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Yunfan Zhang
University of Wisconsin-Milwaukee

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PROBABILISTIC RELIABILITY ANALYSIS OF THE WATER-ENERGY NEXUS USING MONTE CARLO SIMULATION

by

Yunfan Zhang

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ABSTRACT

PROBABILISTIC RELIABILITY ANALYSIS OF THE WATER-ENERGY NEXUS USING MONTE CARLO SIMULATION

by

Yunfan Zhang

The University of Wisconsin-Milwaukee, 2018
Under the Supervision of Dr. Lingfeng Wang

Nowadays, with the development of science and technologies, our modern society is more and more dependent on the reliable performance of the critical infrastructures. Both water systems and power systems are national critical infrastructure supporting our daily life and the development of economic growth. These two types of systems are highly interconnected and complex networks, which consist of various system elements. Similarly, the core function of water and power system is to deliver satisfactory quality water and power to consumers, and at the same time it should satisfy all the demands at all load points. The reliable performance of these critical infrastructure is becoming more and more important. Therefore, it is very urgent to develop a comprehensive reliability evaluation algorithm to quantify the reliability of these critical systems.

When it comes to quantitatively assessing reliability of the facility infrastructure, there is a need to develop a comprehensive method to consider a comprehensive set of variables and uncertainties such as the random failures of mechanical components, the amount of water demands, the power supply reliability, maintenance scheduling, and so forth. The rapidly growing urban population is also a great challenge to the aging drinking water distribution networks. The water facilities are aging and in need of expensive repairs. Therefore, this thesis will aid in making informed decisions on infrastructure repair, maintenance, and staffing planning when the available budgets are limited. This thesis proposes a probabilistic reliability evaluation methodology for water distribution systems considering the impact of power supply reliability based on the sequential Monte Carlo simulation (MCS), which can guide cost-effective preventative measures before system failures. A previously developed C++ software tool is used to help perform the simulation.

The probabilistic reliability assessment algorithm can be appropriately applied for both the electric power systems and water distribution system is due to the similar stochastic system nature and modeling manner of the system elements. First, the reliability characteristic of each system component in electric power system can be modeled by a two-state model (i.e., up state and down state). Then, the probability of failure for each component can be calculated and a chronological operating sequence can be further determined based on the sequential Monte Carlo Simulation. Likewise, the reliability models for the water distribution system components can be represented using this method. All these similarities result in the similar reliability assessment procedure.

The commonly used deterministic criteria in industrial circles lacked the ability to model and quantify the stochastic nature of system behaviors such as the mechanical failure of system elements. Besides the uncertainties come from water distribution system itself, power supply may also affect the performance of the water distribution network and system reliability. Therefore, the two systems are interactive and physically connected. The purpose of this study is to develop a suitable algorithm to evaluate the water sector and power system as an integrated Water-Energy Nexus (WEN) system. This thesis proposes an integrated, probabilistic reliability evaluation method for the WEN model based on the sequential Monte Carlo Simulation. In the proposed evaluation procedure, both mechanical failures and hydraulic analysis are taken into consideration.

Case studies are performed base on a representative water-energy nexus system to demonstrate the effectiveness of the proposed algorithm. The simulation results demonstrate that the proposed probabilistic methodology is appropriate to integrated quantitative reliability modeling and assessment of coupled critical infrastructures (i.e., electrical power networks and water distribution networks) by incorporating the emerging smart grid technologies such as electrical microgrids.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

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Chapter 1 Introduction

1.1 Background Information

Water and electricity are the back bone of our modern society. Reliable water and power supply are of great importance to support economic development and human life. Multiple phases of power generation and energy production requires water consumption. Conversely, power supply is critical for conveying, treating and delivering water for human uses. Thus, the water and energy systems are tightly interconnected at a basic level. In the history, the nature of these links is commonly accepted, electricity is never a threat to water supply. However, with the rapidly growing demand, this assumption about the relationship between water systems and power systems are being challenged. Based on the predictions from report of [1] and [2], water supply will become one of the most serious national problems by the year of 2025.

While the power supply can largely affect the performance of water distribution system. More and more attentions are paid to the links between water systems and energy systems. The water distribution system is a very complex interconnected network, which consists of one or several water sources and various system components, such as pipelines, valves, reservoirs, tanks, pumps and other element. The water distribution system in normal condition should have the ability to satisfy all the water demands of load point within the network with the accurate pressure and required water quality. When in the abnormal condition with one or several system component failures, the core function of the water distribution system may not be guaranteed. The ability to deliver satisfied amount and quality of water may be affected or even interrupted. Therefore, it is critically important to maintain a reliable water distribution in the presence of various uncertainties including the power supply. An integrated reliability evaluation of the water-energy system is very meaningful in enabling more informed decision making considering the energy supply reliability.

However, performing a comprehensive reliability evaluation on a real Water-Energy system is a very challenging mission. In the history, several algorithms were developed for reliability evaluation of water distribution system in [3]. In [4], considering the impact of storage unit in the distribution system, a reliability assessment method was proposed. Various techniques were developed for power systems reliability evaluation. However, most of them were not applied for reliability assessment on the water distribution systems.

Generally, there are two types of failures models are used in water distribution reliability assessment, which are the hydraulic failures and mechanical failures [5]. A hydraulic failure is a system level failure that due to unsatisfied load demands, which means the total load demands exceed the total system supply capacity [5, 6]. While mechanical failures are the failures that caused by system component failures such as the breakage of pipelines or shutdown of pumps, etc. Therefore, when modeling the hydraulic failures of water systems, the demand variation curves at each load point are required. Conventionally, for the hydraulic failure analysis, all the heads and pressures at each load point should be evaluated based on a system network analysis. For water system reliability evaluation, there are two commonly used software tools are developed in the software market, KYPIPE [7] and EPANET [8]. In the literature of water system reliability assessment, several studies have been conducted in this field, considering only the mechanical failures [9-11] or hydraulic failures [5, 12, 13]. An algorithm considering both the mechanical failures and hydraulic failures are proposed in [14], however, the techniques proposed in the paper cannot perform a reliability evaluation of the water network on the system level.

This study proposes a probabilistic algorithm for reliability evaluation of the Water-Energy Nexus incorporating energy supply reliability, mechanical failures and hydraulic failures. The proposed method can provide a system level reliability assessment. To enable informed decision-making of the water-energy system, several system reliability indices are developed and determined based on the proposed methodology.

1.2 Introduction to Reliability Assessment of Electric Power Systems

With the rapid development of power system, more and more smart grid technologies are applied in the electric power system. As a result, the modern electric power system is becoming more and more complex. The advanced technologies improve the overall performance of the electric power system, but it also brings more uncertainties, such as the intermittent of renewable energy resources, the demand side uncertainties, extreme weather conditions, etc. These uncertainties lead to higher requirements for the system planning and operations. Therefore, to maintain the reliable performance of the entire power system while considering the economic cost at the time, electric utilities are highly needed to find some cost-effective technologies to provide comprehensive decision support for evaluating the reliability of the systems and making informed decisions on system operation, maintenance, and staffing. In the past, some advanced technologies for electric power system are considered to be impossible to be applied in the real-world system. However, the research in recent years taking the practicality into consideration, smart grid technologies are becoming more and more realistic, some of them are already implemented to the modern electric power system.

1.3 Introduction to Reliability Assessment of Drinking Water Distribution System

Water distribution systems are highly complex, interconnected networks consisting of various components, such as pumps, pipes, valves, tanks and regulators, etc. The distribution system is the core part of the entire water system network. Its function is to deliver satisfactory quality water to consumers, and at the same time it should satisfy all the water demand at all load points. Therefore, the reliability of a water distribution system is very important to both human life and economic development. Reliability evaluation is an efficient way to guarantee the performance of a water distribution system. The system components may fail due to aging or other causes, and the failure of a system component could lead to system inadequacy.

Due to the size and complexity of the system, to perform a comprehensive reliability assessment of the drinking water distribution network is still a very challenging work. In the literature, some algorithm for reliability assessment of the water distribution network have been proposed, these studies either considered the mechanical failures [15-17] or the hydraulic failures [18, 19]. Both the mechanical failures and hydraulic failures are considered in [20], however, the conducted reliability assessment is not able to evaluate the distribution network on a system level. Two types of failures are mainly considered in the water distribution system evaluation: mechanical failures and hydraulic failures[21]. The mechanical failures indicate the system failures caused by the failures of system components, i.e. the breakage of pipelines, the shutdown of pumps, etc. While the unsatisfied water load demand will lead to a system hydraulic failure[21, 22], which is highly relevant to the water pressure at each load point and the total water demand in the network. Therefore, when modeling the hydraulic failures that may occur in the system, the water demand curves or detailed data at each water distribution node is necessarily required. Generally, the major task to consider the system hydraulic failures is to estimate the water heads and pressures at each load point based on the network hydraulic flow analysis. Fortunately, in the current software market, several open source software tools such as KYPIPE [23] and EPANET [24] are available for performing the hydraulic flow analysis in this study.

1.4 Research Objectives and Thesis Layout

The major objective of this thesis is to develop a probabilistic reliability assessment algorithm to evaluate the water sector and power system as an integrated Water-Energy Nexus (WEN). This thesis proposes a probabilistic reliability evaluation method for the WEN model based on the sequential Monte Carlo Simulation (MCS). In chapter 2 the model and the methodology for the reliability evaluation of the microgrid in power system will be introduced. The proposed methodology for water distribution system reliability evaluation is described in chapter 3. The model of the Water-Energy Nexus and the algorithm for performing reliability evaluation on the integrated system will be presented in Chapter 4. And some case studies will be conducted on the proposed test systems to illustrate the effectiveness of the method and corresponding case study results for the WEN will also be given in the same chapter. The overall simulation procedure starts from modeling the reliability characteristic of one single systems component, and then further to form a comprehensive evaluation method for the entire system. When performing the required hydraulic analysis in this study, a previous developed Visual C++ and EPANET based simulation software tool is implemented. Chapter 5 draws the conclusion of this thesis and lists some future research directions based on the current work.

