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RELIABILITY EVALUATION OF ACTIVE DISTRIBUTION NETWORKS AND WASTEWATER TREATMENT PLANT ELECTRICAL SUPPLY SYSTEMS

by

Haodi Li

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ABSTRACT
RELIABILITY EVALUATION OF ACTIVE DISTRIBUTION NETWORKS AND WASTEWATER TREATMENT PLANT ELECTRICAL SUPPLY SYSTEMS

by

Haodi Li

The University of Wisconsin-Milwaukee, 2017
Under the Supervision of Dr. Lingfeng Wang

As energy demand increases in U.S. society, especially in terms of electricity and water, it becomes crucial for the operator to ensure the reliability and security of power distribution systems and wastewater treatment facilities. In the past, deterministic approaches were developed in evaluating the reliability of power supply systems. However, deterministic approaches lack the stochastic characteristic modeling, which makes it ineffective in modeling practical systems with increasing uncertainties. In this thesis, a set of probabilistic, quantitative reliability indices will be calculated for the active power distribution networks and wastewater treatment plant (WWTP) electrical supply systems.

First, the probabilistic reliability evaluation for active distribution networks is performed. Due to the higher pressure from the environment, the integration of renewable resources and application of storage units has become more prevalent in the past several decades. Consequently, using the conventional deterministic approach to evaluate the reliability of active distribution networks may not be effective anymore. In this thesis, a new method is proposed to evaluate the active distribution system reliability containing microgrid and energy storage. The power output of distributed generator (DG) within the microgrid is first calculated based on the approach of generalized capacity outage tables (GCOTs). Then, the Monte Carlo Simulation (MCS) is utilized for performing power system reliability evaluation. The results obtained considering different energy storage capacities are compared. Furthermore, real-time pricing strategy is incorporated in optimizing the control strategy of the storage device. The reliability indices are then recalculated to inform the system operator in power system planning and operations.

Second, the probabilistic reliability evaluation for WWTP electrical supply systems is conducted. Due to the rapid development of industry development and population growth, the electrical power supply system in WWTPs also demands a more comprehensive reliability evaluation, which is currently treated as a mechanical reliability problem in the wastewater treatment industry. In fact, the electrical part also plays an essential role in ensuring the availability and reliability of WWTPs. In this thesis, reliability evaluation mainly focuses on the electrical power supply system instead of the mechanical equipment. Furthermore, the Intelligent Power Motor Control Center (IPMCC) model is incorporated, which is widely used in WWTP control systems. A time-sequential MCS simulation method is used to derive the system reliability indices, and several other techniques are also utilized including the reliability model of IPMCC and the load based reliability indices calculation.

A comparison is conducted between the reliability analyses of active distribution system in power systems and the electrical supply system of WWTP. In fact, both systems do have some similarities, such as the component reliability model and the evaluation procedure. However, in terms of some specific characteristics of each system, reliability modeling and evaluation methods may need some changes correspondingly.

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Chapter 1 Introduction

1.1 Research Background

Electricity plays an indispensable role in the modern society, not only for the industrial usage but also for our daily life. Therefore, the security and reliability of the electricity becomes more important for the social development. More specifically, the power system which is the “carrier” of the electricity should be secured carefully. Similar to the electricity, water also plays an important role in ensuring smooth functioning of society. Without a reliable and secured source of fresh water, our human life is also between the beetle and the block.

On November 24, 2012, the Hurricane Sandy impacted 24 American states. Including but not limited to Florida, Maine, Michigan, Wisconsin, New Jersey and New York. It was reported that more than 25 billion dollars was lost due to the attack of the Sandy, according to the analysis firm IHS Global Insight. More than 8.1 million homes lost power, the power outage was spread to 17 states [1].

On September 08, 2011, a system disturbance occurred in the Pacific Southwest area. According to the report of NERC, this disturbance resulted in cascading outage and 2.7 million people without power supply. The impacted area including: Arizona, Southern California, Baja California and the entire area of San Diego. The power outage happened during the business day, so many schools and businesses had no other choice but to close. The worse condition was that the public transportation was highly disrupted and caused millions of losses [2].

On August 14, 2003, Northeastern and Midwestern United States experienced a severe power outage. Compared with the Northeast Blackout during 1965, this power outage event affected more than 45 million people over 8 states [3].

Similar to the power system, the power outage event may also lead to inestimable loss for WWTP electrical supply system. Effective and reliable wastewater facilities are crucial for all communities. It is more like a firewall which guards the public health and safety, and supplying a base for the social progress. But still, there are increasing concerns about the availability of wastewater facility. The relationship between water and energy consumption for better controlling energy usage is still under drastic debate.

More recently, on February 16, 2017, a short power outage in West Seattle caused 330,000 gallon wastewater discharging into the Puget sound without any treatment. It will take very long time to fully digest the harmful substance within the wastewater. "The pump station, which is designed to send flows to the nearby Alki CSO facility, discharged such large amount untreated wastewater during the power outage, which lasted from approximately 4:45 p.m. to 5:05 p.m. Thursday," a King County news release said [4].

On December 29, 2015, a heavy rain in Fenton, MO caused the wastewater treatment plant inflow exceeded the largest capacity. As a consequence, the wastewater overflowed the plant controls and a power outage event was also caused to the entire wastewater treatment. The large amount of polluted water which should be normally treated at this treatment plant was directly diverted into the nearby rivers [5].

More recently, on October 8, 2016, millions of gallons of wastewater were released into the nearby rivers. According to the report by JEA, the responsible WWTP within this polluted area, they blamed the incident on power outage.

There were two incidents on that day, in the first incident, JEA said, “roughly five million gallons of sewage were diverted into the rivers.” overflowed into the Ortega River after an electrical fault took offline a lift station located on 118th Street in southwest Jacksonville. The fault happened at 2 p.m., JEA said, and the pumps were reset at 11:45 p.m.

“Recreational activities such as swimming and fishing in the Ortega River in the vicinity of the Timuquana Road bridge and upstream should not occur until further notice,” reported by JEA, which said water sampling in the area would continue “until the Ortega River is back within regulatory limits.” [6]

In terms of the second incident, it is still under investigation and the report will be posted when result is prepared.

By introducing these power outage accidents, there is no doubt that these incidents resulting in enormous loss to our society. In fact, the number of these unexpected incidents is increasing every day. So, we could not ignore or underestimate the consequence of these events. To fully ensure the security and reliability of these critical infrastructures, the reliability evaluation could be conducted on the power distribution systems and WWTP electrical supply system. In the early stage of the power system reliability theory, the historical data and deterministic approach are commonly used for the evaluation process. But nowadays the power distribution systems are highly interconnected and the complexity is also much higher than the early system. At the same time, the rapid development of the digital computer creates the possibility of doing the large amount probabilistic system calculation. Because of all these factors, stochastic approach could have a better performance than the deterministic one. More specifically, the Monte Carlo method is adopted as the stochastic approach in this thesis. In terms of the Monte Carlo Simulation (MCS) method, it is widely used in the scientific research that allows researcher to conduct the quantitative risk assessment. MCS is not only used in electric engineering, but also mathematics, finance, energy management and other subjects. To have a better understanding of the application of MCS in power system field, some conceptions need to be introduced:

Random Number Generation, to conduct the MCS for a power system network, the random number is an essential factor to ensure the accuracy of the results. There are three basic requirements for a random number generator [7]:

Uniformity: the random number should be well distributed between the interval [0,1].

Independence: The correlation between two random numbers should be minimized.

Long period: The repeat period of random number should be long enough.

State duration sampling, in the Sequential Monte Carlo method, we need to generate the Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR). Before conducting the duration sampling, the distribution of the component should be determined firstly. In this thesis, exponential distribution is assumed for all of the components. With the MTTF and MTTR, the reliability indices could be calculated by following the simulation procedures step by step. Chapter 2 will introduce more details and results of MCS.

Considering all of these tragic events, this thesis proposes a probabilistic method to evaluate the distribution networks incorporating the real-time electricity price and the storage unit. Furthermore, the WWTP electrical supply system reliability evaluation is also conducted and relevant reliability indices are calculated.

1.2 Introduction to Reliability Analysis of Distribution Systems Considering Energy Storage and Real-Time Electricity Pricing

In the existing research, there have been many studies for determining the size and locations of energy storage devices based on different design goals and control strategies [8], [9]. For the Wind Turbine Generator (WTG) and PV panel, some previous work aimed to fully utilize the complementary characteristics of WTG with the PV for smoothing out the fluctuation of power injected into the grid. Some existing work was focused on studying how to optimize the size of the distributed battery energy storage system (BESS) and conduct cost-benefit analysis based on voltage regulation and peak load [10]. In this thesis, we consider the impact of microgrid operations in reliability evaluation and calculate the corresponding reliability indices. In the past, the distributed grid reliability was mostly evaluated by the conventional methods without considering renewable resources [11], [12]. In this thesis, the reliability of the active distribution grid is evaluated with the consideration of the renewable sources and operating modes. Then, the active distribution system reliability is evaluated accounting for real-time electricity pricing, which is different from the conventional electricity distribution contract.

1.2.1 Microgrid and Energy Storage

Microgrid has been mentioned many times since it is created. But in fact, several decades ago, most of us or even some scholars in power area they have little knowledge of microgrid. Generally speaking, the microgrid could be treated as a cluster of interconnected distributed energy sources and loads. According to the U.S. Department of Energy, the conception of microgrid is defined as follows [13]: "A microgrid, it is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode." As an import component of microgrid, energy storage unit could be charged when the electricity price is lower than the threshold value and it could also discharge the stored energy to the market to realize the monetary objective. On the other hand, the energy storage unit can be utilized as a back-up electricity "bank" when there is a failure within the microgrid. The reliability and availability of the whole distribution system could be enhanced due to the existence of energy storage unit.

1.2.2 Real-Time Electricity Pricing (RTP)

In recently years, the pressure of providing the sufficient and secured electricity to customer increases much more than before. There are many factors contributing to this result, the rapid development of manufacture, the large number of household appliances, the expansion of electric vehicle and so forth. The real-time electricity pricing could relieve the pressure by motivating customer monetary incentives. The real-time electricity pricing is varying continuously which could reflect the retailed price of electricity. In the electricity market, there are many utilities provide the RTP for different purpose, in [14] and [15], their RTP prices are different since they serve different geographic area. Nowadays, RTP becomes more attractive since the demand-side management (DSM) technology becomes more practical than before. In chapter 2, the RTP is utilized to regulate the charging and discharging or the energy storage unit.

1.3 Introduction to Reliability Analysis of WWTP Distribution Networks

As we all known, water is the most valuable treasure in earth, but nowadays the security of water is facing stern challenge. According to [16], the water pollution is a major cause of human-being death. There are more than 14,000 death because of water pollution every day. What's worse, there are various kinds of water pollutants, including organic, inorganic, radioactive and so on [17]. So, the WWTP plays an essential role in changing such a poor condition.

