RELIABILITY IMPACT OF DEMAND SIDE MENAGEMENT (DSM) IN A WIND INTEGRATED POWER SYSTEM

YUSUF BIN SABAR

Thesis submitted to Universiti Sains Malaysia
in fulfillment of the requirement
for the degree of
Bachelor of Engineering (Electrical Engineering)

Supervisor:
Dr. Teh Jiashen

JUNE 2017

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my advisor Dr. Teh Jiashen for his continuous support and guidance throughout this project. It would not be possible for me to complete this project without his sharing of knowledge.

Completing this work would have been more difficult were it not for the support from my fellow friends namely Farihan, Izzat and Saiful and by the other members of the School of Electrical and Electronic in USM Engineering Campus. I am indebted to them for their help. Special thanks to Yayasan Tenaga Nasional scholarship for sponsoring my four years of studies at USM.

Last but not the least, I would like to express mu boundless appreciation to my family for their continuous support, love and patience. I am forever indebted to my parents for giving me the opportunities and experiences that have made me who I am. May Allah accept all these efforts as ibadah to Him and delivers us all in His Jannah.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

CHAPTER 2: LITERATURE REVIEW

CHAPTER 3: METHODOLOGY

CHAPTER 4: RESULT AND DISCUSSION

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOL AND ABBREVIATIONS

WTG	Wind Turbine Generator
IEEE-RTS	IEEE Reliability Test System
MCS	Monte Carlo Simulation
HL1	Hierarchical Level 1
HL2	Hierarchical Level 2
HL3	Hierarchical Level 3
WECS	Wind Energy Conversion System
LOLE	Loss of Load Expectations
LOEE	Loss of Energy Expectations
FOR	Forced Outage Rate
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
TTF	Time to Failure
TTR	Time to Repair
λ	Failure Rate
μ	Repair Rate
U	Random Number

t	time
Pr	Rated Wind Turbine Output Power
Vci	Cut-in Speed of Wind
Vr	Rated Speed of Wind
Vco	Cut-out Speed of Wind
SWt	Surplus Wind at time t
LS80	Load shifting at 80%
LS85	Load shifting at 85%
LS90	Load shifting at 90%

Abstract

Wind energy conversion system (WECS) are becoming popular because of their economical values compared to conventional sources. The biggest problem face by WECS is the inconsistent availability of wind potential and this will affect the overall power system reliability. Demand side management (DSM) is one of the potential method in meeting this problem by improving the overall system reliability by load shifting. The objectives of this thesis are to study the reliability impact of DSM in a wind integrated power system, modify IEEE Reliability Test System (IEEE-RTS) by incorporating WECS and DSM as a test system and simulate the real behaviour patterns of a wind integrated power system by using Monte Carlo simulation (MCS). The load models for all busses and generation capacity at each hour in a year of the modified IEEE-RTS is stimulated and the system Expected Energy Not Served (EENS) is computed as a reliability index. From this project, it is known that DSM load shifting technique give a significant improvement in the system overall reliability especially load shifting at 80%. Applying load shifting to each individual bus yield slightly better improvement in system reliability compared to applying it to the system total load. Load shifting also shows positive improvement to system reliability for various Wind Turbine Generator (WTG) power capacity.

Abstrak

Wind Energy Conversion System (WECS) sudah menjadi semakin popular kerana kelebihan ekonominya berbanding sumber kovensional. Masalah utama yang dihadapi adalah ketidakseragaman potensi angin dan ini akan mempengaruhi reliabiliti sistem kuasa secara menyeluruh. *Demand Side Management* (DSM) adalah salah satu cara yang berpotensi dalam menyelesaikan masalah ini dengan meningkatkan kesuluruhan reliabiliti sistem kuasa melalui peralihan beban. Objektif tesis ini ialah untuk mengkaji impak DSM ke atas reliabili sistem kuasa, mengubahsuai *IEEE Reliability Test System* (IEEE-RTS) dengan mengintegrasikan WECS dan mensimulasikan tindak balas sebenar sistem kuasa yang telah diubahsuai mengunakan teknik *Monte Carlo Simualtion* (MCS). Model beban untuk semua bas dan kapasiti penjanaan pada setiap jam dalam setahun bagi IEEE-RTS terubahsuai disimulasikan, seterusnya *Expected Energy Not Served* (EENS) ditentukan sebagai indeks reliabiliti. Hasil daripada projek ini, dapat diketahui bahawa DSM memberi penambahbaikan yang signifikan kepada keseluruhan reliabiliti sistem kuasa terutamanya pada 80% peralihan beban. Peralihan beban pada setiap beban bus menghasilhan penambahbaikan yang serupa berbanding peralihan beban pada keseluruhan beban sistem kuasa. Peralihan beban juga menunjukan penambahbaikan yang positif kepada reliabiliti sistem kuasa bagi berbagai kapasiti *Wind Turbine Generator* (WTG).

CHAPTER 1

INTRODUCTION

1.1 Background

Electricity has become one of the most vital aspect of human needs, from residential lighting to industrial workloads, all of them need electricity to operate. Fulfilling the consumer demands for electrical energy are important and any interruption should be avoided to prevent any financial loss. However, because of the complex nature of power system, failures in any part of the system will cause failures and interruption which range from small number of local resident to a huge catastrophic disruption of supply. An estimated huge loss up to $79 billion cause by power failures and interruption in US alone are studied by Kristina and Joseph (2006) [11]. Usually the term “reliability” is used to define the ability of a power system to provide customers with an adequate supply [12]. To reduce most of the interruption, the reliability of the power system should be increased. There are two common ways which many electrical power utilities use to evaluate the power system reliability potential which are deterministic and probabilistic approaches during planning phase [13-21].

A wide range of system behaviour can be incorporated by using probabilistic techniques and are more preferred compared to deterministic techniques [13]. A considerable probabilistic techniques are now available in the form of computer softwares for reliability analysis [21]. Wind energy conversion system (WECS) are becoming increasingly popular compared to conventional sources due to their increasingly economical values [1]. WECS is based on naturally available resources and has minimal or no negative impact on the environment compared to conventional sources like fossil fuels. Wind energy is now “utility scale” and can affect utility planning and operation of both generation and transmission [2].

