

PROBABILISTIC RELIABILITY ANALYSIS OF ELECTRIC POWER SYSTEMS WITH
SMART GRID TECHNOLOGIES AND WATER DISTRIBUTION NETWORKS:
MODELING, ASSESSMENT, AND COMPARISON

by

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ABSTRACT
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With the rapid growth of population, the modern human society is becoming more and more dependent on the proper operation of critical infrastructures - the interconnected electrical power system, the drinking water distribution and supply system, the natural gas transmission and distribution system, and so forth. It has become an important issue to maintain reliable functions of these critical systems. As a result, comprehensive reliability evaluation is highly needed to quantify their reliability in an objective manner. Conventionally, deterministic criteria were used in reliability evaluations. However, it lacked the ability to model and quantify the stochastic nature of system behaviors such as component failures. In light of these facts, this thesis deploys probabilistic methodologies for conducting quantitative reliability modeling and assessment for nation's critical infrastructures including electrical power networks incorporating smart grid technologies and water distribution networks.

Power system operators are faced with the increasingly complicated operating conditions in bulk power systems. Yet due to the huge investment needed to build new power delivery facilities, cost-effective solutions such as new operational strategies are becoming more attractive and viable in recent years. Optimal transmission switching (OTS) and dynamic thermal rating (DTR)

are two such technologies which offer a potential solution to improving the power system reliability by more fully utilizing the existing power delivery assets. In this thesis, these two technologies are first discussed, which are then incorporated into the power system reliability evaluation procedure. Case studies are conducted on modified RTS-79 and RTS-96 systems using MATLAB and IBM CPLEX. The obtained simulation results have shown that with the enforcement of either OTS or DTR technology, the overall system reliability can be improved, and system reliability can be further improved if both technologies are enforced.

The growing urban population has brought great stress to the aging drinking water distribution systems. It is becoming more challenging to maintain a reliable drinking water distribution system so as to meet the growing water demand. Thus, a comprehensive reliability evaluation of the aging water delivery infrastructure is of critical importance to enable informed decision-making in asset management of the potable water sector. This thesis also proposes a probabilistic reliability evaluation methodology for water distribution systems based on Monte Carlo simulation (MCS) that takes into account both mechanical failures and hydraulic failures. Additionally, a C++ based software tool is developed to implement the proposed method. Case studies based on two representative water distribution systems are performed to demonstrate the effectiveness of the proposed method.

A comparison is made between the reliability analysis of electrical power systems and that of water distribution systems. As interconnected capacitated networks, both systems share similarities in certain aspects such as component modeling and adequacy constraints. However, the specific features of the target systems should also be taken into consideration in the reliability

modeling and evaluation in order to obtain a more comprehensive and accurate estimation of the actual system reliability.

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Chapter 1 Introduction

1.1 Research Background

The modern human society is highly dependent on the reliable operations of critical infrastructures including electrical power systems, drinking water distribution systems, sewage and drainage systems, natural gas transmission and distribution systems, and so forth. These complex systems serve as fundamental infrastructures to support our daily lives. Failures or malfunctions of these systems could cause severe problems such as economic loss, public health crisis or even big panic, riots and human deaths.

On August 14, 2003, northeastern America experienced a catastrophic wide-area blackout. It is reported during nearly a week the blackout affected approximately 50 million people in areas of about 61,800 MW electrical load [1]. The associated economic cost was estimated to be between \$4.5 and \$8.2 billion in US [2], while gross domestic product (GDP) of the month of August in Canada was estimated to be down by 0.7% [1].

On July 30, 2012, India experienced two severe power blackouts which were believed to be the largest in the history. The blackouts hit 20 of 28 India's states, and nearly 600 million people, namely nearly half of the India's population or 9% of the world population at that time, were left without power supply [3]. Hospitals stopped operating, transportation lost traffic control, and protests with riots took place in many places [4].

In 2001, North Battleford in Canada experienced a drinking water crisis during which approximately 14,000 people were affected [5]. This outbreak has also been believed to be the

cause of 5,800 to 7,100 reported diarrheal illness cases at that time [6].

More recently in January 2016, a water crisis took place in Flint, Michigan when this city chose to switch the main drinking water source from Lake Huron and Detroit River to Flint River since April 2014. Corrosive water in Flint River impaired old aging pipelines in the local drinking water system, releasing lead contamination in the water supply which caused severe damages to public health and finally led to a designated state of emergency for Genesee County. As one of the results, it was reported later that in groups of children in Flint, the blood-lead levels were found to rise from about 2.5% to as high as 5% [7].

List of incidents related to these critical infrastructures is still growing, and all these tragedies have led to one truth: it is becoming more critical and urgent to improve the reliability of these critical infrastructures. However, in view of the fact that most of these infrastructures are large-scale interconnected networks, it is commonly believed to be unrealistic to mathematically model all aspects of these systems. Conventionally deterministic reliability criteria are adopted for the reliability evaluation of many systems. For example, in electric power systems, the $N-1$ or $N-z$ criteria, which requires the whole power system to perform its full functionality to deliver electricity with the demanded amount and quality in the presence of one or z component failures, has long been used as the reliability criteria in practical system designs, planning, and operations [8]. Similarly in drinking water distribution system, traditionally the system is designed to be, if not completely reliable, highly dependable with deterministic reliability design guidelines – e.g., each demand point must be supplied by at least two supply paths or the system should maintain its reliable operation with no more than one pump failure [9]. Research about the similar concept – availability can also be found in [10, 11]. However, in real systems the reliability characteristics

of typical components, such as the widely used parameters - mean time to failures (MTTF) and mean time to repairs (MTTR), are mostly stochastic. Deterministic criteria fail to account for these stochastic characteristics, and therefore probabilistic reliability evaluation methodologies are preferred in order to more comprehensively evaluate the reliability performance of critical systems or infrastructures with high uncertainties.

In light of these considerations, this thesis adopts the probabilistic methodology to perform reliability evaluation for both electric power systems incorporating the emerging smart grid technologies and drinking water distribution systems.

1.2 Introduction to Reliability Analysis of Electric Power Systems Incorporating Cost-effective Smart Grid Technologies

With the increasing uncertainties due to renewable energy resources integration, system load uncertainties, volatile weather conditions, and so forth, electric utilities are faced with an increasingly complex and uncertain environment for system planning and operations. In order to maintain the desired power system reliability while making the operation more economical, power utilities are in an urgent need of cost-effective technologies for power delivery network enhancement. While these technologies are usually considered to be too difficult to be implemented in practices in the past, recently with the rapid development of smart power grid, they are becoming more and more realistic. Several such technologies are being actively investigated in the recent years, including optimal transmission switching (OTS) [12], dynamic thermal rating (DTR) [13], network topology optimization (NTO) [14], and so forth.

1.2.1 Dynamic Thermal Rating

Conventionally in the power system operation, overhead line (OHL) ratings are considered as static quantities which are calculated in a conservative assumed condition [15, 16]. However, in fact real ratings of OHLs are affected by the actual weather conditions. It has been reported that line ratings could increase by 10% to 30% when they are calculated accounting for real weather conditions. In some windy areas, this increase may even be as high as 50% [17]. Thus the DTR technology has been deployed to calculate actual ratings of overhead lines in terms of transmission line conductor thermal limitations based on real-time weather and conductor conditions. Various research and field tests have already been conducted to analyze the potential benefits brought by the DTR technology.

In early research related to DTR [18-21], algorithms for calculating the dynamic thermal rating of OHLs are studied and examined. Field tests and simulations have proven the potential benefit of deploying DTR and associated issues on implementing DTR in real systems are also discussed.

In [22] a practical case for DTR deployment in a UK distribution system is discussed. The DTR prototype system is deployed over 90 km of 132 kV OHLs and serves as long-term operating strategies.

In [15] a comparison between the current application of DTR in UK and US is made. The existing networks, climates, load patterns and adopted standards for both of these countries are discussed in detail, which provides very useful information on implementing DTR in practice.

In [23] the potential reliability benefit brought by both OHL and underground cable DTR in a distribution system was investigated. The result not only shows the significant reliability improvement brought by DTR, but also proves the fact that DTR enforcement on OHLs has a greater impact than underground cables.

In [16], the economic benefits brought by enforcing DTR on a certain power system with integrations of wind power was studied. The result shows that with the enforcement of DTR, more wind power generation can be implemented and a great economic benefits can be brought with the enforcement of DTR.

Furthermore in [17] the reliability performance of DTR enforced system with wind farms integrated was examined. The simulation has been conducted on the IEEE 24-bus reliability test network consisting of 21 DTR systems and 3 integrated wind farms. And the result shows that a higher reliability along with a greater amount of wind power delivery can be achieved.

However, while the effect of DTR and other smart grid technologies on the overall system reliability remains a compelling research topic, most existing literature showed only the impact of DTR. So far, very limited studies have been performed to investigate the potential benefits and issues when DTR and other smart grid technologies are deployed simultaneously in a power system. Thus it remains as a very interesting, open research topic.

1.2.2 Optimal Transmission Switching

In traditional power system operations, generating units are dispatched to minimize the total operating cost. During system operations, transmission networks are usually treated as static

topologies. Yet in fact, the topologies of these transmission networks could be adjusted by the system operator in a short time period, based on this consideration OTS was proposed in order to solve challenging problems. In [24], the mechanism of OTS was first introduced. Other goals of deploying OTS have also been studied for reducing the cost/loss [25] and cutting costs while satisfying the N-1 standard [26]. In [12], OTS was first formulated as a mixed integer programming problem to optimize the dispatch cost with DC optimal power flow (DCOPF) analysis, and in [27] OTS was extended to a multi-objective (MO) optimization problem for both minimizing generating cost and improving system reliability. The existing literature has indicated the significant benefits that OTS can bring to the power system. Nevertheless, the integration of OTS and other cost-effective technologies such as DTR have not been fully explored.

1.3 Introduction to Reliability Analysis of Water Distribution Networks

Water is one of the most precious resources on earth, and the drinking water distribution system is one of the most critical infrastructures for supporting human lives. Also, drinking water systems in urban areas are faced with the increasing pressure of meeting the growing demand. It has been reported in [24, 28] that by the year of 2025, most countries in the world will experience serious problems of water supply shortage. A drinking water distribution system is a complex interconnected system consisting of one or several water sources and a number of pipelines, valves, reservoirs, tanks, pumps, and other components. A normal drinking water distribution system should have the ability to fulfill the demands of all nodes within the service area with the required pressure and desired water quality. One or more failed components may impair such ability or even interrupt the water supply to some areas, jeopardizing human health and hindering firefighting services, etc. Thus, it is rather urgent to maintain a reliable drinking water system in the presence of various uncertainties. An objective reliability evaluation of drinking water

distribution systems is useful in enabling more informed decision making considering the aging water delivery infrastructure.

However, comprehensive reliability evaluation of a real drinking water distribution system is a challenging task. Conventionally, two types of failures, i.e., mechanical failures and hydraulic failures, are taken into account in water distribution system reliability evaluation [29]. Mechanical failures refer to the system failures due to component failures such as breakage of pipelines or loss of pumps. Hydraulic failures refer to the system failures due to unmet user demands where the customer demands exceed the total water system capacity [29, 30]. To model a possible hydraulic failure, nodal demand variation curves or profiles are required. Typically, to analyze hydraulic failures, a network analysis should be performed to determine all nodal heads and pressures. Several useful software tools have been developed for this purpose such as KYPIPE [31] and EPANET [32]. Various reliability studies have been conducted considering either mechanical failures [33-35] or hydraulic failures [29, 36, 37]. In [38], both mechanical failures and hydraulic failures are taken into consideration, yet the proposed method cannot offer a systematic reliability performance estimation.

1.4 Research Objectives and Thesis Layout

This thesis seeks to develop and perform the probabilistic reliability evaluation method for the power system with smart grid technologies incorporated and the drinking water distribution system. In chapter 2 the model and the methodology for bulk power system reliability analysis incorporating DTR and OTS will be developed. Case studies will be conducted on two test systems to illustrate the effectiveness of the method. In chapter 3 the probabilistic method for reliability evaluation of drinking water distribution system will be presented. The methodology starts from

the reliability modeling of single component and then forms a comprehensive estimation method. A Visual C++ based simulation software tool is developed, based on which case studies are carried out to prove the effectiveness of the method. Then, discussions, conclusions and future work will be presented in chapter 4.