The reliability evaluation of WWTP is mainly conducted focus on the mechanical component failures nowadays [18]. The wastewater treatment procedure could be divided into three parts: primary, secondary, and tertiary treatment. In each treatment procedure, there are many steps. In fact, the distribution networks within the WWTP have strong impact on the entire treatment procedure. For any component needs power supply, it will be out of proper working status if the power supply is not available. So, the entire WWTP distribution networks are responsible for maintaining the functionality of mechanical components need power supply. In this thesis, the reliability evaluation is conducted on the WWTP distribution networks, the MCS is utilized to calculate the load-based reliability indices. With these reliability indices, the system operator could have a better view of the system reliability assessment.

1.4 Research Objectives and Thesis Layout

In this thesis, the holistic probabilistic reliability evaluation is performed on the active distribution system and WWTP distribution networks respectively. In chapter 2 the reliability evaluation of active distribution system considering the renewable energy and real-time pricing strategy will be studied. And a detailed case study will be conducted on the RBTS system to demonstrate this methodology. In chapter 3 the probabilistic method for reliability evaluation on WWTP distribution networks is conducted. Different types of WWTP distribution networks are well discussed and studied. Some improvements and useful indices are also shown to further enhance the reliability and availability of the system. In the chapter 4, the scientific comparison, conclusion and future work are studied.

Chapter 2 Reliability Evaluation of Active Distribution Systems Considering Energy Storage and Real-Time Electricity Pricing

2.1 Introduction

As introduced in chapter 1, the active distribution system is more complex compared with the conventional distribution system. There are more factors should be incorporated into the active distribution system, such as the energy storage unit, island mode of microgrid and SOC control strategy considering RTP. In this chapter, an integrated reliability evaluation of active distribution system considering energy storage unit and real-time electricity pricing will be conducted. The Sequential Monte Carlo approach is used to calculate the reliability indices: SAIFI, SAIDI and EENS.

The structure of this chapter is organized as follows. In section 2.2, the system modeling and methodology will be introduced. Section of 2.3 presents the detailed procedures of evaluating active distribution system and some techniques applied in this evaluation. Section of 2.4 shows the case study based on RBTS system and the reliability indices. Section of 2.5 is the conclusion of this chapter.

2.2 System Modeling and Methodology

In this section, the system modeling and methodology will be introduced in detailed. Different from the conventional distribution system, the active distribution system considers the impact of Distributed Generators (DGs), energy storage, RTP. The three main approaches and assumptions for the system are explained as follows.

2.2.1 Zone Partition and Upward Equivalent Approach

The zone partition approach can be used to partition the distribution system into different zones. The zone is partitioned based on the locations of breakers and sectionalizers [19]. The distribution networks upward equivalent approach is adopted to simplify the load points (LPs) in the Microgrid (MG), which is illustrated in Figure 2-1.

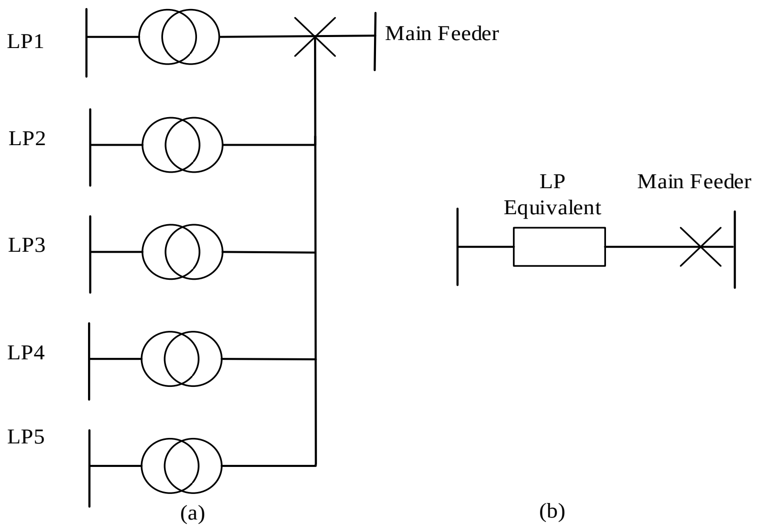

Figure 2-1 Upward equivalent approach:

(a) Before upward equivalent (b) After upward equivalent

The equivalent failure rate λ_e, unavailability u_e and repair time r_e are derived from the following equations:

$$\lambda_e = (1 - P_b) \sum_{i=1}^{n} (\lambda_{jl} + \lambda_{jt}) \tag{2.1}$$

$$u_e = \sum_{i=1}^{n} (\lambda_{jl} + \lambda_{jt})\, t_1 \tag{2.2}$$

$$r_e = \sum_{i=1}^{n} (\lambda_{jl} + \lambda_{jt})\, t_1 / (1 - P_b) \tag{2.3}$$

where P_b is the reliable disconnection rate of breaker of sub feeder, λ_{jl} represents the transmission line failure rate of node j inside the sub feeder and λ_{jt} represents transformer failure rate, and t_1 is the operation time of disconnector which is matched with a breaker.

2.2.2 Power Output of DG Based on GCOT Approach

The power output of DG is calculated based on the approach of generalized capacity outage table (GCOT) [20]. The GCOT approach first categories the generator power output into certain states S based on the apportionment approach, and the corresponding operating capacity $C_T(i)$ is found out. Then, the power output of WTG and thermal generator for each state can be calculated by:

$$C_T(i) = \frac{P_{rated}}{S}(\mathrm{S} - \mathrm{i}) \quad \mathrm{i}=1, 2, \ldots, \mathrm{S} \tag{2.4}$$

The probability of each state is calculated by

$$P_T(i) = \frac{T_i}{T_{total}} \tag{2.5}$$

The cumulative probability is assumed to determine the power output of each state, which is

$$P_{T,cum}(i) = \sum_{i=k}^{S} P_T(k) \tag{2.6}$$

Where T_i represents for the time of each state, and T_{total} denotes the total time.

2.2.3 Energy Storage Model and SOC

In this model, the specific type of energy storage is not defined because different capacities of storage devices are used to calculate the system reliability indices. The battery lifetime and degradation are also omitted since they are not the main concerns of this study. Here, the model of energy storage is built to reflect the relationship between the battery sizes and system reliability indices.

The charging and discharging rates are assumed to be sufficiently high so that the charging or discharging process can be completed in the same electricity price interval. Here the relationship between the electricity price and the system reliability is the main concern in this study.

2.3 Active Distribution System Reliability Evaluation Method

The active distribution system, compared with the traditional distribution system, is made up of more components and facilities such as DGs and storage batteries. As a result, reliability evaluation of the active distribution system is more complicated with the integration of these assets. The traditional analytical reliability evaluation approaches may not be suitable or effective for this kind of system anymore. Here MCS is chosen to estimate the system reliability by randomly generating system states.

Moreover, in case the RTP structure is adopted in our study, the charging and discharging strategies of the battery also change. Based on the variation of electricity prices, the SOC may be changed correspondingly to meet the reliability requirements.

2.3.1 The Impact of Microgrid on Reliability Evaluation

The microgrid is composed of local generation, energy storage devices, and load points that are normally connected to the main grid. It can operate in islanded mode or grid-connected mode. The system works as a traditional grid when the microgrid is connected to the main grid. When there is a fault in the system, the microgrid operates in the islanded mode. The load points are supplied by either DGs or energy storage in the microgrid.

Before evaluating the distribution system reliability, the zone partition and upward equivalent approaches are utilized to simplify the system. Then the GCOT is used to calculate the DGs power output in the microgrid.

With the DGs power output, the evaluation of distribution system could be conducted in the following steps:

Step 1: Based on the types of components, sample each component and find out the time to failure (TTF) and time to repair (TTR) according to the following equations [7]:

$$TTF_a = -\frac{1}{\lambda_a} lnU_1 \tag{2.7}$$

$$TTF_p = -\frac{1}{\lambda_p} lnU_2 \tag{2.8}$$

$$TTF = min\{TTF_a, TTF_p\} \tag{2.9}$$

$$TTR = \frac{1}{\mu} lnU_3 \tag{2.10}$$

where TTF_a is the time to active failure; TTF_p denotes the time to passive failure; λ_a and λ_p represent active failure rate and passive failure rate, respectively; μ denotes the repair rate; and U_1 , and U_2 and U_3 are three random numbers which are uniformly distributed between [0,1].

Before the failure happens, the SOC of batteries in the microgrid is determined based on the power output of WTGs and thermal generators. If the WTGs and thermal generators are able to fully satisfy the load demand in the microgrid, the battery will be charged with the surplus energy. Otherwise, the load point demand will be supplied first.

Step 2: Determine the repair time of each load point based on the location of the failed component and the available energy stored in the battery. Here are the three scenarios:

Scenario 1: The load points in the microgrid are influenced by the failed component without considering the available energy stored in the battery. The load points distributed along the main feeder are not influenced as long as the breaker or switch works properly; otherwise, they will be influenced. The type of the failed component determines the TTR of the influenced load points.

Scenario 2: The energy storage can satisfy the load points in the microgrid. The available energy can fully satisfy the load demand in the microgrid. The load points in the microgrid can operate in the islanded mode. Surplus energy is delivered to the main feeder that is not affected by the failed component. Load restoration process is determined by the distance between the battery and the load point. TTRs for those affected load points are determined by the type of the failed component.

Scenario 3: The energy storage is unable to fully satisfy the load demand in the microgrid. The load points in the microgrid are influenced, and the TTRs of those load points are calculated based on the type of the failed component and the available energy. For the load points outside of the microgrid, if they cannot be isolated by the breaker or the switch, they are also affected. The TTR is also determined by the type of the failed component.

Step 3: Once the TTF, TTR and system state is determined, the reliability indices of SAIFI, SAIDI, and EENS can be calculated based on the following formulas [20]:

$$\text{SAIFI} = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{2.11}$$

$$\text{SAIDI} = \frac{\sum U_i N_i}{\sum N_i} \tag{2.12}$$

$$\text{EENS} = \sum L_{a(i)} U_i \tag{2.13}$$

where λ_i is the failure rate of load point i, U_i is the annual outage time of load point i, N_i is the number of customers at load point i, and $L_{a(i)}$ is the average load connected at load point i.

Step 4: The whole system reliability indices are calculated when any stopping criterion is satisfied. The overall Monte Carlo simulation flow chart is illustrated in Figure 2-2.

2.3.2 Reliability Evaluation Considering Real-Time Pricing

When taking the RTP into consideration, the determination of the SOC of the batteries becomes more complicated. The charging and discharging strategy of the battery will also change. It is obvious that charging the battery to a high SOC at a low hourly electricity price can improve the system reliability with a lower cost. And the battery can also discharge when the hourly electricity price is higher than a certain threshold value.

The percentage of SOC and the corresponding price interval can be determined by customer side requirements. Meanwhile, the operator can adjust the hourly electricity price based on the response of the demand side.