Increasing awareness of environment conditions and high cost of infrastructure investment because of continually increasing demand for electricity are some problems faced by electric power utilities [4]. Demand Side Management (DSM) is the alteration of consumer demand for energy through various methods mainly load management (LM) or in other words encouraging consumer to use less energy during peak hours [4]. Recently, DSM is also used in balancing intermittent generation from solar and wind units, especially when the generation does not meet with the magnitude and timing of energy demand.

This paper describes a sequential Monte Carlo simulation (MCS) method for incorporation of DSM in the capacity adequacy evaluation of electric power system using wind energy [1, 4]. In the sequential approach, a system operating cycle is obtained by combining all the component cycles by simulating the up and down cycles of all components [6]. This project will provide with better understanding of the reliability of a wind integrated power system and the effects of DSM on the system. Thus, in return would prove to be beneficial not only to electric power utilities but also to the consumer by improving energy efficiency and system reliability. This project would also be an informative source for effective implementation of DSM in a wind integrated power system.

1.2 Problem Statement

The biggest problem faced by WECS is the inconsistent availability of wind potential. Wind energy is proportional to the wind speed thus giving a different impact on the reliability performance of a generating system compared to conventional sources [3]. A significant amount of research had been done to come up with mathematical models and techniques for reliability evaluation of power systems containing wind energy [1-3]. Previous studies are done to improve the reliability of wind integrated power system by incorporating energy storage [10]. DSM is one the solutions in meeting the problems faced by electric power utilities [4]. Studies had been done in investigating its effect on power systems and all of them gave positive impacts on the reliability, environmental and economic cost [7-9]. DSM is just a technique used to improve energy transfer from the generating site to the customer by means of altering of consumer demand for energy through various methods and are more cost efficient than incorporating energy storage system in wind integrated power system. Direct analytical method in accessing the reliability of power system are still relevant compared to simulation methods since it is faster to implement and the fact that there is no equation or mathematical models with can be justified either with logic or mathematical derivation in simulation methods, instead it fully depends on the use of a random number generated by a computer software. However, the real benefits of MCS is that it can produce extended result like frequency histogram or probability distribution which was impossible with the analytical approach.

1.3 Objectives of Thesis

1.1.1 To study the reliability impact of DSM in a wind integrated power system.

1.1.2 To use and modify IEEE RTS by incorporating WECS and DSM as a test system.

1.1.3 To stimulate the real behaviour patterns of a wind integrated power system with the effect of DSM on IEEE Reliable Test System (RTS) using Monte Carlo simulation (MCS).

CHAPTER 2

LITERATURE REVIEW

2.1 Monte Carlo simulation process: A review

The main function of a Monte Carlo simulation application is to predict and examine the actual behaviour patterns for a stochastic system [23]. The output of a Monte Carlo simulation is usually the probability distribution and frequency of various reliability parameters. Random number generation is an important part of Monte Carlo simulation [23]. Random number are generated using computer software, usually between 0 to 1. These random numbers are usually used in appropriate distribution functions before utilization in the simulation process. A Monte Carlo simulation should be stopped when the estimated value is close enough to the actual value which involve convergence analysis. Fluctuating convergence process is created when running Monte Carlo simulation as shown in Figure 1 [23].

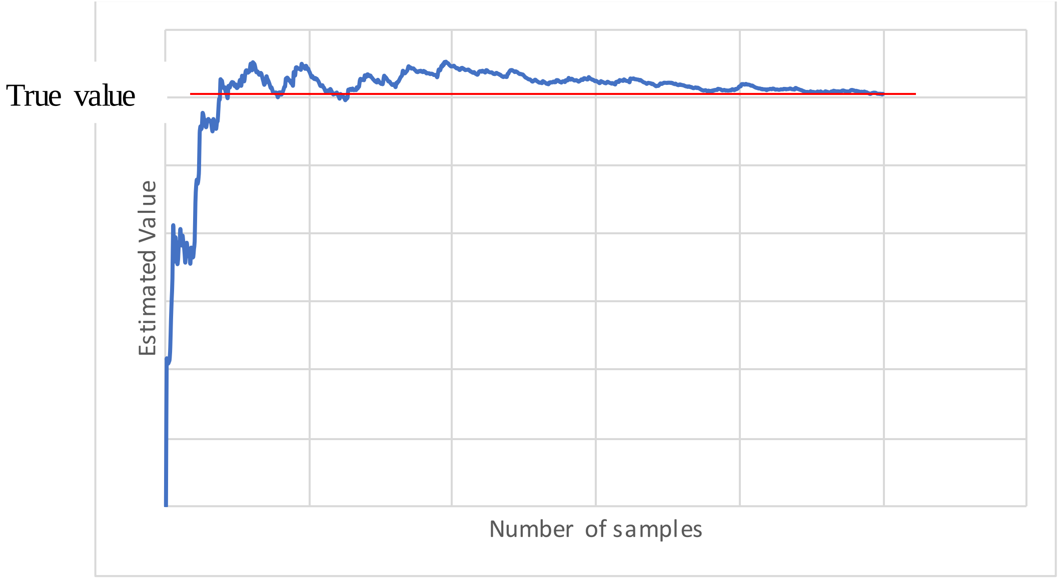

Figure 1: Fluctuating convergence

The coefficient of variation of the output is usually the stopping criteria Monte Carlo simulation. Many reliability indices are produce by MCS and all of them have different speed of convergence. So normally ne indices are selected as an indicator for convergence. Normally the Expected Energy Not Served (EENS) index has the lowest speed of convergence and used as the convergence indicator [24]. There are two general methods of MCS which are sequential and non-sequential methods. Sequential MCS consider the chronological analysis of the system and component states. Whereas non-sequential MCS does not consider the chronological aspect of the system and can be divided into two categories of state and state transition sampling.

Non-Sequential: State Sampling Approach

In this method, all component states irrespective of the chronological aspect or event are sampled to obtain the system state [23]. The component states (up/down) are determined by using a random number generator. The probability of occurrence of every system state as to the component states is calculated with this method [23]. The disadvantage of this method is that it cannot obtain a very accurate frequency index. The following steps describe the process of this method:

1. Each system state is sampled by generating a random number and comparing it with the system Forced Outage Rate (FOR). If the random number generated is higher than FOR, then the system is in the up state, otherwise it is in the down state.
2. Load curtailment occurs if system state is predicted as an abnormal state. If this occur, action is taken to determine the extent and the location.
3. The wanted adequacy indices are calculated and recorded and step 1 and 2 are repeated until the variation coefficient satisfy the criterion value.