Chapter 2 Reliability Model for the Microgrid in the Water-Energy System

2.1 Introduction

Nowadays, various reliability evaluation algorithms based on the probabilistic theory has been developed [25] and frequently applied in most fields of electrical system analysis [26]. When evaluating the reliability of Water-Energy Nexus (WEN), the first step is to model the status of all system elements. In the proposed reliability evaluation method, all the system components in WEN are assumed to be physically repairable. Then, each element status will be modeled by a two-state model: “Up” state and “Down” state. “UP” status indicates the component is working in normal condition, and “DOWN” status indicates the component operates in faulty condition. The component states vary with respect to time, and at a specific time, the status of all system elements in the WEN constitute an overall system state as presented in Figure 2-1.

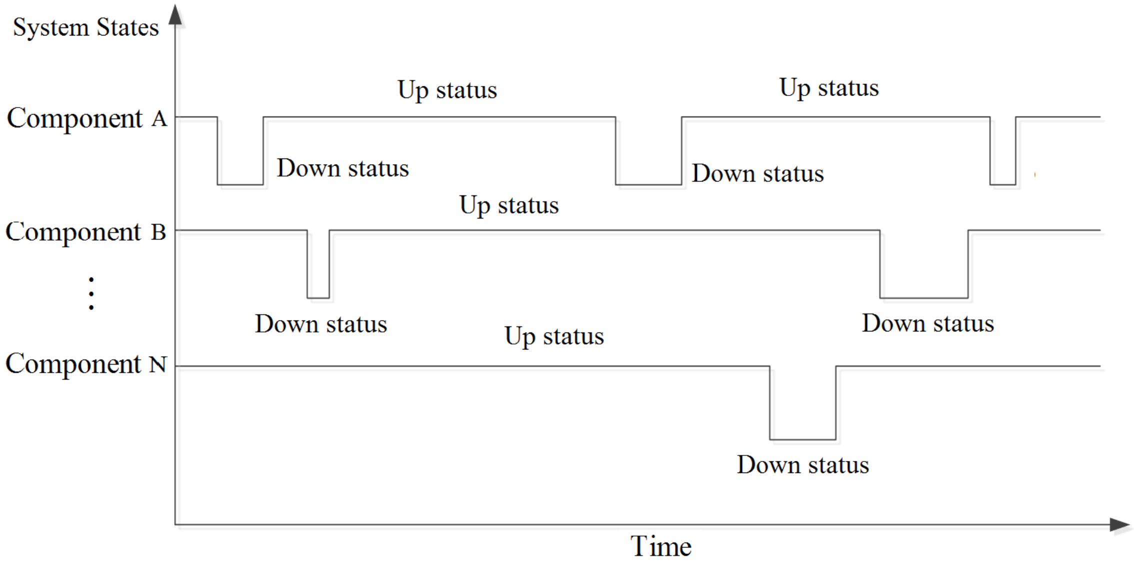

Figure 2-1 Relationship between system states and component status

For a water-energy system with N repairable components in total, then the number of possible system states should be 2N. In the real world, even for a middle-large size water-energy system may have hundreds of system components, which leads to an enormous system state space. When the proposed algorithm is performed on large scale systems, traditional analytical methods are basically impossible to solve the problem. As a result, simulation methods are more suitable choice for reliability analysis [27, 28] in such cases. In this study, a sequential Monte Carlo Simulation (MCS) method is used for reliability evaluation of the water-energy network. MCS algorithm has been well established and commonly applied in electric power grids analysis [29].

For the MCS-based reliability evaluation, the system component status is sampled based on a random number generator. In the sequential MCS, the status of system components will be determined based on two randomly generated time chains of the component, such as the time to failure (TTF) and the time to repair (TTR). Then, based on the time chains, component is in the "UP" status within the time to failure, and in the "DOWN" status within the time to repair. Once all the values of TTF and TTR are generated, the system states at each time could be determined based on the TTF and TTR values. The formulation is given as follows:

$$TTF = -\log(Random) \cdot MTTF \tag{2.1}$$

$$TTR = -\log(Random) \cdot MTTR \tag{2.2}$$

where MTTF indicates the mean time to failure; and MTTR is the mean time to repair.

Based on the values of TTF and TTR, for each sampled system state in the state space, the proposed reliability analysis will be performed to evaluate the system state. Once the number of sampled and evaluated system states reached an adequate level, the results obtained from the MCS are considered as reasonable estimates of the desired reliability indices.

2.2 Power Electronic Devices in the Microgrid

With the development of microgrid techniques, more and more power electronic devices are applied in the micro networks to improve the system performance, especially when the renewable energy resources are integrated in the microgrid. However, with more and more power electronic devices are included in the network, it also causes an impact on the reliability of microgrids; it is of great importance to learn how significant the influence is and how to void those negative impacts, so a reliable energy supply from the microgrid can be further guaranteed. The power electronic devices reliability is considered in the microgrid of the WEN model.

Generally, there are two main types of models are used in the reliability evaluation of power electronics: the empirical-based reliability model and the physics-of-failure model. The former model uses historical data to evaluate the reliability of power electronics. While the physics-of-failure model refers to the specific environmental data and operational states of the component to evaluate the reliability. The physics-of-failure model can reflect power electronics reliability under different operational conditions. When considering the physics-of-failure model, two types of failures for the electronic devices are commonly investigated, namely the failures caused by over-temperature and failures caused by thermal cycling [30]. The following microgrid [31, 32] in figure 2-2 is used as the power supply system in the water-energy nexus.

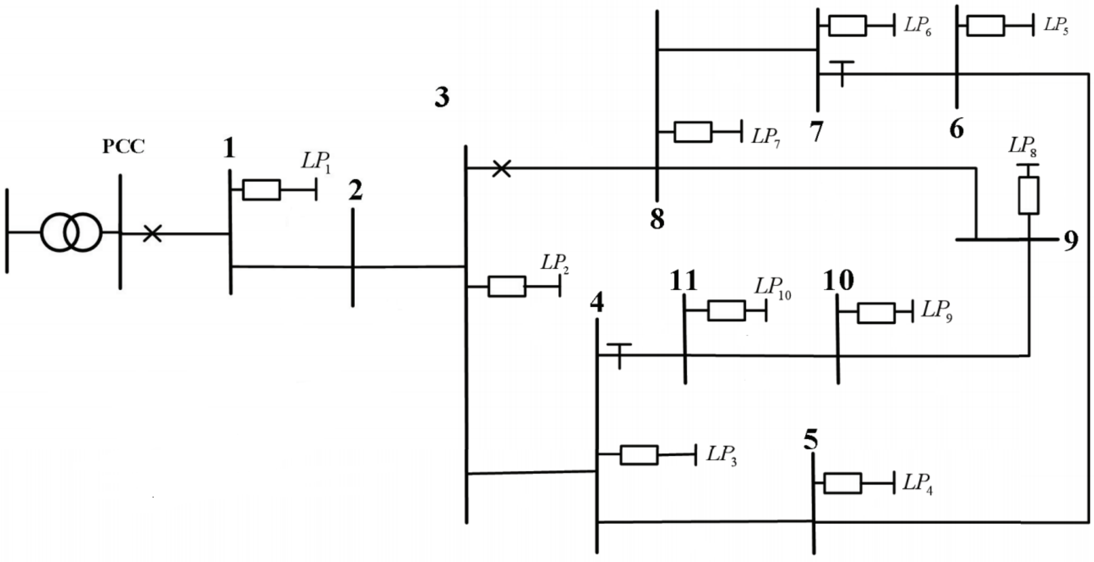

Figure 2-2 Microgrid in the Water-Energy Nexus

The location of renewable energy resources and corresponding generation capacity are listed in the table 2-1. And the related reliability characteristics for system components are listed in table 2-2.

Location (Bus #)	**Type of Resources**	**Generation Capacity**
6	Wind	1 MW
3	Solar	3 MW
5	Solar	1.5 MW
10	Solar	1.5 MW

Table 2-1 Location and generation capacity of renewable resources

Type of Component	**Failure Rate (Failures/year)**	**Repair Rate (Repairs/year)**
Photovoltaic Arrays	5	3
Wind Turbines	2.5	3
Energy Storage Unit	2	5
Breakers	8	2

Table 2-2 Reliability characteristics of system components

2.2.1 Renewable Energy Generation

The generation of renewable energy resources include wind turbines and PV arrays will be largely affected by the meteorological conditions, such as wind speed, temperature, solar radiation, etc. For wind turbine generators, the power generation is mainly determined by the wind speed, the mathematic formulation of wind turbine generators is as follows [31]

$$P_w = \begin{cases} P_{wr}, & v_r \le v < v_{off} \\ P_{wr} \cdot \frac{v - v_{ci}}{v_r - v_{ci}}, & v_{in} \le v < v_r \\ 0, & otherwise \end{cases} \tag{2.3}$$

in which P_w stands for the power generation of the wind turbine, P_{wr} is the rated power output of the wind turbine, v is the wind speed, v_r is the rated wind speed, v_{off} and v_{in} are the cut-off wind speed and cut-in wind speed.