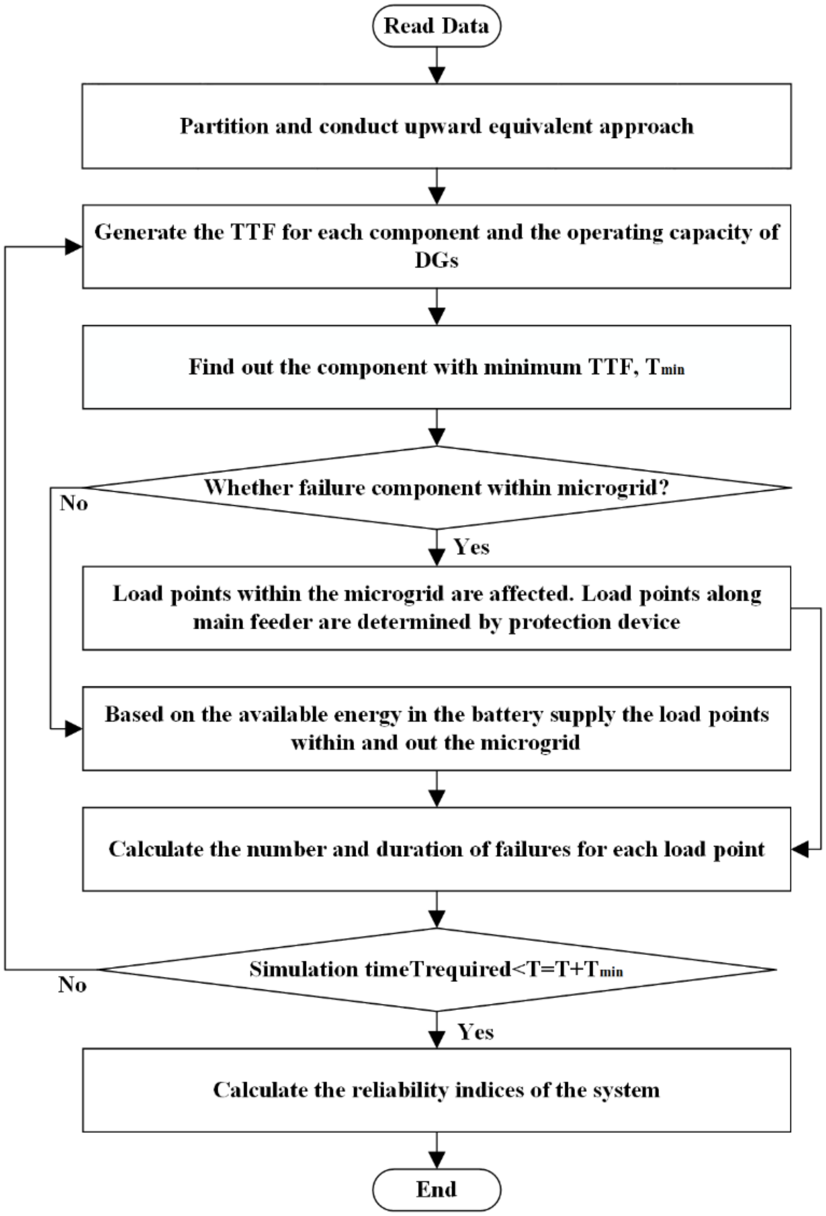

Figure 2-2 Overall Monte Carlo Simulation Flow Chart

2.4 Case Study Analysis

Case studies are conducted on the RBTS-Bus6 F4 system. The influence of energy storage on reliability indices is first analyzed. Then the real-time electricity price is also considered, and system reliability indices are recalculated.

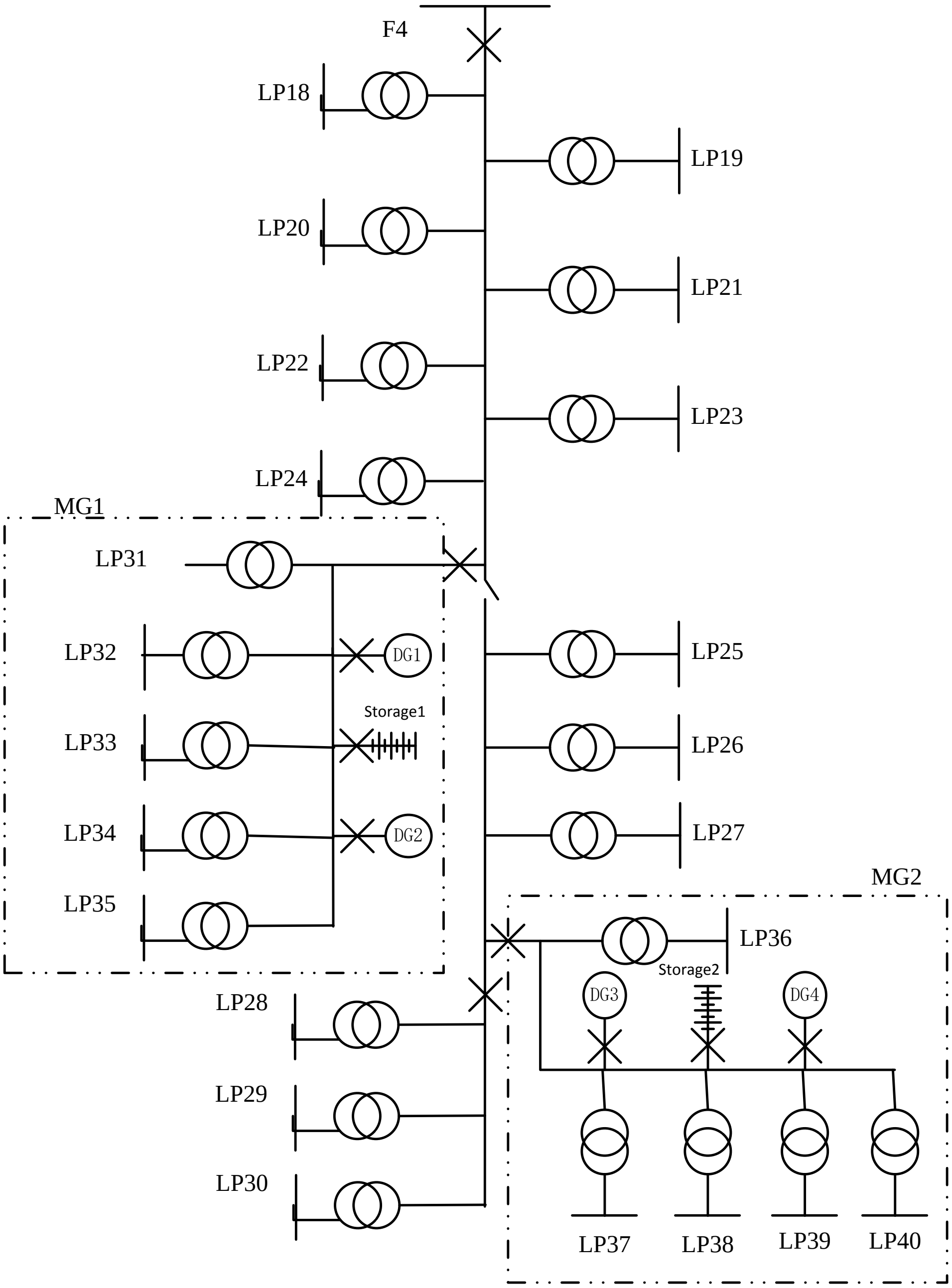

Figure 2-3 The RBTS Bus6 Feeder4 System

2.4.1 Modified RBTS Bus6 Feeder4 System

Figure 2-3 is the schematic diagram of the modified RBTS Bus6 F4, which consists of 23 load points, 30 transmission lines, 23 distribution transformers, 23 fuses, 10 breakers (the original system has 4 breakers, the additional 6 breakers are installed for DGs and batteries) and one disconnector [11]. Microgrid has two WTGs and an energy storage unit, and both of the WTGs are rated 2 MW [19]. The capacity of storage units in MG1and MG2 are not fixed, and a set of reliability indices will be derived based on different energy storage capacities. All the component parameters are obtained from the RBTS system.

Table 2-1 Reliability Indices of The Modified System

Indices	SAIFI (Int./Cus.yr)	SAIDI (hrs/Cus.yr)	EENS (MWh/yr)
Without DG, Energy storage	1.4648	11.9630	94.5876
With DG, 0.1MWh Energy storage	0.6301	4.805	33.9559
With DG, 0.5MWh Energy storage	0.6102	4.2391	31.9292
With DG, 5MWh Energy storage	0.4578	4.1676	30.799
With DG, 20MWh Energy storage	0.3456	3.9741	28.5596
With DG, 50MWh Energy storage	0.2666	3.5698	23.9183
With DG, 100MWh Energy storage	0.2655	3.5592	23.8853
With DG, 500MWh Energy storage	0.2599	2.9362	19.6745
With DG, 2000MWh Energy storage	0.2599	2.9362	19.6745

The reliability indices of the modified RBTS Bus6 Feeder 4 are calculated which are shown in Table 2-1. Initially, the system reliability is evaluated without considering the DGs and energy storage. After incorporating the DGs and energy storage, the system reliability is much improved. For instance, the SAIFI decreases from 1.4648 Int./Cus.yr to 0.2599 Int./Cus.yr. With DGs and 500MWh energy storage installed, SAIFI decreases by 82.25% compared with the system without

DGs and energy storage. Similarly, SAIDI and EENS decrease by 75.45% and 79.19%, respectively.

To further analyze the impact of energy storage on reliability indices, Figure 2-4 to Figure 2-6 show the changes of SAIFI, SAIDI and EENS with the increase of energy storage capacity. The results indicate that the reliability indices converge to certain values. This is because some failures cannot be fixed with the integration of energy storage. So choosing the appropriate size of the energy storage can not only enhance the system reliability but also achieve monetary savings.