Non-Sequential: State Transition Sampling Approach

This method can give more accurate frequency indices compared to the state sampling approach but consume more time. It uses the system state sampling transition to calculate the system indices and not the component state like in state sampling approach. The state transition of any component causes the transition of the system state. The following step describe the process [23]:

1. The initial state of all components of the system are assumed to be in the up state.
2. The state transition of any component is determined by random number generation and any transition of the component may lead to the transition of the system. If load curtailment occurs if the present system state is a contingency state in which at least one component is on outage then a long system state transition sequence is required in order to evaluate the indices of each system state.

3. When the coefficient of variation in within the acceptable value of the criterion value, the simulation is stopped.

Sequential: State Duration Sampling Approach

This process of this method generates the chronological state transition for all the system components. Their state sequence is generated using state duration distribution function which also utilize random number in it. The chronological system state transition is generated from the component state sequences. Any type of distribution function can be used in the state duration sampling method. This method produces accurate frequency indices. The problem with this method is that it requires more computational power and memory to stimulate than the non-sequential method. The steps used for reliability evaluation is as follows [23]:

1. The initial state of the components is assumed either in the up or down state.
2. The chronological sequences of state for each component are generated.
3. The chronological system state is determined from the combination of the chronological component state.
4. The desired reliability indices can be obtained by performing system analysis on the resulted system states.
5. Steps 1-5 are repeated until the coefficient of variation are within the acceptable criterion value.

2.2 Generation Systems Hierarchical First Level (HL1) Adequacy Using MCS

The concept of hierarchical levels (HL) has been created to produce a consistent means of knowing these subsystems. The first level (HL1) represents to the generation facilities and their ability to supply enough energy to the end-loads. All the other components are assumed to be 100% reliable in this level. Hierarchical level 2 (HL2) involves the combination of generation facilities and the transmission system and is represented as the composite or bulk system and their ability to satisfy load requirements at the assigned load points. Hierarchical level 3 (HL3) refers the combination of three functional zones which are the generation, transmission, and distribution. Reliability analysis at this level is very complex and rarely done [25]. In this paper, the HL1 analysis are chosen for the reliability assessment of wind integrated power system with the implementation of DSM.

2.3 IEEE Reliability Test System

The IEEE-RTS is used for the reliability assessment. This system was created in 1979 to provide a basis for comparison of result achieved from different methods or in other words to provide a reference system which have the main data required in reliability evaluation [5]. This model has been used extensively especially in composite systems. The system describes a generation system, transmission network and load model [5].

As presented in the report, the generating systems contains 32 units, ranging from 12 to 400 MW and 24 load/generation busses connected by 38 lines at two voltages, 138 and 230 kV. The load model provides annual peak load of 2850 MW and an hourly load for a year. (8736 hours). The single line diagram of the test system is shown in Figure 2.

