RELIABILITY IMPACT OF ENERGY STORAGE IN A WIND INTEGRATED POWER SYSTEM

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By

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LIST OF ABBREVIATIONS

OECD	Organization for Economic Cooperation and Development
WTG	Wind Turbine Generator
IEEE-RTS	IEEE Reliability Test System
MCS	Monte Carlo Simulation
HL1,2,3	Hierarchical Level 1,2,3
WECS	Wind Energy Conversion System
LOLE	Loss of Load Expectations
ESS	Energy Storage System
FOR	Forced Outage Rate
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
TTF	Time to Failure
TTR	Time to Repair
ESWE	Expected Surplus Wind Energy
EWEB	Expected Wind Energy Stored in Battery

ABSTRACT

This thesis presents the reliability evaluation of wind farms incorporating with energy storage. Wind power are intermittent in nature, and may cause risk for continuous power supply. In order to minimize the risk, energy storage is introduced where it is used to supply power to the system when wind power is inadequate. Monte Carlo Simulation is used in this research to evaluate generating system reliability. This method described in this thesis are tested using IEEE Reliability Test Systems, in which it has been modified for research purpose. In this approach, a few parameters are tested to evaluate effects of the parameters adjusted towards the working scenario of an energy storage. Reliability studies conducted on wind systems incorporated with energy storage demonstrates that overall power system reliability increases with the aid of energy storage. The energy storage reliability and the power system reliability as a whole can further be improved by selecting the most appropriate working scenarios for the energy storage. This is illustrated by the implementation of two different models of energy storage to the system.

ABSTRAK

Tesis ini memberikan penilaian terhadap keberkesanan penyimpanan tenaga terhadap turbin angin. Tenaga angin adalah bersifat tidak selanjar secara semulajadi, dan ini menimbulkan risiko terhadap pergantungan bekalan tenaga angin dalam sistem kuasa secara berterusan. Dalam usaha mengurangkan risiko tersebut, penyimpan tenaga diperkenalkan dimana penyimpanan tersebut digunakan untuk membekalkan tenaga apabila tenaga angin tidak mencukupi. Simulasi Monte Carlo digunakan dalam kajian ini untuk menilai sistem jentera elektrik. Kaedah yang digunapakai dalam tesis ini menggunakan 'IEEE Reliability Test Systems' sebagai sistem ujian yang telah diubah bagi tujuan kajian. Dalam kajian ini, beberapa pemboleh ubah telah diuji bagi menilai kesan-kesan yang boleh mempengaruhi kepergunaan system penyimpanan tenaga bagi konfigurasi berbeza. Kajian keberkesanaan yang dijalankan terhadap sistem kuasa angin yang bersambung dengan stor penyimpanan tenaga menunjukkan bahawa keberkesanan sistem kuasa secara keseluruhannya meningkat naik dengan bantuan stor penyimpanan tenaga. Keberkesanan stor penyimpanan tenaga dan keberkesanan sistem tenaga secara keseluruhannya boleh ditambah baik sekiraya konfigurasi stor peyimpanan tenaga dipilih dengan betul. Ini boleh dinilai melalui ilustrasi terhadap dua konfigurasi penyimpanan stor tenaga terhadap sistem kuasa.

CHAPTER 1

INTRODUCTION

1.1 Project Background

Electricity has becoming one of the most essential needs in humans' lives. From individual usage to heavy industry applications, electrical power are consumed to meet humans' needs. The paper *How Will Energy Demand Develop in Developing World*, written by Catherine Wolfram et al. (2012) demonstrates that by the year of 2035, energy consumption in OECD countries will grow by 14 percent, while electricity consumption growth in non-OECD countries will largely expand by 84 percent. In electric utilities industry, power outages is the main concern, as consumers are expecting a readily supply continuously throughout the year. This readily supply is termed as "reliability", which further defined as reliability of a power system to provide adequate output to consumers as discussed in [1].

There have been several studies to provoke discussions on the consequences of power interruptions to consumers. A study performed by Kristina and Joseph (2006) estimated that power interruptions in US alone cause a massive loss up to $79 billion [2]. Distribution systems have generally grown in unplanned manner, resulting in high technical and commercial losses, in addition to poor quality of power. Other reasons are caused lack of efficient tools for operational planning, leading to increasing system losses [3]. The practical way to reduce major power interruptions is to increase the reliability of power systems. Many electric power utilities use two kinds of approaches, which are probabilistic and deterministic approaches during planning phase to evaluate the power system reliability potential [4-12]. Probabilistic method is preferred over deterministic method because of its flexibility of usage on wide range of power systems available [4].

A probabilistic approach describing a sequential Monte Carlo simulation method is now widely implemented to the calculate reliability indices [18].

Utilization of wind and other renewable sources for electric power supply has received inclining attention due to global environmental concerns associated with conventional energy generation [13, 14]. Large-scale integration of wind power in electric grid causes higher risks to sudden power outages, due to its intermittent nature. Since wind energy produces high variability output, power system incorporating renewable energies are often faced with instability, as conventional units may not be able to respond quickly to the changes created by the sudden fluctuations. In order to maintain system stability, wind energy dispatch is usually restricted. A technology which rises people's attention now is energy storage, which is bonded to sources of renewable energy generation to supply energy to power grid when power from the renewable sources are not adequate and thus it relieves the rapid fluctuations from the high variability output [14-17].