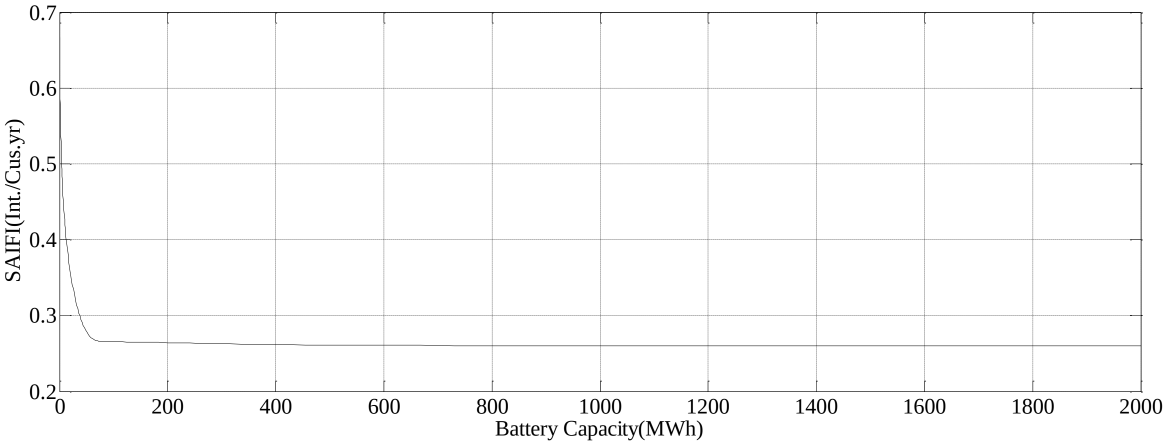

Figure 2-4 SAIFI values with different battery capacities

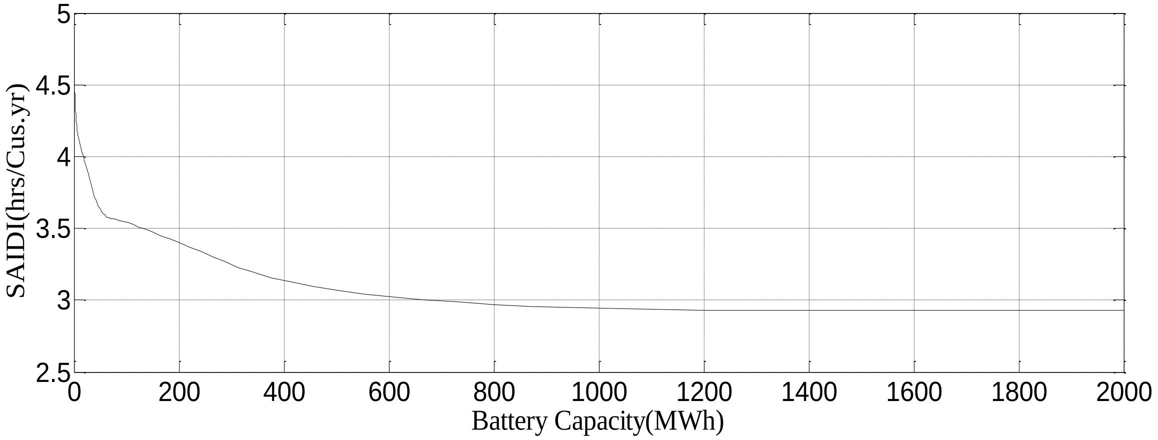

Figure 2-5 SAIDI values with different battery capacities

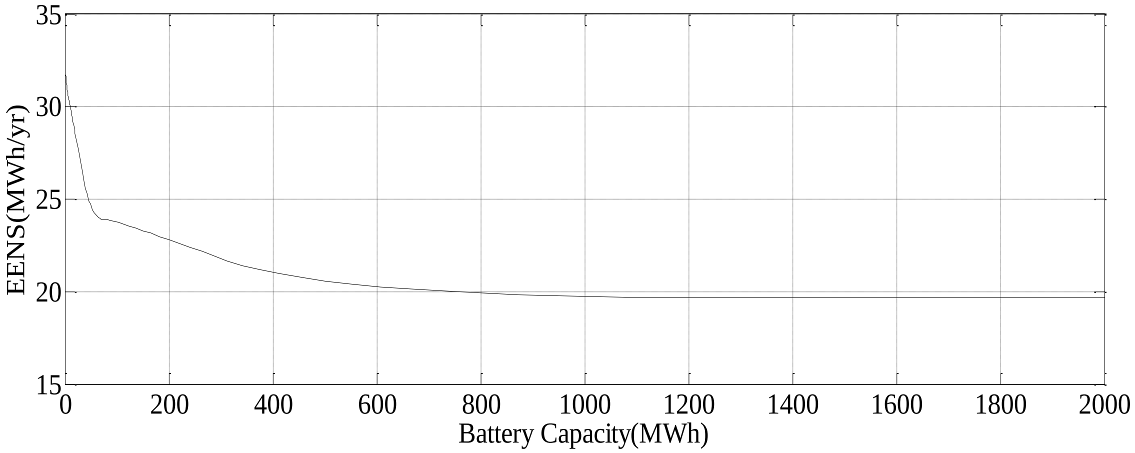

Figure 2-6 EENS values with different battery capacities

2.4.2 24-hour Real-Time Electricity Pricing Impact on Reliability Indices

Figure 2-7 shows 24-h electricity prices [21] used in the simulations, where the prices range from 12.18 cents/kWh to 27.40 cents/kWh. In order to enhance the system reliability, the capacity of energy storage should be adequately large. However, the investment of installing large energy storage or battery bank could be enormous. Therefore, an appropriate size of energy storage should be determined to guarantee the system reliability and meet the capital requirement. After conducting calculation and comparison, 5 MWh is chosen as the size for the two storage devices in MG1 and MG2.

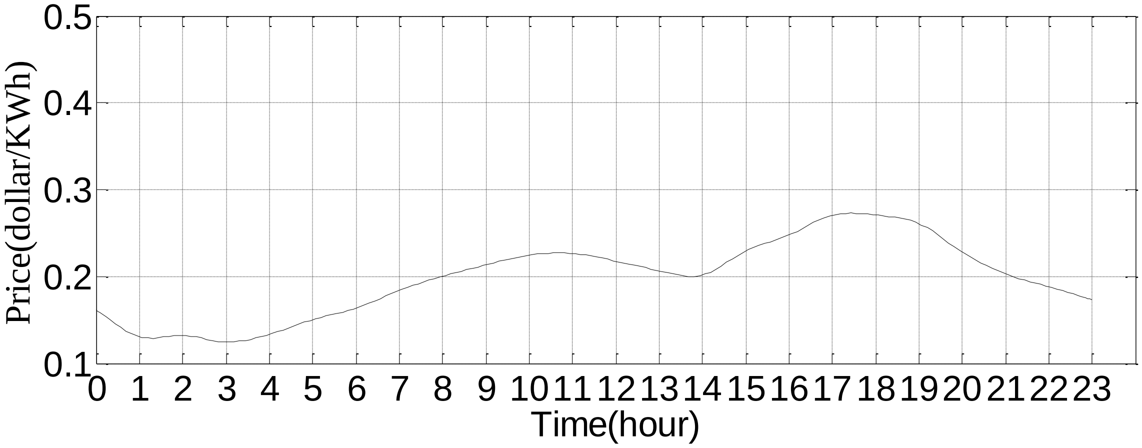

Figure 2-7 24-h electricity prices from PJM

The SOC can be specified by the operator or decided by the customer's own preference. Moreover specifically, when the hourly electricity price is lower, the SOC can be set to a higher percentage to obtain a more reliable system with a lower cost. When the hourly electricity price increases, to cut the cost of purchasing electricity, SOC can be set to a lower level. Table 2-2 shows the detail of the charging and discharging strategy.

Table 2-2 SOC of Battery

Price (cents/kWh)	SOC (%)
12-14.99	Charging to 100
15-17.99	Charging to 80
18-21.99	Charging to 50
22 and above	Discharging to 20

Based on Table 2-2 results, when the price is lower than 15cents/kWh, the battery will be charged to 100%. In this condition, the energy storage can enhance the power system reliability significantly and the cost is acceptable. When the price is higher or equal to 15 cents/kWh but lower than 18 cents/kWh, the battery will be charged to 80%. When the price is higher or equal to 18 cents/kWh but lower than 22 cents/kWh, the battery will be charged to 50%. When the price is higher than 22 cents/kWh, the battery will be discharged to 20%. In this condition, the tradeoff between system reliability and economic aspect is considered. Figure 2-8 to Figure 2-10 show that SAIFI, SAIDI and EENS change with the variation of 24-hour electricity prices.

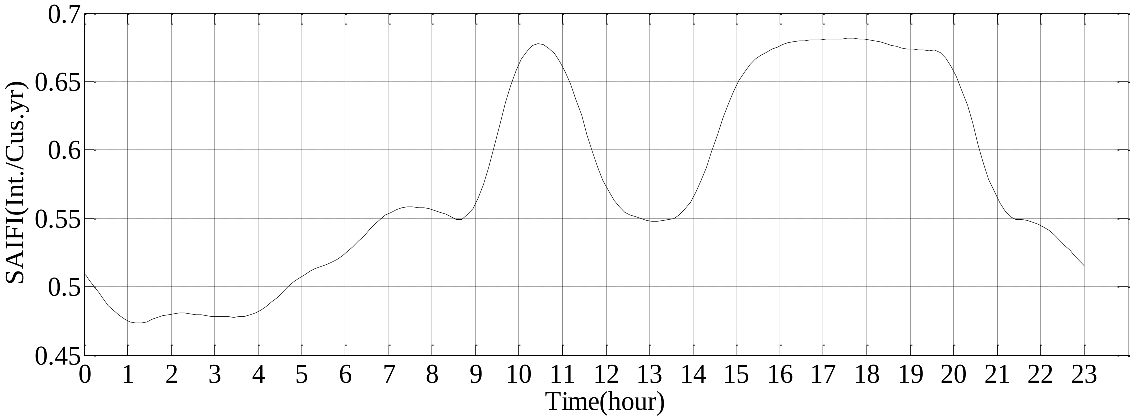

Figure 2-8 SAIFI considering 24-h electricity prices

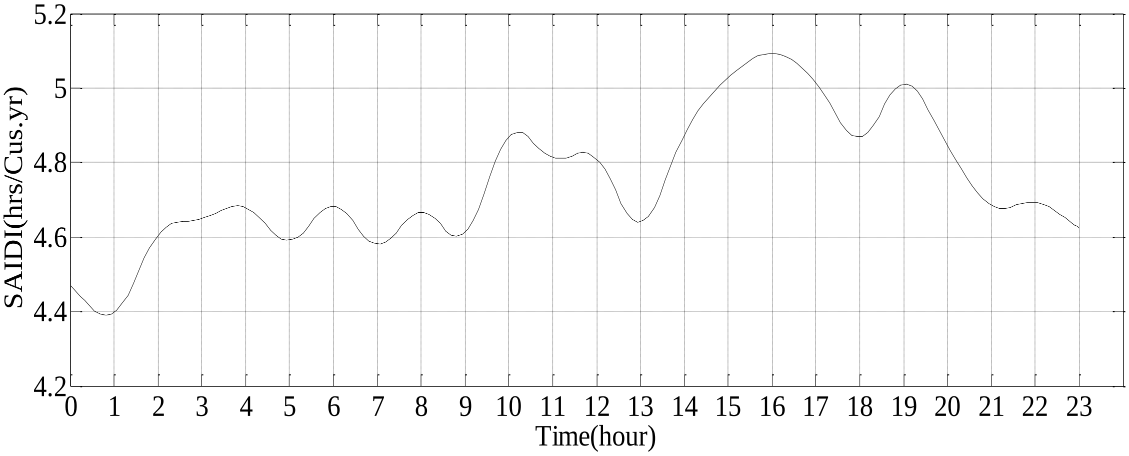

Figure 2-9 SAIDI considering 24-h electricity prices

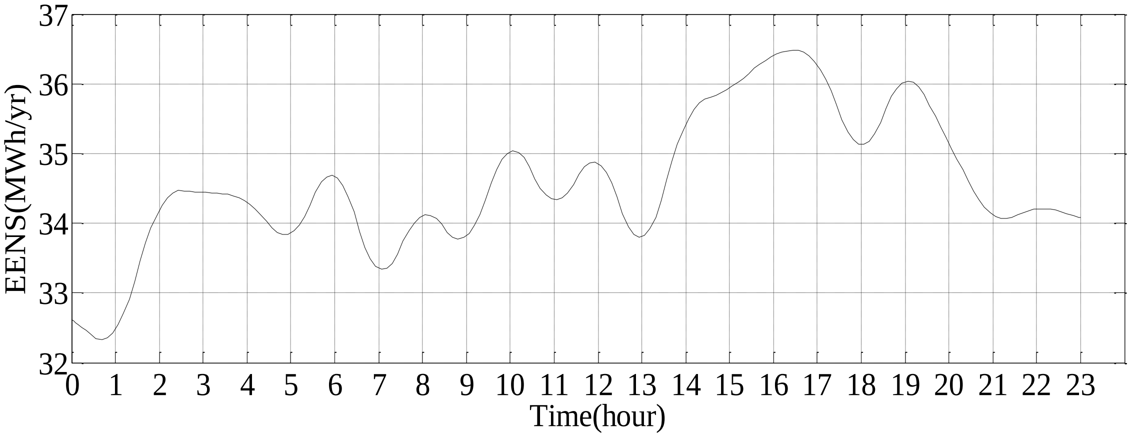

Figure 2-10 EENS considering 24-h electricity prices

From Figure 2-8 to Figure 2-10, it is obvious that the SAIFI, SAIDI and EENS values decrease (or increase) when the electricity price decreases (or increases). This is because when the price decreases (or increases) the battery will be charged (or discharged) correspondingly. The average daily cost of the whole power system is 18,565 dollars/day.