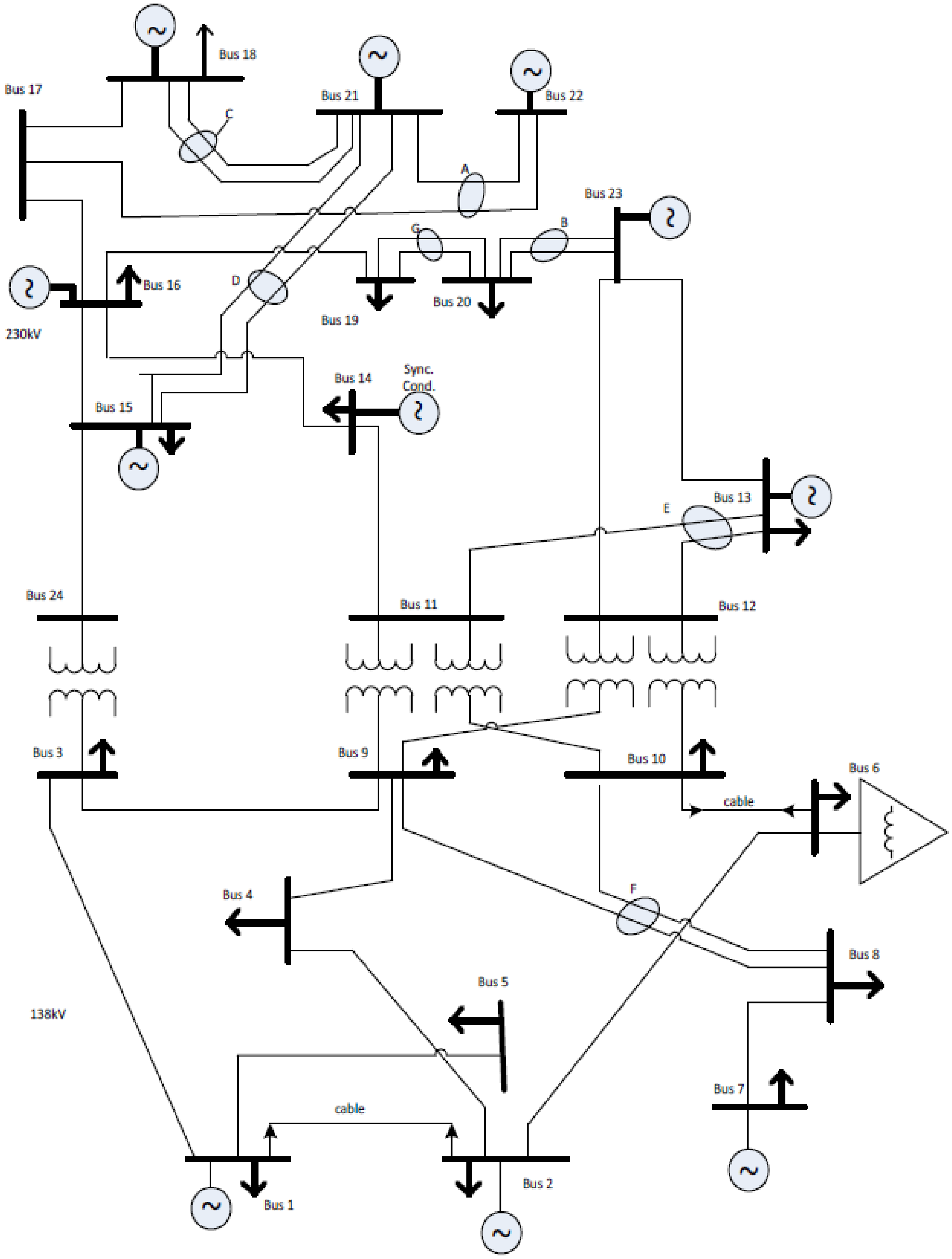

Figure 2: IEEE-RTS single line diagram

2.4 Demand Side Management (DSM)

DSM represent to techniques that can be incorporated by electric power utilities to promote customer to adopt energy efficient practices [4]. DSM is not only beneficial to utilities but also to customers by improving energy efficiency, system reliability, reduce capital and operating cost, transmission congestion, environmental damage, and customer cost [4,7,8,9]. Thus, DSM programs are very vital and practical in aiding electric power utilities to meet the challenges ahead [4]. Load shifting is one of the various technique and objectives in DSM. All part of the energy not supplied during peak hours are transferred to the off-peak hours if possible in the load shifting initiative. Load has been seen to improve system reliability with by modifying the load model [4].

2.5 Wind Farm Incorporating Energy Storage

Wind energy conversion system (WECS) are becoming increasingly popular compared to conventional sources due to their increasingly economical values [1]. WECS is based on naturally available resources and has minimal or no negative impact on the environment compared to conventional sources like fossil fuels. Wind energy is now “utility scale” and can affect utility planning and operation of both generation and transmission [2]. The degree of wind speed correlation affects the system and load point reliability indices [1].

The impact of wind power integration on power systems is elaborated in [26] and [27]. 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 [28]. 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 [28, 29].

CHAPTER 3

METHODOLOGY

3.1 Process Flow of Reliability Assessment

The overall flow of the WECS with DSM reliability assessment is shown below. The simulation is started by modifying the IEEE Reliability Test System (IEEE-RTS) depending on the criteria needed which is to incorporate a wind farm to the system. A Wind Energy Conversion System (WECS) is added to bus 1 with the annual peak load remained at 2850 MW. The WECS has a varying rated capacity of 200 MW to 500 MW.

Next, wind turbine generation is simulated which is further explain in section 3.3. With the WECS capacity at different hours obtained, the status of all the generators either up or state are simulated using random numbers generator. The total capacity of the generators is calculated at each hour for a sample year. DSM load shifting method are applied to all load busses by transferring all or part of the energy not supplied during the peak hours to the off-peak hours if possible. This is discussed in detail in section. Since this is a HL1 level reliability assessment, the line status is not considered, assumed to be 100% reliable and based on the modified load model by the load transfer initiative of DSM and the generating capacity of the modified IEEE-RTS system, reliability assessment can be done by MCS.

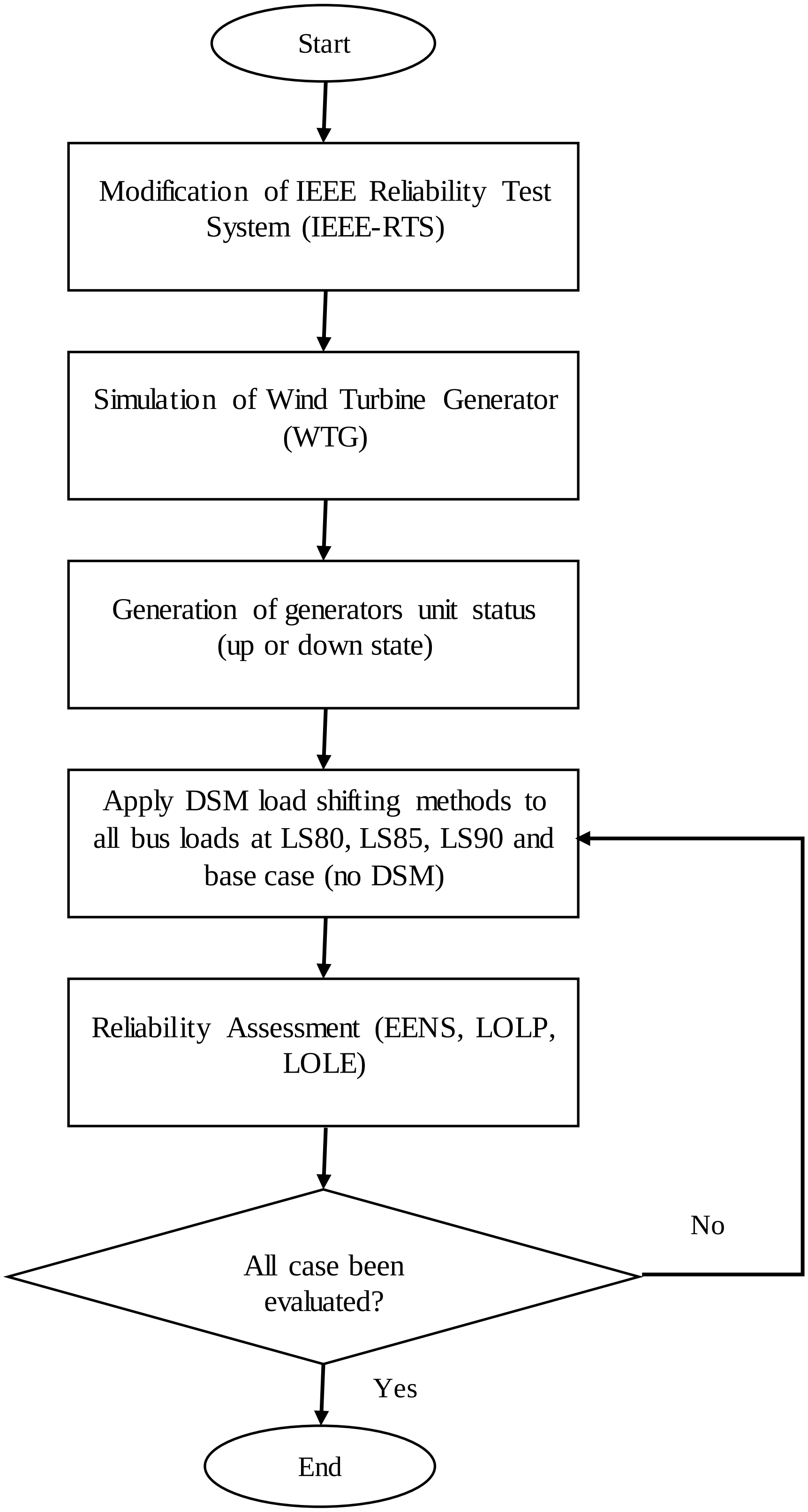

Figure 3: The overall flow chart of the WECS with DSM reliability assessment.

