level will be introduced in this part.

3.4.1 Development of Energy Storage Technology

In island microgrid , when there is a mismatch between power supplied by generation systems and loads requirement, the ESS is to balance the power supply [56]. The ESS acts as a transfer station to store the remaining energy and supply the system when needed. Table 3-1 summarizes the different storage units and their key features respectively. In other words, the power flowing in the ESS components varies greatly based on the operational generation system and loads demand. In addition, the power flow of storage units can be divided into high-frequency parts, such as great increase or increment in loads demand or low-efficiency caused by natural behaviors [57]. The former one generally requires storage units have ability to response fast, while for low-frequency power flowing, the storage elements should have high-energy density.

Energy storage system	Energy density	Power density	Cycle life	Response time	Cost
Chemical battery	high	low	short	medium	low
NaS battery	medium	low	short	slow	medium
flywheel	low	high	long	fast	high
Super-capacitor	low	high	long	fast	medium

Superconducting magnetic energy storage	medium	high	long	fast	high

Table 3-1 Characteristics of different ESS elements [55]

Batteries is widely applied in hybrid or electric vehicles, and even in utility power systems [57]. However, this application has a problem, it is difficult to recover from fast power fluctuations, and this process will reduce the batteries' lifetime. On the one hand, according to Table 3-1, they all do not have the characteristics of optimal response to high-frequency and low-frequency power exchange at the same time [58]. Compared with batteries, energy is stored in a super-capacitor by static charging or discharging instead of an electro-chemical process in a battery, thus, the super-capacitor has a higher power density and responses faster than the battery, but it lasts shorter than the battery.

3.4.2 Improvement of island microgrid from subsystem-level

From the analysis above, combining different energy storage devices to form a HESS (hybrid energy storage system) can have better performance [59,60]. This method combines the advantages of different storage technologies and improve the reliability of power system [59]. Battery-supercapacitor storage system stands out in numerous hybrid energy storage system because of their availability, similarity in operating principles, relatively low cost, and mutual restraint. In islanded microgrid, when the power generated by generation systems exceeds the demand of loads, the remaining power will be stored in the storage units. Otherwise, converters will transfer the energy from the storage units to the loads when required.

In HESS, The topology provides more control flexibility compared to the topology which connects the storage units directly to the voltage bus [6]. A bidirectional DC-DC converter is embedded to construct two stage electronic system, and it has two main advantages: (1) to accomplish the power flow between the batteries and the inverter's DC bus (2) to control the dc link voltage[55]. The topology for HESS is shown in figure 3-10. From the existed work, although the HESS is widely applied in several applications, the reliability assessment considering the operational failure rate of power electronic devices hasn't been studied. Thus, this paper will analyze the reliability improvement based on islanded microgrid with HESS. This section focuses on analyzing reliability improvement of HESS in subsystem level.

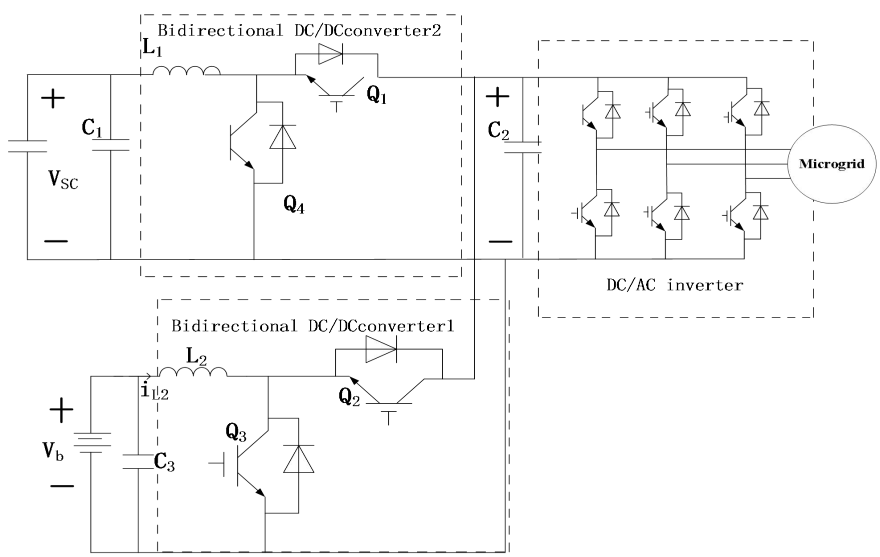

Figure 3-10 A typical grid converter topology of HESS

Based on the model of HESS shown in Figure 3-10, from the perspective of component-level, the addition of super-capacitor greatly decreases the electrical stresses of battery. Because the battery has low power density, if it is applied in the condition which always being charged or discharging suddenly, the failure rate of battery will increase greatly, thus, decreasing the reliability performance of ESS. Some advantages of the HESS are listed: prolong the lifetime of batteries; fast energy storage; energy storage for intermittent sources; a smaller environmental impact. From the perspective of system-level, the parallel configuration provides a backup leg for ESS, thus improving the reliability in subsystem level.

3.5 Conclusion

This chapter establishes operational failure model for power generation systems and energy storage systems respectively in section 3.2. It analyzes the operational conditions of power electronics, including the influence of meteorological factors and different stress factors. Then the systematical failure model for each subsystem is established.

In the systematical failure model, the power model obtains the power flow of generation systems and the energy storage system to obtain the electrical stresses of power electronics. Based on the operational conditions of power electronics, the power loss of each component and the temperature variation can be obtained. From the perspective of reliability, the components within the power electronic converter can be regarded as a series connection. To verify these models, the tests have been done in section 3.3, as shown in the results, the failure rates of power electronic systems in WTGs have close relationship with the real-time temperature; the failure rates of power electronic systems in PVs has closely relationship with the real-time solar illumination.

Based on the reliability improvement methods introduced in section 2.3. To improve the reliability performance of microgrid, the development of energy storage system and reliability improvement of islanded microgrid from subsystem-level are introduced in section 3.4.

Chapter 4 Case Study

4.1 Introduction

In this chapter a low voltage benchmark system is studied and analyzed. The remainder of this chapter is organized in the following way. In section 4.2, topology of this system is simplified to several fault trees by using network reduction method and fault tree analysis, then combining the logical relationship among events to calculate the failure rate of each subsystem. Finally, take the operational failure rate and repair rate as inputs to the short-term outage model to get the reliability indexes of overall system. Then the components in the system and their reliability parameters referenced in [8] will be introduced in section 4.3. The algorithm steps of reliability assessment of system are illustrated in section 4.4. Last part 4.5 is the conclusion.

4.2 Modified benchmark 0.4 kV test system

The modified benchmark 0.4 kV test system referenced from [20] is carried out as a case study. The proposed system is consisted of 11 nodes. The load profile of each load point and parameters of the transmission lines are provided in [20]. This distribution system is composed of 12 feeder lines connected between loads and distribution generation. In addition, there are tie switches in L4 and L11, when microgrid work properly, the L4 and L11 are open circuit. Distribution generations is composed of PV, WTG, ESS and MTG system. When there are all uncontrollable micro-sources like PVs and WTGs supplying in this islanded microgrid. The microgrid system is composed of three PVs, one WTG system and one ESS system as shown in figure 4-1. The rated output and location of renewable energy generation system and energy storage system can be referenced in [20,21] which is listed in table 4-1.

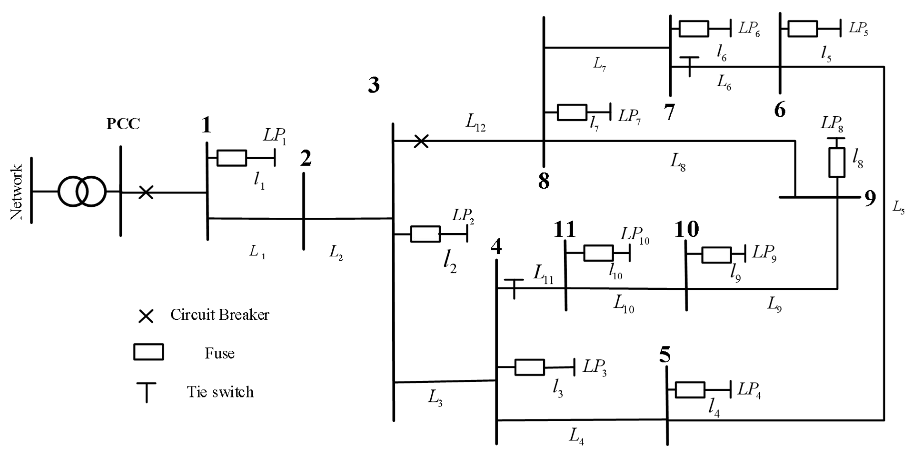

Figure 4- 1 Modified benchmark 0.4 kV test system

Node.No	Types of μS	Grate/kW
3	Photo-voltaic	7750
5	Photo-voltaic	6600
6	Wind Turbine generator	1000
8	Energy storage	1000
10	Photo-voltaic	3000

Table 4-1 Location and capacities of microsources

Firstly, based on meteorological statistics (hourly wind speed, ambient temperature and solar illumination) of a given day in summer 2010 in Milwaukee and reliability evaluation methods introduced in chapter 1, the reliability metrics from component level and systematical level can be evaluated. At the system level, the FTA method combined with network conduction method are applied to the reliability evaluation of power electronic systems of subsystems. Then the obtained reliability metrics are applied to short-term outage model to evaluate the reliability of islanded microgrid from customers perspective. The overall system can be simplified to the Figure 4-2 as below.