2.5Conclusions

This chapter studies the reliability evaluation of distribution system with the consideration of energy storage and RTP. Monte Carlo Simulation and GCOT approach are applied for the test system. The simulation results show that the reliability indices of the distribution system could be improved significantly with the increase of energy storage capacity. Furthermore, the 24-h electricity price impact is reflected by the variation of reliability indices. The electricity cost of the power system is also calculated.

Chapter 3 Reliability Evaluation of WWTP Electrical Supply System Considering Open-Loop Transmission Line

3.1 Introduction

In United States, the wastewater industry is a major segment of energy consumption. According to the report from ERPI, Water & Sustainability, in 2000, nearly 123 billion kWh were used to transport and treat wastewater, which is almost 3.5% of all U.S. end user electricity consumption [22].

To have a better understanding of wastewater industry, first, the definition of wastewater facilities should be clarified: public wastewater treatment facilities, it means the municipal wastewater facilities and other treatment plants serving the public. Private wastewater treatment facilities, it means the private owned facilities which deals with the wastewater from isolated industrial and commercial sources.

In fact, the reliability conception was put forward by Environment Protection Agency (EPA) in a very early stage. In 1974, EPA published a reliability assessment report in terms of the mechanical and electrical systems in wastewater facilities. In this report, the reliability assessment indices of wastewater treatment plant are categorized into three types [23]:

First type: the wastewater treatment discharges to nearby water that will be permanently polluted by effluent that could be degraded in quality for a short term.

Second type: the wastewater treatment discharges the short-term effluent to nearby rivers which would not pollute or do damage to the environment permanently by its degradation but the rives could be ruined by continuous effluent quality degradation.

Third type: The wastewater treatment plant cannot be categorized into first or second type.

Generally speaking, the power supply for first type wastewater treatment is capable to provide electricity for the essential process components during peak hours and severe condition. A typical two wastewater treatment facility is pretty same as type one, only the essential components for secondary processes is not required as long as equivalent to sedimentation and disinfection is supplied.

Different from first type and second type, a typical type three wastewater treatment plant needs to be capable to operate the screening and shredding processes, wastewater pumps and, sedimentation basins and disinfection during peak hours considering the lighting and ventilation. Typically, two separate power sources will be supplied to the plant. This could also be achieved by taking two separate primary feeders as the electricity source.

Furthermore, according to this report, the power supply system configurations are also classified into three types: primary selective, secondary selective and radial feeder system.

Primary selective system: The primary selective type generally is consisted by two main feeders, they are connected to the main bus bar. Both of two main feeders are supported by the electricity utility company, such as We Energies, SCE and so on. Then the bus bar connects to the subfeeder and distributes the power to each load points.

Secondary selective system: The schematic of this configuration has two bus bars, unlike the primary selective system, each of the bus bar is responsible for 50% load demand. Once a feeder is out of working status, the rest one will take care of the whole load demand.

Radial feeder system: In a typical radial feeder system, only a single feeder is provided to the switch that changes power supply between source or back-up generator.

In fact, each system has its own benefits and drawbacks. So, choosing the most suitable and reliable system should consider many aspects, including the capital budget, construction time, present system condition and available resources, etc.

Another problem is the complexity of the wastewater, according to the [24], the types of wastewater could be summarized as Table 3-1.

Table 3-1 Wastewater Types

Wastewater from society	Wastewater generated within WWTP
Domestic wastewater	Thickener supernatant
Wastewater from institutions	Digester supernatant
Industrial wastewater	Reject water from sludge drying beds
Infiltration into sewers	Drainage water from sludge drying beds
Storm water	Filter wash water
Leachate	Equipment cleaning water
Septic tank wastewater	

From Table 3-1, it is obvious that there are many different types of wastewater. To fully treat the different types of wastewater, the treatment procedures and the reliability of electrical supply systems are two essential parts for ensuring the effluent qualities. Based on [18], the different part of the treatment procedure, their electricity demand also varies. The most significant electricity consumption part is the aeration part. It is also most suitable for applying demand response mechanism.

In the past, the electrical supply system of WWTP was only evaluated in a deterministic way, while the probabilistic evaluation still remains as an intractable issue. At the same time, the related studies on this area are also limited. A probabilistic reliability evaluation of WWTP electrical supply system considering the IPMCC model is studied in this chapter. This approach is developed to be capable to get some useful reliability indices for the system operator. Different from the power electric systems, the reliability indices of WWTP electrical supply system is customer-based but not the load-based.

3.1.1 WWTP Electrical Supply System Characteristics

As everyone knows, the water is one of the most precious resource in our earth. With the rapid industrial development, the water pollution is also unavoidable in this process. In such circumstance, the wastewater facility plays an essential role in securing the safety of the water. The WWTP must treat the water under a strict and reliable standard, and supply the water suitable for industrial and human-being consumption.

To cope with this severe situation, one of the knotty challenges is the reliability and security of WWTP. The reliable power supply for WWTP is the core for maintaining the clean and safe water.

More specifically, there are five main systems in the wastewater treatment cycle [25]:

- System one: pump station system, it includes the pumps and motors. The main functionality of this system is to transport the wastewater into the tree treatment procedures (primary, secondary and tertiary).
- System two: process automation system, it includes the process control system, network communication and SCADA. This system is the main process part of the WWTP which is responsible of treatment the wastewater.
- System three: storage station system, which takes charge of sediment process and storing the redundant wastewater cannot be treated immediately.
- System four: data system, it is designed for monitoring and collecting the real-time data during the wastewater processing.
- System five: Remote control system, this system is the control center for WWTP. It will send instruction to the equipment.

3.1.2 WWTP Electrical Supply System Specialized Requirements

In the wastewater industry, different facility has their unique power supply requirements depended on the amount of wastewater needs to be treated, the technology and equipment of treatment, and the type of wastewater needs to be treated.

In general, the power consumption is highly related to the intensity of the wastewater processing and treatment equipment. The wastewater facility places great electricity on aeration and pumping procedures. Either pumping or aeration procedure goes offline because of the power outage, the entire wastewater facility will be influenced or even halted [26].

To have a better estimation of the electricity consumption [27], a typical energy intensity table from medium size WWTP is shown in Table 3-2.

Table 3-2 Estimate of Medium Size WWTP Energy Intensity

	Unit Process	Percentage (%)	Total Percentage (%)
Primary Treatment	Wastewater Pumping	8.4	17.5
	Odor Control	7.8	
	Grit Removal	0.5	
	Primary Clarifier	0.8	
Secondary Treatment	Trickling Filters	19	59.6
	Biological Nutrient Removal	3.5	
	Aeration with Nitrification	34.5	
	Secondary Clarifiers	2.6	
Solid & Sediment Handling	Anaerobic Digestion	3.75	22.9
	Gravity Belt Thickener	0.93	
	Dissolved Air Flotation	6.7	
	Centrifuge Thickening	1.4	
	Centrifuge Dewatering	9.8	

Options available to maintain or control the electricity costs include equipment upgrade, system change, improved management varies from system to system. Choosing appropriate options for the tested system should be determined by the system characteristics [28].

The rest of this chapter is organized as follows: Section 3.2 introduces the background of probabilistic reliability evaluation methodology. Section 3.3 studies the approach of reliability evaluation of WWTP electrical supply system. Section 3.4 shows the case studies and results. Section 3.5 concludes the chapter by discussing the reliability indices results and some future work.

3.2 Reliability Evaluation Background

Although the probabilistic reliability evaluation conception has been widely applied in the power system area [20], it is a relatively new word in the field of wastewater treatment. To conduct the reliability evaluation of the WWTP electrical supply system, some conceptions need to be introduced. First, each component state of the electrical supply system needs to be modeled. In this case, the two-state model is adopted to simulate the component condition. In Figure 3-1, “UP” and “DOWN” status represents the normal and fault condition respectively. These states change with respect to time, and the overall system status is constituted by the state of each component [7].

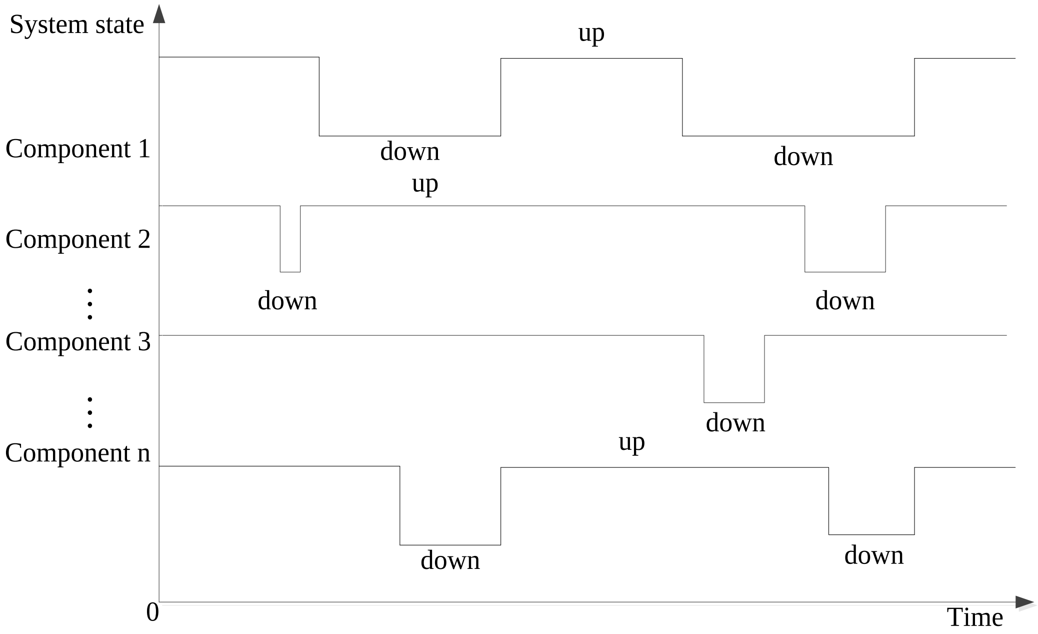

Figure 3-1 Component state transition process

To simulate the real condition of the WWTP electrical supply system, the number of components should be large enough to yield an accurate result. Consequently, a huge state space will be created.