1.2 Problem Statements

Wind power implementation in power systems is rapidly increasing globally as a solution towards a better power generation option due to environmental concerns on conventional generation usage. However, due to its intermittent nature, it causes instability in power systems which results in loss in demands and cost [14, 16]. In addition, large penetration of wind power on power systems can result in high risk in providing a continuous power supply.

Studies on the reliability of wind power incorporated with energy storage have been carried out successfully in previous studies using analytical method [23]. Studies using Monte Carlo simulation approach on the reliability of WTGs are still limited due to complex computational progress and also time-consuming [25-26].

Test systems are used to evaluate wide range of generation and composite systems [24]. A paper published on wind farming incorporated with energy storage used Roy Billinton Test System (RBTS) to evaluate reliability indices. This test system is used to be applied for a small system, to ease understanding for educational purposes [24]. However in practical world, power systems are complex and large, therefore other test systems for practical studies are more preferable over RBTS.

1.3 Objectives of Thesis

1. To analyze the reliability impact of energy storage in a wind integrated system.
    - Energy storage is seen to be a possible solution to overcome fluctuations caused by high variability wind power output. The motivation of this study is to analyze the best working operation strategy of energy storage on power systems from reliability evaluations indices.
2. To implement sequential Monte Carlo simulations to analyze the reliability of wind farm incorporated with energy storage.
    - Simulations is used as a method over analytical because of it considers sequential nature of wind source.
3. To use IEEE Reliability Test System as a test system in analyzing the reliability of a power system.
    - IEEE RTS is practical for large and complex power systems.

1.4 Review of Power System Reliability Assessment

Power system evaluation involves considerations of the system states and whether they are adequate and secure, as to be described as an alert or any relevant status [19]. Power system reliability can be divided into two forms of division, which are adequacy and security. This is done so that assessment of power system reliability can be assessed in logical and simpler manner [7-12].

Adequacy is conceptualized as sufficiency in fulfilling consumers' demands from the system's facilities. These facilities are expected to generate adequate amount of energy, considering associated transmission and distribution networks required to deliver the energy to intended load point, which in this case is the consumers. Security on the other hand relates to the response of the system to disturbances occurring within the system. It considers the factors or conditions which are affecting local and widespread effects and the loss of major generation and transmission facilities [19].

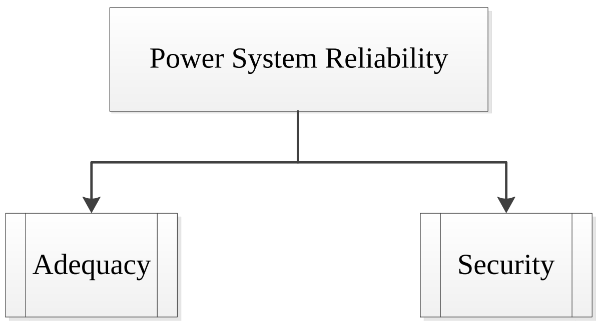

Figure 1.1: System Reliability Concepts

Electric power systems are extremely complex and large, therefore even current high-tech computers are unable to analyze in a completely realistic manner of a power system as a single entity. Therefore, the system is divided into three distinguished subsystems which can be analyzed separately. The subsystems are also knows as functional zones, generally as generation systems, composite generation and transmission and lastly, distribution systems [20].

The concept of hierarchical levels (HL) has been developed to obtain a consistent means of identifying these subsystems. The first level (HL1) refers to generation facilities and their ability to supply energy adequately to end-loads. Hierarchical level 2 (HL2) refers to the composite generation and transmission and its ability to feed energy to the bulk supply points. Lastly, hierarchical level 3 (HL3) refers a complete system, including distribution and its ability to supply demand of individual consumers [20]. Figure 1.2 illustrated the hierarchical level which becomes a relevant referring point of reliability studies until now.

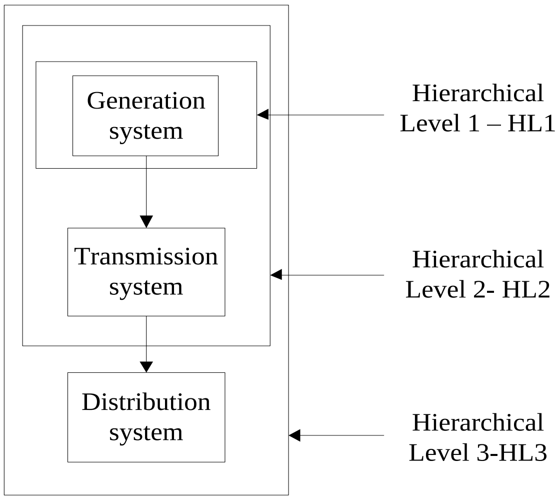

Figure 1.2: Hierarchical Level

1.5 Review of Generating System Reliability with Wind Farms and Energy Storage

Generating system reliability can be analyzed by focusing on hierarchical level 1 which deals with generation facilities and their abilities to deliver enough supply to system load. There are two approaches which can be used to assess reliability indices, which are analytical and simulation based. Analytical technique uses numerical solutions directly to evaluate reliability indices by representing the system in the form of mathematical modelling. However, analytical approach is unable to be of much efficient when the power systems are complex. Hence, Monte Carlo simulation comes in light [12].