3.2 Modification of IEEE Reliability Test System (RTS)

IEEE Reliability Test System (RTS) is a standardized load model, generation system and transmission network which can be used to test reliability of power systems. The model consists of 24-busses network, connected by 38 lines at two voltages, 138 and 230kV. It is modified by adding a WTG unit at bus 1 as shown in Figure 4. with a varying capacity of 200 MW, 400 MW, 600 MW, 800 MW and 1000 MW. The annual peak load of IEEE-RTS is maintained at 2850 MW.

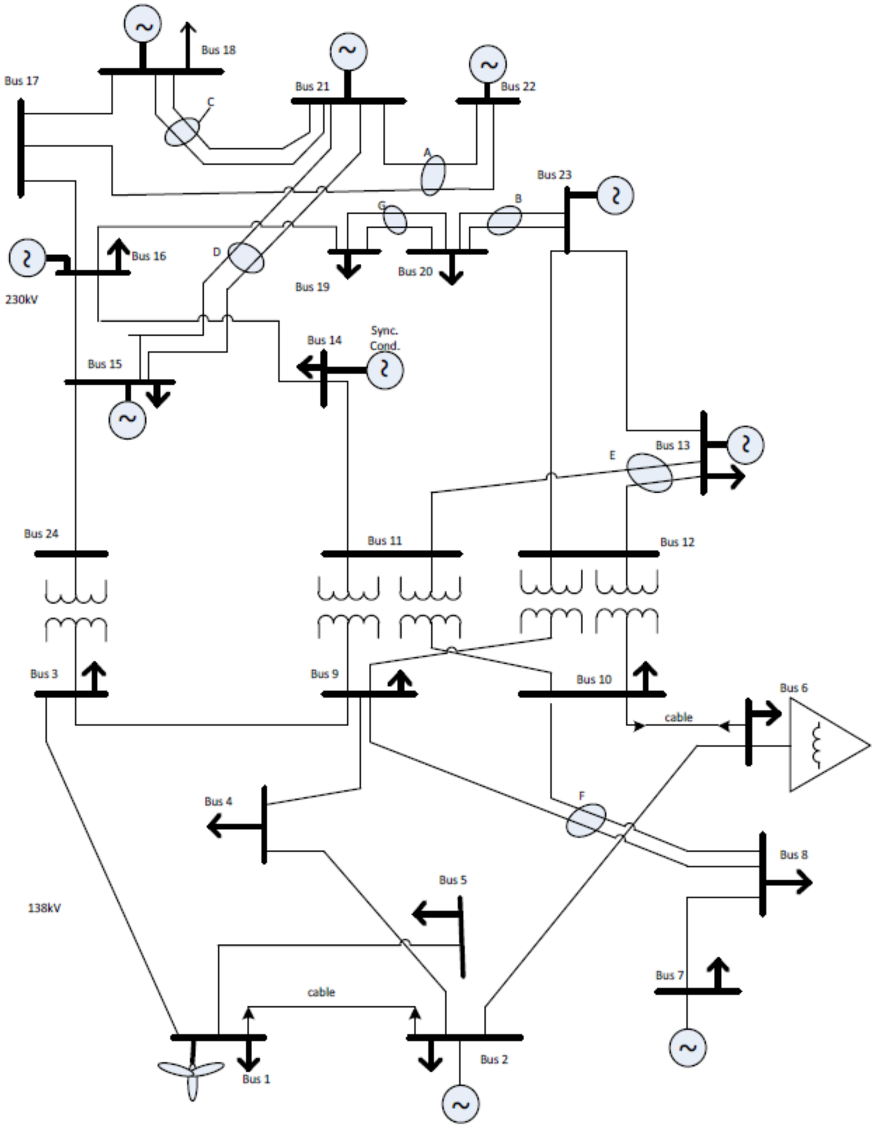

Figure 4: Modified IEEE Reliability Test System

3.3 Simulation of Wind Turbine Generator (WTG)

The actual wind turbine generator (WTG) and the wind resource are the two basic parts of a wind conversion system. Wind speed can be simulated using autoregressive moving average (ARMA) time series model. The ARMA models for the two wind sites in the Province of Saskatchewan, Regina and Swift Current, are as follows [1]:

Regina: ARMA (4, 3):

$$y_t = 0.9336y_{t-1} + 0.4506y_{t-2} - 0.5545y_{t-3} + 0.1110y_{t-4} + \alpha_t - 0.2033\alpha_{t-1} - 0.4684\alpha_{t-2} + 0.2301\alpha_{t-3} \quad (1)$$

$\alpha \in NID(0,0.409423^2)$

Swift Current: ARMA (4, 3):

$$y_t = 1.177y_{t-1} + 0.1001y_{t-2} - 0.3572y_{t-3} + 0.0379y_{t-4} + \alpha_t - 0.5030\alpha_{t-1} - 0.2924\alpha_{t-2} + 0.1317\alpha_{t-3} \quad (2)$$

$\alpha_t \in NID(0,0.524760^2)$

From mean wind speed μ_t and its standard deviation σ_t at a time t, the simulated wind speed SWt can be obtained as follows:

$$SW_t = \mu_t + \sigma_t \times y_t \quad (3)$$

Using the cross correlation, the wind speed correlation between two wind farms can be calculated as follows:

$$R = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)(y_i - \mu_y)}{\sigma_x \sigma_y} \quad (4)$$

where x_i and y_i are elements of the first and second time series, respectively, μ_x and μ_y are the mean values of the first and second time series, σ_x and σ_y are the standard deviations of the first and second time series, and n is the number of points in each time series. Using the functional relationship between the power output of the WTG and the wind speed the power output of a WTG can be determined [22].