Chapter 2 Bulk Power System Reliability Analysis Considering DTR and OTS Techniques

2.1 Introduction

As previously discussed, smart grid technologies like DTR and OTS could all be potential solutions for optimizing power system operations and improving the overall system reliability. In this chapter the integration of these technologies into the conventional bulk power system reliability evaluation procedure and the effects of OTS and DTR will be studied.

The rest of this chapter is organized as follows. Section of 2.2 gives a brief introduction about the DTR methodology of OHLs. Section of 2.3 discusses model and methodology of OTS. Section of 2.4 presents the proposed reliability evaluation methodology considering OTS and DTR. Section of 2.5 gives the case studies and results. And section of 2.6 draws the conclusion of this chapter.

2.2 Methodology of OHL Dynamic Thermal Rating

Traditional ratings of OHLs are usually calculated in an assumed conservative weather condition where the ambient temperature is 40 °C, wind speed is 0.61m/s and full sun [39]. However, the OHL's rating in practical operations can be increased in some cases, such as when the ambient temperature is lower or the wind speed is higher. Therefore, the dynamic thermal rating (DTR) method can possibly provide the ability to loosen capacity constraints of the transmission network and achieve an improved overall system reliability [13].

Several standards and guidelines have already been developed for deriving line ratings in terms of conductor thermal ratings such as IEEE Standard 738 [39] and the standard stipulated by CIGRE

[40]. Since in the U.S. thermal overhead line ratings are traditionally obtained according to IEEE Standard 738 [39], the DTR model of OHLs in this standard is chosen as the DTR model in this thesis. In IEEE Standard 738, a non-steady-state heat balance equation of the overhead line is represented as follows:

$$Q_c + Q_r + mC_p \frac{dT_{avg}}{dt} = Q_s + I^2 R(T_{avg}) \quad (2.1)$$

$$\frac{dT_{avg}}{dt} = \frac{1}{mC_p} [Q_s + I^2 R(T_{avg}) - (Q_c + Q_r)] \quad (2.2)$$

where Q_c represents the convection heat loss rate, Q_r represents the radiated heat loss rate, mC_p represents the total heat capacity of the conductor, Q_s represents the heat gain from sun, $R(T_{avg})$ is the AC resistance of conductor at a certain average temperature of aluminum strand layers T_{avg} , and I represents the conductor current. It can be seen that in the non-steady-state case, rates of conductors' temperature will increase exponentially with respect to the increase of the ambient temperature.

The calculations of convection heat loss rate are listed as follows:

$$Q_{c1} = K_d [1.01 + 1.35 N_{Re}^{0.52}] K_f (T_s - T_a) \quad (2.3)$$

$$Q_{c2} = 0.754 K_d N_{Re}^{0.6} K_f (T_s - T_a) \quad (2.4)$$

where K_d represents the wind direction factor; N_{Re} represents the dimensionless Reynolds number, which is determined by conductor diameter, wind velocity and air density; K_f thermal conductivity of air at the average temperature of the boundary layer; T_s conductor surface

temperature; T_a represents the ambient temperature. And after calculating Q_{c1} and Q_{c2} , the larger one of the two will be adopted as the value for convection heat loss rate.

The calculation of radiated heat loss rate is listed as follows:

$$Q_r = 17.8D_c\varepsilon\left[\left(\frac{T_s+273}{100}\right)^4 - \left(\frac{T_a+273}{100}\right)^4\right] \quad (2.5)$$

where D_c represents the conductor diameter; and ε is the emissivity factor, representing the surface condition of the conductor.

The calculation of rate of solar heat gain is listed as follows:

$$Q_s = \alpha I_{se} \sin(\theta) A \quad (2.6)$$

where α represents the solar absorptivity factor; I_{se} represents the elevation corrected total solar and sky radiated heat intensity, which is determined by total solar and sky radiated heat intensity and solar altitude correction factor; θ represents the effective angle of incidence of the sun's rays, which is determined by the altitude of sun, azimuth of sun and azimuth of line; A represents the projected area of conductor.

The calculation of conductor electrical resistance at a certain temperature will be estimated using a liner interpolation given as follows:

$$R(T_{avg}) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}} \right] (T_{avg} - T_{low}) + R(T_{low}) \quad (2.7)$$

where $R(T_{high})$ represents a known value of conductor resistance at a high temperature; $R(T_{low})$ represents a known value of conductor resistance at a low temperature. Then conductor resistance

value at a certain average temperature of aluminum strand layers can be calculated using this interpolation.

Typically, for Drake ACSR, 1 hour (in most cases) is sufficient for temperatures of the conductors to reach a steady state value [39]. The heat balance equation can then be expressed as a steady-state form as follows:

$$Q_c + Q_r = Q_s + I^2 R(T_{avg}) \quad (2.8)$$

Then after completing calculations of each heat loss rate and heat gain rate, the actual line rating of OHLs in a certain hour can be expressed as:

$$I = \sqrt{\frac{Q_c + Q_r - Q_s}{R(T_{avg})}} \quad (2.9)$$

In this study, a type of 795 kcmil 26/7 Drake ACSR conductor is chosen for all OHLs in the test system. The normal operating environment of OHLs is assumed to be a weather condition with an ambient temperature of 40 °C, full sun and a wind speed of 0.61m/s. For each hour, the ratio between line ratings calculated using hourly environmental parameters and ratings calculated using normal operating parameters will first be obtained. Then ratings of OHLs in the test system will be modified as the product of this ratio and the original ratings.

2.3 Methodology of Optimal Transmission Switching

As discussed previously, OTS can be seen as a promising technology for enabling more flexible and economical operations of electric power systems. In [12], OTS is formulated as a mixed integer programming problem with the objective for minimizing the total generation cost. In this thesis,

by modifying the objective function for minimizing the total load curtailment, OTS can be accounted for in bulk power system reliability evaluation.

With the goal of minimizing the load curtailment, the OTS problem can be modeled as follows:

$$\min \sum PC_d \quad (2.10)$$

$$\theta_n^{min} \leq \theta_n \leq \theta_n^{max} \quad (2.11)$$

$$PG_g^{min} \leq PG_g \leq PG_g^{max} \quad (2.12)$$

$$-PL_l^{max} \leq PL_l \leq PL_l^{max} \quad (2.13)$$

$$0 \leq PC_d \leq PD_d \quad (2.14)$$

$$\sum_{g \in G_n} PG_g - \sum_{d \in D_n} PD_d + \sum_{d \in D_n} PC_d - \sum_{l \in LF_n} PL_l + \sum_{l \in LT_n} PL_l = 0 \quad (2.15)$$

$$B_l(\theta_n - \theta_m) - PL_l + (1 - z_l)M \geq 0 \quad (2.16)$$

$$B_l(\theta_n - \theta_m) - PL_l - (1 - z_l)M \leq 0 \quad (2.17)$$

$$\sum_l (1 - z_l) \leq M_l \quad (2.18)$$

where PC_d is the load curtailment at load point d ; θ_n is the voltage angle of bus n ; θ_n^{min} and θ_n^{max} is the lower and upper bounds of the angle respectively; PG_g is the active power output of generator

g ; PG_g^{min} and PG_g^{max} are the lower and upper power output bounds for the generator; PL_l is the power flow on line l ; PL_l^{max} is the transmission capability of line l ; PD_d is the load demand at load point d ; G_n is the set of generators at bus n ; D_n is the set of load demands at bus n ; LF_n is the set of lines of which the power flow is defined from bus n to another bus; LT_n is the set of lines of which the power flow is defined from another bus to bus n ; B_l is the electrical susceptance of line l ; z_l is a binary number which indicates the status of line l : if z_l is 0, the line is open, otherwise it is closed; M is a significantly large number [41]; and M_l is the maximum number of lines that are allowed to be switched.

As shown in (2.10), the OTS problem aims to minimize the total load curtailment in the power grid when a contingency occurs. Constraints of this programming problem are listed in expressions (2.11)-(2.18): expressions (2.11)-(2.14) indicate the limitations associated with the bus angle, generation output, power flow, and load curtailment, respectively; equation (2.15) ensures the power flow balance at each bus; expressions (2.16)-(2.17) refer to the power flow of a line, which is affected by the line switching. In expression (2.18) a limitation of maximum number of switchable lines is defined.

Then in the reliability evaluation methodology of this thesis, OTS will be incorporated into the reliability evaluation procedure aiming to further reduce the load curtailment, if such loss of load exists after running an optimal power flow (OPF). For further results analysis, both the reduced load curtailment and the original load curtailment value will be recorded, along with the number of times that OTS actually takes effect.

2.4 Reliability Evaluation Framework Incorporating DTR and OTS

Based on the previous discussions about DTR and OTS, as they both have the potential to improving the power system reliability, utilizing both technologies simultaneously could be more beneficial to increasing the system reliability. Since DTR requires chronological weather data, sequential Monte Carlo simulation (MCS) based reliability evaluation method will be used to tackle the problem.

A typical sequential MCS based reliability evaluation procedure mainly contains the following basic steps [42]. First, component reliability characteristics should be properly modeled, and the related reliability parameters as well as the configuration data of the power system are needed. Then system states will be randomly generated using the sequential MCS method. For each randomly generated system state, an OPF analysis will be then conducted to calculate the amount of load curtailment. And after a sufficient number of system states have been sampled and analyzed, based on the sampled system states coupled with their corresponding curtailed loads, reliability indices such as loss of load probability (*LOLP*), expected demand not supplied (*EDNS*), and expected energy not supplied (*EENS*) can be calculated. These indices represent system reliability from different perspectives.

With DTR being taken into consideration, static line ratings will be modified with hourly weather data, then the configuration data of the system will be changed with chronologically sampled system states thereby. And the OTS technology will take effect after running DCOPF and may affect the curtailed load in step III. For each sampled state, if the load curtailment calculated using DCOPF is larger than that later calculated using OTS, the load curtailment will then be updated with the smaller value and this system state will be marked as “OTS successfully enforced” in such a case.

So the basic procedure of the reliability evaluation considering OTS and DTR can be illustrated as follows:

- Step 1: Model the reliability characteristics of all generating units, transformers and transmission lines, etc. in the power system, gather the reliability parameters for each component and obtain the system configuration.
- Step 2: Gather hourly weather data and calculate the line rating ratios of each hour.
- Step 3: Generate a random state of the system using sequential MCS.
- Step 4: Modify all transmission line ratings with the calculated line rating ratio with respect to the current sampled state accordingly.
- Step 5: Run DCOPF and calculate the amount of load curtailment of the current system state, for both system configurations with and without transmission line ratings being modified.
- Step 6: If the calculated load curtailment amount in step 5 is not zero, then run OTS to minimize the value. If the new load curtailment amount could be reduced by OTS, save the load curtailment value and mark this state as “OTS successfully enforced”. If not, save new load curtailment amount which is the same as that of the OPF.
- Step 7: Update reliability indices. Check if any stopping criterion for MCS is satisfied. If not, go back to step 3.
- Step 8: Calculate the final values of all reliability indices.