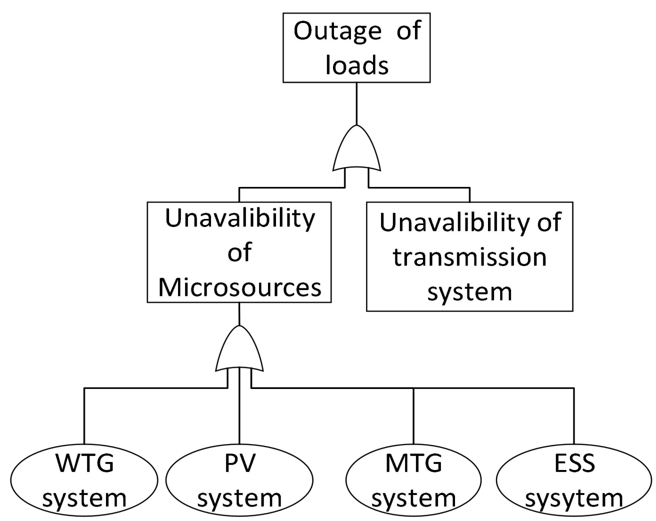

Figure 4- 2 Fault tree for improved benchmark 0.4 kV test system

As shown in above figure 4-2, the causes of loads outage can be the failure of DGs or transmission subsystem. For the failure of DGs, the causing event can be any failure of four subsystems, which consists of converters, generators and storage units. For the converters, the failure caused by control system is also considered.

A PV system and conventional BESS

As shown as below, the failure of PV system regarded as top event can be caused by four sub-events (the failure of PV modules, DC-link capacitor, control system, inverter or breaker).

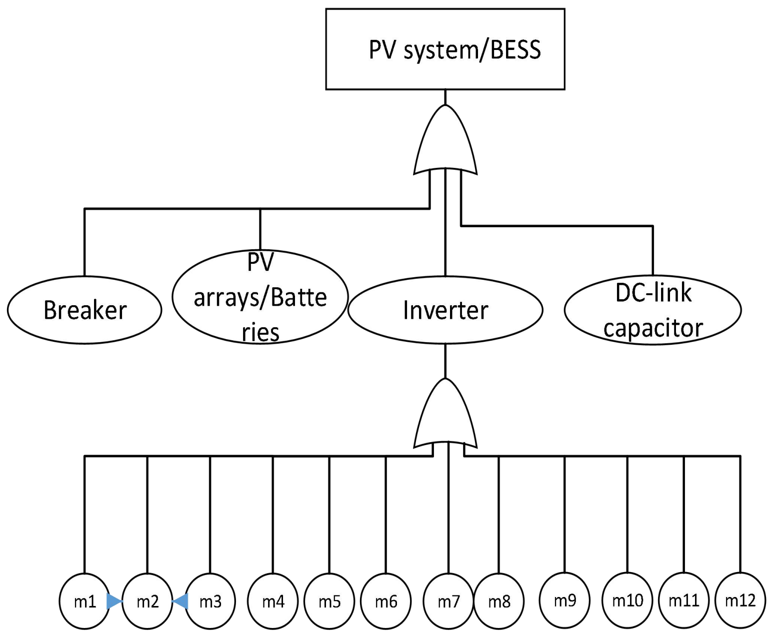

Figure 4- 3 Fault tree for PV system

For subsystems in microgrid, the systematical failure rate can be expressed by:

$$\lambda_{PV/ESS} = \lambda_{inverter} + \lambda_{capacitor} + \lambda_{PV\,\mathrm{mod}ules} + \lambda_{control} + \lambda_{brea\mathrm{ker}} \tag{4.1}$$

B WTG and WTG system

As shown as below, the failure of WTG system regarded as top event can be caused by five sub-events (Wind turbine generator, DC-link capacitor, rectifier, inverter, breaker or control system).

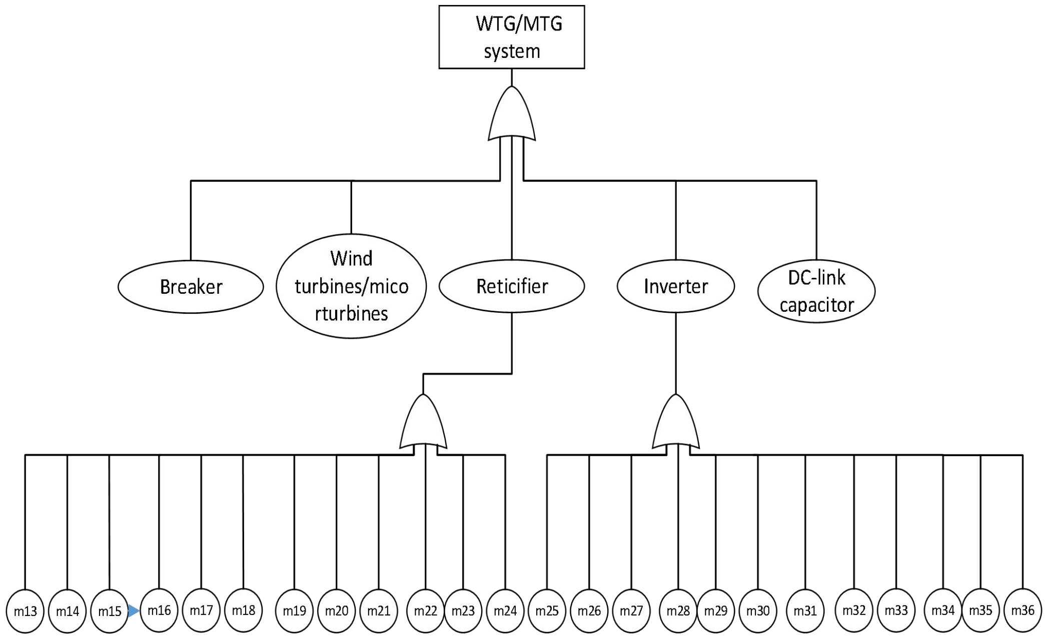

Figure 4- 4 Fault tree for wind turbine generation system

For subsystems in microgrid, the systematical failure rate can be expressed by:

$$\lambda_{WTG/MTG} = \lambda_{breaker} + \lambda_{inverter} + \lambda_{rectifier} + \lambda_{capacitor} + \lambda_{generator} \quad (4.2)$$

C ESS system

As shown in Figure 4-5, the failure of BESS regarded as top event can be caused by five sub-events (battery modules, bi-directional DC/DC converter, breaker and control failure). Then the operational failure rate of ESS can be expressed as below:

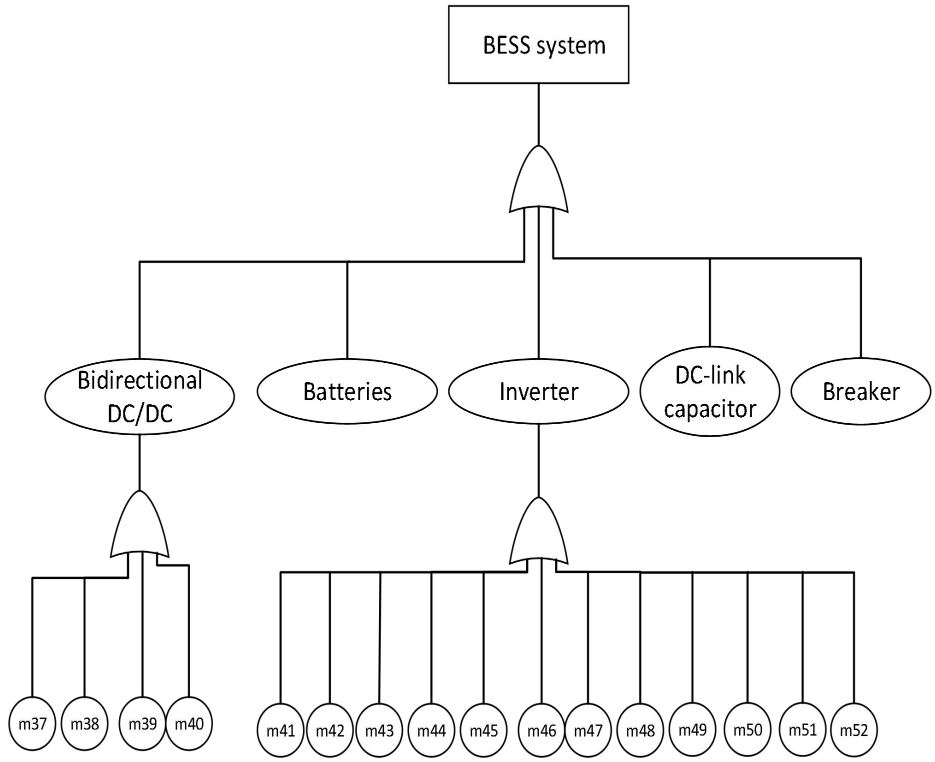

Figure 4-5 Fault tree for battery energy storage system

$$\lambda_{BESS} = \lambda_{inverter} + \lambda_{Bi-DC/DC} + \lambda_{batteries} + \lambda_{capacitor} + \lambda_{breaker} \tag{4.3}$$

To improve the reliability performance of microgrid in a subsystem-level, replacing the one stage battery storage system with parallel hybrid energy storage system, the failure of HESS can be caused by three sub-events and the fault tree is constructed in Figure 4-6, then the operational failure rate of HESS can be expressed as below:

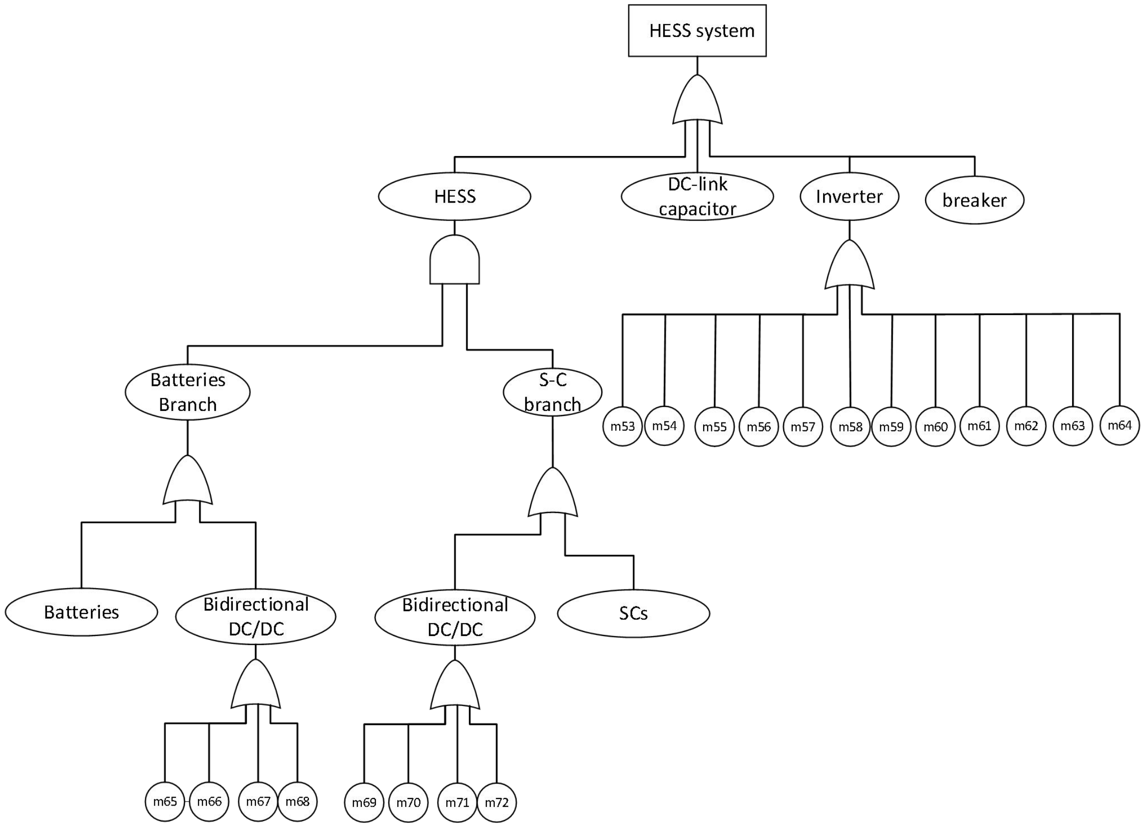

Figure 4- 6 Fault tree for hybrid energy storage system

$$\lambda_{HESS} = \lambda_{inverter} + \lambda_{HESS} + \lambda_{capacitor} + \lambda_{breaker} \tag{4.4}$$

No.	Types	No.	Types
m1-m6,m13-m18,m25-m30 m53-m58,m41-m46	IGBTs	m67,m71 m39	Inductances
m7-m12,m19-m24,m31-m36 m59-m64,m47-m52	Diodes	m68,m72 m40	capacitors
m37,m38,m65,m66,m69,m70	MOSFETs		

Table 4-2 components in fault trees

4.3 Component parameters

This thesis focuses on studying the influence of operational failure rates of power electronics due to the volatile and intermittent renewable generation on microgrid reliability, and the failure rates of wind turbine, PV arrays and battery are chosen according to statistical databases [20][21].

A. Feeder line

As shown in figure 4-1, there are 12 feeder cables in this islanded micro-grid, the parameters are referenced in [20] and listed in table 4-3.

No.	$R(\Omega/km)$	$X(\Omega/km)$	$C(nF/km)$	$L(km)$
L1	0.579	0.367	9.93	0.282
L2	0.164	0.113	413	0.442
L3	0.262	0.121	405	0.061
L4	0.354	0.129	285	0.056
L5	0.336	0.126	343	0.154
L6	0.256	0.130	235	0.024
L7	0.294	0.123	350	0.167
L8	0.339	0.130	273	0.032
L9	0.339	0.133	302	0.077
L10	0.367	0.133	285	0.033
L11	0.423	0.134	310	0.049
L12	0.172	0.115	411	0.130

Table 4-3 Parameters of Feeder lines

B. Load model

In addition, the loads are divided into two types: residential and commercial loads. The related hourly variable load demand and number of customer at each point are referenced in [20] and listed in Table 4-4.

Node. No	**Residential**		**commercial**	
	Load value/kVA	Number of customers	Load value/kVA	Number of customers
1	7.5+j*1.55	50	2.5+j*0.50	2
2	——	——	——	——
3	2.76+j*0.69	50	2.24+j*1.39	2
4	4.32+j*1.08	50	——	——
5	7.25+j*1.82	50	——	——
6	5.5+j*1.38	50	——	——
7	——	——	0.77+j*0.48	2
8	5.88+j*1.47	50	——	——
9	——	——	5.74+j*3.56	2
10	4.77+j*1.20	50	0.68+j*0.42	2
11	3.31+j*0.83	50	——	——

Table 4-4 Parameters of loads

B. Parameters of power electronics in subsystems

The main parameters for electronic power systems in this tested islanded microgrid are shown as below:

parameters	values	parameters	values
V_{IGBT}	1.54V	E_{diode}	0.39J
R_{IGBT}	$0.84\times10^{-3}\Omega$	U	690V
f	3000Hz	N_1	6
E_{on}	0.50J	N_2	6
E_{off}	0.57J	R_{ha}	0.454°C/W
V_{DC}	1100V	Π_{PM}	0.16
$V_{ref,IGBT}$	1700V	$\Pi_{process}$	0.4
$I_{ref,IGBT}$	2400A	$\Pi_{induced}$	7.12
U_g	563.4V	γ_{TH}	0.359
V_{LL}	690V	γ_{TC}	0.523
V_{diode}	0.81V	γ_M	0.9
R_{diode}	1.5Ω	γ_{RH}	0.028

Table 4-5 Parameters of power electronics in subsystems

For the converters in subsystems in islanded microgrid, the real-time failure rate can be calculated based on the model proposed in chapter 3. To calculate the reliability indices, the repair rate and failure rate for modules and breaker are provided in Table 4-4 which are referenced in [20].

Types	**Failure rate λ**	**Repair rate** r
Wind turbines	2.5	3
PV arrays	5	3
Batteries	2	5
breakers	8	2

Table 4-6 Reliability parameters of Component

In fault trees, assuming the components in one subsystem are in series connection, in another word, when one component in subsystem fail, the subsystem can't realize its function. Considering the effect of the real-time hourly meteorological factors, when calculating the operational failure rate. The hourly meteorological factors of one day in the Summer of 2010 in Milwaukee were used and given in figure 4- 4 and the figure 4- 5.

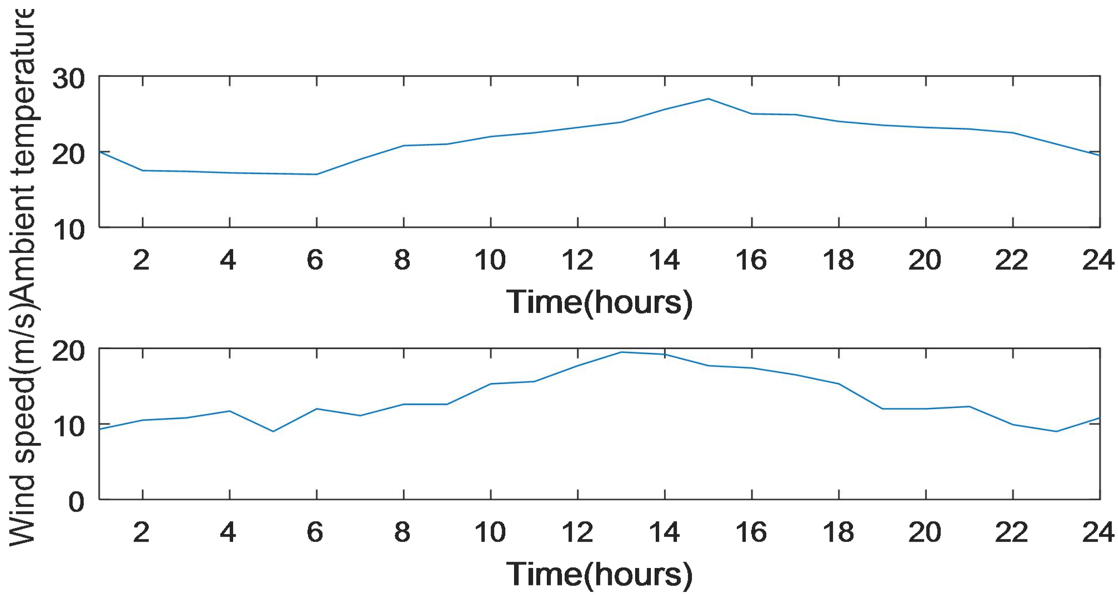

Figure 4- 7 Hourly ambient temperature and wind speed

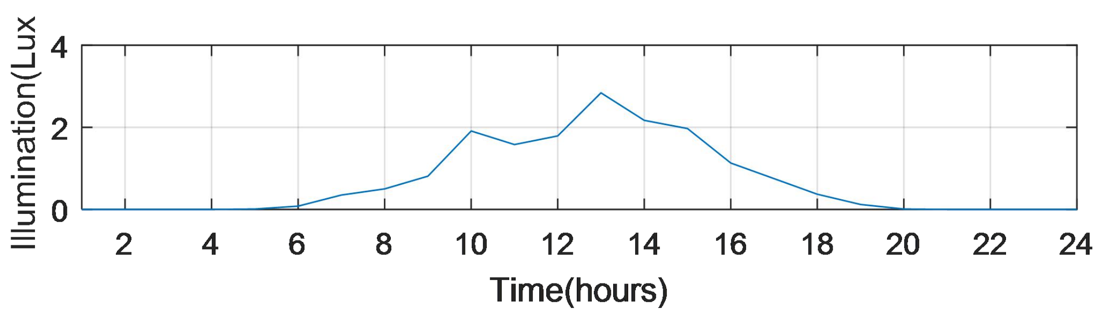

Figure 4- 8 Hourly solar illumination

4.4 Simulation

4.4.1 Solution Process

The solution process is shown in Fig.4. 7 and related steps are illustrated as follow.