Similarly, for the PV arrays, the total power generation is largely influenced by the solar radiation and ambient temperature. The power generation can be expressed as [31]

$$P_{PV} = P_{PVr}[1 - 0.0045(T - T_r)]\frac{I}{I_r} \tag{2.4}$$

in which P_{PV} is output power of the photovoltaic array for certain illumination I, P_{PVr} is the rated output of the photovoltaic array, T is the ambient temperature, T_r and I_r are the reference temperature and reference illumination respectively.

2.2.2 Control Strategy of the Energy Storage System

In the proposed WEN model, the microgrid is assumed to be isolated from the main power grid, which means it is operated in the island mode. All the load points are supposed to be supported by the power delivered from renewable energy generation and energy storage system. The control strategies adopted in the microgrid determines the input and output power of the energy storage system. In this study, all load points will be recovered in an order based on the electrical distance to the micro sources as the algorithm applied in [31]. Once all the load demands are fully satisfied, then the energy surplus will be used to charge the storage unit. It is assumed that the storage unit is sufficient to store all the over capacity. Then the input and output power of the energy storage system could be given by

$$P_{ESS} = \sum_{i=1}^{N} P_i - \sum_{j=1}^{M} L_j \tag{2.5}$$

where N and M are the number of renewable sources and load points respectively. P_i indicates the output power of the renewable source, L_j is the load demand at each load points.

2.2.3 Power losses of Power Electronic Devices

As mentioned in [33], the photovoltaic arrays usually have a DC/AC inverter in the network topology, and the wind turbines needs an AC/DC module as well as a DC/AC module. The power losses of the electronic devices will lead to temperature rises on these modules. The IGBTs and diodes have great influences on the power losses on these modules. The power loss on a diode can be calculated by

$$P_{Loss-d} = V_d I \left(\frac{1}{2\pi} \mp \frac{\varepsilon_M}{8} \cos\theta\right) + R_d I^2 \left(\frac{1}{8} \mp \frac{\varepsilon_M}{3\pi} \cos\theta\right) + \frac{f}{\pi} \cdot \frac{V_{DC} I}{V_{ref} I_{ref}} L_d \qquad (2.6)$$

where V_d and R_d are the voltage and conduction resistance of the diode; V_{ref} and I_{ref} represent the reference commutation voltage and current, and θ is the angle difference between the current and voltage. L_d indicates the rated switching loss on the diode.

The power loss on an IGBT can be expressed as in [34], [35]

$$P_{Loss-I} = V_I I \left(\frac{1}{2\pi} \pm \frac{\varepsilon_M}{8} \cos\theta\right) + R_I I^2 \left(\frac{1}{8} \pm \frac{\varepsilon_M}{3\pi} \cos\theta\right) + \frac{f}{\pi} \cdot \frac{V_{DC} I}{V_{ref} I_{ref}} (E_{on} + E_{off}) \qquad (2.7)$$

Similarly, V_I and R_I are the voltage and conduction resistance respectively. f is the switching frequency, E_{on} and E_{off} are the energy losses of the IGBT during the on and off states. ε_M is the modulation index, for the generator-sider converter [36]

$$\varepsilon_{M-gen} = \frac{U_{max}}{V_{DC}/2} \qquad (2.8)$$

in which U_{max} is the maximum generator output voltage, V_{DC} is the voltage of the DC link. For the grid-side converter [38]

$$\varepsilon_{M-grid} = \frac{2\sqrt{2}V_L}{\sqrt{3}V_{DC}} \tag{2.9}$$

where V_L is the rms value of the line-to-line voltage on the grid side.

I in (2.5) and (2.6) is the peak value of the phase current and can be given by [34]

$$I \approx \frac{\sqrt{2}P}{\sqrt{3}U} \tag{2.10}$$

in which P is the output power of the renewable sources and U is the line-to-line voltage.

The total power loss of the power electronic module can be calculated by combing these two parts

$$P_{loss} = \sum_{i=1}^{N} P_{Loss-d,i} + \sum_{j=1}^{M} P_{Loss-I,j} \tag{2.11}$$

in which N and M are the number of diodes and IGBTs in the electronic module.

For the temperature of each module, it should be calculated as the sum of ambient temperature and temperature rises caused by power loss [34]

$$T_{module} = T_{ambient} + R_{th}P_{loss} \tag{12}$$

in which $T_{ambient}$ is the ambient temperature and R_{th} is the thermal resistance.

2.2.4 Failure Rates of Power Electronic Devices

Based on the mathematic formulation in the physics-of-failure model [37], the failure rates of power electronic devices can be determined. Two major factors that can lead to electronic device failures are the over-temperature and thermal cycling [38]. Therefore, both conditions will be considered. Different from the study in [38], a short-term model will be applied, the reliability evaluation is performed on an hourly basis for one-year period. The failure rate of system component is assumed as one in each hour, which means only one single phase of operation is included. Then the failure rate of power electronics can be given by [37]

$$\lambda = \Pi_{PM}\Pi_{process}\Pi_{induced}(\gamma_{TH}\Pi_{TH} + \gamma_{TC}\Pi_{TC} + \gamma_{M}\Pi_{M} + \gamma_{RH}\Pi_{RH}) \qquad (2.13)$$

in which Π_{PM} represents the part manufacturing factor, $\Pi_{process}$ is the quality control factor, $\Pi_{induced}$ is the overstress factor. $\gamma_{TH}, \gamma_{TC}, \gamma_{M}, \gamma_{RH}$ are the basic failure rates related to temperature, thermal cycling, mechanical factor and humidity, respectively.

Π_{TH} and Π_{TC} are the thermal factor and thermal cycling factors, which can be formulated as [37]

$$\Pi_{TH} = \exp(11604 \times 0.44 \times [\frac{1}{293} - \frac{1}{T_{ambient}+\Delta T+273}]) \qquad (2.14)$$

$$\Pi_{TC} = 12 \times \sqrt[3]{0.5} \times \left(\frac{\Delta T_{cycling}}{20}\right)^{2.5} \times \exp(1414 \times [\frac{1}{313} - \frac{1}{T_{max+273}}]) \qquad (2.15)$$

where ΔT is set to $10°\mathrm{C}$, $\Delta T_{cycling}$ and T_{max} indicate the temperature variation and the maximum temperature in a phase respectively.

2.3 Conclusions

For the energy side of the WEN model proposed in this thesis, a microgrid is used to serve as the power supply system in the Water-Energy Nexus, which is given in this chapter. Several uncertainties are considered in this microgrid, including the renewable energy resources, energy storage system and power electronic devices. An operational model is applied to each subsystem, then based on the simulated performance of each subsystem, the reliability of the entire power energy system can be further evaluated. And the mathematic formulation for calculating the power loss of power electronic devices is also presented in this chapter.

For some possible extending work based on the current model, other scenarios such as power exchange with the main grid may be further analyzed. Therefore, the power generated by the renewable energy resources in the microgrid is not the only power supply for WEN. When there is a shortage of power supply, purchasing electricity from the main can be another option. As a result, some economic considerations and constraints can be added to this new model. What is more, the model of the microgrid and power electronic devices can be further explored and improved for achieving more comprehensive simulation results.

Chapter 3 Reliability Assessment of the Drinking Water Distribution Network

3.1 Introduction

In the literature review, there is few studies about the reliability assessment of drinking water distribution network. The research in this field is very limited. Hence, this chapter proposed a probabilistic algorithm taking the system component mechanical failures and network hydraulic failures into consideration, which can be implemented for quantitatively assess the reliability of the water distribution network. Both the formulation for hydraulic flow analysis and methodology of reliability evaluation will be presented in this chapter.

3.2 Hydraulic Analysis of the Drinking Water Distribution Network

For the hydraulic part in the proposed WEN model, a powerful software tool is applied to help performing the water flow analysis. EPANET is a very commonly used software for water flow hydraulics analysis. It can be adopted to analyze the water flow within a period consisting of multiple time steps. In this study, for the reliability evaluation of the water distribution system, a hydraulics water flow analysis considering the physical failures of all system components is performed, the status of each element in the system (e.g., pipes and pumps) is simulated in the procedure.

In the proposed algorithm, the status of each system component in each time step can be obtained by applying the Monte Carlo sampling method. Based on the system state sampling results, if a pipe failed, then EPANET input files will update its statues to down, which means the pipe is not working. The same situation applied on the system pumps. Once the status of all system components has been updated for each time step based on the sampling results, the input files will be sent to EPANET to further perform water flow analysis. The water supply status at each demand point can be seen based on the simulation results.

The method used in EPANET to solve the flow continuity and head loss equations is called the 'Gradient Method', developed by Pilat and Todini. A hybrid node-loop approach will be employed to simulate the hydraulic state of the pipe network. The detailed formulation of this method is given in [30] as follows.

For a given water distribution system, which has N junction nodes and NF fixed grade nodes (e.g., tanks and reservoirs). The water head loss between two points in the network can be expressed as

$$H_i - H_j = h_{ij} = rQ_{ij}^n - mQ_{ij}^2 \tag{3.1}$$

In which H indicates the nodal head, h is the head loss between two points, r is the resistance coefficient of the pipes, Q is the flow rate, n is the flow exponent, and m is the minor loss coefficient.

When neglect of the water head gain introduced by the pump, the head loss for the pumps can be formulated as

$$h_{ij} = -\omega^2(h_0 - r(Q_{ij}/\omega)^n) \tag{3.2}$$

where h_0 and ω are the shutoff head and speed setting for the pump, r and n are the coefficients of the characterize curve.

For all the nodes in the distribution network, equation (3.3) is applied for the flow continuity analysis

$$\sum_j Q_{ij} - D_i = 0 \qquad for\ i = 1,2, \dots N. \tag{3.3}$$

In which D_i denotes the flow demand at each load point. The solution for all heads H_i and flows Q_{ij} that satisfy equation (3.1) -(3.3) will be found based on a set of known heads at the fixed grade nodes.