An issue for the original analytical method is its weak ability of dealing with such a huge and complicated system. So, the probabilistic method is more suitable for reliability analysis. In the power system area, the Monte Carlo Simulation (MCS) method is widely used for the reliability evaluation process. Similarly, it could be utilized for reliability evaluation of WWTP electrical supply system.

In the sequential MCS, the time to failure (TTF) and time to repair (TTR) will be randomly generated to determine the status of each component. The equations of TTF and TTR can be derived as chapter 2 introduced.

Before conducting the system reliability calculation, the repair time of the failed component needs to be determined. Here are the three scenarios：

In the first scenario, the failed component is located in the main feeder, and the subfeeder is connected to the open-loop transmission line. The failure can be fixed by switching the open-loop transmission line.

In the second scenario, the failed component is located in the main feeder, and the subfeeder is not connected to the open-loop line. The failure cannot be fixed by switching the open-loop transmission line.

In the third scenario, the component is located in the subfeeder. The failure cannot be fixed by switching the open-loop transmission line.

The whole system reliability indices are calculated when any stopping criterion is satisfied. The whole reliability evaluation procedure can be summarized as shown in Figure 3-2.

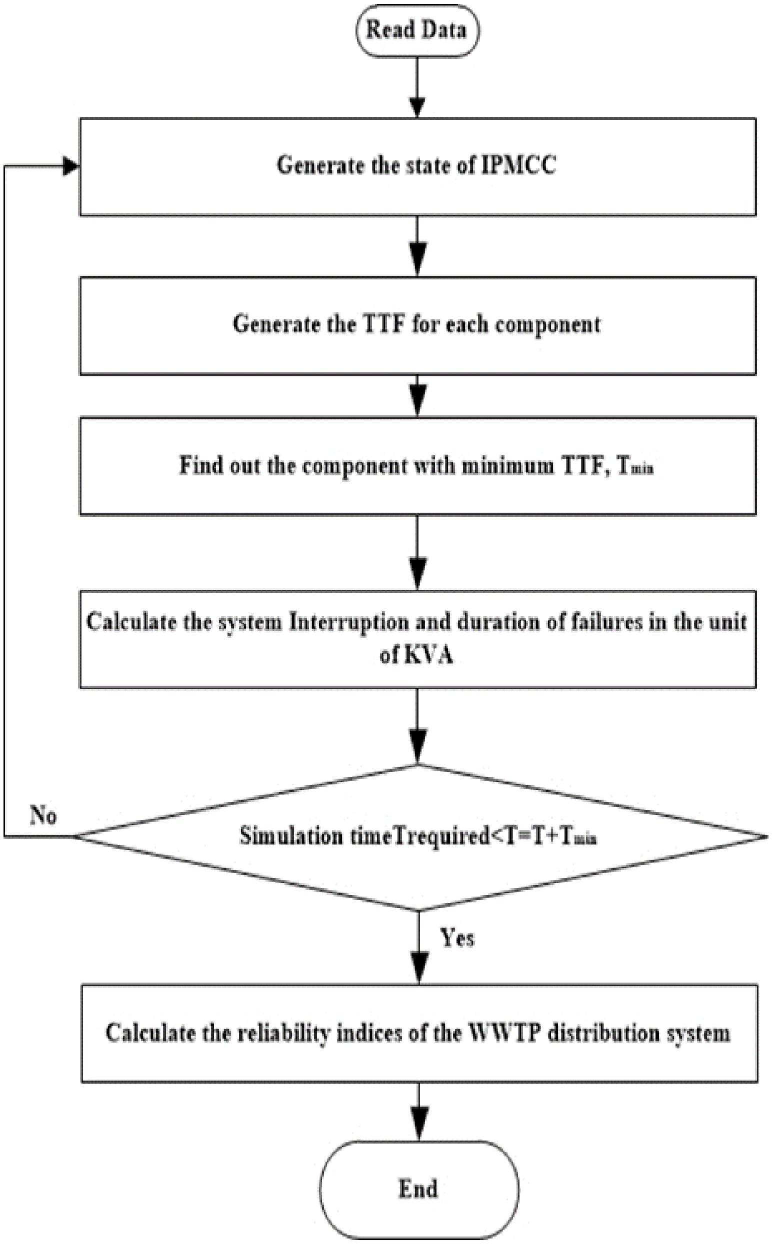

Figure 3-2 Flow chart of MCS based reliability evaluation

3.3 System Modeling and Methodology of WWTP Electrical Supply System

In this chapter, the reliability indices of WWTP are calculated considering the open-loop transmission line. The IPMCC system and load-based reliability indices are discussed as follows.

A. IPMCC System

The IPMCC is a system that integrates Intelligent Motor Protection Relays (IMPR) into a reliable Power Control Center (PCC) and Motor Control Center (MCC) switchboard, while communicating with plant control systems through an industrial communication networks [29].

Compared with the traditional protection devices, the IPMCC has many advantages in not only the reliability aspect but also the operation and design aspects. More specifically, the IPMCC could improve the efficiency of the entire project due to the higher standardized starter utilized in the IPMCC. It could also reduce the wiring time and set-up time thanks for the highly-centralized modeling and design.

Once the IPMCC system is installed, there are also many benefits for the end user as the following list [30]:

- Improve the duration time of reliable service, the holistic treatment process is enhanced due to a better protection of the motors and loads. The IPMCC system uses high-precision sensors which can acquire more accurate data.
- Improve the management system efficiency, the installed alarm will give timely warning for fixing problem before tripping happens. Meanwhile, all the data of protective infrastructure will be recorded.
- Save the operation cost, the energy consumption is lower than the traditional protection device.

- Reduce the maintenance fee, as introduced previously, the compact and integrated design of IPMCC makes the downtime is less and the problem fixing is much quicker than the traditional design.
- Reduce the upgrade time and cost, since the IPMCC could be upgraded as an integral system, so the operator does not have to identify the specific part needs to be upgrade or not.

After the comparison between different commercialized IPMCC products [31] - [33], a generalized IPMCC topology model is illustrated in Figure 3-3.

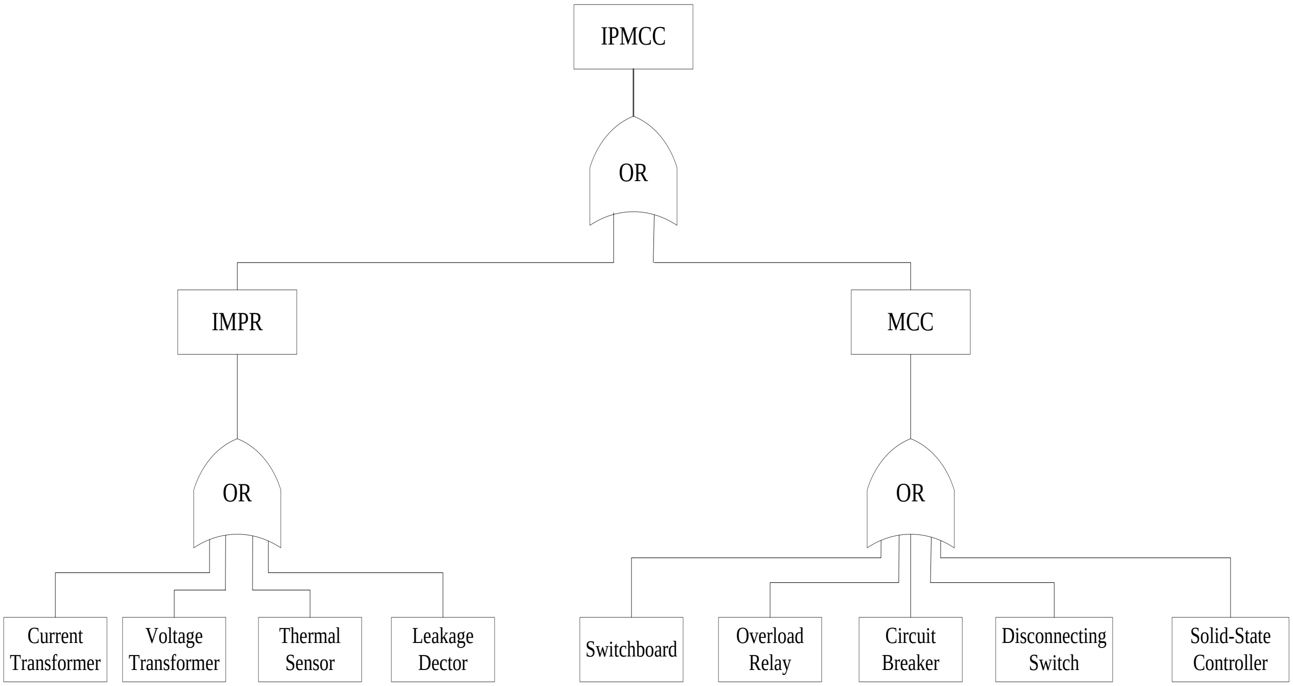

Figure 3-3 IPMCC Topology Structure

Based on the topology structure of IPMCC, the failure of any singular component will result in the failure of the whole IPMCC system. The equivalent failure rate λ_{IPMCC}, repair time r_{IPMCC} are derived from the following equations:

$$\lambda_{IPMCC} = \lambda_{IMPR} + \lambda_{MCC} \tag{3.1}$$

$$\lambda_{IMPR} = \sum \lambda_{i_{MPR}} \tag{3.2}$$

$$\lambda_{MCC} = \sum \lambda_{i_{MCC}} \tag{3.3}$$

$$r_{IPMCC} = \frac{\sum \lambda_{i_{MPR}} r_{i_{MPR}} + \sum \lambda_{i_{MCC}} r_{i_{MCC}}}{\lambda_{IPMCC}} \tag{3.4}$$

where $\lambda_{IMPR}\ and\ \lambda_{MCC}$ is the failure rate of IMPR and MCC, respectively. $\lambda_{i_{MPR}}\ and\ \lambda_{i_{MCC}}$ is the failure rate of the component within the IMPR and MCC, respectively. Similarly, $r_{i_{MPR}}$ and $r_{i_{MCC}}$ is the repair time of the component within the IMPR and MCC, respectively.

B. Reliability Indices Analysis

The WWTP electrical supply system differs from the conventional power distribution system, for which the customer-based reliability indices are utilized, as introduced in chapter 2. Since the customer number of WWTP cannot be simply determined by the resident number within this area, the load-based reliability indices are more suitable for WWTP.

There are two indices within the load-based reliability system. The following equations are utilized [34]:

Average System Interruption Frequency Index (ASIFI):

$$\text{ASIFI}=\frac{Connected\ KVA\ Interrupted}{Total\ Connected\ KVA\ Served} \quad \text{Int./KVA.yr} \tag{3.5}$$

$$\text{ASIDI}=\frac{Connected\ KVA\ Hours\ Interrupted}{Total\ Connected\ KVA\ Served}\quad \text{hrs/Cus.yr} \tag{3.6}$$

In terms of the WWTP, using ASIFI and ASIDI could represent better measures of the reliability than the SAIFI and SAIDI. Larger KVA corresponds to higher revenue and it should be considered when doing the investment decisions.