Step 1) Initialization and analyze power flow in microgrid.

Step 2) Based on the power flow and loss model, calculating the power loss of power electronic devices, then using the thermal model to get the operational rate of components.

Step 3) Identifying failure events which contribute to outage of loads and construct fault trees, then calculating the reliability indices in system level.

Step 4) Calculating average outage times and failure rate of load points, as explained in short term outage model.

Step 5) Calculating the reliability indices of load points mentioned in Chapter 1.

Step 6) Checking whether all intervals have been analyzed.

Step 7) While "No", repeating the process; if "Yes", evaluating the short-term reliability indices of microgrid system based on functions mentioned in Chapter 1.

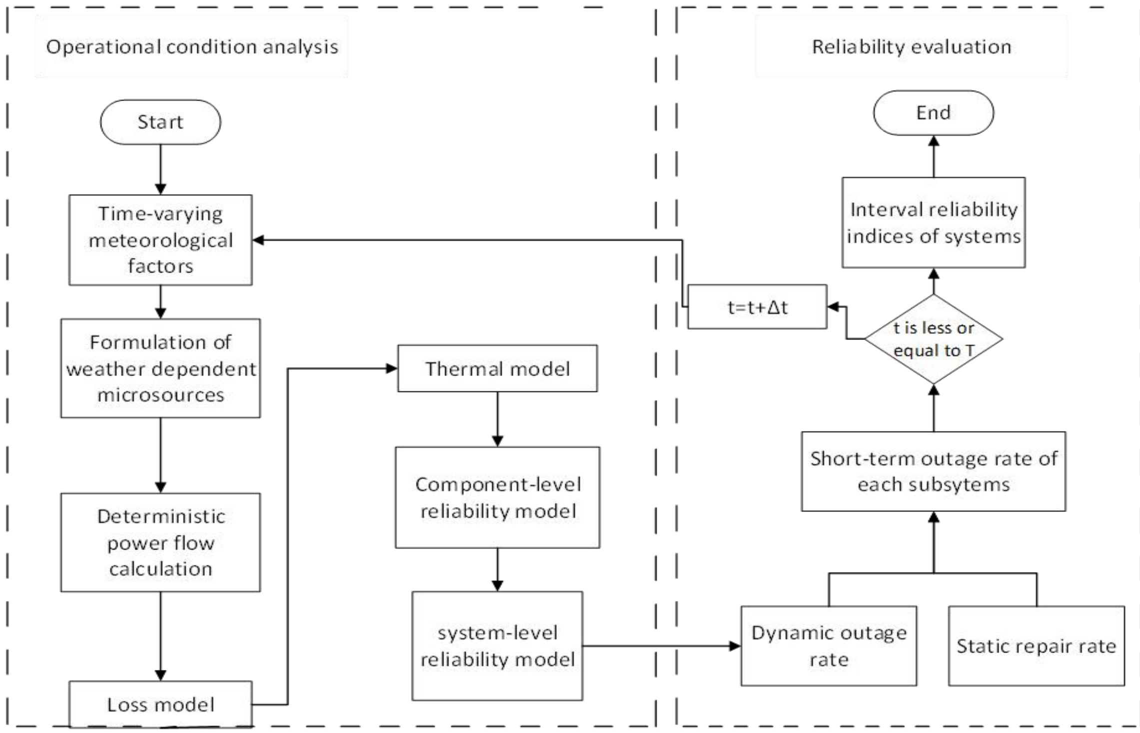

Figure 4-9 Proposed operational reliability evaluation procedure

4.4.2 Simulation results and analysis

As shown in figure 4-8 and 4-9, it can be found that the peak of the wind speed is around 13:00 and the peak of the ambient temperature is around 15:00. Based on the proposed systematical failure rate model in chapter 3, the operational failure rate model for each component can be obtained. Combined with proposed reliability assessment method in chapter 1, the operational failure rate for the converters of subsystems in islanded microgrid system is calculated. The operational failure rate of the subsystems are obtained as below:

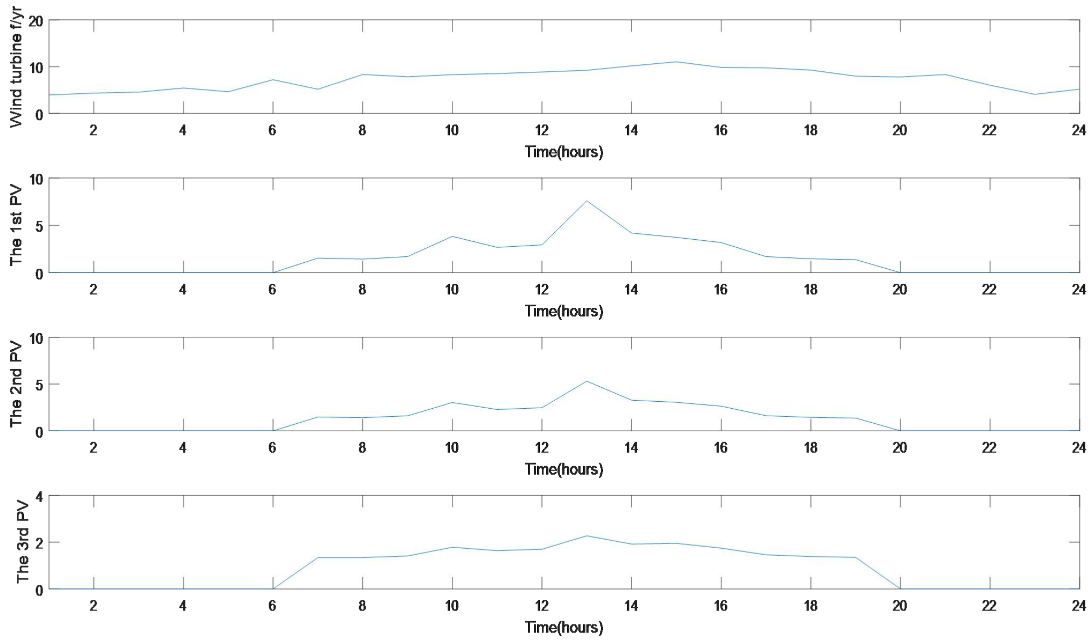

Figure 4-10 Failure rates of power electronics for PV systems

From the Figure 4-11, it can be found that the failure rates of three PV systems have close relationship with the solar illumination. Take the interval from 9:00 to 13:00 as an example, the solar illumination increases greatly from 9:00 to 13:00 but decreases from 13:00 to 15:00, while during this period ambient temperature it increase linearly, the failure rate reaches peak point around 13:00 and decreases after that point. The operational failure rate of WTG has close relationship with ambient temperature, even the wind speed begins to decrease, the failure rate still increases because of the rise of temperature from 13:00 to 15:00.

A. Considering the operational failure rate of electronic power system

To verify the proposed model, two cases are studied. For case 1, the operational failure rates of power electronics are taken into consideration, while the islanded microgrid in case 2 dose not. Both of them use the short-term model to calculate the reliability indices shown as below.

Conditions	Short-term outage model	Operational condition	Microsources included
Case 1	Yes	Yes	Yes
Case2	Yes	No	Yes

Table 4-7 Two cases under different conditions

Comparing case 1 and 2, case 1 ignores the impact of power electronics failures on the system reliability index, and only considers the influence of operating conditions on the impact of micro-sources' fluctuating supply on the system reliability index. As shown in Figure 4-12, the red line represents the reliability index of case 2, and the blue line is result of case 1. The reliability indices of case 1 are all greater than case 2. When considering the operational impact of power electronics, the reliability performance of microgrid shows negative. In addition, the curves of three indices are similar to each other. It can be seen that in case 2, with the empirical failure rates adopted, it can't reflect the effect of the operational condition on the failure rate of the devices. Since the microgrids' operational conditions are changeable. The failure rate of power electronic devices, and the parameters such as component failure rate, will directly affect the calculated reliability index of the load points and the reliability of the system.

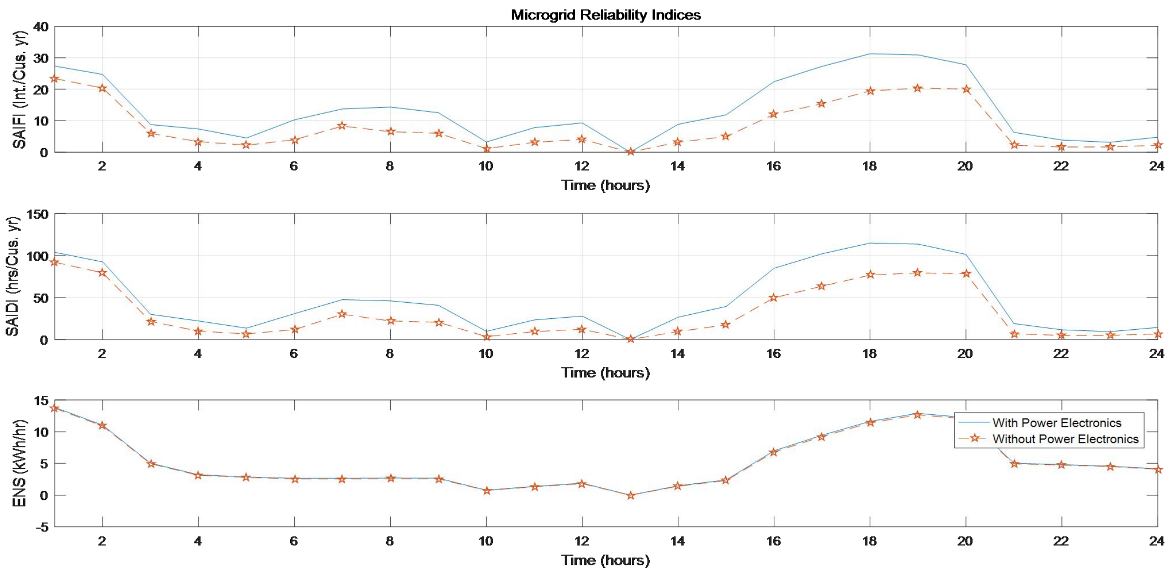

Figure 4-11 Reliability indices of two cases

B. Verify the proposed reliability improvement method

After building the energy storage system operational failure model, to do research on impact of different types energy storage system on the islanded microgrid and verify the effective of HESS, case 3,4 and 5 are studied. First, BESS (battery energy storage system) without Bi-DC/DC converter model is built in case 1. Then adding Bi-DC/DC converter model and building the operational failure model of BESS in case 3. To improve the reliability performance of the ESS in subsystem level, applying the HESS to islanded microgrid and build the operational failure model of HESS in case 4. The hourly indices of these cases are calculated and illustrated as below.