Monte Carlo methods are more flexible when complex power systems are incorporated. The technique includes random events such as repair and failure time by general probability distribution, as well as other different kinds of operating conditions. There are two types of Monte Carlo simulation, which are non-sequential and sequential simulations [21]. As further discussed in [22], non-sequential simulation assess any intervals of time in the simulated period in random manner. On the other hand, sequential takes into account of each interval of time in chronological order. The sequential approach is required if history of the system affect the present system behavior.

Wind source is intermittent as its nature changes over time. It can be fast at one time and next, it can be totally absent. Hence, to evaluate wind energy as a power source, sequential method must takes place to have accurate assumptions on the reliability of wind as energy source. This method incorporates an energy storage modelling, with chronological nature of wind speed [14, 16]. The simulation works by generating wind speed hourly over a period of time for a specific site. The hourly wind speed is used to determine the power output from a wind turbine generator [15].

1.6 Thesis Outline

This thesis comprises of five chapters. The first chapter is an introductory chapter to give an overview on power system reliability analysis and its implementation on wind farming and energy storage. The first chapter also includes the objectives of this thesis, resulting from problem statements arising from previous studies.

Basic concepts on power systems reliability are explained in the second chapter. The difference between analytical and simulation techniques are also discussed in this chapter. Wind energy theories and previous studies on energy storage are presented.

Chapter three deals with a method in analyzing impacts of energy storage on wind farm in more detailed manner. This method is presented described using examples. This method is then used to include different strategies of wind farm and energy storage are presented.

The results and analysis from a wide range of studies considering variations in key factors are discussed in chapter four. Reliability indices which are used to evaluate the reliability benefit from energy storage are presented.

Chapter five concludes overall findings and analysis obtained from this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As described in Chapter 1, the main goal of this research is to evaluate reliability analysis of a power system incorporating wind farm and energy storage. Monte Carlo Simulation will be utilized as a technique of probabilistic approach in finding the reliability indices. IEEE RTS is the test system used as a standard to perform the simulation technique.

Developments in power systems have expanded over the decades. The main concern of electric power utilities companies are to be able to provide uninterruptible power supply to end-loads all the time but it is still not practicable in real situations. Hence, utilities strive for ways that consider costs and reliability in an effective manner [25]. Approaches to evaluate reliability of a power system are available at different levels i.e. generations, composite generation and distribution. Reliability evaluation helps utility in decision making and future planning for best optimization solution.

The methods used for reliability assessment are divided into two branches, which are probabilistic approach and deterministic approach. The difference between these two methods is by its method’s response towards each system state scenarios [25]. Analytical method use direct numerical solutions based on mathematical modelling based on Markov models. This method is ideal for simple system as it requires less computational time [25, 26]. However, Monte Carlo Simulation comes in light when complex power systems evaluation is needed. Monte Carlo Simulation offers a simpler method when facing complex and difficult systems. [25].

IEEE Reliability Test System (IEEE-RTS) gives a standard of reliability evaluation of a power system. It describes a load model, generation system and composite system which can be used to test methods for reliability analysis. The goal of developing this system is to establish a core system which can be used by researches with modified parameters according to their research [27].

Among all renewable energy resources, wind energy has high significant contributions on electric power supply. However, system reliability concerns about its ability to provide continuously power supply due to its intermittent behavior [15, 28]. The impact of wind power integration on power systems is elaborated in [29] and [30]. The amount of wind energy that can be absorbed by electric power system has high variability over time. Problems occur as conventional generating units are not able to respond to the fast changes due to wind fluctuations [14]. Energy storage is one of a few solutions that can be used to reduce the negative impact of this problem. The energy storage acts as a store for the wind energy to be kept during high speed, and it acts as supplier when wind is totally absent or slow [14, 16].

2.2 Power System Reliability

Power systems development has evolved rapidly over the years. But their main objective remains the same which is to supply a safe and adequate amount of power supply to the consumers [20]. Due to the changes of scenario of the power systems, conventional evaluation techniques are not relevant due to the complexity of the systems. Modification in evaluation techniques are required because of the existence of new designs, inclusive of renewable energy and also new devices [25].

Reliability evaluation involves a consideration of system states, whether they are adequate or secure [19]. Adequacy is defined as sufficient energy supplied within the system to be supplied to consumers, whereas security involves consideration of disturbance within the system [25]. The difference between adequacy and security division is that, adequacy responds to static conditions, which neglects the impacts of system disturbances.

Adequacy is easier to calculate and analyzed than security. This is because adequacy is assumed to be at a steady-state condition at all time. Hence, there is no consideration of the actual entry to and departure from the state [6, 31]. The state of the system is analyzed and assumed to be adequate if the system requirements such as the load, voltages and VAR are satisfied. Security, in other hand considers the dynamic and transient behavior of the system in which it is believed that as a system enters one state to another, it does not behave in steady-state manner [31].

Due to the evolvement of power systems, most power systems are complex and highly integrated. Therefore, the evaluation of the power system as whole is impossible with any existing techniques available. To overcome this problem, power systems are divided into functional zones or knows as systematic hierarchical manner. The main reason to do so is to makes calculations and analysis becomes possible and accurate in any sense [25, 31]. Power systems are divided into three functional zones which are generation systems, composite generation and distribution system.