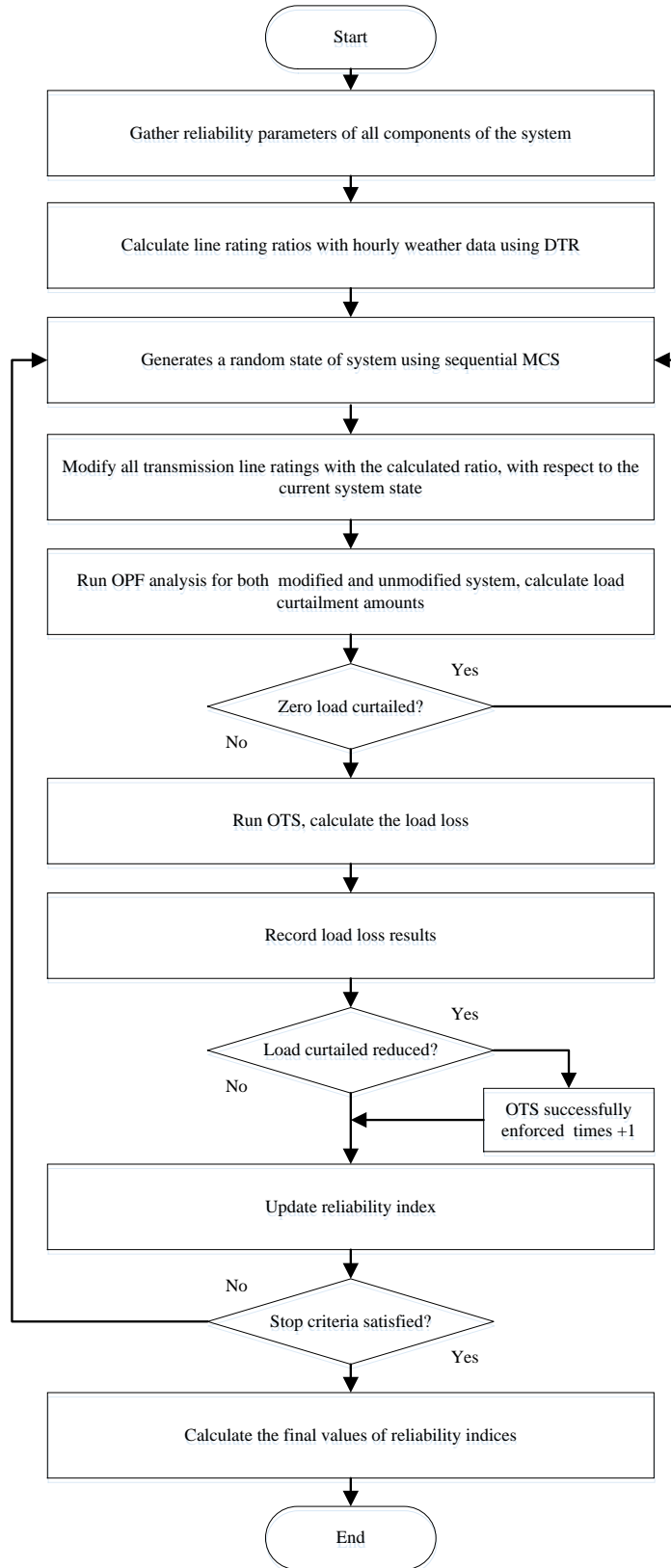


Figure 2-1 Flowchart diagram of reliability evaluation considering OTS & DTR

2.5 Case Studies

To illustrate the effectiveness of the proposed methodology, two systems are used as the test bulk power systems for case studies: Test system A - IEEE RTS-79 system [43] with all capacities of transmission components being modified to 85% of the original values in [43] (shown in Figure 2-2); Test system B - IEEE RTS-96 system [44] with all capacities of transmission components being modified to 60% of the original values in [44]. The simulation is conducted based on MATLAB and IBM CPLEX. Hourly weather data of Milwaukee, WI in the year 2010 [45] is used for calculating the actual line ratings of OHLs in this thesis, which are shown in Figure 2-2 and 2-3.

System reliability will be evaluated for the following four test scenarios:

- I. Base case: original system with OPF.
- II. System with OTS enforced.
- III. System with DTR enforced.
- IV. System with both OTS and DTR enforced.

Sequential Monte Carlo simulation time has been set to be 100 years (876,000 hours) for test scenarios in test system A and 20 years (175,200 hours) for test scenarios in test system B. Settings of the simulation duration will be enough to guarantee the coefficient of variation of the *EDNS* index for both test systems to be less than 0.5%. And in order to analyze the exact benefits brought by DTR, OTS or the combination of these two technologies while eliminating the uncertainty

caused by the random sampling, all four test scenarios will be analyzed based on the same sampled states in each reliability evaluation process loop.

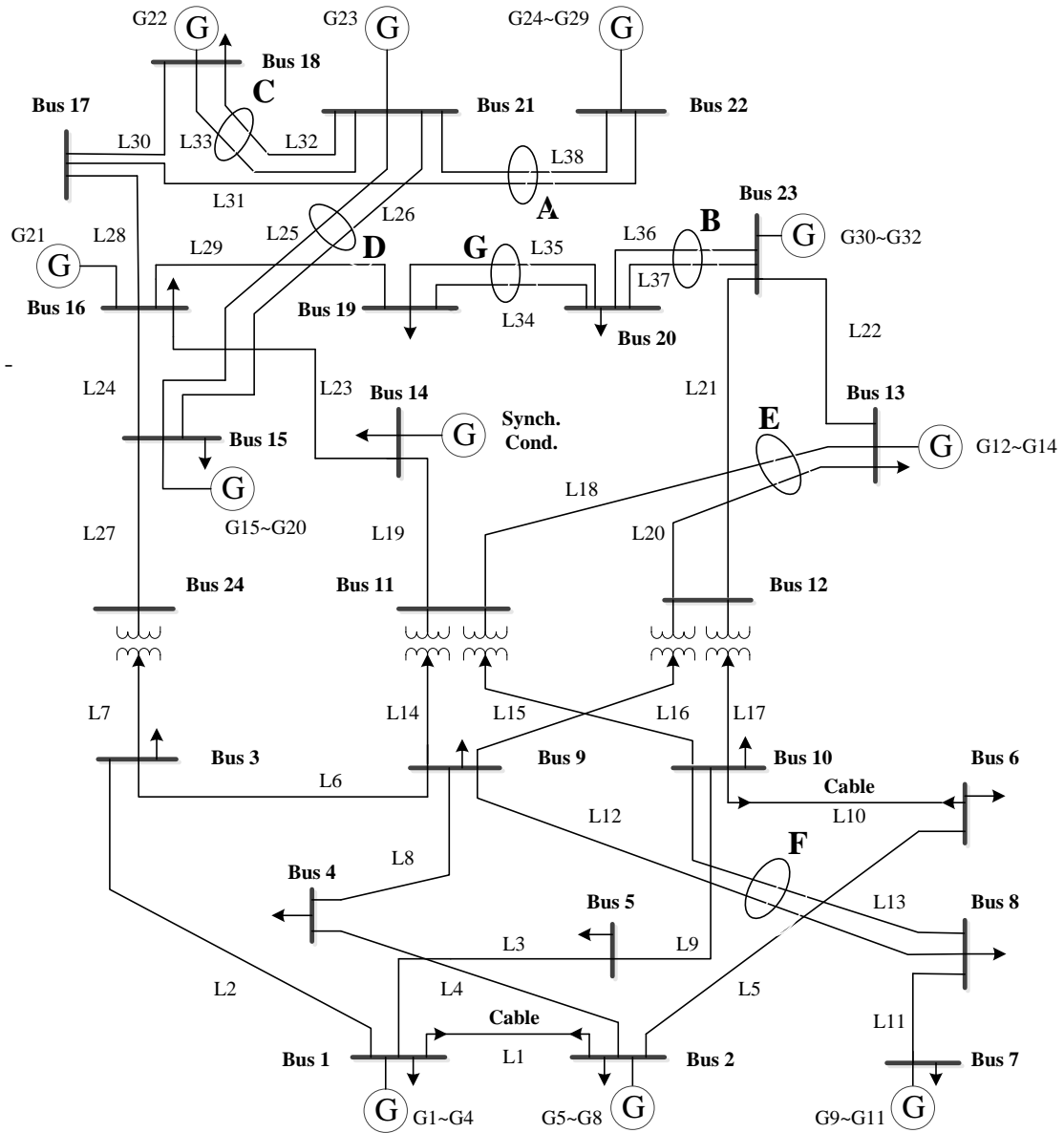


Figure 2-2 Test system A: one-line diagram of modified IEEE RTS-79 [43]

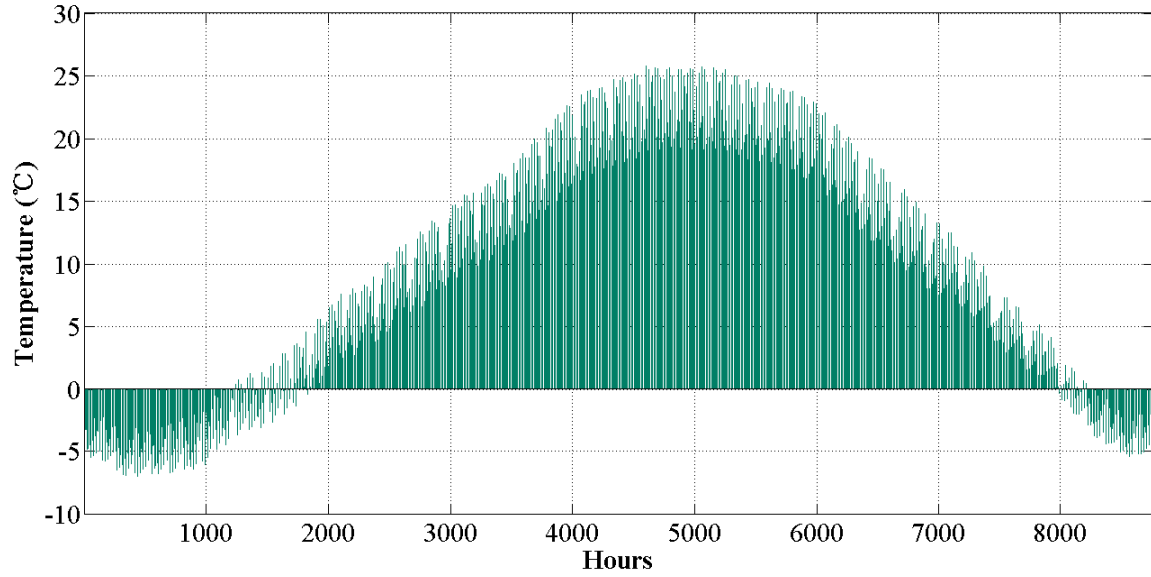


Figure 2-3 Hourly air temperature of Milwaukee, WI, 2010 [45]

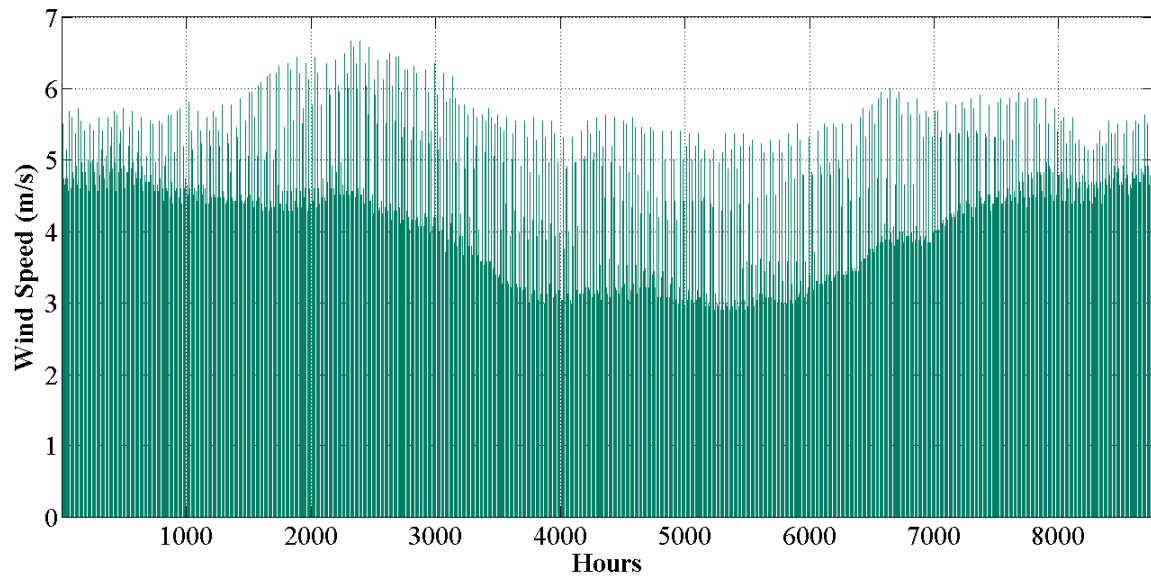


Figure 2-4 Hourly wind speed of Milwaukee, WI, 2010 [45]

The values of the reliability indices for test system A obtained using the proposed reliability evaluation method are shown in Figure 2-4 to Figure 2-6.