Conditions	Short-term outage model	Operating condition	Microsources included	ESS types
Case 1	Yes	Yes	Yes	BESS
Case3	Yes	Yes	Yes	BESS with Bi-DC/DC

Case 4	Yes	Yes	Yes	HESS

Table 4-8 Three cases under different conditions

Indices	SAIFI	SAIDI	ENS
Case 1	272.3503	999.6307	122.9010
Case3	313.8186	1029.7	122.9794
Case 4	299.9514	974.2912	115.2170

Table 4-9 Three reliability indices under different conditions

From the results shown in the table 4-9, compare the case 3 and case 4, the reliability indices decrease obviously, which means microgrid with HESS shows better performance than microgrid with BESS. When HESS is applied in islanded microgrid. In other words, this approach adds redundant path to energy storage system, when the batteries or super-capacitors have failure, the energy storage system can still achieve its partly performance to supply to customers. Thus, the comparison of two cases verify the reliability improvement method mentioned in Chapter 3.

Compare case 1 and case 3, the addition of bidirectional DC/DC converter increase the operational failure rate of ESS, because in these two cases, the failure rates of batteries are assumed as same value. In reality, the bidirectional DC/DC converter will decrease the electrical stresses and amount of battery, thus the failure rate of batteries can be smaller. Thus, finding a balance between the adding redundancy to system and increase of failure rate caused by power electronics is of great significance. From these results, it can be seen that the large-scale application of power electronic devices also brings new hidden danger for the reliability of microgrid systems, and improving the reliability of high-power converter circuits is an urgently needed part of the microgrid technology.

C. Considering the different types of micro-sources

This section explains the different types of micro-sources' impact on the reliability performance on the island microgrid. Considering the PV systems and WTG system as uncontrollable generation system and MTG system as the controllable generation system.

Indices	SAIFI(total)	SAIDI(total)	ENS(total)
Case1	272.3503	999.6307	122.9010
Case 5	226.3619	814.8822	122.6831
Case6	298.9334	1170.8	123.7309

Table 4-10 Three cases under different conditions

Conditions	Short-term outage model	Operating condition	Microsources types
Case 1	Yes	Yes	3PVs+1WTG
Case5	Yes	Yes	all PVs
Case 6	Yes	Yes	all WTGs

Table 4-11 Three reliability indices under different conditions

For the 1^{st} condition, when the islanded microgrid is fully supplied by renewable energy generation systems (WTG system, PV system), the reliability indices for the whole system were calculated.

As shown in Table 4-11, the reliability index of case 5 when the system is fully supplied by PV systems, compared with case 1, SAIDI, SAIFI decrease while the ENS increase. Compared with case 1, the PV system shows better performance because of the operational failure rate of PV system (one stage) is smaller than WTG system (two stages). However, When the system is fully powered by all WTG systems in case 6, the reliability performance of the system decreases greatly since the SAIDI, SAIFI and ENS all increase. Because of the largely applied power electronics, the impact of power electronics failures on the reliability index is negative.

For the 2^{nd} condition, to compare the reliability performance of microgrid with controllable generation system, replacing WTG system or PV system by MTG systems micro-turbine generation system in case 7 and case 9. Then the comparison is done and reliability of different cases are listed in below.

Conditions	**Short-term outage model**	**Operating condition**	**Microsources types**
Case 7	Yes	Yes	1GT+3PV
Case8	Yes	Yes	1GT+2PVs+1WTG
Case 9	Yes	Yes	1GT+3WTGs

Table 4-12 Three reliability indices under different conditions

Indices	SAIFI(total)	SAIDI(total)	ENS(total)
Case7	194.7459	868.1	118.1624
Case8	201.5688	923.7063	120.4036
Case9	256.1621	1061.4	122.3541

Table 4-13 Three reliability indices under different conditions

Case 7 replaces the WTG system with MTG system of case 1. From the results shown in Table 4-13, the microgrid in case 7 shows better performance, the three indices all decrease greatly, especially the ENS. Because of the MTG system has the same topology as WTG system, the effect of operational failure rate is similar. In addition, the power output can be controlled based on the requirement of loads and rated power of MTG is greater than WTG system. Based on case 7, replacing one PV system with WTG system, the resulting indices SAIDI and SAIFI of case 8 increase because of the impact of electrical devices is greater. Because the WTG show better performance in power supply, ENS decreases.

Based on case 6, replacing the WTG system with MTG system to get case 9, as analyzed in transformation from case 1 to case 7, the microgrid has better performance, the reliability indices all decrease. From the analysis above, the types of micro-sources should have great influence of reliability indices of system.

4.5 Conclusions

In this chapter, the first, second and third section have briefly introduction for a modified 0.4kV islanded microgrid system, focusing on the configuration, parameters of different components, loads requirements. Then, the simplified fault tree for overall system and each subsystem are built and analyzed.

To verify the reliability improvement method proposed in Chapter 3, applying the HESS in islanded microgrid system and doing the comparison, the results show that combined with the operational failure rate model of the converter, reliability indices can reflect the reliability of the islanded microgrid system more accurate. In addition, with the HESS replacing the conventional BESS, the islanded microgrid has better reliability performance. Then, to study the effect of different types of micro-sources, the reliability indices for different the tested cases were calculated based on the solution process and compared in section 4.4.

Chapter 5 Sensitivity Analysis

Based on the case study above, to evaluate the influence of the different factors, a set of sensitivity analysis will be done considering the following aspect:

1). The effect of wind turbine parameter setting;

2). The effect of PV parameter setting;

3). The effect of ESS capacity.

4). Yearly operational failure rate characteristics;

For these further sensitivity tests, based on case study in this paper to do the system-level reliability metrics evaluation and analysis.

5.1 The effect of wind turbine parameter setting

The parameters of the wind turbines can affect the output power of wind turbines generation and then effect the reliability metrics of the components, thus having influence on failure rate of electrical power systems. In this section the effect of three parameters on wind turbines performance are studied. First, based on the hourly time-varying wind speed and temperature in one day in spring. Taking one wind turbine generation as an example and change its one parameter while keeping other two parameters as the same. The case study in different conditions are illustrated as below.

A. Cut-in speed

To study the impact of V_{ci} (cut-in speed)on reliability performance further, setting the V_{ci} as different values from 2.5m/s to 4.5m/s in one case. The setting parameters are all less than the V_r (rated wind speed), the average hourly wind generations are shown in figure 5-1.

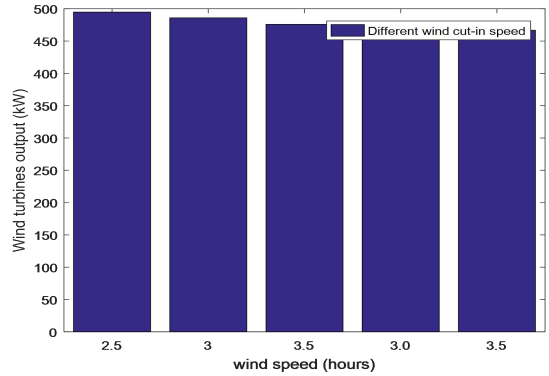

Figure 5- 1 Average hourly wind generation

As we can see above, it is obvious that when increasing the V_{ci}, generation of wind generators decreases, and the failure rate of the converter was also calculated:

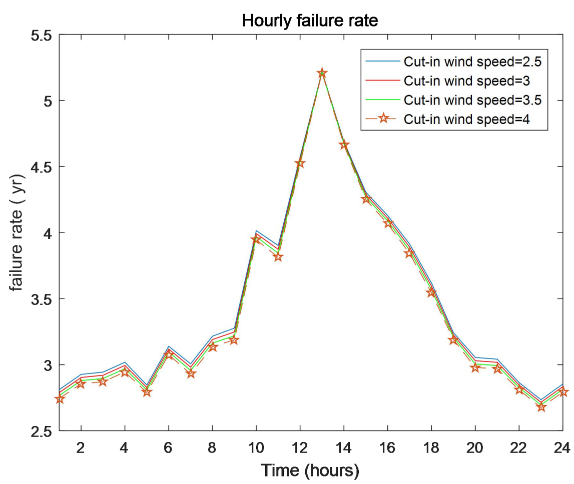

Figure 5- 2 Hourly converter failure rate

As shown in Figure 5-2, the V_{ci} has effect on the operational failure rate of the converter. From the 0 to 11:00, the effect is more obvious, because during this period, the wind speed is less than rated speed, so the growth of output of WTG is related to wind speed. From the 11:00 to 14:00, the effect is slight. With the cut-in speed increasing, the power generation ability is weakened, which means the power supplied decreases, the electrical stresses decrease, thus the failure rate is lower. The reliability indices of the overall system are calculated as below:

Indices	SAIFI(total)	SAIDI(total)	ENS(total)
2.5	274.1065	1003.1608	122.8857
3	273.6183	1002.7884	122.8928
3.5	272.3503	999.6307	122.9010
4	272.2335	999.2166	122.9205
4.5	272.1020	999.1627	122.9515

Table 5-1 Daily reliability indices for different cut-in wind speed

From the reliability metrics shown in table, when the cut-in speed is increasing, as shown in Figure 5-1, the generation of WTG decreases, so the ENS increases lightly. In addition, the reduction of failure rate results in reduction of SAIDI and SAIFI slightly.