The concept of hierarchical level is discussed in [20] to establish a consistent means of identifying these functional zones. The first level (HL1) refers to generation system and its ability to meet customer demand at load end. The second level is defined as the composite generation and its ability to deliver energy at main load points. The third level which is (HL3) describes the ability of the complete system, considering transmission and generating system to deliver energy to individual customers [20, 31]. Table 2.1 presented in [25] explained the needs of evaluating the power system at each level in simpler form.

Table 2.1: Interpretation Indices of Hierarchical Levels

Hierarchical Level	Components Involved	Indices Interpretations
HL1 (Generation Systems)	• Generating stations • Generating capacity • Interconnected system (tie line between system)	Measures the sufficiency of generating network to supply energy at end-loads
HL2 (Generation + Transmission Systems)	• Generating stations • Composite generation network • Substation switching station	Measure the ability of the system to continuously supply energy at main load points
HL3 (Generation + Transmission + Distribution Systems)	• Distribution network • Substation, switching station	Measure the adequacy to supply to individual customers

Two categories classified the techniques used to evaluate power system reliability, which are analytical technique and also simulation technique [25, 31]. Analytic approach has major implementation for previous studies, but recently a question is brought out on how well the technique can respond to stochastic behavior of the system. With that concern, simulation technique comes in light. The main difference between analytical and simulation technique is how the technique responds to the system states scenario [25]. Figure 2.1 provided in [25] gives an overview of the division of reliability assessment techniques. These methods can be applies at various power levels [32] as implied in Table 2.2, presented in reference [25].

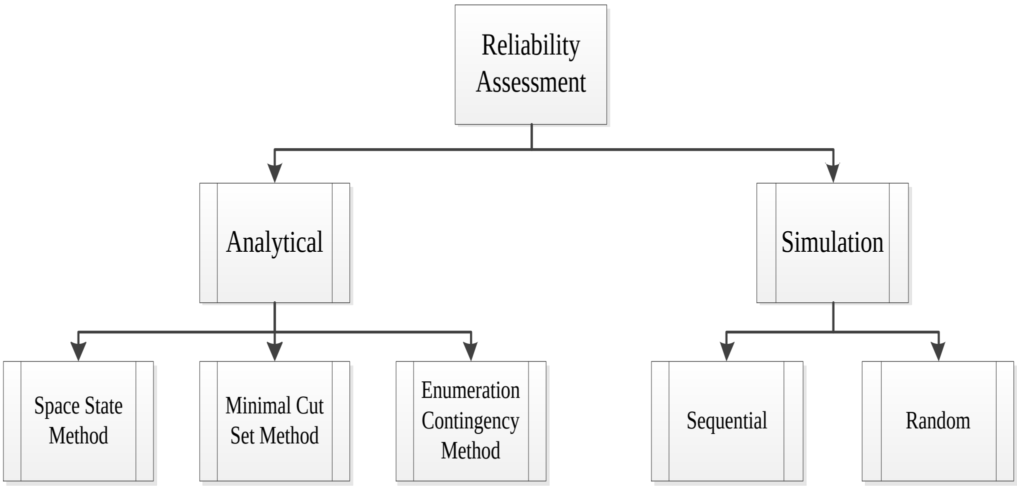

Figure 2.1: Reliability Assessment Technique

Table 2.2: Methods Used for Different Functional Zones

Functional Zones	Methods Available
Generation	• Monte Carlo Simulation • Contingency Enumeration Method [33-34]
Composite	• State Space Method • Contingency Enumeration Method • Minimal Cut Set Method • Monte-Carlo Simulation [35-36]
Distribution	• State space method • Contingency enumeration method • Minimal Cut Set Method • Monte-Carlo Simulation [37-38]

2.3 Monte Carlo Simulation

Monte Carlo simulation responds to stochastic behavior of a system [31]. When a real system is analyzed, the occurrence of the events depends on the models and probability distribution used to represent the components and variables [31]. In Monte Carlo simulation, generation of random number is an essential part of the technique. Uniform random numbers [21] are generated computationally in the range of 0 to 1 by a random number generator. The values are then converted into values of non-uniform probability distribution.

Monte Carlo simulation stops simulating as the results are close to the actual values and this applies convergence technique [21]. The stopping criteria of Monte Carlo simulations often use the coefficient variation of the output. Indices are obtained from the simulation to evaluate power system reliability. Loss of Load Expectations (LOLE) has the lowest speed of convergence and this indices is most often used as stopping indicator [21].

Stochastic simulation can be either be implemented using random or sequential techniques [31]. These two methods are chosen based upon the requirement of a system. Sequential simulates basic intervals in chronological order, in contrast with random technique. Random technique simulates basic intervals by choosing any random intervals. This technique can further be divided into state sampling technique and state transition sampling technique [25]. Figure 2.2 below shows the division of Monte Carlo simulation techniques.