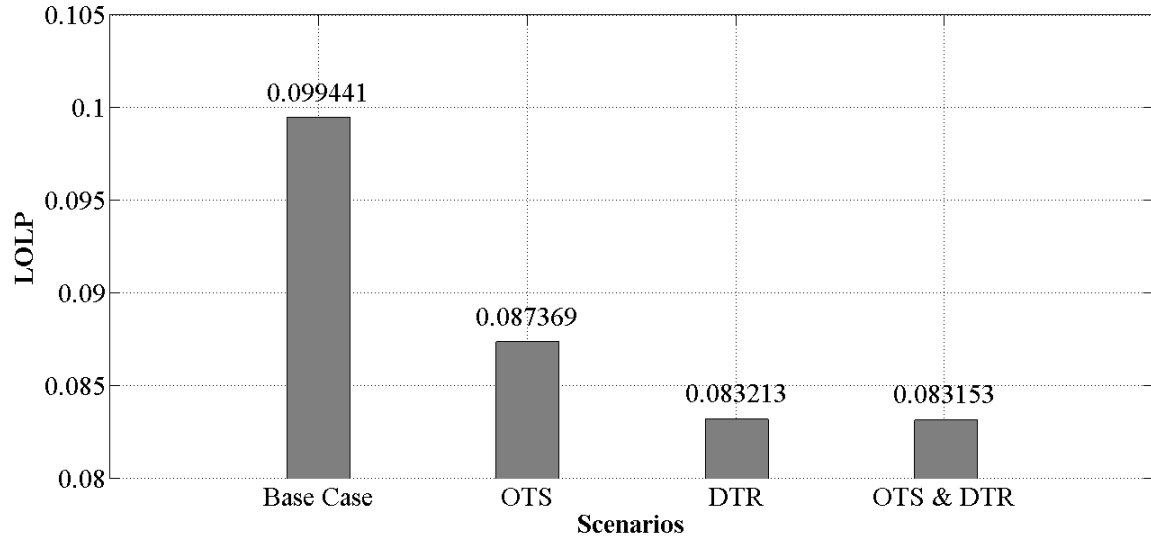


Figure 2-5 Test system A: LOLP of four test scenarios

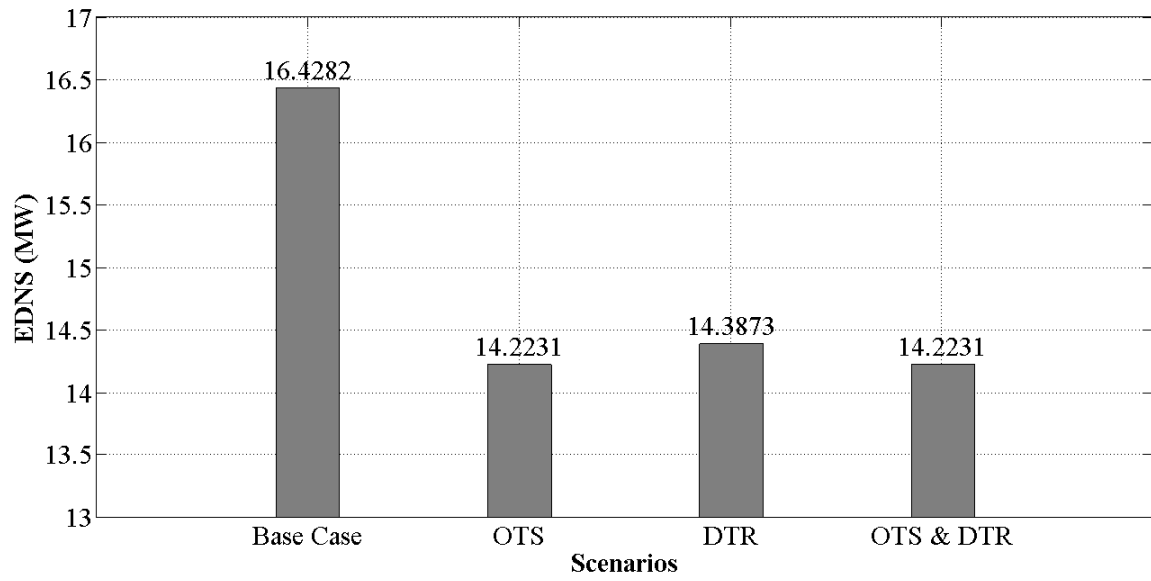


Figure 2-6 Test system A: EDNS of four test scenarios

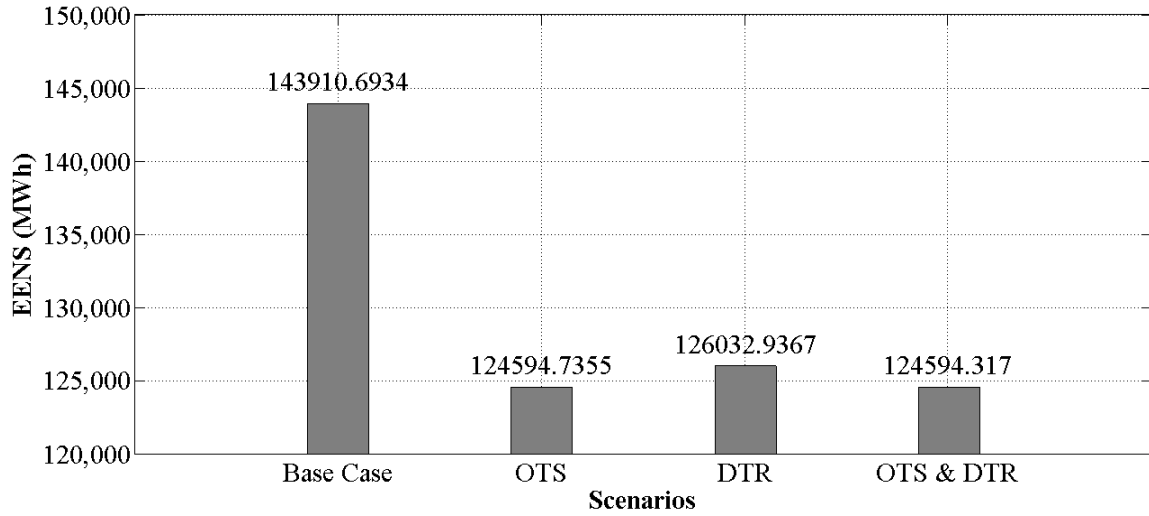


Figure 2-7 Test system A: EENS of four test scenarios

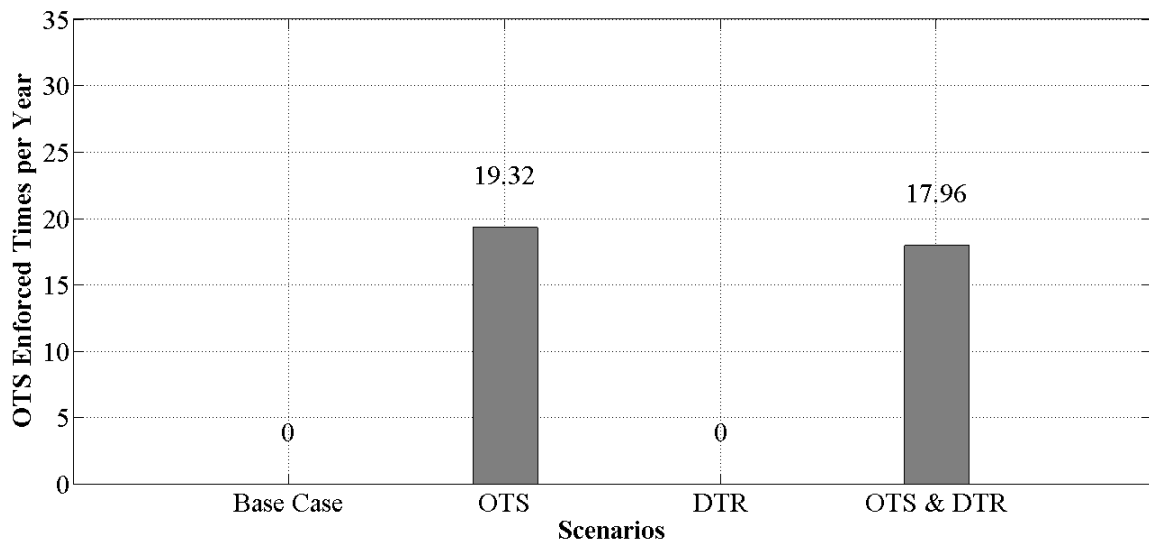


Figure 2-8 Test system A: Times that OTS takes effect per year in the four test scenarios

Since the ambient temperature in Milwaukee, WI is usually far below 40 °C, the dynamic thermal rating of the transmission network will very likely lead to a better system reliability performance. System reliability may also be improved as OTS could reduce the load curtailments in some cases.

Figure 2-4 indicates that, by enforcing OTS or DTR in test system A, the *LOLP* index can be markedly reduced by 12.14% or 16.32%. And when both DTR and OTS are enforced, *LOLP* of

the system will be further decreased by 16.38%. Figure 2-5 and 2-6 list the system *EDNS* and *EENS* results. The results indicate that by enforcing OTS, DTR, and both OTS and DTR, the system *EDNS* index will decrease by 13.42%, 12.42%, and 13.42%, respectively.

As previously described, in the reliability evaluation methodology of this study, OTS takes effect only when the amount of the optimized load curtailment using OTS is reduced with respect to the original load curtailment amount. Figure 2-7 shows the average number of times per year when OTS takes effect. For a 100-year Monte Carlo simulation, in average OTS takes effect for 17.96 and 19.32 times per year with and without DTR enforced, respectively.

The simulation has also been conducted on test system B which consists a larger number of various components with the transmission network more severely impaired comparing to test system A. The values of the reliability indices of test system B obtained using the proposed reliability evaluation method are shown in Figure 2-8 to Figure 2-10. And Figure 2-11 shows the average number of times per year when OTS takes effect in test system B. It can be seen from the results that the proposed methodology remarkably enhances the reliability of test system B. The *LOLP* index is reduced by 46.87%, 51.89% and 62.22% when OTS, DTR and both of them are enforced. And for *ENDS* index the reduction rate would be 19.13%, 36.43% and 37.49%. Then the average number of times per year when OTS takes effect is shown in Figure 2-11. With the higher number of the enforcement of OTS, the results shows not only the effectiveness of the proposed method, but also the potential benefit to large-size bulk power systems.