3.4 Demand Side Management (DSM) (Load Shifting)

Load shifting in wind integrated power system reliability assessment are described in the following [4]. All part of the energy not supplied during peak hours are transferred to the off-peak hours if possible in the load shifting initiative. The load shifting measures are incorporated in the reliability evaluation process by modifying the load model as in (5).

$$L(t)^{*} = \begin{cases} P, & t \in \Omega \\ L(t) + A, & t \in \psi \end{cases} \tag{5}$$

$$A = \alpha \left[\frac{\sum_{t \in \Omega} (L(t) - P)}{N} \right] \tag{6}$$

where,

P	:	pre-specified peak,
t	:	time (hours)
L(t)	:	basic load model,
L(t)*	:	modified load model,
Ψ	:	set of off-peak hours during which the energy is recovered,
Ω	:	set of on-peak hours during which the energy is reduced,
A	:	MW load added to each off-peak hour of ψ,
N	:	number of off-peak hours in ψ,
α	:	percentage of the energy reduced during on-peak hours that is recovered during off-peak hours. α is set to be 100%.

Pre-specified peak is the percentage value of the load model peak load. Pre-specified peak that are considered in this project are 80% (LS 80), 85% (LS 85) and 90% (LS 90) of the peak load. The time at which the load model exceeds the pre-specified peak are considered as the on-peak time, meanwhile the time at which the load model is below the pre-specified valley are considered as the off-peak time. The load at the on-peak time are reduced to the pre-specified peak meanwhile the remaining load at this time is transferred to the off-peak time as shown in (5) and (6). The pre-specified peak and the pre-specified valley load values are shown in Table 1.

Table 1: Shows the pre-specified peak and valley for each case of load shifting in DSM.

DSM	Applied To	Pre-Specified Peak (%)	Pre-specified Valley (%)
LS80	Bus Load	80	50
LS85	Bus Load	85	50
LS90	Bus Load	90	50
Base Case	No DSM	-	-

3.5 Reliability Indices using Monte Carlo Simulation (MCS) Method

MSC is used as the method to assess the reliability of DSM in wind integrated power system with chronological load to consider the random nature of wind speed. Generating unit states are discrete mutually exclusive state []. It can be in up, down or derated state. Whereas the up state means that the generating units are running at their rated capacity, down means zero capacity and derated at values lower than the rated capacity. In this paper, only up or down state are considered. The up-down sequence of all the generating units in the wind integrated power system in sample year are generated by the formula:

$$TTF = -\frac{1}{\lambda} \ln U1 \quad (7)$$

$$TTR = -\frac{1}{V} \ln U2 \quad (8)$$

where,

U1 & U2 : random numbers from 0 to 1.

TTF : time to failure (hours)

TTR : time to repair (hours)

λ & V : failure rate

The generating unit are considered to be in the up states initially and remains in the state until TTF is reached, then it will enter the down state for period of TTR, then re-enters the up state and the cycle continues if the total hours have not reached 8736 hours (hours in one year) which would produce an up and down sequence for the generating unit for a year. These sequences are then combined to produce the generating capacity sequence for the system in sample year and superimposed by the chronological loads model. The number of hours which the load exceeds the available generating capacity is accumulated for each sampling year. The energy not serve at this particular time is calculated by the following formula

$$£ = L - C \quad (9)$$

where £ represent energy not serve, L is the load and C is the generating capacity. £ is also accumulated for each sampling year.

The loss of load expectation (LOLE) and loss of energy expectation (LOEE) can be calculated by the following formula:

$$LOLE = H/N \tag{10}$$

$$EENS/LOEE = £\times 8760/N \tag{11}$$

where H is hours of trouble, N is the years simulated and 8740 represent the number of hours in one year. The simulation is repeated until a stopping criteria is reached. This simulation is down by MatLab software.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The electric system reliability assessment was conducted for the modified wind incorporated IEEE-RTS using a Sequential Monte Carlo Simulation program with application of DSM as explained in the methodology chapter. This chapter is divided into two sections. The first section illustrates the impact of various load shifting technique on system EENS. Meanwhile, section two illustrated the effect of DSM load shifting technique for various WTG power capacity. The number of simulated years are set to 5000 iterations. The FOR of the WTG is not considered in this simulation. The effect of load shifting at 80% on load model of bus 1 is illustrated in Figure 5.

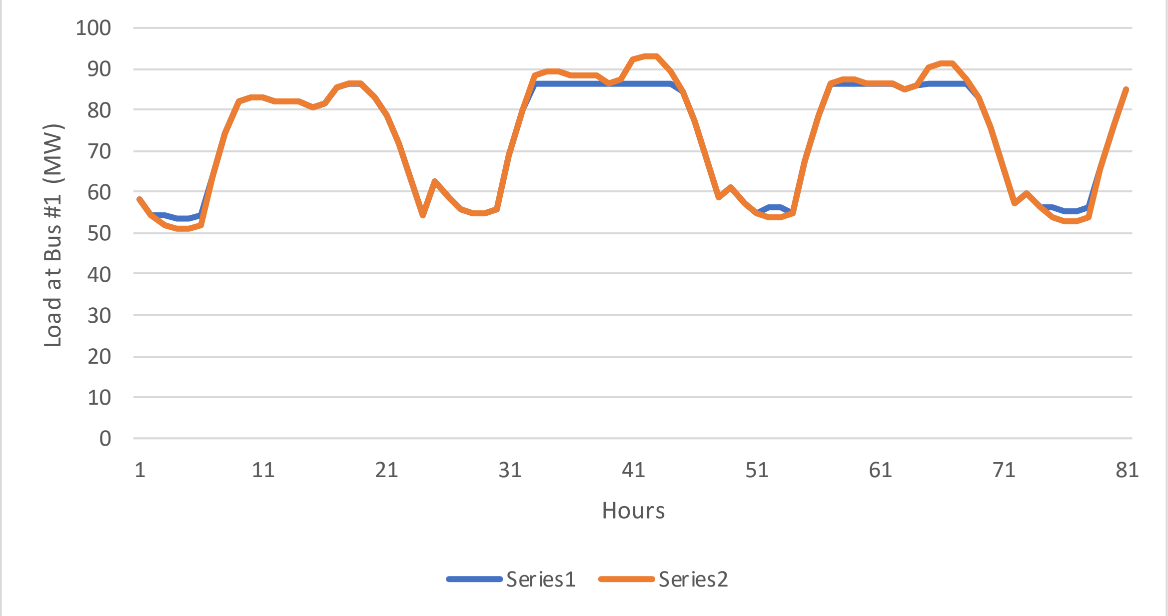

Figure 5: The hourly load models at bus #1 for the IEEE-RTS with load shifting at 80%. (Series 1: LS80. Series 2: Base case.)