When applying the Gradient method, initial flow values should be set to all the pipes in the network, these values may violate the flow continuity constraints at the first iteration. But after running several iterations, the new nodal heads can be determined by solving the following matrix equation:

$$\boldsymbol{AH} = \boldsymbol{F} \tag{3.4}$$

where A is a $N \times N$ Jacobian matrix, H is a $N \times 1$ vector with of unknown nodal heads, and F is a $N \times 1$ vector of right hand side terms.

The diagonal elements (3.5) and off-diagonal terms (3.6) of the Jacobian matrix are given by

$$A_{ii} = \sum_j p_{ij} \tag{3.5}$$

$$A_{ij} = -p_{ij} \tag{3.6}$$

In which p_{ij} represents the inverse derivative of the head loss between two points with respect to the flows go through the pipeline.

$$p_{ij} = \frac{1}{nr|Q_{ij}|^{n-1}+2m|Q_{ij}|} \tag{3.7}$$

While for pumps, it is given by

$$p_{ij} = \frac{1}{n\omega^2 r(\frac{Q_{ij}}{\omega})^{n-1}} \tag{3.8}$$

The net flow imbalance plus a flow correction factor at each load point can be formulated as

$$F_i = \left(\sum_j Q_{ij} - D_i\right) + \sum_j y_{ij} + \sum_f p_{if} H_f \tag{3.9}$$

The flow correction factor y_{ij} can be expressed as

$$y_{ij} = p_{ij}(r\left|Q_{ij}\right|^n + m\left|Q_{ij}\right|^2)sgn(Q_{ij}) \tag{3.10}$$

For the pumps, $sgn(x)$ is 1 when $x > 0$ and it is -1 otherwise.

While for the pipes, the flow correction factor can be expressed as

$$y_{ij} = -p_{ij}\omega^2(h_0 - r(Q_{ij}/\omega)^n) \tag{3.11}$$

The new heads can be calculated by solving equations (3.4) -(3.11), and the new flows can be updated by equation (3.12)

$$Q_{ij} = Q_{ij} - (y_{ij} - p_{ij}(H_i - H_j)) \tag{3.12}$$

If the sum of absolute flow changes relative to the total flow in all links is larger than some tolerance (e.g., 0.001), then the procedure of equations (3.4) -(3.12) will be iterated until the tolerance is satisfied. The simulation results given by EPANET includes the water demand, head, pressure of each node; water flow, velocity, and head loss for each pipeline. Based on the simulation results, several reliability indices designed for the system can be calculated. For example, the amount of supplied water can be determined based on the calculated head of each node.

3.3 Methodology of Reliability Evaluation

For all the system element in the water network (pipes and pumps), a two-state model will be applied in the reliability evaluation. Each pipeline may be open or closed and the pump is also modeled in a similar fashion. Then the MCS method is employed to sample the system states. For each system state, the hydraulic simulator EPANET is integrated for performing the water flow analysis.

The performance of water distribution system is mainly influenced by the pressure. Insufficient pressure may lead to water demand losses. For each node, the real supplied water can be obtained based on the pressure, which is expressed as [39]

$$D_{ai} = \begin{cases} D_{ri} & \text{if } P_{ci} \geq P_{min} \\ D_{ri}\frac{\sqrt{P_{ci}}}{\sqrt{P_{min}}} & \text{if } P_{ci} < P_{min} \end{cases} \tag{3.13}$$

where D_{ai} is the actual amount of water supplied to the node; D_{ri} is the water demand required at each load point; P_{ci} is the calculated pressure at each node point; P is the threshold pressure within the system, and it is set to be 40 psi in the case study. Once the threshold pressure cannot be satisfied at any load point, the loss of water demand can be calculated by the following formula

$$D_{lossi} = (1 - \frac{\sqrt{P_{ci}}}{\sqrt{P_{min}}})D_{ri} \tag{3.14}$$

In this study, three indices on the system-level are defined to quantify the system reliability, which could help the system planners and operators to make informed decisions.

The percentage of unsatisfied water demand (PUWD) index can be calculated as

$$PUWD = \frac{\sum_n \sum_i D_{lossi,n}}{\sum_n \sum_i D_{ri,n}} \tag{3.15}$$

where $D_{lossi,n}$ is the nodal demand loss in the n-th iteration of Monte Carlo Simulation; and $D_{ri,n}$ is the water demand in the n-th MCS iteration, both are measured in the unit of gallons per minute.

The probability of loss of water service (PLWS) index is given by

$$PLWS = \frac{N_{loss}}{\sum_n \cdot \sum_i} \tag{3.16}$$

where N_{loss} is the number of system states which has a loss of water service.

The expected water not supplied (EWNS) index is expressed as

$$EWNS = \frac{\sum_n \sum_i D_{lossi,n}}{\sum_n \cdot \sum_i} \cdot 0.5256 \tag{3.17}$$

The constant coefficient 0.5256 is used to convert the unit from gallons per minute to millions of gallons per year.

After running the MCS for a reasonable number of iterations, the system-level quantitative reliability indices defined above can be determined. Refer to the obtained simulation results, the system level reliability characteristics can be evaluated from various perspectives.

3.4 Criticality Analysis

More and more reliability evaluation techniques were proposed for electric power systems, which were however not deployed for reliability analysis of water distribution networks. Meanwhile, to enable informed decision making in reinforcing the water distribution facilities, it is important to identify the most critical assets in a water distribution network. A method has been proposed to quantify the importance or criticality of a single system component by conducting a sensitivity study [40]. The general idea of this method is to measure the maximum loss of the overall system when a single system component fails. In other words, this maximum loss is the partial derivative of the whole system's reliability with respect to the failure rate of the target component. Sensitivity analysis is a commonly used method in most recent work regarding critical component identification, which is more straightforward than other approaches.

Identification of the most critical components in a water distribution system is quite a meaningful task in reliability evaluation. On the one hand, the results can help water system operators and planners make the optimal decision for replacing or reinforcing the particular system components so as to improve the overall system reliability. On the other hand, such information could significantly reduce both the investment and maintenance costs of water distribution systems [41, 42]. Informed decision making could also greatly reduce the cost of constructing a water distribution network. The tradeoff between the total cost and reliability for water distribution systems was studied in [43], and a multi-objective optimization problem was formulated by taking the total cost, reliability, and water quality into account [44].

In reliability evaluation of water distribution systems, the status of each system component is assumed to be independent of other system components. Based on the state of each component, the system reliability could be evaluated by the multiplication rule of probability of all the system components [45]. The minimal cut-set reliability assessment method was first proposed by Dr. Roy Billinton in [46]. A cut set (CS) is a set of system components whose failures alone will lead to a system failure. A minimal cut set (MCS) is a cut set that has no subsets of components whose failures will cause system failure independently. An element in the cut set could be any component in the water distribution system such as pipes, pumps, regulators, valves, etc. In the past, several techniques were proposed to generate minimal cut sets to evaluate composite power system reliability [47-51]. Before applying the Minimal Cut Set method, a preset order should be chosen to determine the highest order of system cut sets that will be formed. The process of determining system minimal cut sets is a combinatorial problem which requires an iterative search. All the possible combinations of system components need to be examined. Therefore, the search space is highly relevant to the size of the distribution network. When the system is very large and highly complex, this search process is rather time-consuming. An inappropriate selection of the pre-set order will lead to high computational cost. In general cases, for small and simple systems, the preset order can be the 3rd or even higher order, but for large scale and complex distribution systems consisting of numerous system elements, the preset order is usually chosen to be the 2nd order. This means all the combinations of system components in the first order and second order will be formed as the sampling space for state evaluation.

To improve the simulation efficiency and overcome the computational complexity, an approximate analysis will be used in this study. The upper bound will serve as the approximation of the system reliability index. The minimal cut set approach is used here to determine all the minimal cut sets of a water distribution system. The procedure of this algorithm is shown in Figure 3-1, and the detailed steps are described as follows:

1. Form the sampling space up to a pre-set combinatorial order of system components.

2. Choose a combination from the sampling space and check all existing minimal cut sets to determine whether they are subsets of the selected combination or not. If yes, choose another combination; if not, continue to the third step.
3. Execute the EPANET assuming the chosen system components are unavailable simultaneously.
4. Check if there is a loss of water services: if yes, record the Probability of Loss of Water Services P_L and the Expected Water Not Supplied ΔW, then use these component combinations to make up a MCS set; if no, go back to step 2.
5. Check the sampling space to see if all the combinations have been examined. If no, go back to step 2. If yes, stop the procedure.