B. Cut-out wind speed

To study the impact of V_{co} (cut-out speed) on reliability performance further, setting the V_{co} as different values from 14m/s to 25m/s in one case. The setting parameters are all greater than V_r , the average hourly wind generations are shown in Figure 5-3, it is obvious that when increasing the V_{co} , generation of wind generators decreases.

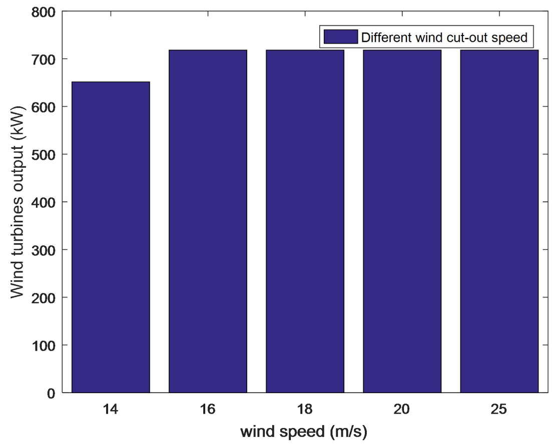

Figure 5- 3Average hourly wind generation

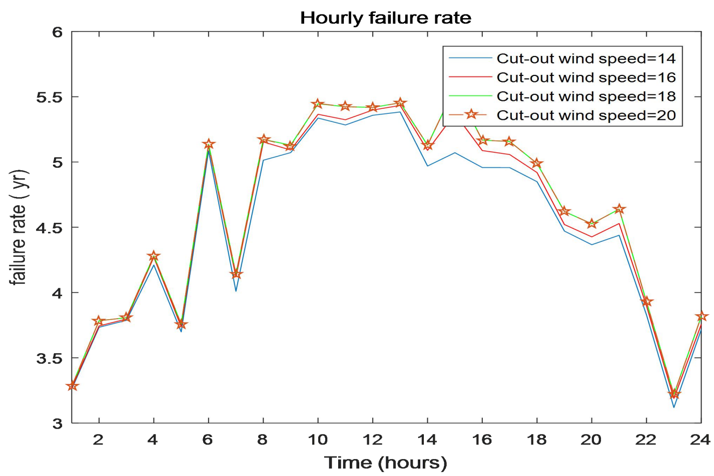

Figure 5- 4 Hourly converter failure rate

As shown in Figure 5-4, V_{co} has slight effect on the operational failure rate of the converter. With the V_{co} increasing, the power generation ability is improved at first parameter changing, then stay as the same. which means the power supplied increases, the electrical stresses increase, thus the failure rate is a little greater. The reliability indices of the overall system are calculated as below:

Indices	SAIFI(total)	SAIDI(total)	ENS(total)
14	221.3102	821.4992	121.0392
16	242.3338	893.0067	120.1647
18	266.9020	976.1993	120.5487
20	272.3503	999.6307	122.9010
25	272.3503	999.6307	122.9010

Table 5-2 Daily reliability indices for different cut-out wind speed

From the reliability metrics shown in Table 5-2, when the cut-out speed is increasing, as shown in Figure 5-3, the generation of WTG increases, the ENS decreases lightly. In addition, the growth of failure rate results in growth of SAIDI and SAIFI slightly.

C. Rated wind speed

To study the impact of V_r (rated wind speed) on reliability performance further, setting the V_r as different values from 11.5m/s to 14.5m/s in one case. The setting parameters are all in the range between the V_{ci} and V_{co}, the operational failure rates of WTG system in different conditions are shown in Figure 5-5.

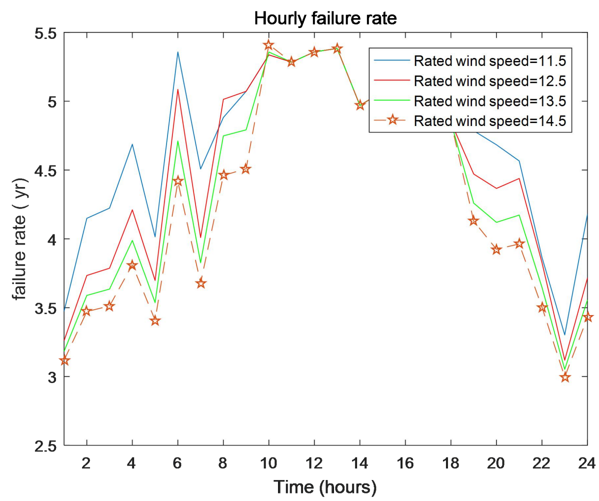

Figure 5- 5 Converter failure rate

As shown in Figure 5-5, V_r has great effect on the operational failure rate of the converter, especially from 0 to 11:00. With V_r increasing, the power generation decreases, which means the power supplied decreases, the electrical stresses decrease, thus the failure rate is lower. The reliability indices of the overall system are calculated as below:

Indices	SAIFI(total)	SAIDI(total)	ENS(total)
11.5	280.6954	1024.7	122.8603
12.5	272.3503	999.6307	122.9010
13.5	266.1047	984.2029	122.9527
14.5	263.1047	978.1207	123.1008

Table 5-3 Daily reliability indices for different rated wind speed

From the reliability metrics shown in table 5-3, when V_r is increasing, the generation of WTG increases and the ENS decreases lightly. In addition, the growth of failure rate results in growth of SAIDI and SAIFI slightly.

5.2 The effect of PV parameter setting

For PV arrays, the parameters like rated temperature and rated solar illumination will also affect output of the PV generation and then affect the operational condition of converters, thus having influence on failure rate of power system. In this section the effect of three parameters on PV arrays are studied. In this section the effect of each factor is studied.

A. Rated temperature

To study the impact of rated temperature on reliability performance further, setting the rated temperature of four arrays as different values 16,20,25,30 centigrade respectively. The average hourly solar generations are shown in Figure 5-6, when the rated temperature rises, the generation of PV arrays increases.

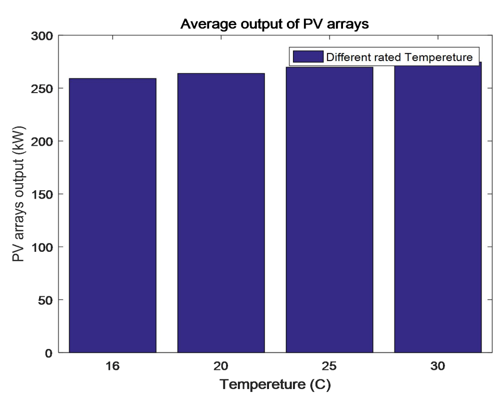

Figure 5-6 Average hourly PV generation

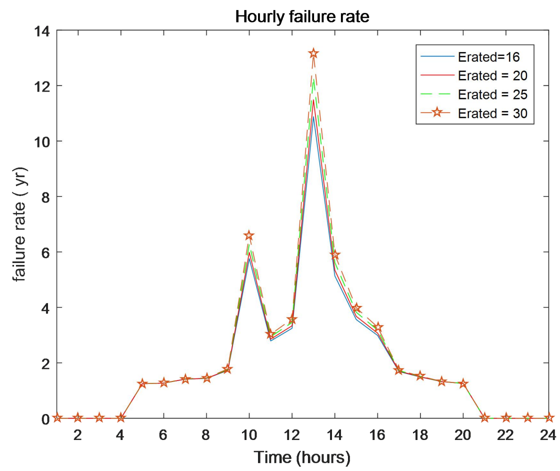

Figure 5-7 Failure rate of PV system at different Erated

As shown in Figure 5-7, the rated temperature has great effect on the operational failure rate of the converter. When increasing this parameter, the output of PV arrays increases, especially from 12:00 to 14:00, the effect is more obvious, because during this period, the solar illumination is stronger, so the output of PV arrays increases greatly. While from the 0 to 9:00. the effect is slight. With the solar illumination gets stronger, the power generation ability increases. The electrical stresses increase, thus the failure rate is higher.

B Rated solar illumination

To study the impact of rated solar illumination on reliability performance further, setting the rated solar illumination of four arrays as different values respectively. The average hourly solar generations are shown in figure 5-8, when increasing rated solar illumination, the generation of PV arrays decreases.