It can be seen in Figure 5 that when LS 80 is applied to the bus load, any load that exceeds 80% of the peak load is reduced by shifting it to the next off-peak hours. The lower the pre-specified peak, more energy is shifted from the on-peak hours to off-peak hours.

4.2 Load Shifting Effects on System EENS

The following figures show the modified IEEE-RTS EENS convergence process by using the Sequential Monte Carlo Simulation for normal condition and for various load shifting measures. The load shifting technique is done in two ways, one is to apply it to the system total load and another is to apply it at each individual bus load. A 200 MW WTG was used in this test.

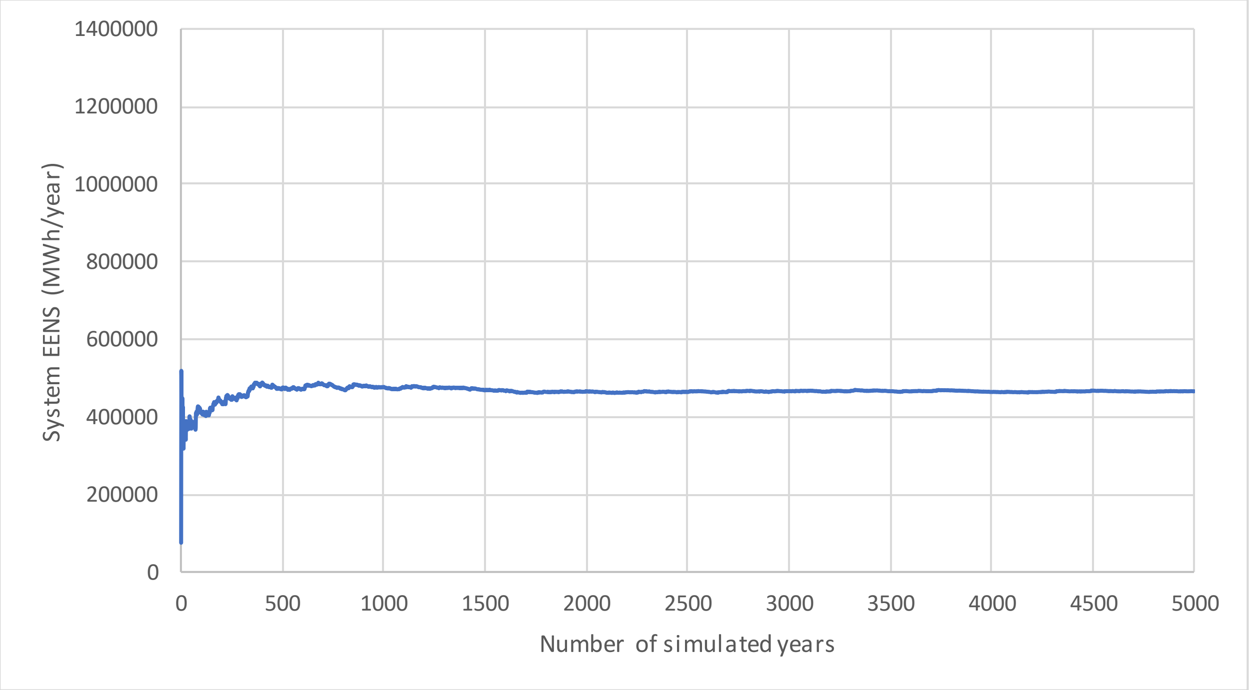

Figure 6: The system ENNS versus number of simulated year for base case.

4.2.1 Various load shifting to system total load.

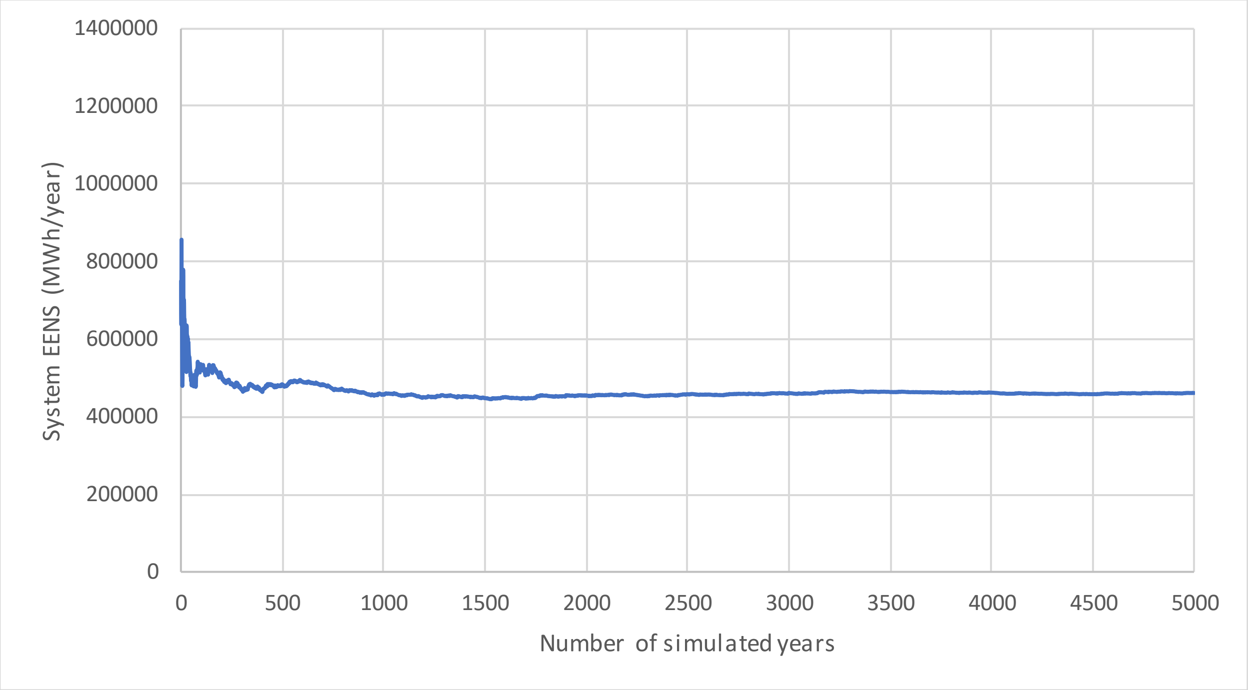

Figure 7: The system ENNS with load shifting at 90% versus number of simulated year.