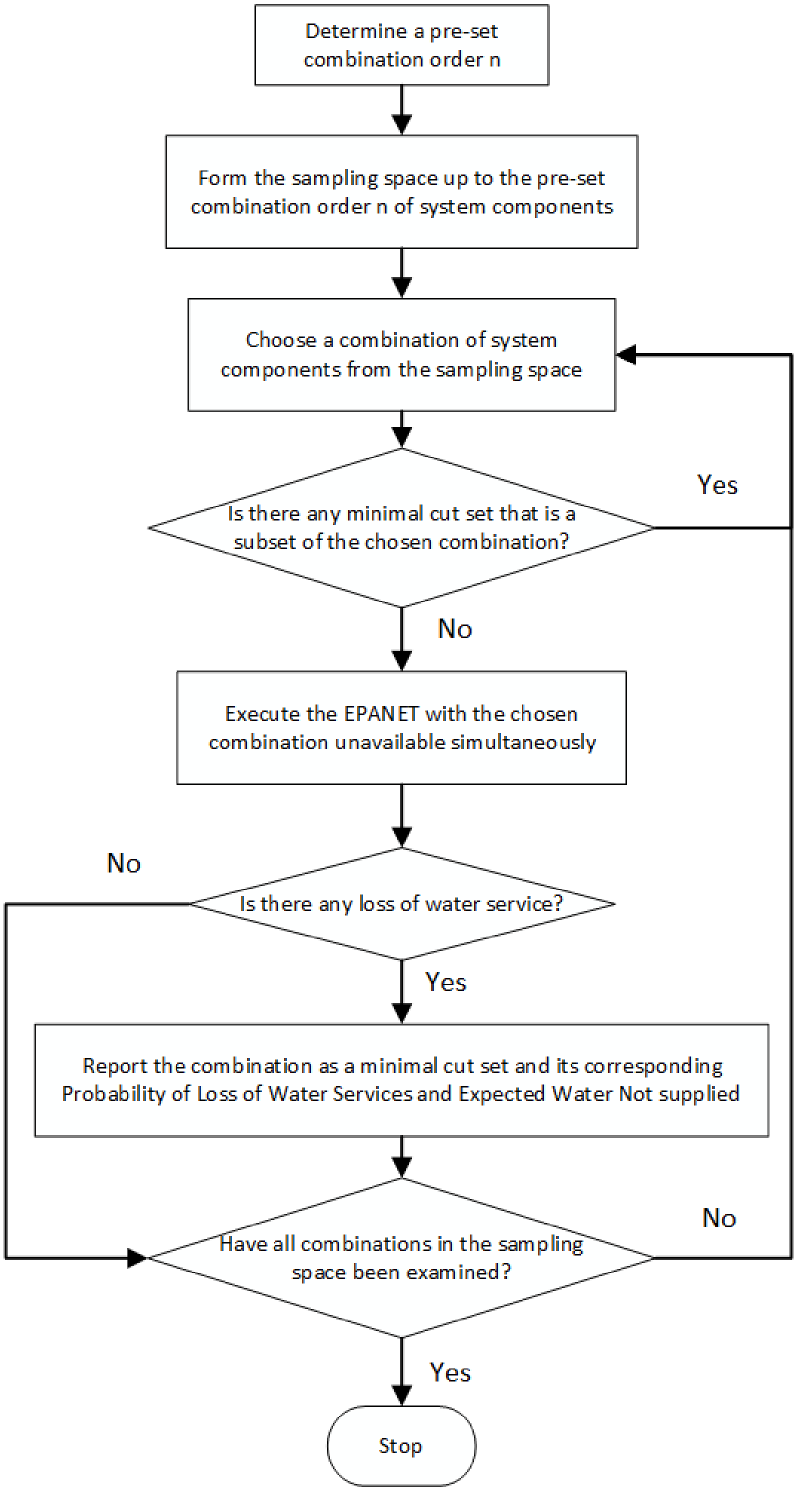

Figure 3-1 Flow Chart for determination of system minimal cut sets

3.5 Conclusions

The probabilistic methodology for quantitative assess the drinking water network reliability is proposed in this chapter. Through this method, both the system component mechanical failures and water flow hydraulic failures can be handled. A criticality analysis based on the proposed algorithm is also presented in this chapter. It can be used to identify the critical components in a water distribution system based on their risks to the system. After the unavailability of each system component is calculated using its failure rate and repair rate, based on EPANET, the minimal cut sets of a certain water distribution system can be determined. Then based on the system minimal cut sets, criticality evaluation can be performed for identifying the most critical components in the entire water distribution network.

Chapter 4 Reliability model of the Water-Energy Nexus

4.1 Introduction

The main reason that the probabilistic reliability evaluation algorithm can be perfectly performed on both the water and energy systems is because of the similar modeling manner of the reliability characteristics of the system components. In the power system, the reliability characteristic of each element can be represented by the two-state model. Probability for the system components to be in either up or down status can be calculated and based on a sampling method (such as MCS algorithm), the system states can also be simulated. Similarly, the reliability modeling of components in the water network, such as pipes, pumps can also be modeled. These similarities make it possible to perform the probabilistic reliability analysis on both systems, as well as the system statistical reliability indices. What is more, the main task of both power system and water system is to satisfy the customers demand with sufficient quantity and quality. When evaluating the reliability of a water distribution network, the core part is to guarantee the water pressure at each demand point is higher than or equal to the required nodal pressure. While in the power systems field, it is of great importance to deliver electricity to each load demand point with satisfactory quality and reliability.

The malfunction or failure of a component in the water system can be caused by its mechanical failure. Also, for the components that need electric power supply, they will be out of service if the power supply is not available. The power supply is influenced by the power network. To link the water system and energy system together, the essential work is to figure out the most energy-consuming component in the water network and analyze how it affect the system reliability. Pump system is the core part of water networks. Its performance may have a huge influence on the water distribution system.

4.2 Water-Energy Nexus Model

A model of the interconnected Water-Energy Nexus (WEN) is proposed in [52]. The mathematic formulation can be used to link the water system and power system is also proposed in this model. Based on this foundation, and the reliability evaluation algorithms mentioned in the previous sections, a reliability evaluation could be performed on the WEN. The problem will be solved in two stages, the first stage is to determine the real power delivered to the coupling point between the microgrid and water distribution system. The second stage is to perform the proposed water flow-based reliability evaluation of the water network based on the results collected from the first stage. The simulation in this study is conducted on an hourly basis for one year (8760 hours). By performing the proposed reliability evaluation algorithm, annual reliability indices can be obtained on the system level.

For a pump operating at a constant speed, the formula for mechanical power can be evaluated from the water flow across the pump and the pump efficiency. The water head gain given by the pump can be expressed as following [39]

$$H_{ij,t}^{G} = \alpha Q_{ij,t} + \beta \tag{4.1}$$

Where $H_{ij,t}^{G}$ is the head gain introduced by the pump in pipe ij. $Q_{ij,t}$ is the water flow go through pipe ij. Both α and β are coefficients of the pump characteristics. In this study, the power factor and efficiency of the pumps are assumed to be constant all the time.

Then, the following equation could be treated as the mathematical formulation connect the microgrid and water distribution system [39]

$$\eta P_{pump} = Q_{ij} \cdot H_{ij}^{G} = \alpha Q_{ij}^{2} + \beta Q_{ij} \tag{4.2}$$

For the mathematic link between the two systems, the main task is to find out how much real power is delivered to the pumps in the water distribution network. An DC-OPF algorithm is employed to determine how much power will be supplied to the coupling point. In the sequential Monte Carlo Simulation, for each hour, the DC-OPF will run once for each sampled system state to determine the real power delivered to the coupling point between the microgrid and water distribution system. The objective is to maximize the power supply to the linking load point. The more detailed DC-OPF is given as

Objective $$Max\ \gamma_C P_{LC} \tag{4.3}$$

Subject to $$0 \le \gamma_C P_{LC} \le P_{LC}^{max} \tag{4.4}$$

$$P_{load_k} = P_{Gen_k} \tag{4.5}$$

$$P_{load_k} = \sum \gamma_i P_{Li},\ 0 \le \gamma_i \le 1 \tag{4.6}$$

$$P_{Gen_k} = \sum P_{Gi} \tag{4.7}$$

in which P_{Li} indicates the real power supplied to each load point and P_{LC} is the power supplied to the coupling point. γ_i is the non-shedding load percentage of each load point. This parameter γ_i is defined to adjust the load curtailment at the coupling point.

The detailed procedure of the proposed reliability evaluation method for the Water-Energy Nexus is shown in the flow chart figure 4-1.