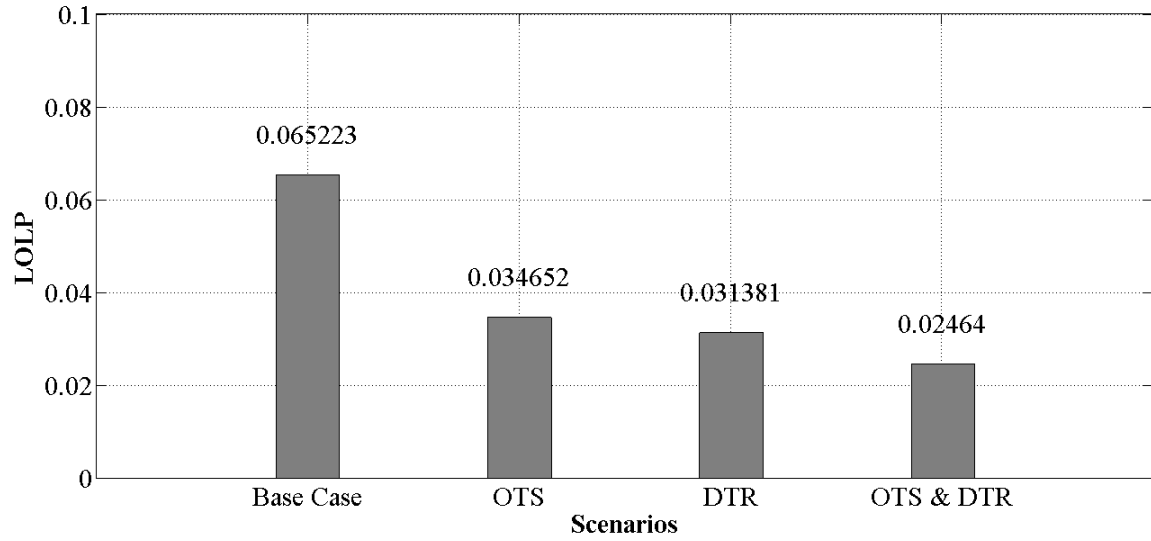


Figure 2-9 Test system B: LOLP of four test scenarios

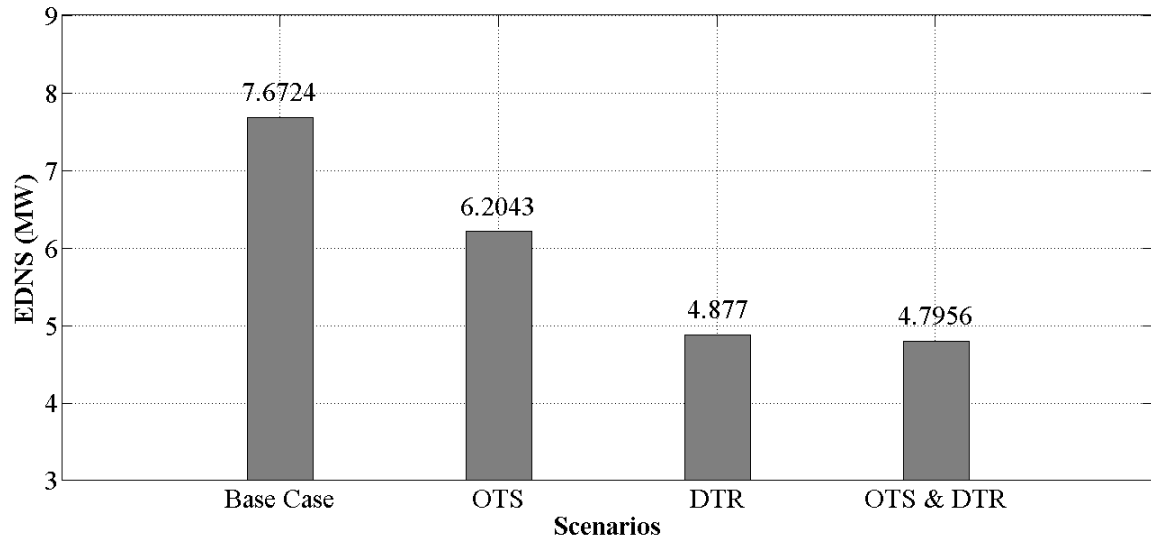


Figure 2-10 Test system B: EDNS of four test scenarios

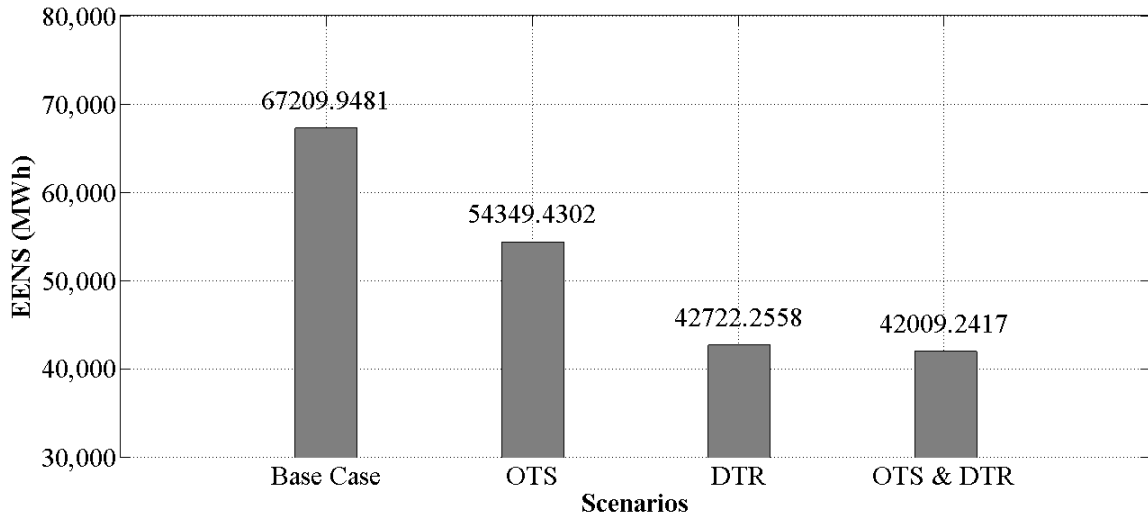


Figure 2-11 Test system B: EENS of four test scenarios

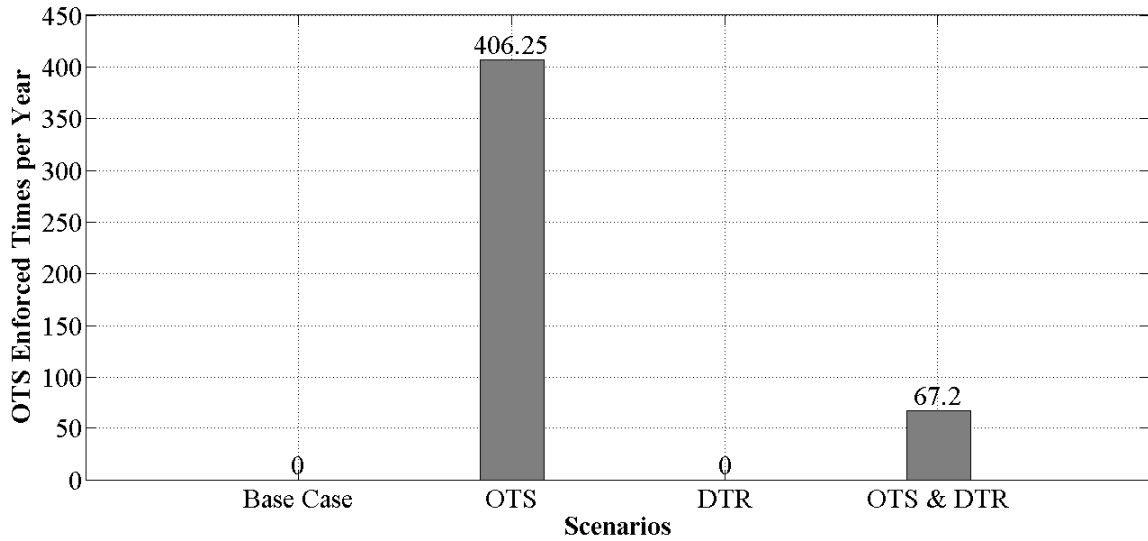


Figure 2-12 Test system B: Times that OTS takes effect per year in the four test scenarios

To further demonstrate the effect of simultaneous enforcement of DTR and OTS, some example system states picked up from the results of test system A are listed in Table 2-1. All these example system states contain some level of combinations of transmission line failures and generator outages. By enforcing DTR, load curtailments in some system states are reduced. Then by enforcing OTS, load curtailments could be further decreased or even fully eliminated (e.g., in the

system states i, ii and iii). Although enforcing DTR and OTS simultaneously does not always fully eliminate the load curtailment of a deficient system state, as shown in system states iv and v, it is quite possible that a significant amount of load curtailment could be reduced.

Table 2-1 Load curtailment results of example system states of test system A

Example States	Failed Components	Load Curtailment (MW)		
		Base Case	DTR Enforced	DTR&OTS Enforced
i.	L30, G3, G9, G32	88.60	4.54	0
ii.	L28, G31, G32	318.25	225.80	0
iii.	L28, G6, G18, G32	195.25	102.80	0
iv.	L30, G12, G20, G32	286.38	179.72	147
v.	L28, G2, G14, G32	380.25	287.80	12

2.6 Conclusions

In this chapter, the study combines both OTS and DTR technologies into the power system reliability evaluation procedure so as to examine their impacts on the reliability of bulk power grids. The mechanisms of OTS and DTR are discussed, and the effects of the proposed reliability evaluation procedure considering OTS and DTR are investigated. The simulations are conducted using MATLAB and CPLEX on both IEEE RTS-79 system and IEEE RTS-96 system. The results show that with either OTS or DTR, the *LOLP*, *EDNS* and *EENS* of the power system could be improved. And when both technologies are enforced, reliability indices will be further improved.

For possible future work, other scenarios such as wind power integration will be analyzed for the proposed methodology. And as IEEE releases a newer version of the OHL thermal rating calculation method [46], the methodology of DTR calculation could be updated and improved. Also, the OTS technology will be further explored for achieving enhanced performance.

Chapter 3 Reliability Evaluation of Drinking Water Distribution Systems Using Monte Carlo Simulation

3.1 Introduction

Reliability evaluation of drinking water distribution systems remains as an important issue. However, a comprehensive reliability estimation of such systems is difficult, and the related studies on this topic are rather limited. A probabilistic methodology for reliability evaluation incorporating both mechanical failures and hydraulic failures is proposed in this chapter. The method is developed to be able to provide both system-level and node-level reliability estimations. And a Visual C++ based software simulation tool is developed based on the proposed methodology to enable informed decision-making.

The rest of this chapter is organized as follows. Section 3.2 presents the probabilistic reliability evaluation background. And in section 3.3 the methodology of reliability evaluation of drinking water distribution system is proposed. Case studies and simulation results are listed in section 3.4. And section 3.5 draws the conclusion of this chapter.

3.2 Reliability Evaluation Background

Probabilistic reliability evaluation theory has been well established [47] and widely applied in various fields such as electric power systems [8]. To evaluate the reliability of drinking water distribution systems, first the status of each component within the system needs to be modeled. In this thesis, pipes and pumps are represented by two-state models as they are physically repairable in most conditions. As shown in Figure 3-1, “UP” status indicates the normal condition and “DOWN” status represents the faulty condition of the component. These statuses vary with respect

to time, and the statuses of all components in the water system constitute an overall system state at a certain time.

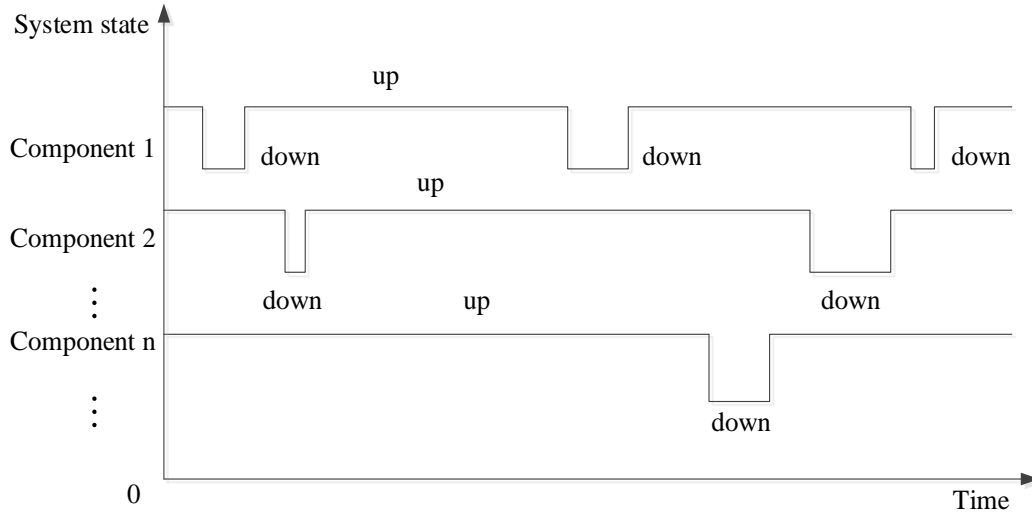


Figure 3-1 Component statuses and system states

Assuming a drinking water distribution system with a total of N repairable components, the number of the states of the system would be 2^N . Real-world drinking water systems may consist of hundreds or thousands of components, leading to an enormous state space. In such cases, analytical methods usually rely on strong assumptions and simulation methods are a more viable choice for reliability analysis [9, 48]. In this thesis, a Monte Carlo Simulation (MCS) method, which has been widely enforced in other capacitated networks such as electric power grids [42], will be used for reliability evaluation of water distribution networks.