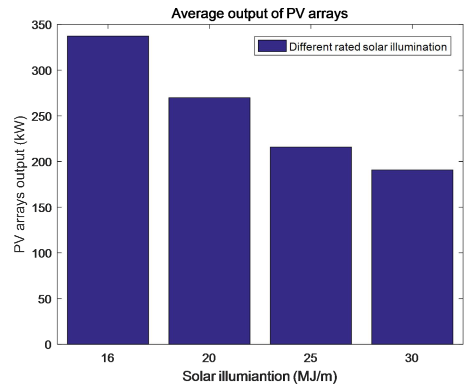

Figure 5-8 Average hourly PV generation

The rated solar illumination will affect the PV generation, then the PV generation will affect the failure rate of electrical devices. Based on the hourly solar illumination for one day, the hourly failure rate of PV system was calculated as below:

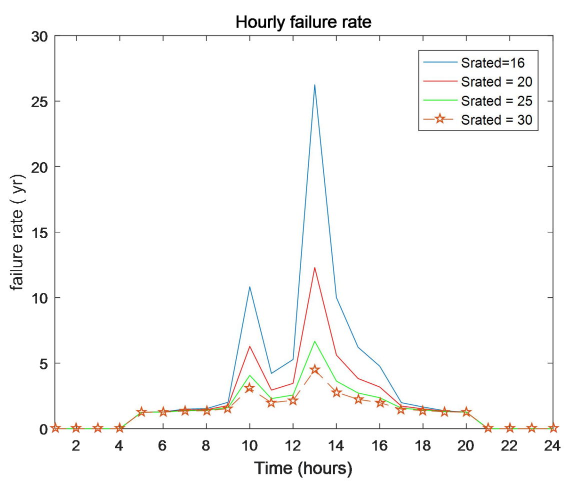

Figure 5-9 Converter failure rate

As shown in Figure 5-9, when increasing rated solar illumination, the output of PV arrays decreases greatly, especially from 9:00 to 15:00, the gap between the curves is bigger, because during this period, the solar illumination is stronger and reaches peak point at 13:00, so the output of PV arrays increases greatly. While from the 0:00 to 9:00. the effect is slight. When the solar illumination becomes stronger, the reduction of power generation is bigger. The electrical stresses decrease greatly, thus the gap between failure rates of $S_{rated} = 30$ is bigger.

C. Rated generation

To study the impact of rated generation on reliability performance further, setting the parameters of four arrays as different values respectively. The average hourly solar generations are shown in figure 5-10, it is obvious that when increasing the rated generation, the generation of PV arrays increases.

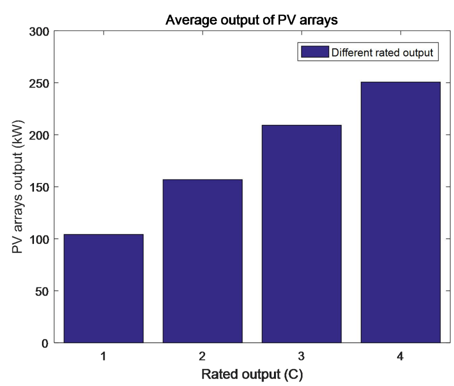

Figure 5-10 Average hourly Generation of PV system at different Grated

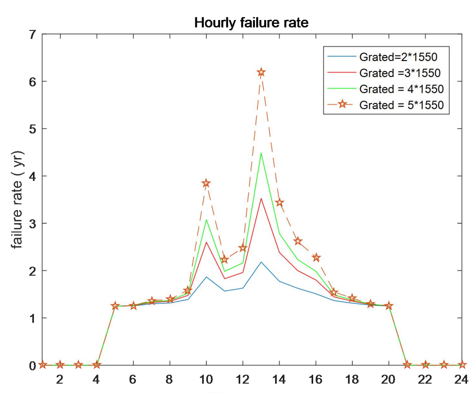

Figure 5-11 Failure rate of PV system at different Grated based on electronics

As shown in Figure 5-11, when increasing rated generation, the output of PV arrays increases greatly, especially from 12:00 to 14:00, the gap between the curves is bigger, because during this period, the solar illumination is stronger and reaches highest point at 13:00, so the output of PV arrays increases greatly. When output of PV arrays increases greatly, the electrical stresses of devices are heavily, so the failure rate increase when rated generation get larger.

5.3 The effect of ESS capacity

For islanded micro-grid highly penetrated with renewable energy generation system, the ESS plays an important role in weakening the uncertain characteristics of renewable power. To confirm the effect of ESS capacity on system reliability, the capacity of the battery in energy storage system was adjusted from 500 kW and 1250 kW. As we can see, with the growth of the battery capacity, the reliability indices also increase.

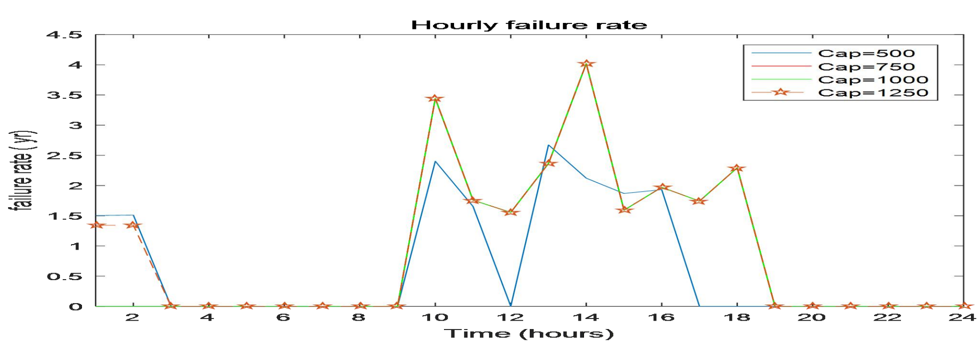

Figure 5-12 Failure rate of ESS system at different capacity

When increasing the capacity of ESS, the power flow through power electronics in ESS gets bigger, thus increasing the electrical stresses of devices, as shown in different curves in Figure 5-12, the failure rate of larger capacity is larger in general. In addition, the reliability indices of microgrid also calculated as below.

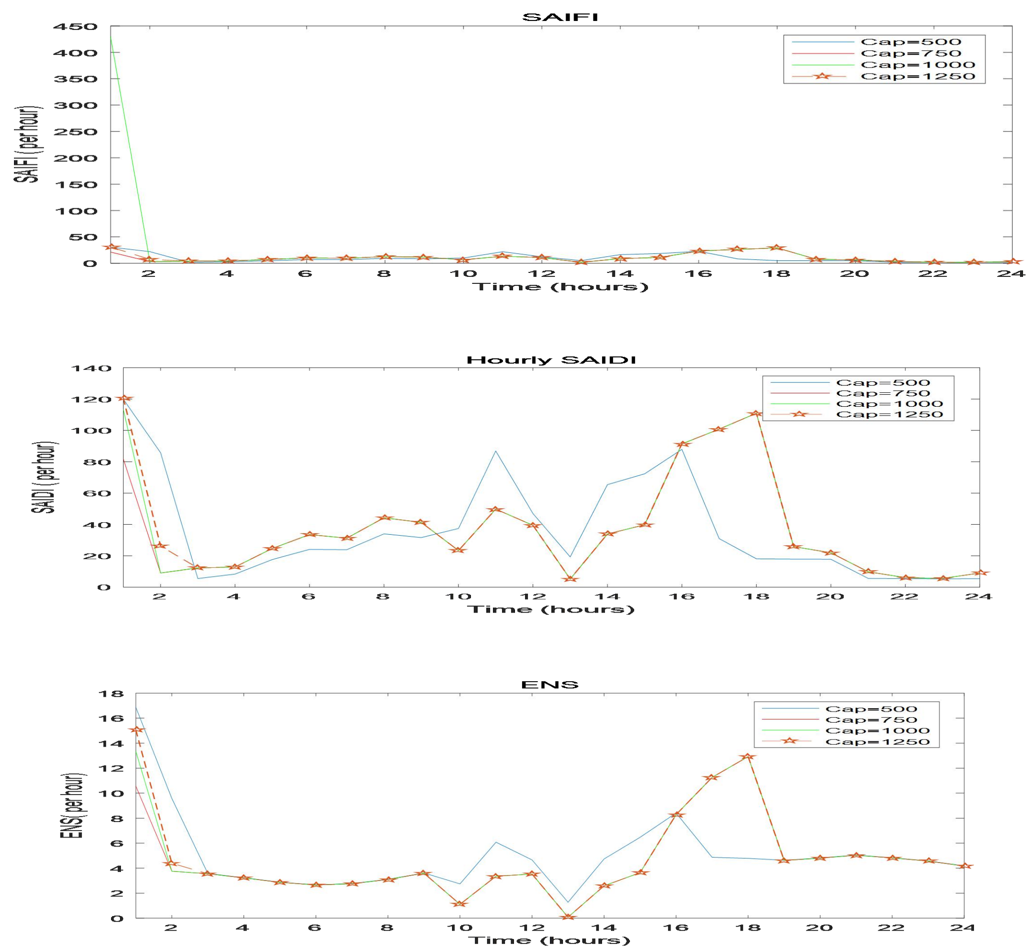

Figure 5-13 Hourly reliability indices for different capacity

As the results shown as above, when increasing the capacity of energy storage system, the electrical stresses of power electronics in conversion system increase, thus the failure rate of this subsystem increases. Thus the value of SAIDI and SAIFI increase in general, the ENS decrease in general, as shown in above figure, the reliability indices of larger capacity are both higher than smaller capacity from 17:00 to 18;00. Because during that time, the loads of microgrid is heavy, thus the power flow of ESS is larger, the probability of loads outage or energy not supplied is larger.

5.4 Yearly operational failure rate characteristics

For islanded micro-grid studied at this paper, to do this analysis, the meteorological statistics in whole year 2010 in Milwaukee are used.