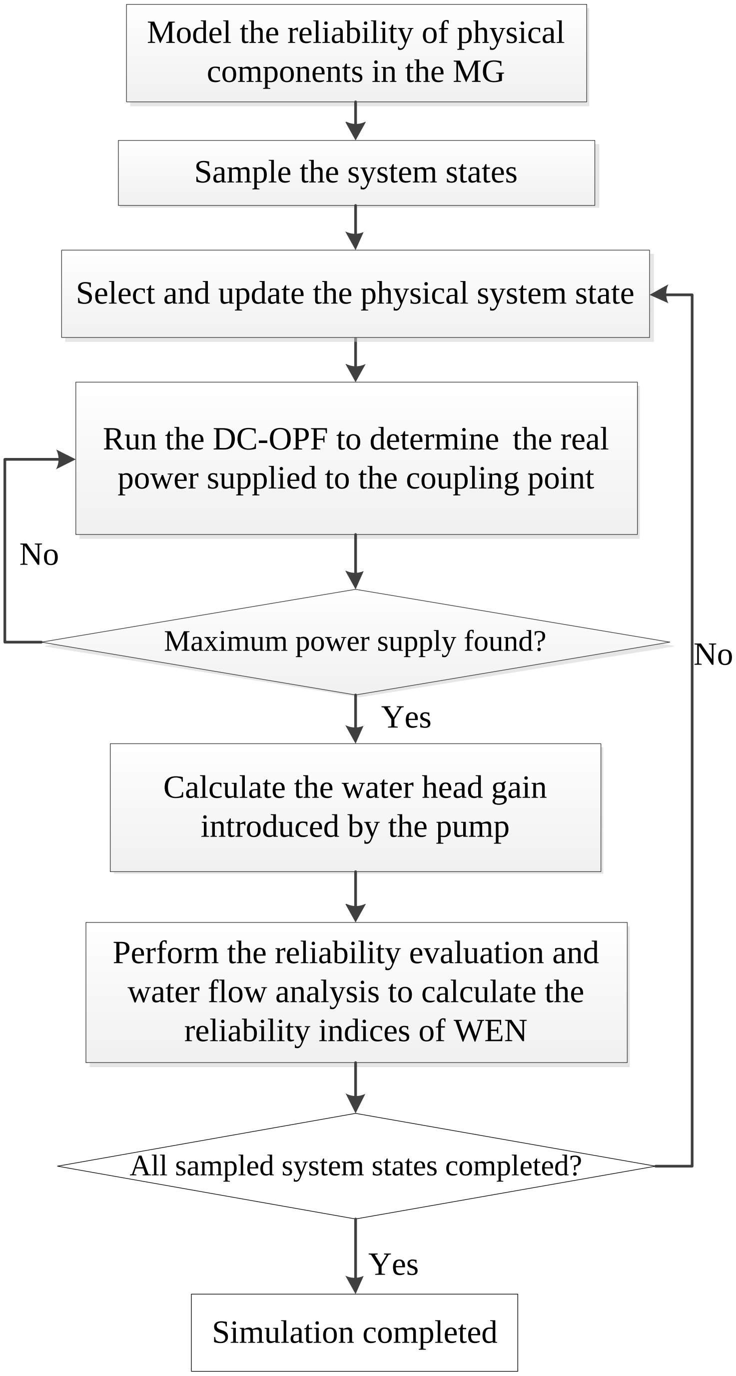

Figure 4-1 Flow Chart of the Proposed Reliability Evaluation Algorithm

4.3 Case Study

Case studies in this thesis are performed on a Water-Energy Nexus, which consists of an 11-node microgrid and a water distribution system given by EPANET. The microgrid is assumed to be isolated from the main grid and served as the only power supply to the water distribution system. The load at each load point and parameters of the transmission lines are available in [31] and modified by increasing both the total load demand and generation capacity. The load demand and line parameters will be kept constant through the one-year period (8760 hours). In the microgrid, there are three PV arrays, one wind turbine generator and one energy storage unit, each with a power electronic interface and a breaker in the network. The rated output of the wind turbine is 1MW, which is located at bus 6. The capacity of three PV arrays in the MG are 3MW, 1.5MW and 1.5MW, and they are located at bus 3, bus 5 and bus 10 respectively. A battery rated 2MWh is used in this network which is connected to bus 8. The water distribution system has 40 pipes, 35 junctions, one tank, and one pump station. These two networks are linked by adding a tie line between the load point 4 in the microgrid and the pump station in the water distribution system. The topological diagram of this Water-Energy system is given in Figure 4-2. The typical three-phase back-to-back converter is adopted for the wind turbine generator, which is shown in Figure 4-4; and as in Figure 4-3, the PV arrays and energy storage are using a full bridge three-phase inverter. The reliability characteristics of wind turbine, PV arrays and storage unit are determined based on the statistical databases in [35-37]; In this study, the failure rate of the wind turbine generators is 2.5 failures/year, the failure rate of PV arrays is 5 failures/year, and the failure rate of the storage unit is 2 failures/year. The failure rate of breakers in the microgrid is 8 failures/year.

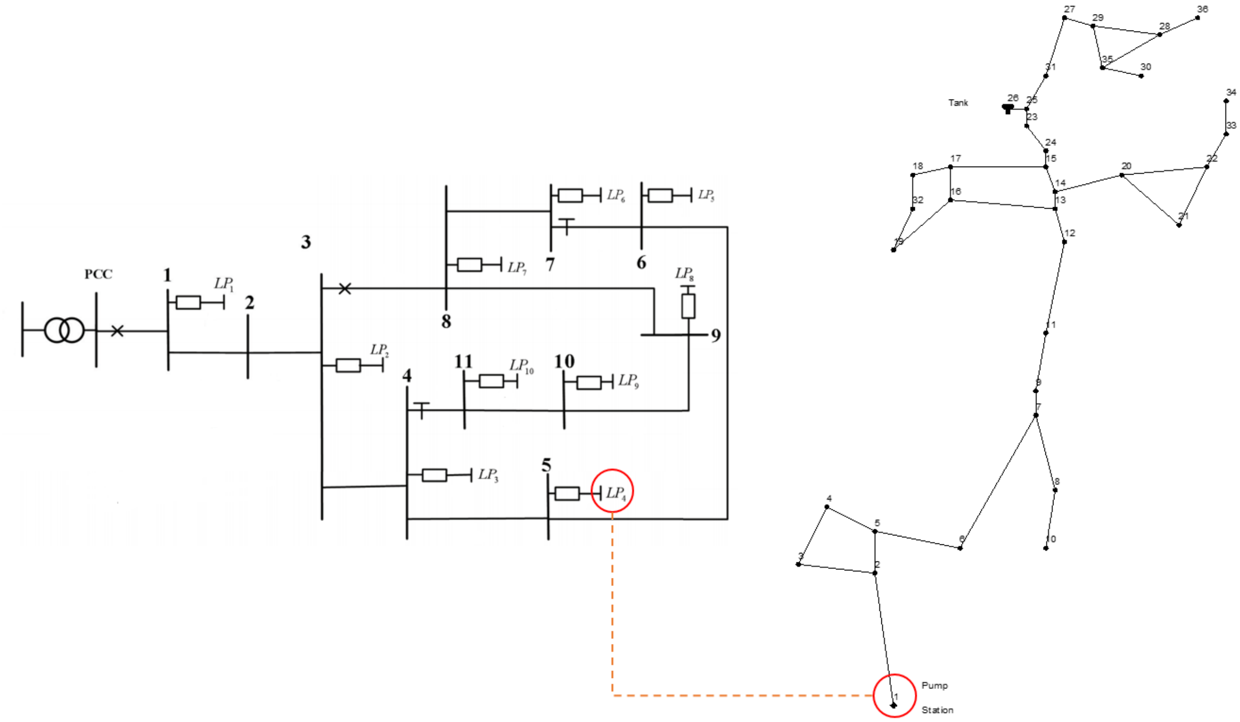

Figure 4-2 The Test Water-Energy System

The annual data for meteorological conditions are found from the Wisconsin State Climatology Office. The historical data of Milwaukee area in 2010 are applied in this study and are shown in figures 4-5 to 4-7. Generally, the PV arrays reach its maximum generation at around the noon as the illumination and temperature is highest by then, and the wind turbine generators will have the maximum power output when the cut-out wind speed is reached.

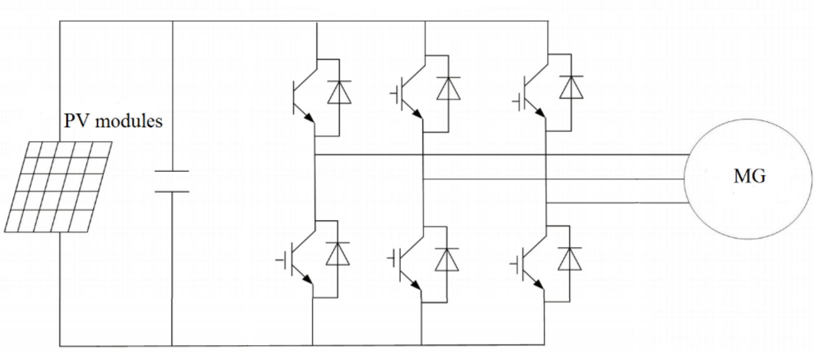

Figure 4-3 Power electronic topology of PV modules

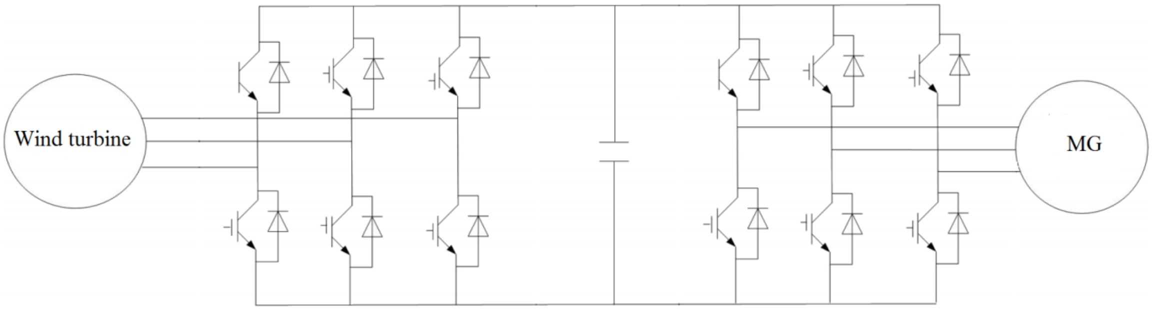

Figure 4-4 Power electronic topology of wind turbine

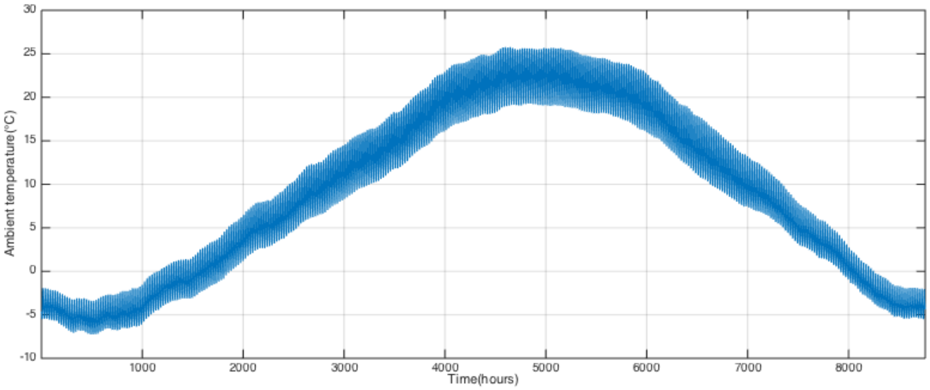

Figure 4-5 Historical data of ambient temperature in Milwaukee [53]