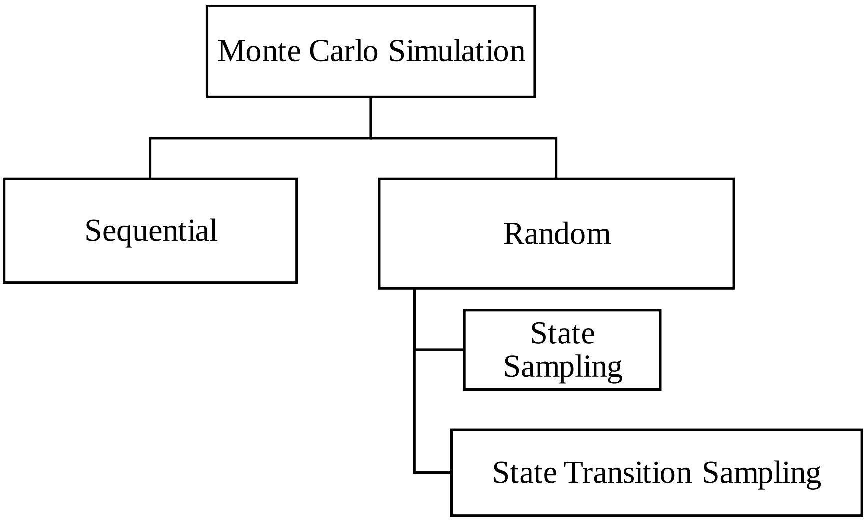

Figure 2.2: Monte Carlo Simulation Division

Non- Sequential: State Sampling Method

For state sampling method, it is assumed that behavior of each component can be considered as a uniform distribution as in [0, 1] to conduct the sampling [25]. The system state is obtained by sampling all components at random interval [40]. This method is used to find the probability of that specific system state happening with provided components outage [21, 25]. Discussion in [25] presents how state sampling method works as below:

1. System state is sampled using components state sampling. The components' state is obtained by generating it with a random number generator in interval [0, 1] with comparison of component forced outage data.
2. Sampling continues until system state obtained to be abnormal. When this happen, load curtailment occurs.
3. Further action is taken to determine the location and extent.
4. Steps (1) to (3) are repeated until the coefficient of variation is less than criterion value.

Non-Sequential: State Transition Sampling Method

Unlike state sampling method, state transition technique considers transition state of the whole system [35-36]. This method does not require sampling state interval of components [25]. Reference [39] explains how state transition sampling method works as below:

1. The first system state is considered in up state.
2. The state transition of components are generated by random number generators. Sampling occurs until there is occurrence of outage component. When outage occurrence observe, load curtailment occurs.
3. The simulation stops when coefficient of variation is less than criterion value.

Sequential: State Duration Sampling Approach

Sequential technique considers system states in chronological manner and distributions of indices then to be calculated [25]. The chronological system state transition are generated from component state in sequence manner using random number generator. Reference [39] explains procedure of sequential sampling as below:

1. Initial states of components is assumed, usually up.
2. Chronological states of components are generated.
3. Chronological states of system are obtained by comparing the system states of components.
4. Indices are evaluated from the analysis of system states.
5. Steps (1) to (4) are repeated until coefficient of variation is less than criterion value.

Reference [25] tabulates data to compare the working of sequential and non-sequential method. Reference from [3] also gives brief comparison of both of the techniques. The data is tabulated as below:

Table 2.3: Comparison between Sequential and Non-sequential

Differences	Sequential	Non-sequential
Computational Time	Computing time and effort is large.	Computationally fast.
Needs of chronological order information	Sampling state duration of all components and chronological order information are needed.	Sampling state duration of all components and the chronological order information are not needed.
Flexibility of Working	Sequential approach will always work.	Non-sequential approach is restrictive.

2.4 Generation Systems (HL1) Adequacy Using Monte Carlo Simulation

Generating systems evaluation (HL1) is used to evaluate the ability of the system generating capacity to satisfy system load [41]. Monte Carlo simulation are preferable compared to analytical approach, according to [41-43]. In an HL1 study, the total system generation is evaluated to determine its ability to meet the total system load requirement. The transmission and distribution systems are ignored in HL1 evaluation [31, 41]. Hence, the main priority in this evaluation is to estimate the generating capacity required to satisfy load demands. Most common indices obtained in HL1 evaluation are loss of load expectation (LOLE) and loss of energy expectation (LOEE) [41].

A generating unit can be represented by two-state model, or more than two-state model. The most general states available are up and down states. For a single load level, generating system adequacy depends on the capacity of states of the system. The behavior of each generating unit can be simulated by a uniformly distributed random number in the range of (0, 1) [31, 41].

As discussed in [41], the available capacity of each generating unit can be determined by generated states. Hence, it can be simplified as the total capacity of the system generation is the summation of individual capacity available at specific time.

In sequential approach, annual load curve is obtained from a multi-step model. The chronological load curve can be converted into load duration curve. Reference [41] describes a procedure in obtaining a load duration curve.

1. Select initial cluster means M_i where *i* denotes cluster *I*.
2. Distance D_{ki} is calculated from each hourly load point. L_k (k = 1 … 8736) to each cluster mean.

$$D_{ki} = |M_i - L_k| \qquad - (1)$$

3. Load points are calculated by assigning them to the nearest cluster and new cluster is calculated.

$$M_i = \frac{\sum_{IC}^{N} L_k}{NI} \qquad \text{-(2)}$$

where NI_i is the number of load points in the i^{th} cluster and IC denotes the set of load points in the i^{th} cluster.

4. Steps (2) and (3) are repeated until all cluster remains unchanged during iterations.

Monte Carlo simulation is a fluctuating convergence process [41]. As simulation goes, output indices will start showing real values. The simulation will terminated when the indices achieve a specific degree of confidence. The coefficient of variance is used as convergence criterion in Monte Carlo simulation [41].