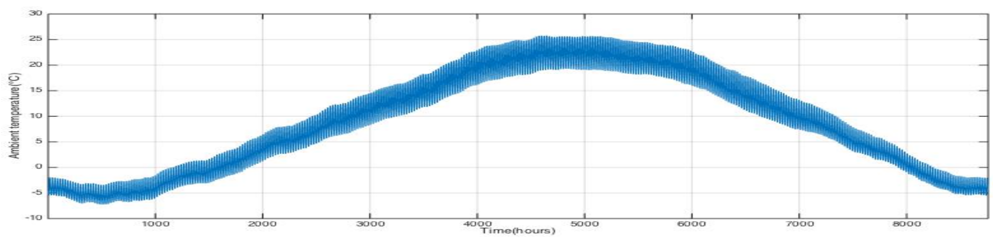

Figure 5- 14 Ambient temperature in Milwaukee, 2010

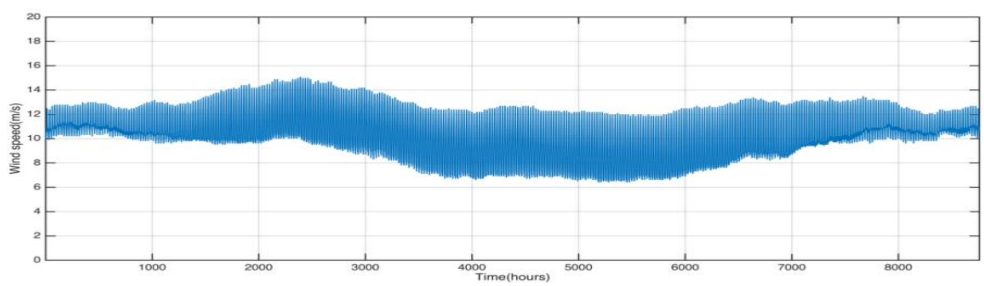

Figure 5- 15 Wind speed in Milwaukee, 2010

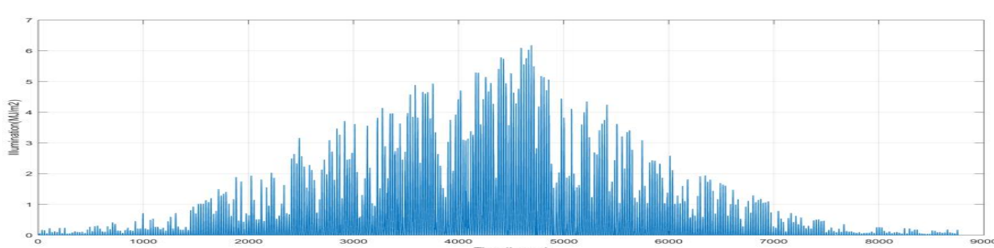

Figure 5- 16 Solar illumination in Milwaukee, 2010

As we can see above, the wind speed and temperature have seasonal characteristics. The wind speed is higher in Spring and Winter and lower in Summer and Autumn, while the ambient temperature is just the opposite. Solar illumination is stronger around Summer. In addition, the wind speed fluctuates more violently in the summer and autumn. Next, then the wind turbines generation and the operational failure rate for the converter calculated.

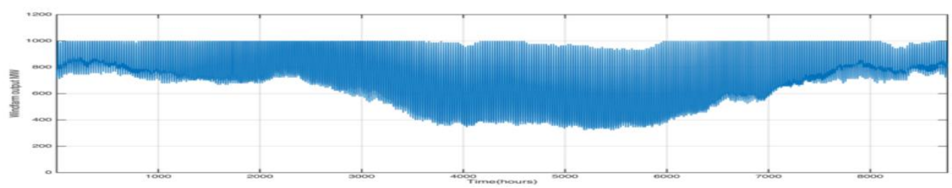

Figure 5- 17 Hourly wind generation

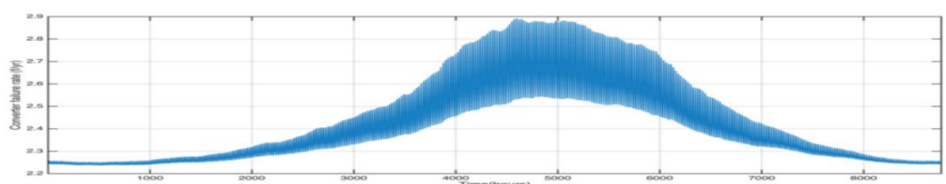

Figure 5- 18 Hourly converter failure rate in WTG system

As we can see above, the wind generation reflects the wind speed fluctuation in the summer and autumn directly and the trend of the hourly generation curve is consistent with the wind speed. The relatively lower failure rate for the WTG system is from 0th hour to 2000th hour and from 7000th hour to 8760th hour. Because the conditional factors like lower wind speed and lower temperature cause less power generation, then the thermal factor and thermal factor of power electronics are smaller, thus failure rate during that time is smaller. The operational failure rate shows closer relationship with ambient temperature, and it also reflects the fluctuation of the wind seasonally.

Then hourly solar illumination and ambient temperature data in whole year 2010 in Milwaukee is used and the generation and the operational failure rate of the converter in PV system are calculated as below.

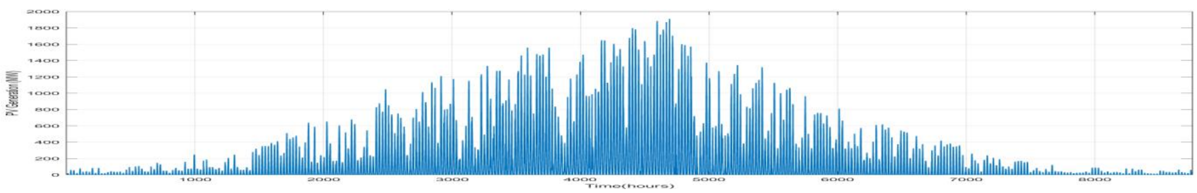

Figure 5- 19 Hourly solar generation

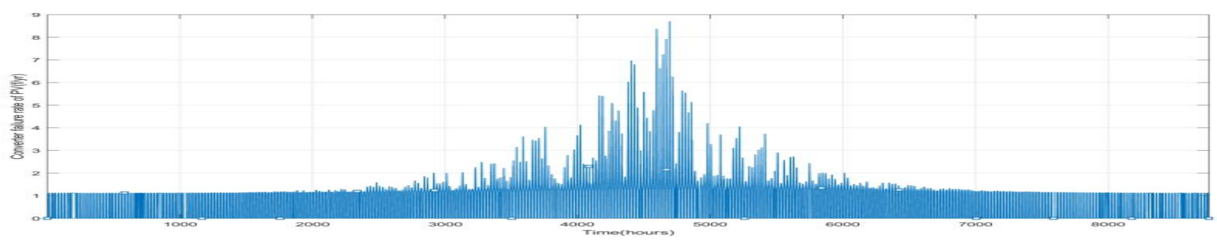

Figure 5- 20 Hourly converter failure rate in PV system

As shown in above figures, from 2000th to 4800th hour, the solar generation reflects the solar illumination hourly in general. For the operational failure rate of PV systems, it shows an upward trend and reaches highest point around 4800th hour. Because of the strong solar illumination and high temperature around that time. Then it becomes to decrease after highest point but still show high level from 4800th hour to 6200th hour. The trend of the hourly converter failure rate curve is consistent with the solar illumination and it also reflects the fluctuation of the ambient temperature in summer and autumn.

5.5 Conclusions and future Works

In this chapter, a set of sensitivity tests have been done considering the effect of wind turbine parameter setting, PV modules parameter setting, battery capacity, and the yearly meteorologic characteristics. Reliability indices for different conditions are calculated based on the hourly meteorological statistics of whole year 2010 in Milwaukee. When changing different parameters of wind turbine generators and PV arrays, the power output for generation systems change partly. Then it will change the electrical stresses and thermal factor of devices, thus the operational failure rate has related changes.

The results show that the yearly characteristic is significant, and it is largely affected by the ambient temperature and solar illumination. The wind speed also has its influences. The worst system reliability performance is in the period with the highest temperature , strongest solar illumination and most fluctuating wind speed in the year. From the analysis above, to improve the system reliability, adjusting the wind turbine parameters, PV arrays parameters, and the capacity of the battery appropriately will improve the reliability performance of microgrids.

Based on above work, future work can focus on the below perspectives: considering the impact of operational failure rate of storage units; combining climate forecast technology to evaluate the operational failure rate; study the outage probability prediction for different loads points; establishment of operational failure rate model in other applications.

Chapter 6 Conclusion and future work

In this thesis, the operational reliability for the islanded microgrid system is studied. The reliability indexes for a modified 0.4 kV islanded benchmark systems are evaluated.

First, based on the operational model, the time-varying failure rate of components can be calculated. Combing the FTA method and Network reduction method to simplify system to several subsystems. For each subsystem, the operational failure model is built. With meteorological factors varying, the failure rate of power electronic systems will have the corresponding change. For the failure rate of the converter in WTG system, the effect of ambient temperature is very significant; For the failure rate of the converter in PV system, the effect of solar illumination is very significant; For the failure rate of the converter in ESS and MTG system, the effect of power flow is very significant. And the outage is more likely to happen during the daytime because of the fast wind speed, strong solar illumination or larger power flow for system. Based on the operational failure rate of components, the time-varying failure rate of overall system can be obtained. By using the short-term outage model, the reliability indexes for system can be evaluated. Then the effect of power electronics on reliability have been proved in simulation, when considering the operational failure rate, the performance of system becomes worse.

Then, to improve the reliability of system, replacing the conventional BESS to HESS. It not only prolongs the lifetime of batteries by reducing the electrical stresses of batteries, but also adds the redundancy to subsystem to improve the reliability. Finally, utilizing the operational failure rate model to evaluate the reliability and verify the improvement of reliability. The results show that, the reliability for the system with HESS have better performance than system with BESS. In addition, the effect of different types of microsources has also been studied.

Lastly, the sensitivity analyses study the influence of parameters setting of PV arrays and wind turbine generation system, yearly characteristics and energy storage capacity. The results show that, the seasonal characteristic is significant, and it is largely affected by the temperature factor. The wind speed also has its influences. To improve the system reliability, we can adjust the wind turbine and PV arrays parameters or the capacity of the storage units.

Future work can be focused on the following aspects:

- Considering more weather condition (natural disasters) in components' failure model, and studying the impact of extreme weather on components' operational failure and on system reliability;
- Building operational failure rate model for other application like HEV, PHEV system.
- Integrating meteorological factors forecast technology; using the predication ambient temperature, wind speed and solar illumination to study the failure rate prediction of the system;
- Calculating the availability of each subsystem and analyzing the contribution of each

component to the system reliability;

- Considering the investment and the maintenance to choose the optimal scheme.
- Calculating the system reliability for grid connected microgrid systems with different topologies; and considering the connection to the area distribution network.

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