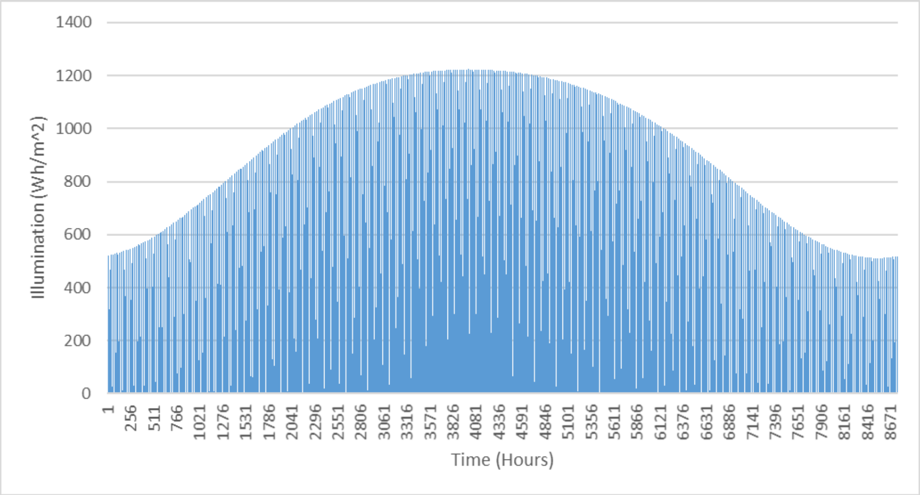

Figure 4-6 Historical data of solar radiation in Milwaukee [53]

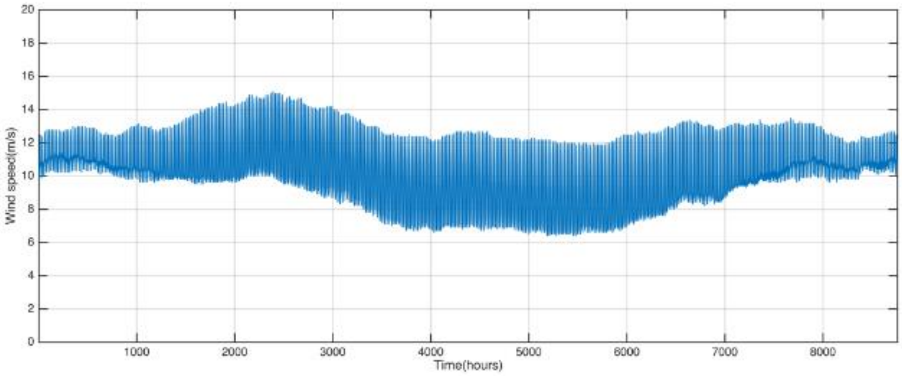

Figure 4-7 Historical data of wind speed in Milwaukee [53]

After model the reliability of electronic element in the Microgrid, the system states of the microgrid is sampled 5000 times in each hour. For each sampled system state, the proposed DC-OPF algorithm is employed to determine the real power supplied to the coupling point, which is load point 4 in the microgrid. The simulation results of the real power supplied to the linked point in the WEN is shown in Figure 4-8.

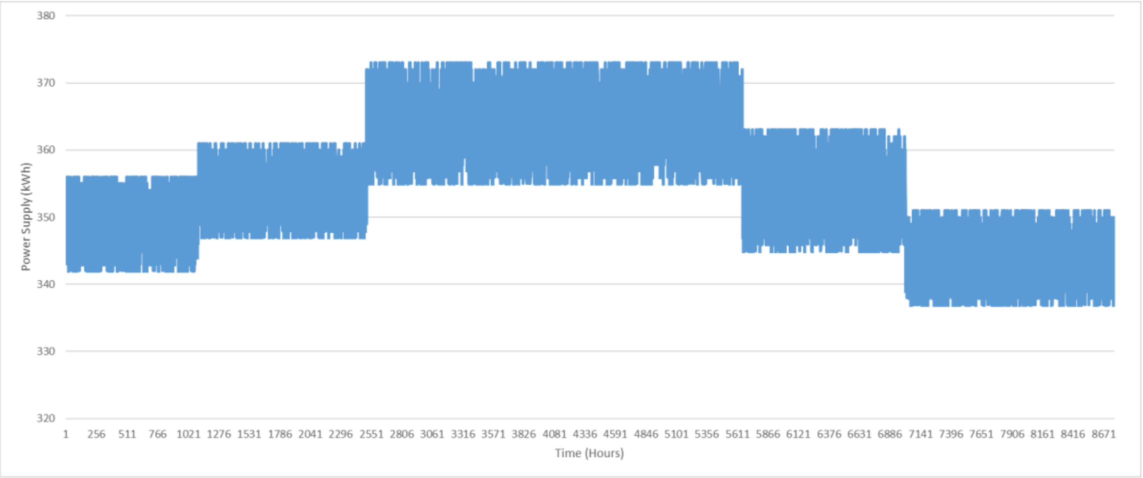

Figure 4-8 Power supply to the coupling point

The simulation procedure will be mainly divided into two stages. First step is to determine the real power supplied to the coupling load point. And based on the results from the first stage, perform a reliability evaluation for the Water-Energy Nexus. For the water system, three input data files are needed: the water system network file, which should have the network topology and parameters of the studied water distribution system; the reliability parameters file with necessary reliability parameters of each system components; and the water system demand file, which contains the water demands of each node.

Based on the power supply to the coupling point, calculate the water head gain introduced by the pump and update the input files for the water system to further perform the hydraulic based sequential Monte Carlo simulation to conduct the reliability indices of the water distribution system. Based on the convergence behavior of the reliability index, it is verified that the specified number of iterations (10,000) is sufficient to achieve reasonably accurate reliability values for the test system.