3.4 Case Study Analysis

Case studies are conducted on two WWTP electrical supply system. Firstly, the reliability indices are calculated without considering the open-loop transmission line. Secondly, the open-loop transmission line is considered and the reliability is recalculated. In the end, system incorporating the back-up thermal generator will be evaluated.

A. System Without Open-loop Transmission Line

Figure 3-4 is the schematic diagram of the WWTP electrical supply system without open-loop transmission line. The system parameters could be checked in the Table 3-3 which is originally from the RBTS system [11] and the Schneider Electric user manual [35]. The components in this electrical supply system could be further categorized, including: transformers, transmission lines, breakers, power outlets, fuse, generators, busbars.

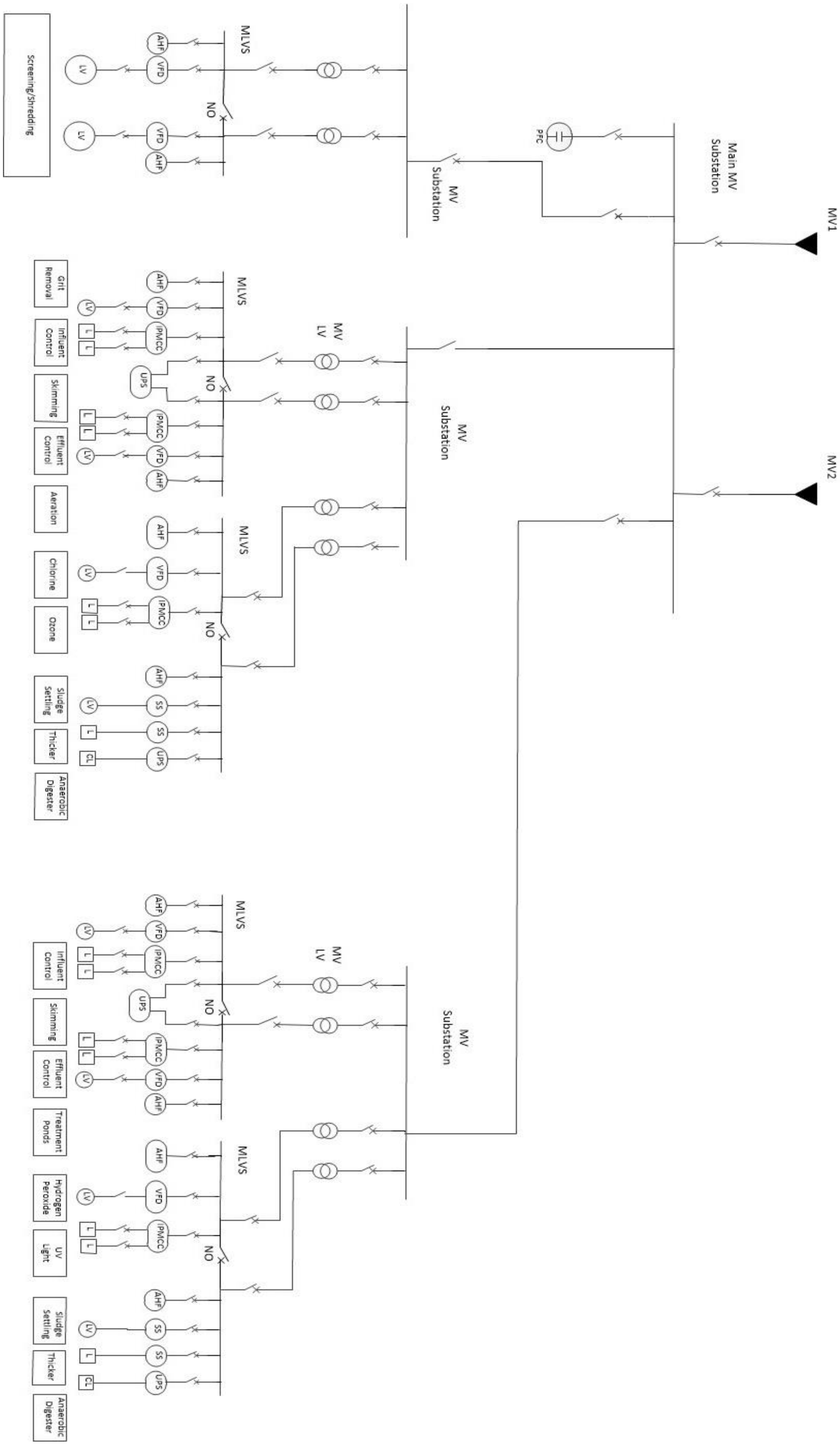

Figure 3-4 WWTP Electrical Supply System without Open-loop Transmission Line

Table 3-3 System Parameters

Parameter	Value
Total load demand	15.73 MW
Total length of transmission line	18.75 km
Transformer failure rate	1.71e-10 failure/hr
Transformer repair time	15 hr
Breaker failure rate	1.45e-11 failure/hr
Breaker repair time	4 hr
Transmission line failure rate/km	7.42 e-6 failure /hr
Transmission line repair time	5 hr
UPS failure rate	2.3e-17 failure/hr
UPS repair time	2 hr
LVS failure rate	1.14e-6 failure/hr
LVS repair time	1.5 hr
SS failure rate	1.14e-7 failure/hr
SS repair time	0.5 hr
AHF failure rate	9.1e-7 failure/hr
AHF repair time	1.2 hr

B. System Without Open-Loop Transmission Line

The Figure 3-5 shows the topology structure of WWTP electrical supply system considering the open-loop transmission line. A 2km transmission line is added between the second MV substation and the third substation. Intuitively speaking, some component failures along the main feeder could be eliminated by switching the open loop transmission line. But when the failure is caused by the failed component within the subfeeder, it may not be eliminated by switching the transmission line since the path source to the load point cannot be fixed.

The load demand of the WWTP is determined by the wastewater flow capacity, table 3-4 is the design flow capacity of a medium size WWTP.

Table 3-4 Design Flow Capacity

Design Flow	Average Day(MGD)
JIWWTP	123
SSWWTP	113
Total	236

C. System with Open-Loop Transmission Line & Back-up Thermal Generator

With the integration of transmission line, the system reliability is enhanced by mitigating some failure scenarios. To further improve the reliability indices of the electrical supply system, the back-up thermal generators could be integrated. Each of the thermal generator is connected MV substation respectively. The schematic is shown as Figure 3-6. Considering the total load demand of the system, different size of the thermal generator is tested, and the result is listed in the Table 3-5.

Table 3-5 System Reliability Indices

Reliability Indices	ASIFI (Int./KVA.yr)	ASIDI(hrs/Cus.yr)
Without Thermal Generator & Transmission Line	0.1974	0.9250
Without Thermal Generator	0.0114	0.0267
With 0.1MW Thermal Generator	0.0109	0.0233
With 0.5MW Thermal Generator	0.00624	0.0148
With 1MW Thermal Generator	0.00611	0.0139
With 5MW Thermal Generator	0.00532	0.0117
With 10MW Thermal Generator	0.00488	0.0106
With 20MW Thermal Generator	0.00488	0.0106