In MCS-based reliability evaluation, the component status is sampled based on a random number generator. The random numbers can be generated based on the mechanism of either sequential MCS or non-sequential MCS. In non-sequential MCS, the unavailability of each component is compared with a random number that is generated within the range of $[0, 1]$. If the generated

random number is greater than the component unavailability, this component will be assumed to be in the “UP” status; otherwise it is in the “DOWN” status:

$$S_i = \begin{cases} 0 & \text{if } Rand > U_i \\ 1 & \text{if } Rand \leq U_i \end{cases} \quad (3.1)$$

where S_i is the simulated status of component i , 0 represents the “UP” status and 1 represents the “DOWN” status; $Rand$ stands for a randomly generated number within the range of [0, 1]; and U_i is the unavailability of component i .

In the sequential MCS, two time chains of the component (i.e., time to failure (TTF) and time to repair (TTR)) will be randomly generated for determination of the status of the component. The component will be assumed to be in the “UP” status within the TTF, and in the “DOWN” status within the TTR. Then after all the TTF and TTR values are generated, system states can be determined for each moment. The values of TTF and TTR can be calculated as follows:

$$TTF = -\log(Rand) \cdot MTF \quad (3.2)$$

$$TTR = -\log(Rand) \cdot MTTR \quad (3.3)$$

where MTF is the mean time to failure; and $MTTR$ is the mean time to repair.

Then for each sampled system state, a network analysis will be conducted to evaluate the system state with respect to the specified reliability criteria. After an adequate number of system states are

sampled and evaluated, the MCS may be halted, and the final results obtained are deemed reasonable estimates of the desired reliability indices.

The whole reliability evaluation procedure can be summarized as shown in Figure 3-2.

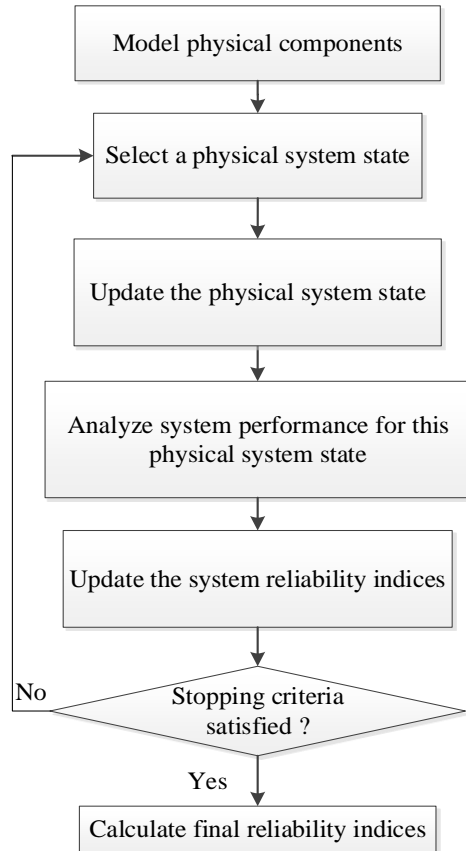


Figure 3-2 Flow chart of MCS based reliability evaluation

3.3 Methodology of Reliability Evaluation of Drinking Water Distribution System

In the software developed based on this study, all pipelines and pumps are considered to be repairable components. Each pipeline may be open (denoted as the “UP” status) or closed (denoted as the “DOWN” status), and the pump is modeled in a similar manner. Then either a sequential or non-sequential MCS method can be used to sample statuses of components. For each system state,

the hydraulic simulator EPANET is integrated with the developed software for performing water flow analysis.

Reliable water supply is dependent on the pressure, and insufficient pressure can result in water demand loss. For each node, the actually supplied water is calculated with respect to the pressure as follows [49]:

$$D_{ai} = \begin{cases} D_{ri} & \text{if } P_{ci} \geq P_{min} \\ D_{ri} \frac{\sqrt{P_{ci}}}{\sqrt{P_{min}}} & \text{if } P_{ci} < P_{min} \end{cases} \quad (3.4)$$

where D_{ai} is the actually supplied water at node i ; D_{ri} is the required water demand at node i ; P_{ci} is the calculated pressure at node i ; P is the threshold pressure for all nodes within the system, which is set to be 40 psi in the following case studies.

If the minimal pressure threshold cannot be reached, the loss of nodal demand can be defined as follows:

$$D_{lossi} = \left(1 - \frac{\sqrt{P_{ci}}}{\sqrt{P_{min}}}\right) D_{ri} \quad (3.5)$$

where D_{lossi} is the loss of nodal demand at node i ;

Then in this thesis, several reliability indices indicating both system-wide and nodal reliability performance are defined in the following.

The percentage of unsatisfied water demand (PUWD) index is defined as follows:

$$PUWD = \frac{\sum_n \sum_i D_{lossi,n}}{\sum_n \sum_i D_{ri,n}} \quad (3.6)$$

$$PUWD_i = \frac{\sum_n D_{lossi,n}}{\sum_n D_{ri,n}} \quad (3.7)$$

where $PUWD$ is the percentage of unsatisfied water demand index of the system; $PUWD_i$ is the percentage of unsatisfied water demand of node i in the system; $D_{lossi,n}$ is the nodal demand loss of node i in the n th iteration of MCS measured in gallons per minute; and $D_{ri,n}$ is the water demand at node i in the n th MCS iteration measured in gallons per minute (gpm).

The probability of loss of water service (PLWS) index is defined as follows:

$$PLWS = \frac{N_{loss}}{\sum_n \cdot \sum_i} \quad (3.8)$$

$$PLWS_i = \frac{N_{lossi}}{\sum_n \cdot \sum_i} \quad (3.9)$$

where $PLWS$ is the probability of loss of water service index of the system; $PLWS_i$ is the probability of loss of water service index of node i within the system; N_{loss} is the number of system states in which there is unsatisfied nodal demand; and N_{lossi} is the number of system states in which the demand of node i is not fully satisfied.

The expected water not supplied (EWNS) index is defined as follows:

$$EWNS = \frac{\sum_n \sum_i D_{lossi,n}}{\sum_n \cdot \sum_i} \cdot 0.5256 \quad (3.10)$$

$$EWNS_i = \frac{\sum_n D_{lossi,n}}{\sum_n \cdot \sum_i} \cdot 0.5256 \quad (3.11)$$

where $EWNS$ is the reliability index indicating the expected water not supplied in the unit of millions of gallons per year; and $EWNS_i$ is the expected water not supplied of node i , which is measured in millions of gallons per year.

With the quantitative reliability indices defined above, in the simulation after a reasonable number of iterations, both the system-level and nodal reliability indices can be obtained, which indicate the system or node level reliability characteristics of the water distribution network from different perspectives.

3.4 Case Studies

Case studies are performed using the developed software tool. Three data files are first loaded to the software: 1) the water system network file, which contains the configuration information and parameters of the studied water distribution system, 2) the reliability parameters file, which contains necessary reliability parameters of the components of the system, and 3) the water system demand profile file, which records the profiles of nodal demands. Then simulation options can be specified, including the choice of sequential or non-sequential MCS, and the maximum number of iterations. After running the software, a set of reliability indices results will be displayed in the “Reliability Evaluation Results” section. The running procedure of the developed software is illustrated in Figure 3-3, whose main interface is shown in Figure 3-4:

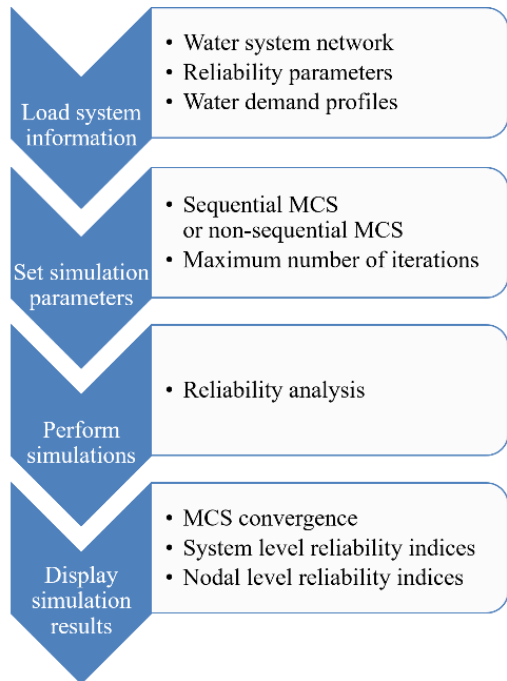


Figure 3-3 Procedure of the software tool

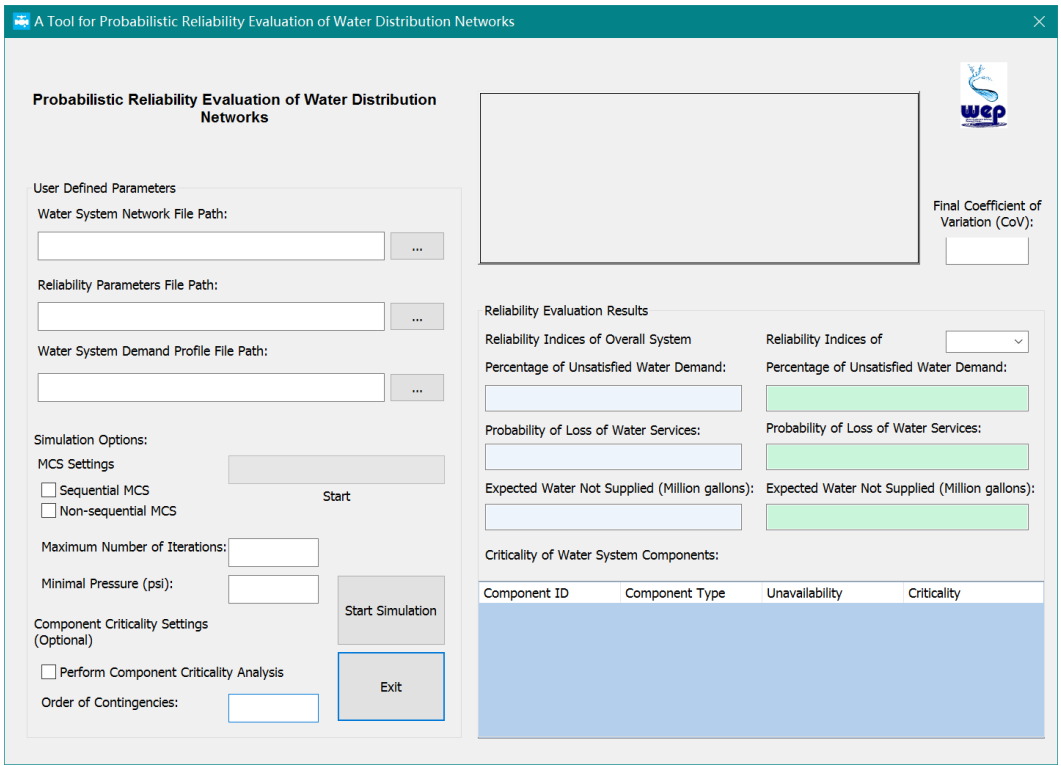


Figure 3-4 Main interface of the software tool

Two test systems provided by EPANET are adopted as the test systems in this thesis [50]. Test system A comprises 40 pipes, 35 junctions and 1 tank, with a total nodal demand of 322.78 gpm. Test system B is a larger system which comprises 117 pipes, 92 junctions, 2 pumps, 2 reservoirs and 3 tanks, with a total nodal demand of 3,052.11 gpm. Topological diagrams of these two test systems are shown in Figs. 5-6 and nodal demand profiles are shown in Figure 3-5 and 3-6.