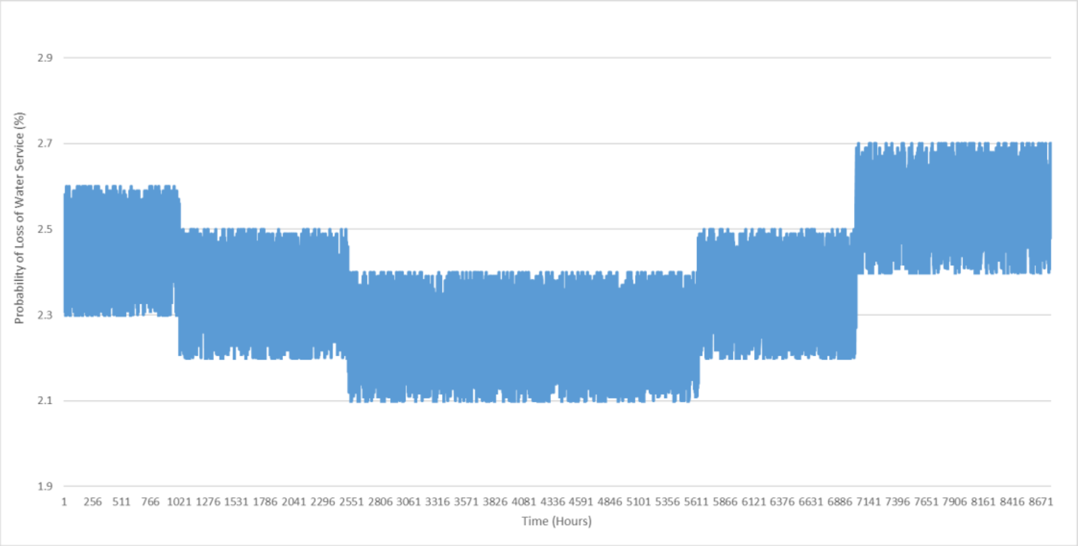

Figure 4-9 PLWS considering the power supply reliability

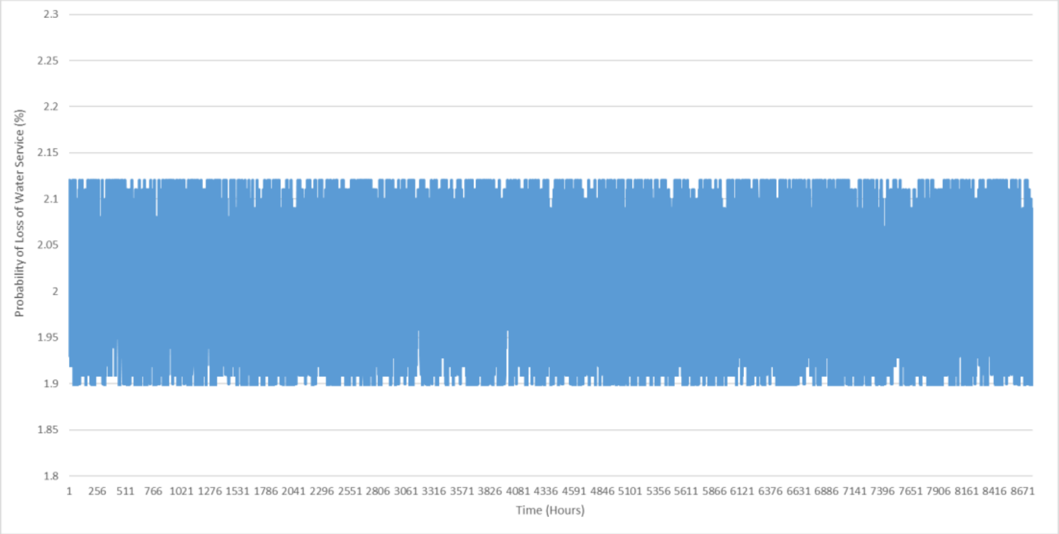

Figure 4-10 PLWS assuming 100% reliable power supply

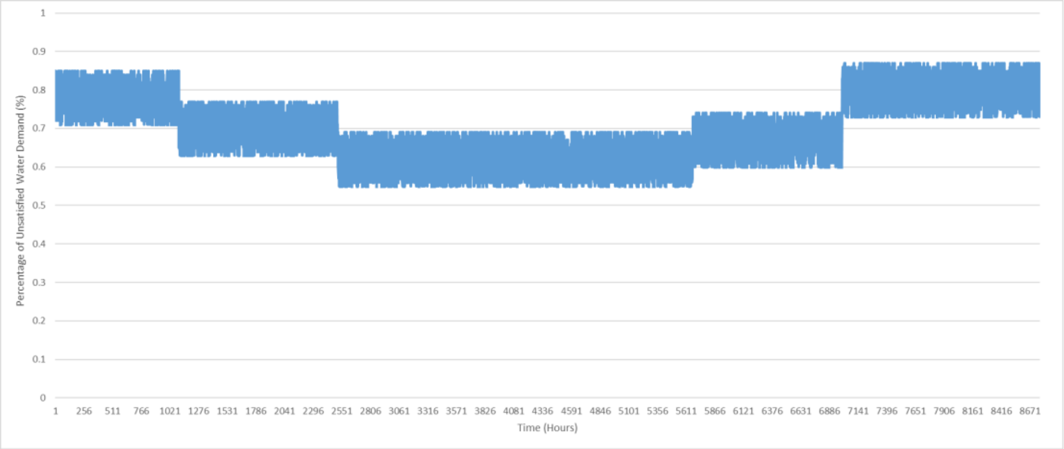

Figure 4-11 PUWD considering the power supply reliability

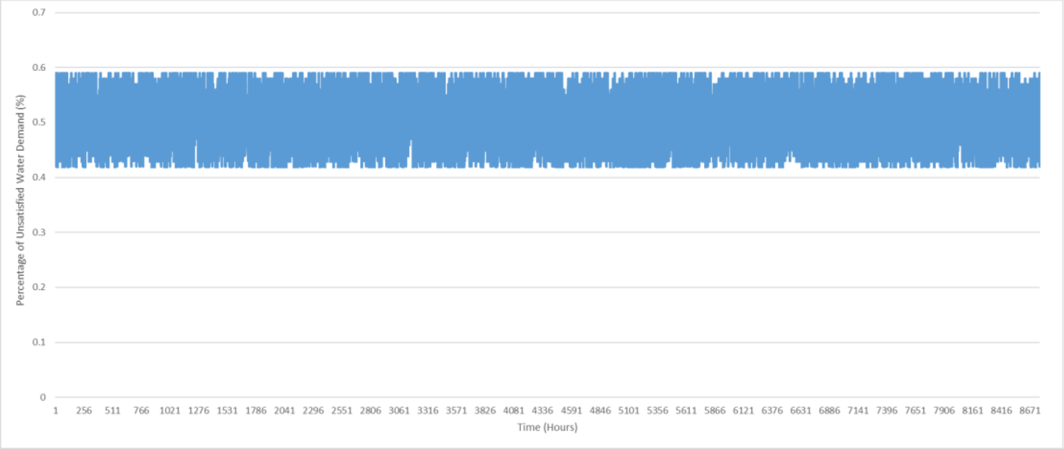

Figure 4-12 PUWD assuming 100% reliable power supply

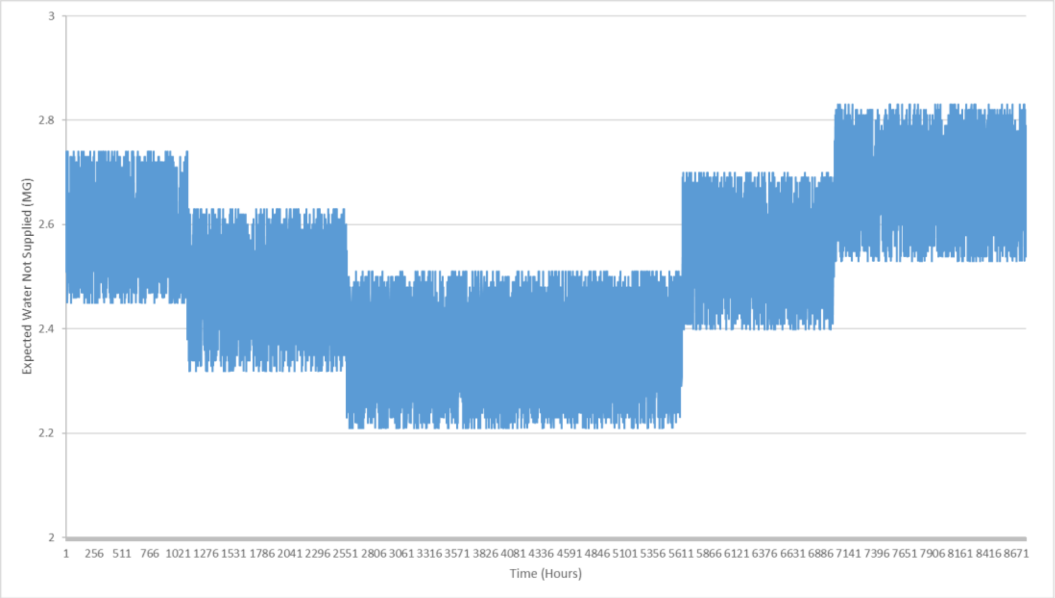

Figure 4-13 EWNS considering the power supply reliability

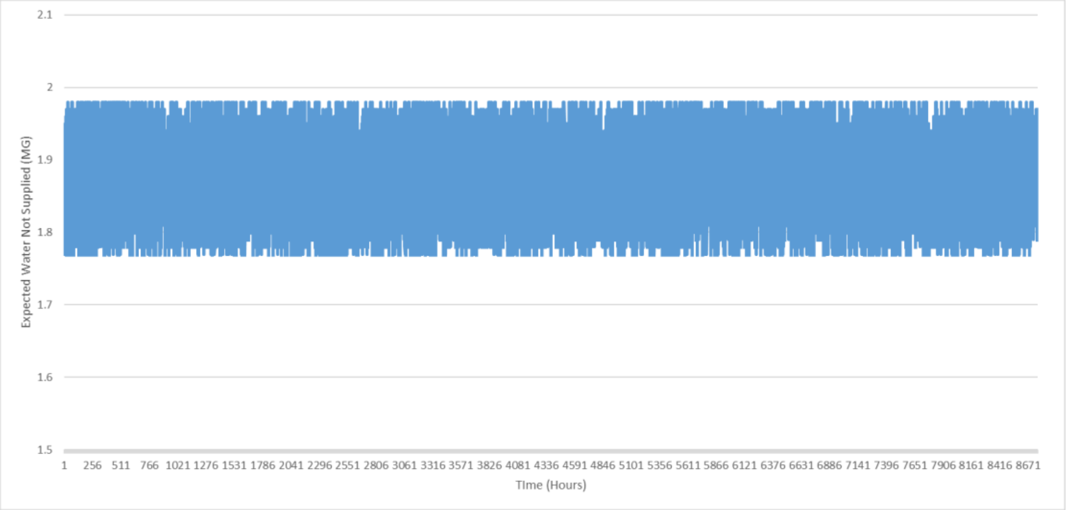

Figure 4-14 EWNS assuming 100% reliable power supply

The reliability indices for the WEN conducted by the proposed algorithm are shown in the figures 4-9, 4-11, and 4-13. Each figure indicates one corresponding reliability indices, including the Probability of Loss of Water Service (PLWS), Percentage of Unsatisfied Water Demand (PUWD), and Expected Water Not Supplied (EWNS). And a comparison study is made to indicate the differences in reliability indices when the power supply is considered as an uncertainty in the evaluation process. While figure 4-10, figure 4-12, and figure 4-14 represent the corresponding reliability indices for the water distribution system without considering the power supply reliability from the microgrid. In other words, these results are obtained assuming that the power supply from the microgrid is 100% reliable.

Due to the radial configurations of the distribution network, there is a certain probability that the system cannot fully satisfy all the system load demands. Some load points are connected to the distribution system through only one pipe, once the only pipeline between two nodes breaks, the load point will inevitably lose all its water supply, resulting in unreliable water supplies to these demand nodes. However, some water demand nodes have a relatively higher reliability. Because these nodes are connected to the distribution network via multiple pipelines. When the fault occurred in one or even more pipes, there is no influence on the water supply to these nodes, as the water demand can be satisfied from other water path. It can be seen from the simulation results that the reliability of the WEN has somehow decreased when the power supply reliability is considered. In the real world, there is no doubt that the power supply for the WEN cannot be 100% reliable. It may have a huge impact on the water-energy system performance. Therefore, it is critical to take this factor into consideration when performing a system level reliability evaluation.

Chapter 5 Conclusions and Future Work

This thesis developed a probabilistic methodology for performing quantitative reliability evaluation of water-energy system considering both mechanical failures and power supply uncertainties. Reliability evaluation is conducted for a typical water-energy system to illustrate the effectiveness of the proposed method.

Both power systems and water systems serve as critical infrastructures of our modern society, and they are highly interconnected. More and more studies are conducted in the reliability performance of Water-Energy Nexus. Although the proposed probabilistic reliability evaluation algorithm has been successfully applied on the WEN, what this study has presented is by no means the best solution to the reliability analysis in this field. There is still large space for further extending the proposed models and algorithms. With a deep understanding of reliability modeling at both component and system levels in other domains, the proposed model and algorithm are also able to be applied on other engineering systems, such as the gas distribution network. For future studies, the reliability model of individual components in the system can be further improved. To obtain a better estimation of the reliability performance of the system, more factors need to be taken into consideration.

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