2.5 Reliability Test Systems

A test system is being utilized in this research which is IEEE Reliability Test System – IEEE RTS [27]. IEEE RTS is developed in 1979 and has been extensively used for testing reliability techniques. The report describes a load model, generation system and transmission network [27].

As presented in [27], the load model provides hourly load for 8736 hours in one year, expressed in chronological basis. The generating systems consist of 32 units, ranging from 12 to 400MW. The transmission systems contain 24 load/generation buses, connected by 38 lines. The annual peak load of IEEE-RTS is 2850MW with rated output power capacity of 3405M. The single line diagram of IEEE-RTS is shown in Figure 2.3.

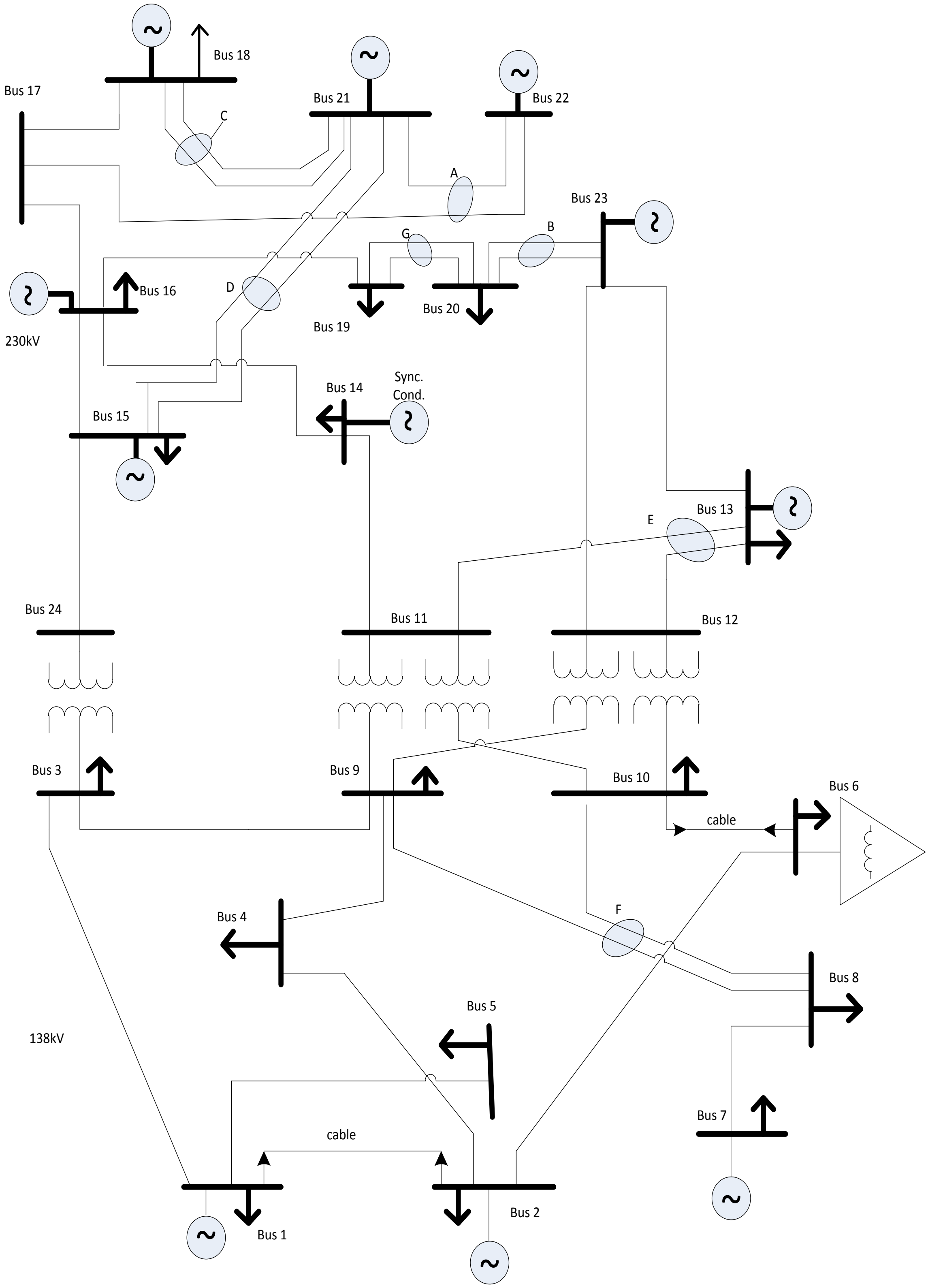

Figure 2.3: IEEE-RTS

2.6 Wind Farm Incorporating Energy Storage

Wind is one of many renewable source of energy which now has becomes competitive option with conventional units of power generations. Utilities with significant wind energy utilization region are actively studying the technical and economic effects of wind incorporating existing conventional units [45]. The wind resource and the actual wind turbine generator unit are basic parts of wind energy conversion system.

Simulated wind speed is the product of wind speed at time t with standard deviation and summation of mean speed [45]. The power output of a wind turbine generator unit can be determined as presented in [46]. The simulation of wind energy is implemented using sequential technique as past use of wind resource affects the ability to generate energy in subsequent time interval [4].