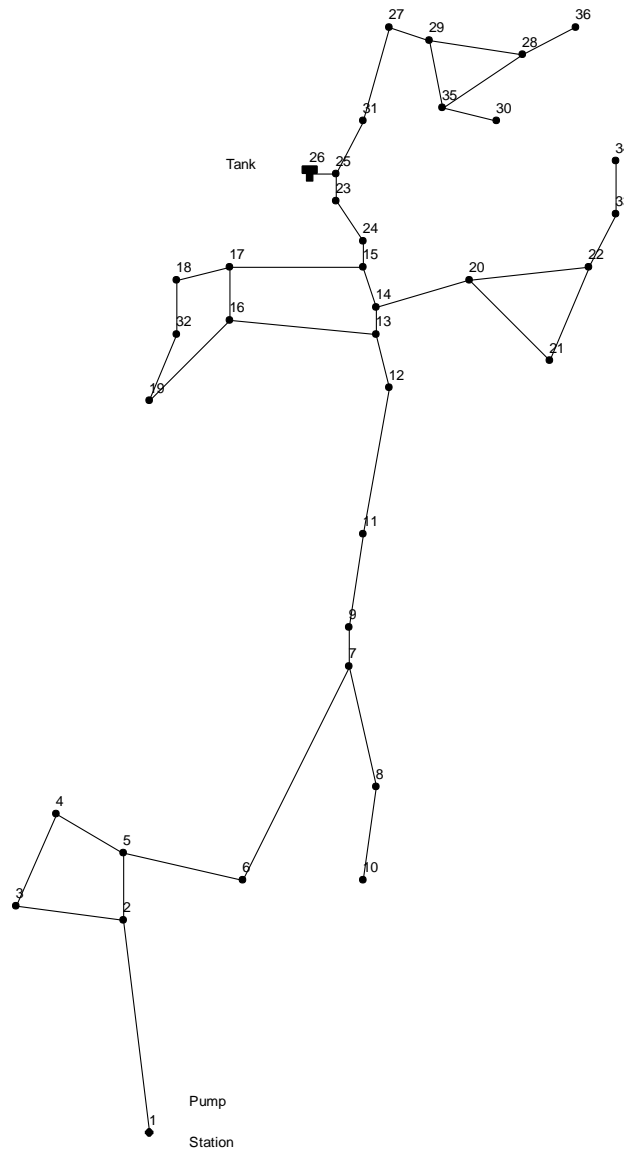


Figure 3-5 Test system A [50]

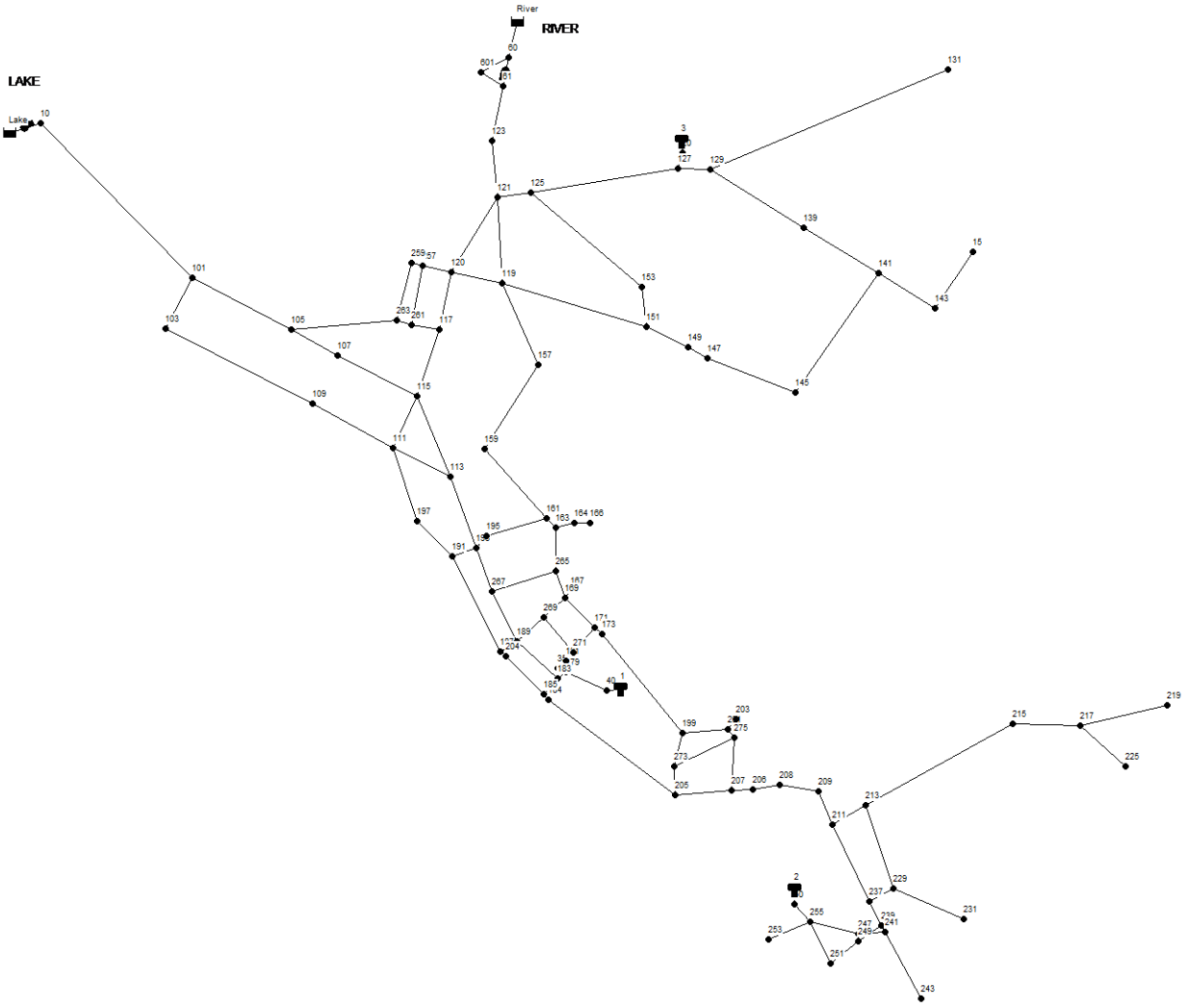


Figure 3-6 Test system B [50]

The number of iterations in MCS is set to be 10,000 in the case study to guarantee the convergence of reliability indices. The convergence curves for the two test systems are shown in Figure 3-7 and 3-8, respectively. The variations of nodal demands are shown in Figure 3-9 and 3-10.

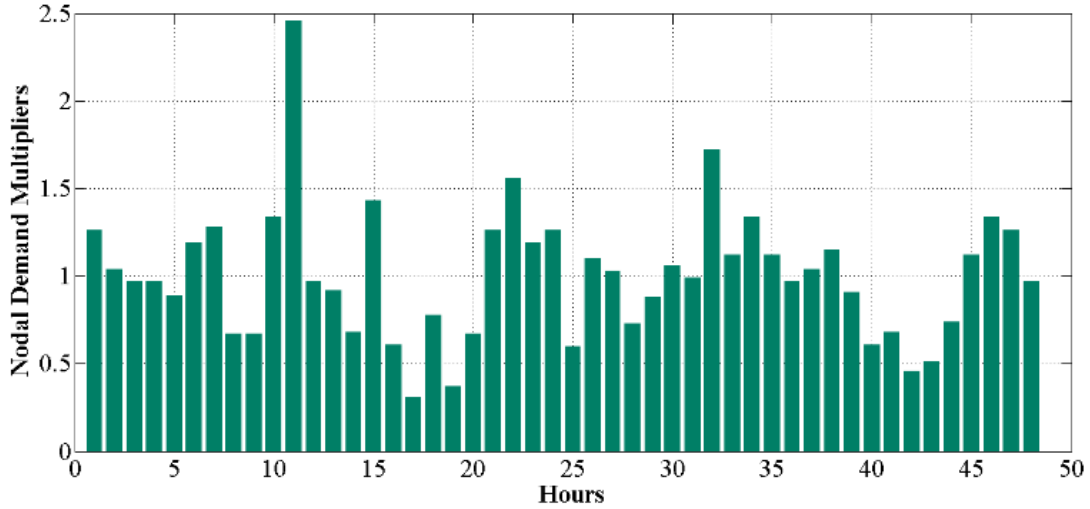


Figure 3-7 Nodal demand profiles for test system A (48 hours)

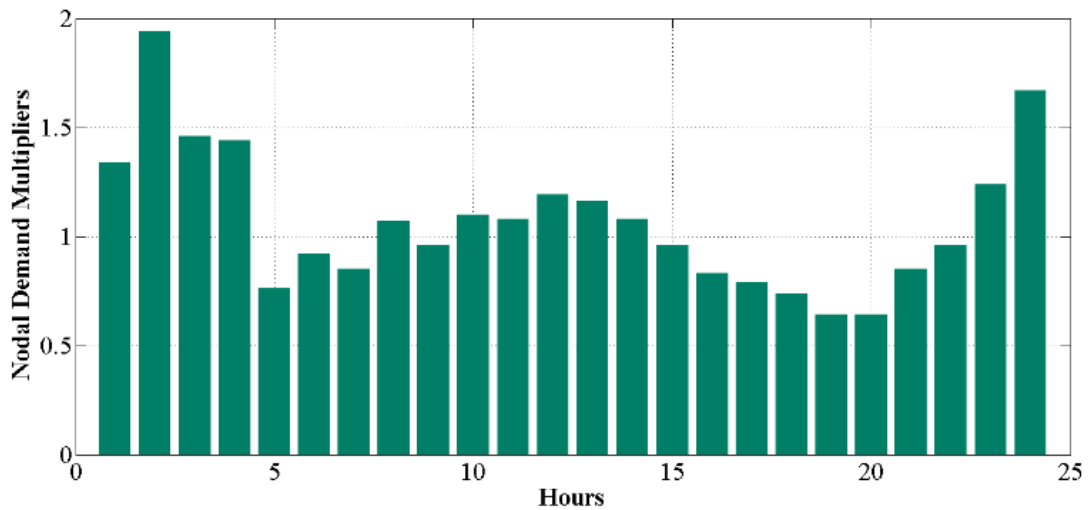


Figure 3-8 Nodal demand profiles for test system B (24 hours)

Then the reliability indices for these test systems can be obtained by running the software tool. As shown in Figure 3-9 and Figure 3-10, the convergence behavior of the EWNS index verifies that the specified maximum number of iterations (10,000) is sufficient to derive reasonably accurate reliability values for both test systems. The reliability indices for each test system using sequential

MCS are shown in Table 3-1 to Table 3-4. Some nodes in the system feature no water demand, so nodal reliability indices of these nodes are not shown in the results.