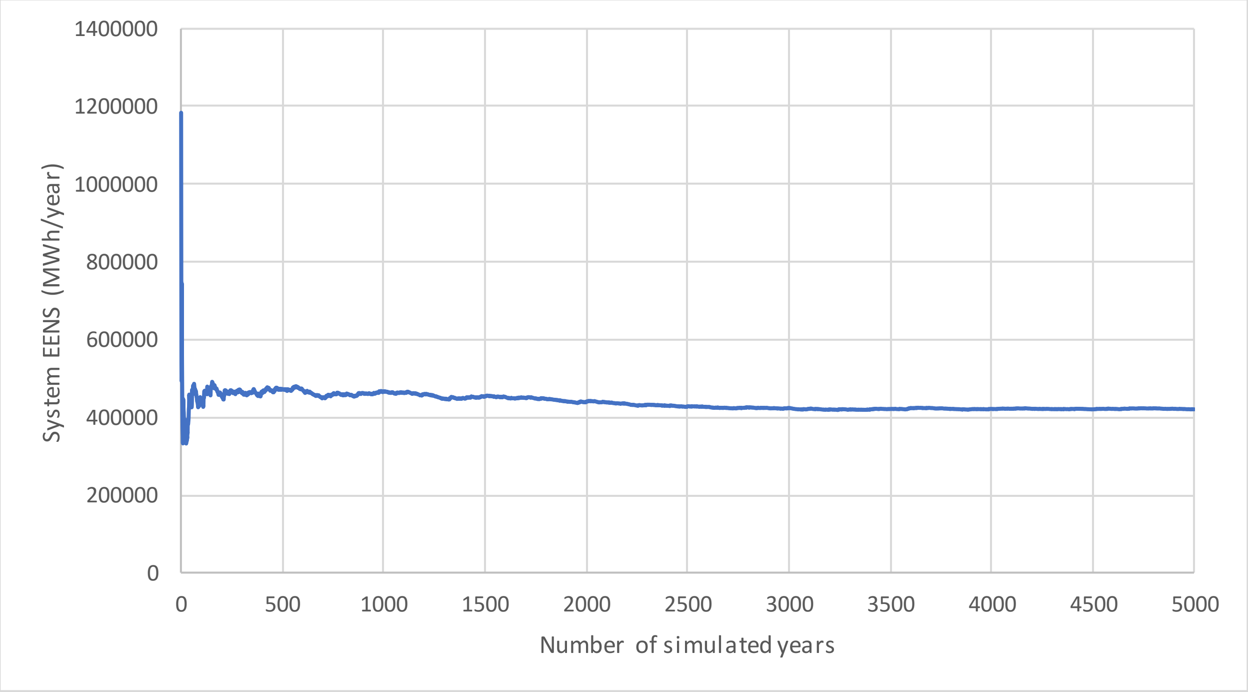

Figure 8: The system ENNS with load shifting at 85% versus number of simulated year.

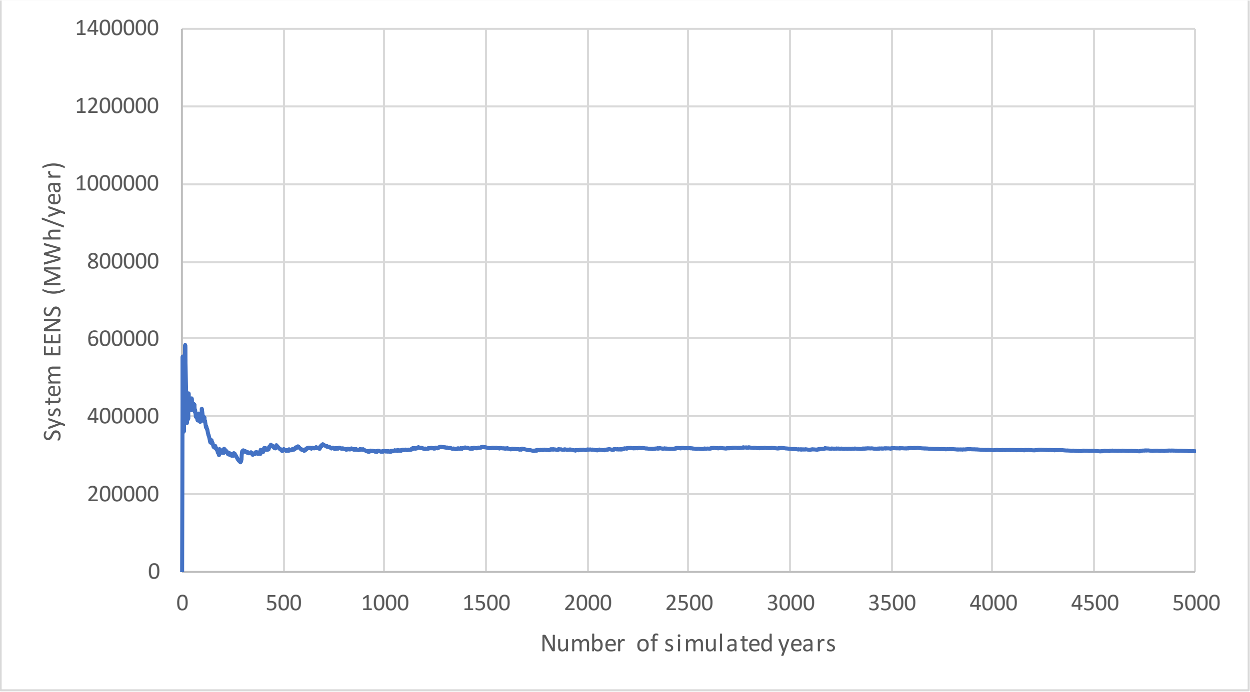

Figure 9: The system ENNS with load shifting at 80% versus number of simulated years.