State sampling procedure is carried with assumptions that the behavior of generators are in uniformly distributed manner in the range of [0, 1], as in explained in reference [15, 45]. As all component states are sampled, the system state is compared and determined. Conventional unit and independent wind energy conversion system are assumed to be independent event in sampling state procedure [45].

There are many indices that can be used to evaluate system adequacy in this case [47]. The most basic and common indices used is Loss of Load Expectations (LOLE) which presents the frequency of hours in which load is lost per year. It is concluded in reference [47] that the degree of wind correlation affects system reliability indices. Large-scale integration of renewable energy in conventional power generation can cause high risk of large fluctuations of energy due to the intermittence nature [48].

The amount of energy that can be absorbed by power grid at a specific time can be largely inadequate as conventional units may not be able to respond to the rapid changes by wind energy fluctuations [14]. To maintain system stability, wind energy dispatch is usually restricted to specified percentages of system load [14, 16]. With wind restriction, effects from high output variability of wind generator can be reduced [16].

A solution is introduced to further reduce the high fluctuations issue arising from WTG, which is energy storage that can be bonded to wind energy [14, 16]. Reference [14] presents a realistic energy storage model that includes energy storage constraints using Monte Carlo simulation for reliability evaluation. Procedures to utilize MCS for wind farm and energy storage is explained in detailed in [49].

The aim of energy storage utilization is to store wind energy when there is surplus energy and use the stored energy when wind energy generation is limited [14]. The idea is that if actual power output from wind farm is greater than load commitment, excess energy is placed in the storage. However, when actual power output form the wind farm is less than commitment, energy from the storage will be used to meet demand constraints.

There are two scenarios in which energy storage can be implemented [14]. These scenarios are tabulated in simpler way as below:

Table 2.4: Different Working Scenarios of Energy Storage

Type of Scenario	Operation of Energy Storage
Scenario 1	If wind power output is less than X% of system load, stored energy will be used to supply the system. The wind and storage energy are combined to meet the load demand.
Scenario 2	Energy storage will be discharged to serve the load if available wind power is greater than X% of system load.

2.7 Summary

This chapter briefly explains on overall definition of power system reliability. Different methods that can be used in reliability evaluation are also presented in this chapter. Monte Carlo simulation are explained in detailed manner, irrespective of sequential or non-sequential techniques.

This research is intended for HL1 assessment and IEEE-RTS is used as the test system. Hence, studies and discussions on HL1 and IEEE-RTS are introduced and discussed as well. Lastly, wind farming and the implementation of energy storage are discussed in the final section.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Wind power generations have significant influence on electrical power utilities nowadays. Many countries are participating in implementing wind energy to show their commitments towards Renewable Portfolio Standard (RPS) [14]. It is expected that the development of wind energy to be incorporated in power systems will be rapid in more years to come. However, wind energy generation produces a high variability in output, in which it brings concern to utilities of its reliability implementations. The amount of energy produced by wind energy might not be able to be absorbed fully by electric power grids due to its high fluctuations output. Hence, engineers are developing a technology to reduce it. One of the solutions is by installing energy storage to wind farms to supply energy when wind energy is slow and insufficient. Studies on the reliability of energy storage on wind farms are carried out on HL 1 level as to evaluate its ability to deliver adequate energy to end-loads.

The sequential simulation of wind power involves in generation of hourly wind speed in a year for a specified site. The load model is a chronological load profile. In implementation of Monte Carlo simulation, the generation capacity is based on the available capacity of generators at a specific time, when generated randomly. IEEE Reliability Test System (RTS) is modified with addition of wind farms and energy storage into the system. This chapter describes a technique used in reliability assessment of implementation of energy storage on wind farms.

3.1 Process Flow of Reliability Assessment

The flow of research conducted is as illustrated in Figure 3.1 presented. The first step is to modify IEEE-RTS based on the criteria needed to evaluate wind farm and energy storage. The annual peak load is remained at 2850MW. Wind turbine generators are added with a rated capacity of varying 200 to 500MW to Bus 1 of the generating system.

Next, wind turbine generation is simulated. The method used to simulate WTG is discussed further in section 3.6. After simulation of WTG, states of generators are generated using random number generators. The available capacity of system generators are dependent on available capacity of total generators at time, *t*.

Energy Storage System (ESS) is modelled based on two different operating strategy scenarios that will be tested in this study. Each model will be varied with a few key factors to relate their effects on the energy storage. Lastly, reliability indices will be analyzed to compare reliability benefits for each energy storage model.