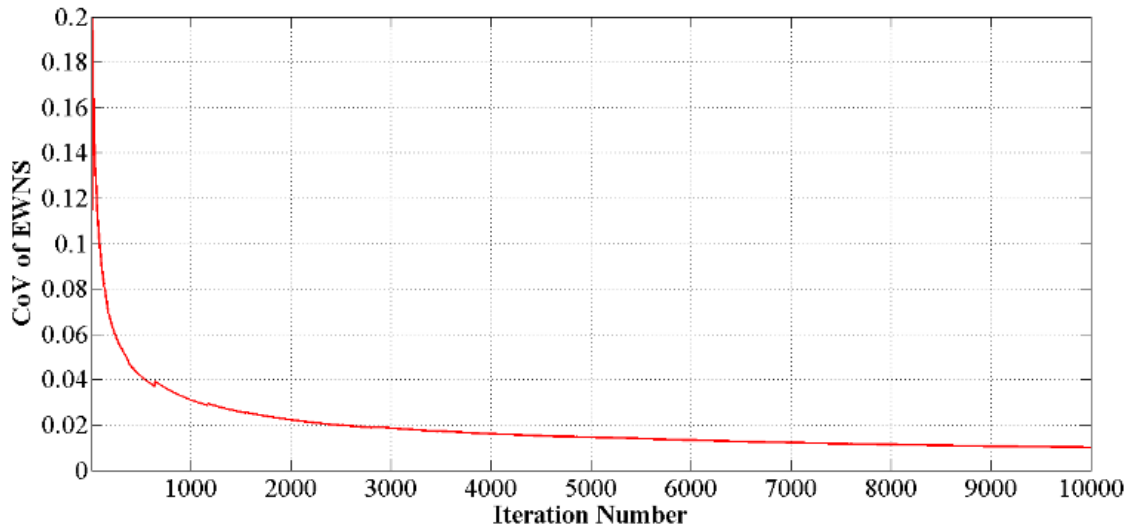


Figure 3-9 Coefficient of variance of EWNS for test system A

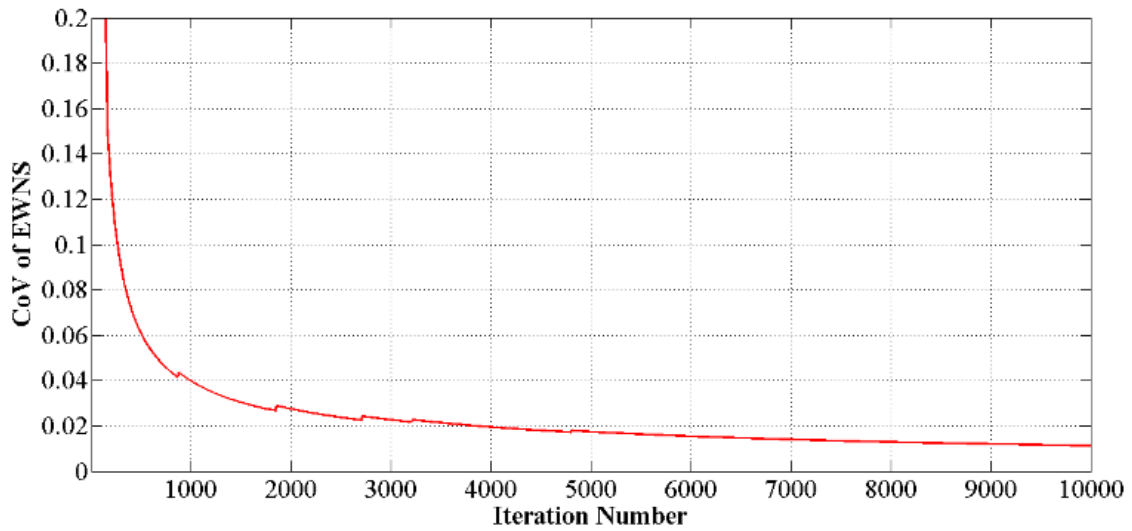


Figure 3-10 Coefficient of variance of EWNS for test system B

Table 3-1 Reliability indices of test system A

PUWD	PLWS	EWNS (Mgal)
0.0176088	0.965703	2.99946

Table 3-2 Nodal reliability indices of test system A

Node ID	PUWD	PLWS	EWNS (Mgal)
2	0.00260381	0.00239976	0.0109188
3	0.00587857	0.00239976	0.0434396
4	0.00934756	0.00589941	0.0394707
5	0.00587857	0.00239976	0.0248227
6	0.00587857	0.00239976	0.0155142
7	0.00587857	0.00239976	0.0124113
8	0.00875811	0.00519948	0.0416044
9	0.00587857	0.00239976	0.0434396
10	0.0629178	0.0593941	0.166047
11	0.00587857	0.00239976	0.107917
12	0.0405407	0.805819	0.342372
13	0.0458199	0.822118	0.0483694
14	0.00630276	0.0646935	0.00665345
15	0.00612351	0.00249975	0.00646423
16	0.00612351	0.00249975	0.0646423
17	0.00612351	0.00249975	0.0646423
18	0.0070973	0.00359964	0.074922
19	0.00612351	0.00249975	0.0161606
20	0.0114445	0.00789921	0.114772
21	0.0114445	0.00789921	0.0966503
22	0.0117014	0.0915908	0.0617626
23	0.170523	0.931907	0.720044

24	0.00465387	0.00189981	0.0270205
25	0.176835	0.965703	0.560024
27	0.00911557	0.00819918	0.0384911
29	0.00985238	0.0089991	0.036402
30	0.0176098	0.0163984	0.0278845
31	0.00551912	0.00459954	0.0495229
32	0.00612351	0.00249975	0.054946
33	0.0301038	0.0263974	0.0238341
34	0.061021	0.0576942	0.0483123
36	0.0189981	0.0189981	0.0099854

Table 3-3 Reliability indices of test system B

PUWD	PLWS	EWNS (Mgal)
0.000176228	0.030497	0.298043

Table 3-4 Nodal reliability indices of test system B

Node ID	PUWD	PLWS	EWNS (Mgal)
15	0.000666962	0.00059994	0.000346861
35	0.002829590	0.00319968	0.00159083
101	0.000027337	0.0009999	0.00291934
103	0.000034188	0.0009999	0.00256024
131	0.000613219	0.00059994	0.0147385
143	0.000178544	0.00019998	0.000622353
153	0.000641868	0.0116988	0.0159395
166	0.004242990	0.00439956	0.0062022

167	0.001096500	0.00089991	0.00897576
203	0.001800400	0.00179982	0.0010122
215	0.000399960	0.00039996	0.0193801
217	0.002599740	0.00259974	0.0330948
219	0.005099490	0.00509949	0.11075
225	0.004299570	0.00429957	0.0515247
231	0.000299970	0.00029997	0.00259831
253	0.000899910	0.00089991	0.0257876

Both sequential and non-sequential MCS give similar reliability estimation results. It can be seen that for both test systems, there is a certain probability that the system cannot fully fulfill all the nodal demands. This is due to the radial configurations within both systems: lots of nodes are connected to the network via only one pipeline, resulting in relatively unreliable water supplies to these nodes.

For instance, in test system A, node 10 is connected to the distribution network via only node 8. Once the pipeline between node 8 and node 7 or the pipeline between node 8 and node 10 breaks, node 10 will inevitably lose all its water supply. The same phenomenon can be observed on nodes 33 and 34, which feature a relatively poor reliability performance. On the contrary, some nodes such as nodes 17 and 18 have a relatively good reliability performance. From the network configuration, it can be seen that they are connected via multiple paths to the distribution network. It is possible in such cases that one or even more pipeline breaks have no impact on the water supply of these nodes.

Similarly, in test system B, while most of the other nodes are connected in a complex form, node 219 connects to the network via only node 217. This vulnerable connection has also made the reliability performance of node 219 the worst among all the nodes in test system B. For the same reason, it can also be seen that the reliability performances of nodes 225 and 217 are relatively poor in test system B.

From the above analysis, it can be summarized that a radial network usually provides poor nodal reliability performance. If no other factors are taken into consideration, from the design viewpoint of a water distribution system, a single node needs to be connected to the main network via multiple pipelines in order to achieve an improved reliability performance.

3.5 Conclusions

In this chapter a probabilistic methodology for performing quantitative reliability evaluation of drinking water distribution systems considering both mechanical failures and hydraulic failures is proposed. With the developed simulation software, case studies of reliability evaluation are conducted on two test systems so as to illustrate the effectiveness of the proposed method.

For possible future work, the reliability model of individual components in the system can be improved. In the real world, the functionalities of various components are affected by various factors such as pipeline roughness and valve on/off statuses. In order to obtain a better estimation of the reliability performance of the system, such factors need to be taken into consideration comprehensively. The piped water quality could also be incorporated to define a set of more comprehensive reliability indicators of the contemporary drinking water system.

Chapter 4 Discussions, Conclusions and Future Work

In the previous chapters, reliability analysis of electrical power system and water distribution system demonstrates some degree of similarities between these two interconnected, capacitated systems. At the same time, differences in the reliability analysis also arise due to their own specific characteristics. In this chapter findings obtained from conducting reliability analysis in both electrical power system and water distribution system will be discussed and briefly compared, then conclusion and future work of this thesis will be presented.

4.1 Similarities between Reliability Analysis of the Electrical Power System and the Water Distribution System

The reason of the effectiveness of probabilistic reliability analysis method for both systems first lies on the stochastic nature and similar modeling manner of the reliability characteristics of their components. In electric power system, as discussed in [42], the reliability characteristic of each component in the system can be modeled by a two-state representation. Probability for the component to be in either status can be calculated, and a chronological historical operating sequence (as used in sequential MCS method) can also be generated. In water distribution systems, reliability modeling of components such as pipelines is performed in a similar manner. For instance, the probability of failure can be determined by the time of repairing the pipe [51]. These similar modeling techniques lead to the similar probabilistic reliability analysis procedures as well as the similar statistical reliability metrics.

Reliability analysis of both systems share quite a few similarities. Since both the electric power system and water distribution system are required to supply the customers with not only the

sufficient quantity but also the demanded quality, reliability analysis is in fact a multi-dimensional problem. Apparently it is more difficult to evaluate the quality since it involves more factors. As mentioned in [30], the quantification of the quality variation of a water distribution system is still a complicated issue. And currently in the field of water distribution system reliability most studies are mainly focused on the reliability concept raised in [52], which defines the acceptable water supply as the water pressure being higher than or equal to the demanded nodal pressure. In the power systems field, for electric utilities it is important to supply electricity to customers with both satisfactory quality and reliability [53]. Power quality related issues remain an active research field in a smart grid environment [54].

4.2 Differences between Reliability Analysis of Electric Power System and Water Distribution System

The differences between electric power system and water distribution system are mainly due to their specific physical properties and operating conditions. Although the components in these systems can be modeled in a similar fashion, in practice these components are very different from each other. For example, roughness for the pipelines in water distribution systems and resistances for transmission lines in electrical power systems are comparable properties. However, in reality they have completely different definitions, and in the reliability analysis they are also treated differently. Resistances of transmission lines are conventionally considered as static values in the reliability evaluation process, but in lots of the studies about water distribution system reliability, pipeline roughness is considered as an important random variable to better characterize the probabilistic hydraulic behaviors of the system.

Other differences may be more at the system level. Differences in terms of operating strategies and network topologies could lead to different reliability performances in these systems. Furthermore, due to the fact that electric energy cannot be stored for a long time at a large scale and the nature of dynamics of electric power system, a number of electric quantities change very rapidly. Therefore, it has become very important to analyze the system behavior in the transient process. In the power system reliability field, the concept of system security is used to evaluate the ability of the system to respond to the disturbances during these transient processes [8]. Yet things are different in water distribution systems. Changes of nodal pressures are not as fast as changes of electrical quantities in the electric power system. In addition, water can be stored in facilities such as tanks and water towers for a long time.

4.3 Conclusions and Future Work

In this thesis, probabilistic reliability analysis of electric power system incorporating smart grid technologies and water distribution system are first introduced and discussed. Then, system reliabilities are modeled and investigated in detail. Finally, the proposed models and methods are validated by simulation studies with a discussion on their similarities and differences.

Smart grid technologies such as DTR and OTS are becoming more and more practical nowadays, which are believed to be viable operating strategies in a smart grid environment. In this thesis, these two technologies are incorporated into the traditional reliability analysis procedure of electric power systems. Simulation results have shown that by incorporating these technologies the reliability of the overall power system can be enhanced. And the proposed methodology is also validated via extensive simulation studies.

As one of the nation's critical infrastructures, reliability performance of the water distribution system has always been highly concerned. In this thesis, a probabilistic reliability analysis method using Monte Carlo simulation is proposed. Case studies are performed to give the estimation of the overall reliability of two test water systems, and also to illustrate the effectiveness of the proposed method.

Although in this thesis the probabilistic reliability analysis method has been successfully applied in the electric power system and the water distribution system, what this thesis presents is by no means the final answer or the best solution to the reliability analysis in these fields. There is still room 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 models and methods developed in this thesis are also promising to be extended to other engineering fields.

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