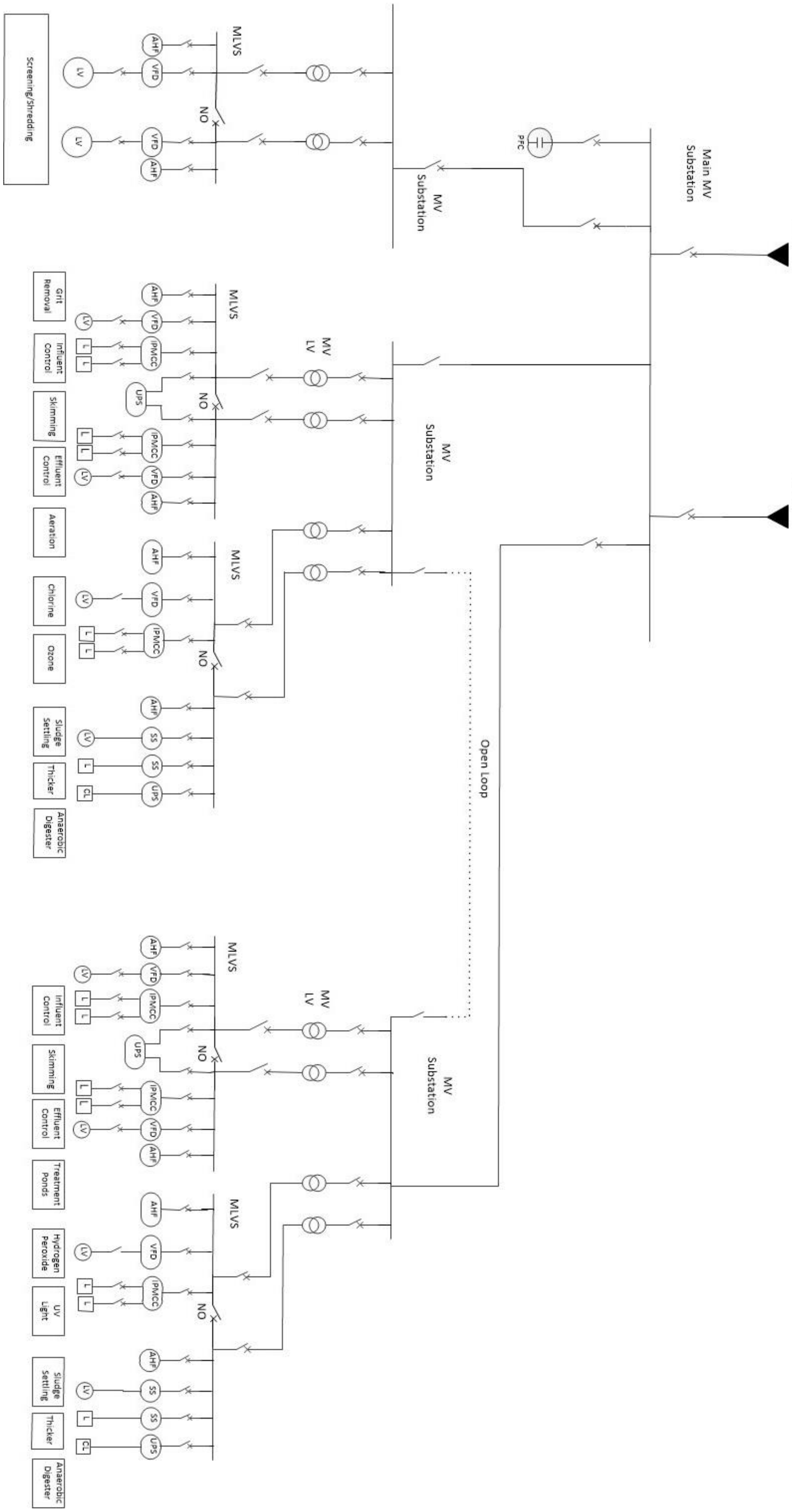

Figure 3-5 WWTP Electrical Supply System with Open-loop Transmission Line

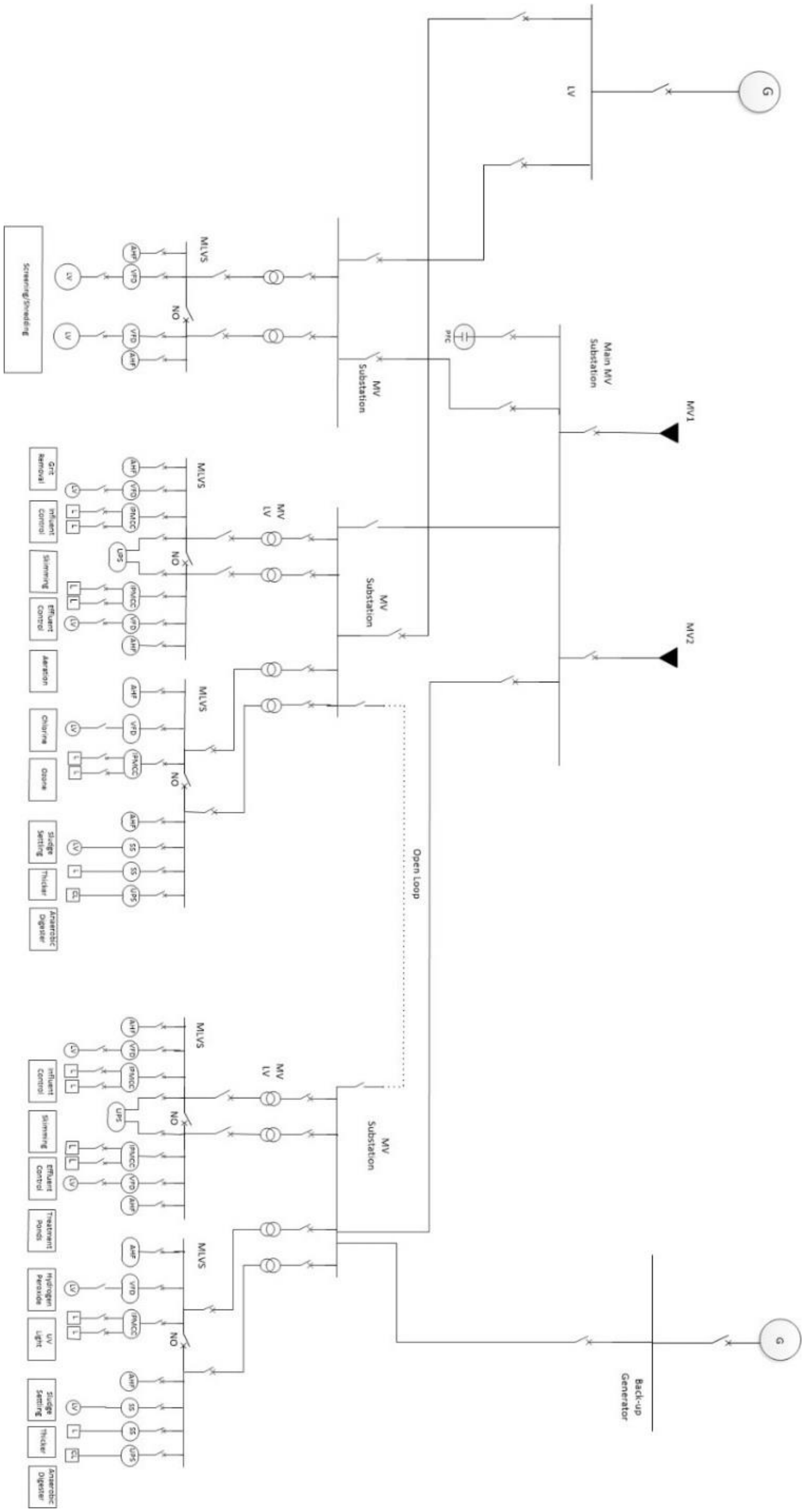

Figure 3-6 WWTP Electrical Supply System with Open-loop Transmission Line & Back-up Thermal Generator

D. Result Analysis

WWTP electrical supply system reliability indices with respect to the integration of transmission line and back-up thermal generator are calculated as shown in Table 3-4. By comparing the results of different scenarios, after incorporating the open-loop transmission line, the ASIFI and ASIDI are reduced dramatically due to the existence of transmission line. Moreover, the reliability of the system could be further improved by incorporating the back-up thermal generator. With the increase of the size of the generator, the ASIFI and ASIDI decreases correspondingly. But the total load demand is 15.73MW. So, when the size of the thermal generator is larger than the load demand, the reliability indices could not be further improved. The Figure 3-7 and Figure 3-8 show the convergence of the ASIFI and ASIDI.

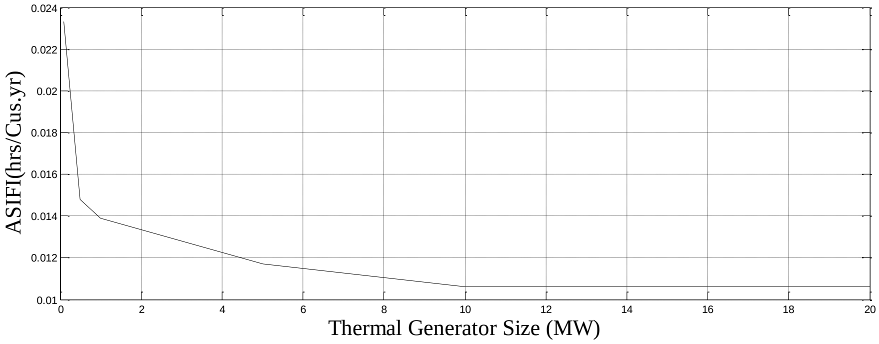

Figure 3-7 ASIFI values with different thermal generator size

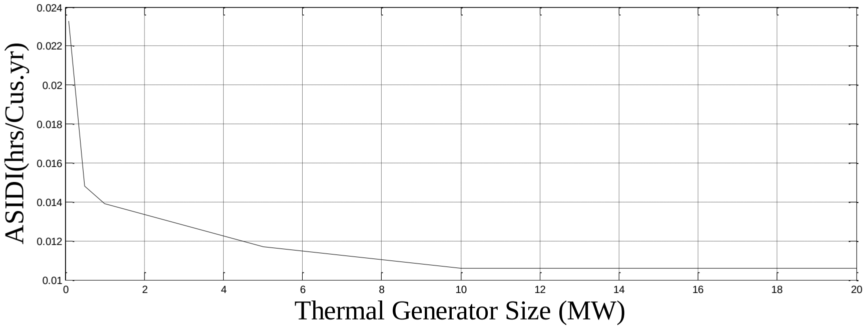

Figure 3-8 ASIDI values with different thermal generator size

3.5 Conclusions

This chapter studies the reliability evaluation of WWTP electrical supply system with the consideration of open-loop transmission line and back-up thermal generator. Monte Carlo Simulation and IPMCC model are applied for the test system. The simulation results show that the reliability indices of the electrical supply system could be improved significantly with the integration of the transmission line. For the future work, the results should be refined since the IPMCC is simplified in the program file. Meanwhile, the convergence of the program is also not good, so further debugging is also needed.

Chapter 4 Comparison, Conclusions and Future Work

As discussed in the previous chapters, the reliability evaluation could be conducted on both active distribution system and the WWTP electrical supply system. To further clarify the characteristics of these two different systems, some comparisons and studies will be shown in this chapter. In addition, the future work of this thesis and conclusion will also be presented.

4.1 Similarities between Reliability Analysis of the Active Distribution System and the WWTP Electrical Supply System

The main reason that the MCS approach could be effective in both the active distribution system and WWTP electrical supply system is that they do share some inherent similarities in system modeling and the reliability methodology.

In power system field, the conception of reliability evaluation is put forward in very early stage. In [36], the reliability evaluation theory is fully discussed considering many potential factors. The entire electric power system, including generation, transmission and distribution system could not be evaluated simultaneously because of the complexity. A three hierarchical levels (HL) is defined to divide these different systems. In terms of the distribution system, it belongs to the HL III which includes the generation, transmission and distribution networks. But doing the evaluation of HL III system is quite difficult due to the system complexity. Generally, the distribution system will be analyzed separately in the assumption that adequate power supply will be fulfilled at the main feeder and bus bar. With these rational assumptions, the reliability indices, including SAIFI, SAIDI, EENS, CAIDI could be calculated correspondingly. In WWTP electrical supply system, through the WWTP has a complicated mechanism of treating the wastewater. But in terms of the WWTP electrical supply system, the basic components and system structure are similar. The electrical supply system could also be evaluated by using the MCS approach.

4.2 Differences between Reliability Analysis of the Active Distribution System and WWTP Electrical Supply System

The major difference between the active distribution system and WWTP electrical supply system are reliability indices. For active distribution system, it is connected to the end user and customer-based reliability indices are more suitable. According to [37], the customer-based indices are prevalent with regulating authorities since a small residential customer is as important as a large industrial customer. Although it has its own limitation, but it is still considered as the best measurements of system reliability in power system area. While in the WWTP electrical supply system, the reliability indices are load-based but not customer-based. The size of WWTP or the ability of treating wastewater is not directly related the number of customer they served. For instance, for some industrial cities, they may have a lot of wastewater need to be treated but their population number is relative small. On the contract, for some tourist cities, like Hawaii and San Francisco, the situation may be just the reverse. So, the load-based reliability indices could have more accurate and comprehensive estimation of the WWTP electrical supply system reliability.

On the other hand, the operation strategies and targets are also quite different. For WWTP, one operational strategy is dealing with the trade-off between the treatment results and operation cost [38]. For instance, to achieve a low BOD, ammonium nitrogen may require much more electricity for the aeration and other related equipment [39]. Furthermore, according to the wastewater treatment manuals edited by EPA [40], the primary, secondary and tertiary treatment procedures could be simplified based on the operation cost requirement. While in the power system, the electricity reliability should be first fulfilled then the economical aspect will be considered.

4.3 Conclusions

In this thesis, first, the active distribution system considering energy storage and real-time electricity pricing and WWTP electrical supply system are evaluated by using the probabilistic methodology. The system modeling and case studies are well discussed in chapter 2 and chapter 3. The comparison between active distribution system and WWTP electrical supply system are also conducted in chapter 4.

Nowadays, with the integration of renewable resources and technologies into the distribution system, the conventional analytical method and evaluation approach may not be suitable anymore. In this thesis, the reliability evaluation of active distribution systems is studied by utilizing the Monte Carlo Simulation and GCOT approaches. The simulation results show that the reliability indices of the distribution system could be improved significantly with the increase of energy storage capacity. Furthermore, the 24-h electricity price impact is reflected by the variation of reliability indices. The electricity cost of the power system is also calculated.

In terms of the wastewater treatment utility, the ability of treating the wastewater is highly determined by the WWTP electrical supply system. If the WWTP electrical supply system cannot maintain a safe and reliable working status, there is a high probability that the entire WWTP will be failed. But nowadays the reliability evaluation of WWTP is only focus on the mechanical failures, including pipes, pumps, tanks and other equipment. While the function of WWTP electrical supply system is underestimated. In this thesis, the holistic WWTP electrical supply systems are well evaluated in different scenarios. The load-based reliability indices are also calculated which may help the operator make decision.

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