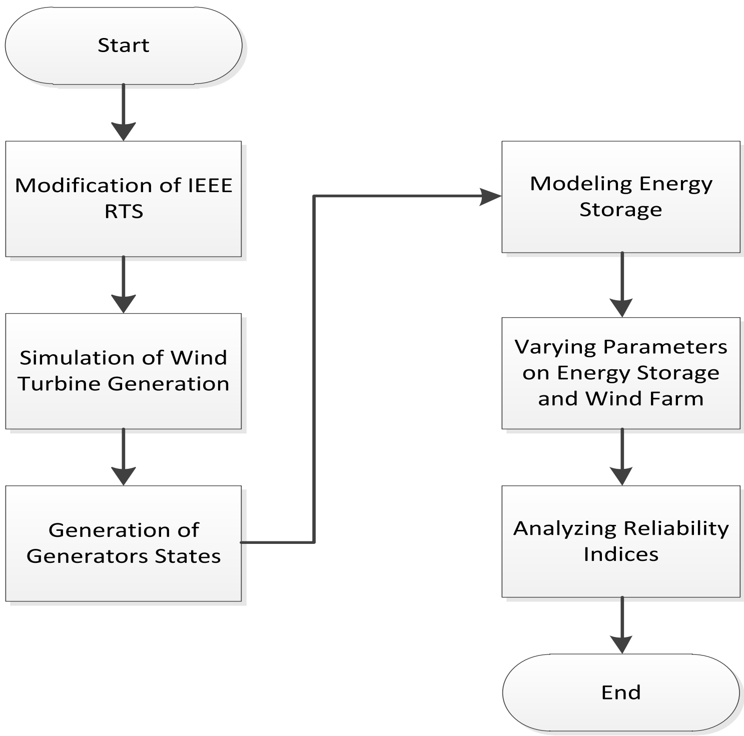

Figure 3.1: Process Flow of Reliability Evaluation

3.3 Modification of IEEE Reliability Test System for Research Purpose

IEEE-RTS is modified by adding wind farms into the system. This is done to evaluate the effect of wind farm addition into power systems. Wind farm with energy storage bonded is installed in Bus 1. The rated capacity of wind farm varies, from 200MW to 500MW. Annual peak load of modified IEEE RTS remains at 2850MW. A single line diagram of a modified IEEE-RTS is as illustrated in Figure 3.2 below:

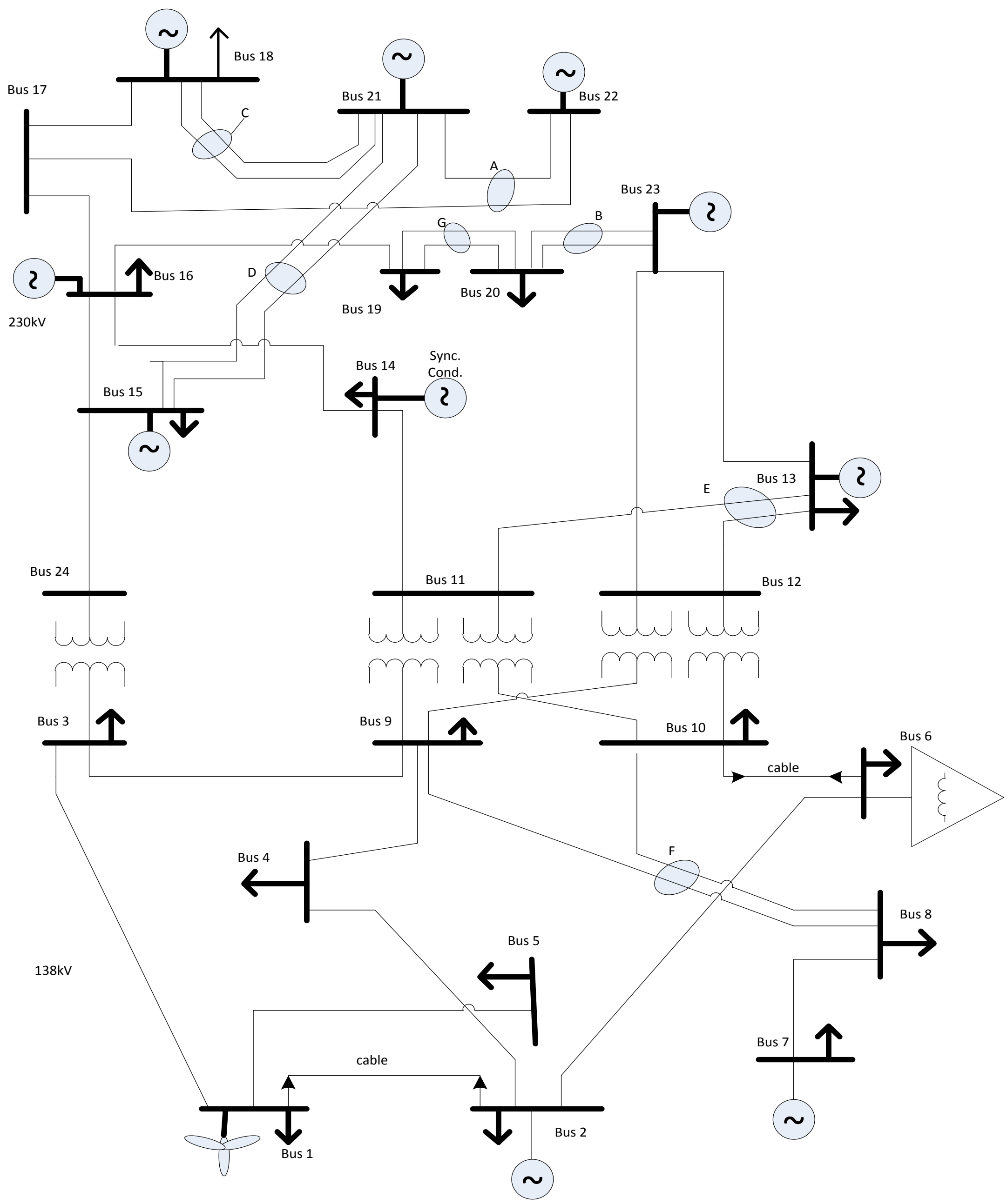

Figure 3.2: Modified IEEE-RTS